ICOAM17

4th International Conference on Optical Angular Momentum

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ABSTRACT BOOK

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Session 1. "Foundations "

Can Laser Optics resolve the Particle Physics angular momentum controversy? - ICOAM 2017

Elliot Leader
Imperial College London,
Blackett Laboratory, Prince Consort Road,
London SW7 2AZ, U.K.

The role of the gluon in the internal structure of the nucleon, and in particular its contribution to the spin of the nucleon, is of central interest in Elementary Particle Physics. Hence, the hullabaloo when a paper appeared in 2008, claiming that our entire understanding of the angular momentum of a gluon, and by implication, of a photon, was incorrect. Included, was the disturbing proclamation that all QED textbooks of the past 50 years were wrong in their stressing that the photon angular momentum cannot be split, in a gauge invariant way, into a spin and an orbital part. A workshop at the Institute for Nuclear Theory in Seattle in 2011, the aim of which was "to resolve the controversy", only succeeded in deepening it. My talk will give a brief summary of the angular momentum controversy in particle physics. I will also suggest that the form of the angular momentum, generally utilized in laser optics papers, based on the Poynting vector, is not the physically relevant one, and that laser optics experiments can possibly resolve the whole controversy.

References

[1] E. Leader and C. Lorcé, The Angular Momentum Controversy: what's it all about and does it matter? Physics Reports, 541, pp. 163-248, 2014.

[2] E. Leader, Controversy concerning the definition of quark and gluon angular momentum, Physical Review D 83, pp. 096012–1 -17, 2011.

[3] E. Leader, The photon angular momentum controversy: Resolution of a conflict between laser optics and particle physics, Physics Letters B 756, pp. 303-308, 2016.

Modeling of OAM beams: theoretical investigations and experimental realizations

Giuseppe Vallone
Dipartimento di Ingegneria dell'Informazione,
Università degli Studi di Padova, Padova, Italia
vallone@dei.unipd.it

The modeling of beam carrying orbital angular momentum (OAM) is very important for many applications. In this framework, circular beams (CiBs) were introduced in [1] as a very general solution with OAM of the paraxial wave equation. The importance of the CiBs is underlined by the fact that they represent a generalization of many well known beams carrying OAM, such as Laguerre-Gauss (LG) modes, hypergeometric-Gaussian modes and hypergeometric modes.

We here report recent results on the properties of the CiBs and their experimental realization. We first derive the expansion of CiBs in terms of LG modes [2]. The expansion depends on the choice of the beam waists of the LG basis: we show how the waist parameter must be chosen in order to optimize such expansion [3]. In particular, we found an analytical expression of the beam waist in function of the CiBs parameters that maximize the overlap of the CiB with the LG mode with lower radial index, namely $\mathrm{LG}_{0,\ell}$, as shown in fig. 1.

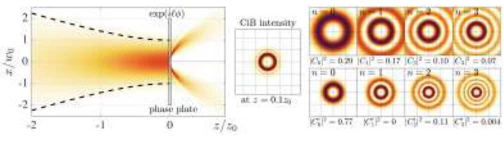


Figure 1: (left) Generation of a CiB by a phase plate with $\ell = 3$. (Center): CiB intensity at $z = 0.1z_0$. (Right): decomposition of the CiB into $\mathrm{LG}_{n,3}$ modes.

We also present the free-space divergence of CiBs [2]: by extending the results for generic beam, we present a general theorem on the divergence of vortex beams [4]. Indeed, the propagation and divergence properties of beams carrying orbital angular momentum (OAM) play a crucial role in long-range communication systems and microscopy. We show that the mean absolute value of the OAM imposes a lower bound on the value of the beam divergence, $M^2_{\mathrm{rms}} \geq 1 + \langle|\ell|\rangle$ [4]. We derive our results for two different definitions of the divergence, the so-called rms or encircled energy.

Finally, we present the experimental generation and their modeling of a subclass of CiBs, easily achieved by applying a phase factor $e^{i\ell\phi}$ to a Gaussian beam. We also experimentally studied their propagation through generic ABCD optical systems [5].

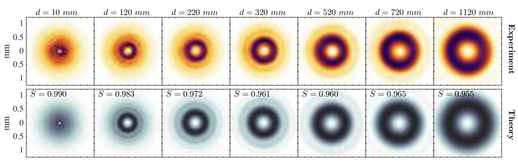


Figure 2: Experimental "birth" of the optical vortex and comparison with the theoretical CiB model.

References

[1] M. A. Bandres and J. C. Gutiérrez-Vega, Opt. Lett. 33, 177 (2008).

[2] G. Vallone, Opt. Lett. 40, 1717 (2015).

[3] G. Vallone, Opt. Lett. 42, 1097 (2017).

[4] G. Vallone, G. Parisi, F. Spinello, E. Mari, F. Tamburini, and P. Villoresi, Phys. Rev. A 94, 23802 (2016).

[5] G. Vallone, A. Sponselli, V. D'Ambrosio, L. Marrucci, F. Sciarrino, and P. Villoresi, Opt. Express 24, 16390 (2016).

Optimal birefringent masks for producing bottle fields

Anthony Vella[1,*], Hippolyte Dourdent[2], Lukas Novotny[2], Miguel A. Alonso[1]
[1]The Institute of Optics, University of Rochester, Rochester NY 14627, USA
[2]Photonics Laboratory, ETH Zürich, 8093 Zürich, Switzerland
*avella@ur.rochester.edu

An "optical bottle" is a field with a finite axial region of low (ideally null) intensity surrounded in all directions by light. Optical bottle fields can be used for efficient trapping, manipulation, and measurement of nanoparticles, and they are also advantageous for STED microscopy. For these applications it is desirable for the intensity minimum to be as narrow as possible, since this is what limits the resolution.

Most existing techniques for bottle field generation involve vortices produced by phase masks or spatial light modulators. These methods typically rely on interferometric superposition of two fundamental Gaussian modes, making them sensitive to alignment errors. Alternatively, polarization vortex beams have been demonstrated by propagating a circularly polarized Gaussian beam through a stress engineered optical element (SEOE). The circular polarization component exiting the SEOE with the opposite handedness acquires a vortex along the axis, so a bottle could be constructed by ensuring that the component emerging with the original polarization has an axial null.

In this work, we treat the problem of a general transparent birefringent mask (BM) placed in the pupil of an aplanatic high numerical aperture (NA) focusing system, and we derive the spatial variation of the BM for which a uniformly polarized incident beam is converted into a bottle field with the smallest possible width. We find that the optimal BM has a rotating pattern of linear eigenpolarizations with topological charge $-1/2$ and a radially varying retardance distribution

$$\delta(u) = \arctan\left(\frac{u}{g + h\sqrt{1-u^2}}\right),$$

where $u \in [0, \mathrm{NA}]$ is the radial pupil coordinate and g and h are constants that are determined by the NA of the system.

Naturally, the optimal solution for $\delta(u)$ varies slightly depending on how one defines the width of the bottle. The solutions obtained using three different metrics are plotted in Fig. 1 for the 0.9 NA case. A dashed line representing the linear retardance distribution of an SEOE is also shown for comparison. Furthermore, the SEOE has the same eigenpolarization pattern as the optimal BM. As seen at the bottom of Fig. 1, the theoretical bottle field produced by an SEOE is nearly identical to the optimal case. Preliminary experiments have been performed at low NA verifying that an SEOE can be used to generate a focused field with a local minimum of intensity on-axis.

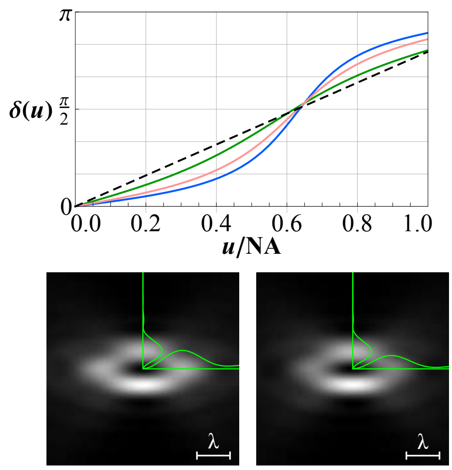


Figure 1: Top: Radial retardance distributions of the optimal BM (solid) and an SEOE (dashed). Bottom: Simulated cross-sectional intensity of bottle fields produced by the optimal BM (left) and an SEOE (right). The green curves show the intensity profiles in the transverse (vertical) and longitudinal (horizontal) dimensions.

References

[1] Vella A. et al, Birefringent masks that are optimal for generating bottle fields, Opt. Express 25, 9318-9332, 2017.

Half quantization of optical angular momentum

Paul Eastham, Kyle Ballantine, John Donegan
School of Physics and CRANN, Trinity College Dublin, Dublin 2, Ireland

easthamp@tcd.ie

It is now well established that the total angular momentum of light consists of two parts: a spin contribution, arising from the polarization, and an orbital contribution, arising from a helical wavefront. The quantum numbers for the spin and orbital angular momentum, giving their projections in units of Planck's constant, are integers. The total angular momentum projection is therefore also an integer, as expected.

However, light can sometimes be described by theories with two space dimensions, as in the paraxial description of a beam. Following the pioneering work of Wilczek in the early 1980s it has been understood that quantum mechanics is different in two dimensions than in three, and in two dimensions particles can have arbitrary "fractional" angular momentum [1]. In this talk I will show that, in analogy to these effects, an unexpected half-integer spectrum can arise for optical angular momentum [2]. I will explain that the double-headed nature of polarization allows for a new definition of total angular momentum, whose spectrum is quantized in half-integer multiples of Planck's constant. This form of total angular momentum is relevant to measurements using inhomogeneous polarizers (e.g. q-plates), and its eigenstates can be generated using conical refraction (see Fig. 1). I will outline the theory of this half-integer angular momentum, and present experimental results which demonstrate the half-quantization.

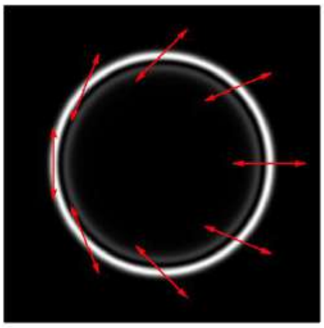


Figure 1: Intensity profile and polarization of beams generated by conical refraction, which are eigenstates of a half-quantized angular momentum.

References

[1] F. Wilczek, Magnetic flux, angular momentum, and statistics. Physical Review Letters 48, 1144-1146, 1982.
[2] K. E. Ballantine, J. F. Donegan and P. R. Eastham, There are many ways to spin a photon: half-quantization of a total optical angular momentum, Science Advances 2, e1501748, 2016.

Session 2. "Foundations & Interactions"

Knotted optical singularities in free space: designed, random and accidental

Mark R. Dennis
H H Wills Physics Laboratory, University of Bristol,
Tyndall Avenue, Bristol BS8 1TL, UK
mark.dennis@physics.org

However complicated it is to tie knots in rope or string, it seems a harder task to tie them in *fields* – the entire field structure must be controlled, not just the points on the knot. Nevertheless, there are several cases in modern optics where knotted singularity structures are known to occur, and these provide a test of our ability to understand, manipulate and measure structure of light in free space in three dimensions.

The first example, and best known, is holographically embed specific optical vortex structures in a propagating Gaussian beam. The hologram design is inspired by mathematical knot theory [1] (particularly knots around singularities of complex hypersurfaces). There has been recent success in extending this construction further to more complicated knots in the so-called lemniscate knot family [2].

In three-dimensional random interference such as optical speckle patterns, dense tangles of optical vortices occur. Numerical studies [3] reveal that a huge range of different knot types appear in these tangles, from vortex curves (resembling random walks) of a few tens of wavelengths long to curves of tens of thousands of wavelengths.

We have recently found [4] a new kind of knot structure appearing in a dark focus of a tightly-focused field, shown in figure 1. Unlike the others, this is a set of knotted singularities in the polarization – the curve of every transverse linear polarization state is knotted, and as the polarization angle varies over 180°, these knots sweep out a torus in 3D. Furthermore, the knotting here is *accidental*, and is a result of focusing an initial beam with homogeneous circular polarization in a pure OAM state; the knotted structure arises from spin-to-orbital angular momentum transfer on tight focusing. By analogy with similar structures in other areas of physics [5], we call this an optical *Hopfion*.

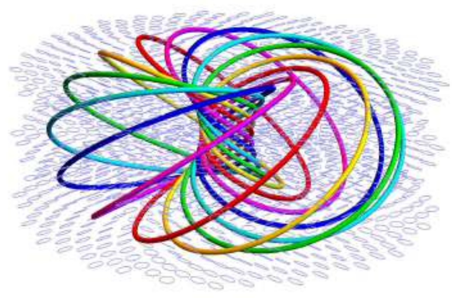


Figure 1: Optical Hopfion structure. Each curve is a trefoil knot, corresponding to a vortex line in a different linear polarization component.

References

[1] Dennis M.R, King R.P, Jack B, O'Holleran K, Padgett M.J, Isolated optical vortex knots, Nature Physics 71, 89-144, 2010.

[2] Bode B, Dennis M.R, Foster D and King R.P, Knotted fields and explicit fibrations for lemniscate knots, arXiv: 1611.02563.

[3] Taylor A.J, Dennis, M.R, Vortex knots in tangled quantum eigenfunctions, Nature Communications 7, 12346, 2016.

[4] Sugic D, Dennis M.R, in preparation.

[5] Hall D.S, Ray, M.W, *et al*, Tying quantum knots, Nature Physics 12, 478–483, 2015.

Photons in the lowest Landau level: from topological invariants to singular surfaces

N. Schine, M. Chalupnik, A. Ryou, A. Gromov, A. Sommer, and J. Simon
Department of Physics, The University of Chicago
Chicago, Illinois, USA
nschine@uchicago.edu

Quantum materials in which the constituent particles are photons trapped in an optical resonator offer an exciting platform with which to study quantum many-body physics. Recent parallel efforts have realized broad control over the single particle Hamiltonian including a strong synthetic magnetic field for resonator photons, [1] and strong single photon-photon interactions via hybridization with Rydberg atoms. [2] Combined, the resulting system enters the fractional quantum Hall regime where we can prepare and explore highly correlated, topologically nontrivial photons with quantum-optical techniques.

Conceptually, we build upon the connection between the transverse degrees of freedom of a resonator photon and the 2d quantum harmonic oscillator. Making a four-mirror running wave resonator nonplanar introduces an effective magnetic field. Removal of residual harmonic trapping then brings angular momentum eigenmodes into degeneracy, and thus creates a Landau level. The resonator is stabilized against astigmatism by imposing an additional threefold rotational symmetry, equivalent to confining photons to the surface of a cone.

We use holographic mode preparation and measurement to inject arbitrary light fields into the resonator and to reconstruct the full electric field on the output. By injecting and measuring maximally localized modes in the lowest Landau level we can measure spatial projectors. Non-reciprocal products of these projectors then provide a real-space measurement of the Chern number. We also measure the local density of states, which has non-trivial response near the point of singular spatial curvature at the cone tip. This provides access to two additional topological quantum numbers, revealing a complex interplay between geometry and topology.

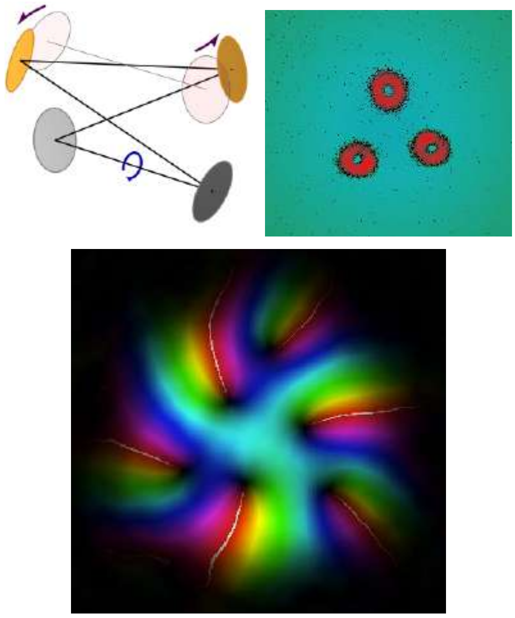


Figure 1: (**a**) Photons to travelling through nonplanar round trips rotate about the resonator axis, experiencing a synthetic magnetic field. (Fig. from Ref. [1]). (**b**) In the photonic Landau level, photons undergo cyclotron orbits, but an additional threefold rotational symmetry of the modes confines photons to a cone. (**c**) In a nearly degenerate Landau level, we track the introduction of vortices via holographic imaging and subsequent electric field reconstruction (brightness and hue are amplitude and phase, respectively).

Finally, we will discuss progress towards combining strong interactions with the synthetic magnetic field and the various routes this system presents towards the creation of few-particle Laughlin states and other exotic highly-correlated states of photons.

References

[1] Schine, et al. *Nature* **534**, 671 (2016)
[2] Ningyuan, et al. *in preparation*

Excitation of an Atomic Transition with a Vortex Beam or: How Atoms Learned to Stop Worrying and Love the Twist

Christian T. Schmiegelow
Departamento e Instituto de Física de Buenos Aires, UBA-CONICET
WA Quantum, JGU-Universität Mainz
schmiegelow@df.uba.ar

I will discuss experimental results where orbital angular momentum from a photon was transferred to the internal electronic degrees of freedom of a single atom. We observed strongly modified selection rules showing that an atom can absorb two quanta of angular momentum from a single photon: one from the spin and another from the spatial structure of the beam. Moreover, the results show in some cases, the longitudinal component of the field in a vortex beam plays a crucial role in determining the interaction characteristics. Furthermore, I'll show that parasitic ac-Stark shifts from off-resonant transitions are suppressed in the center of the vortex beam. The experiments were done probing a quadrupole transition in a single trapped Calcium ion.

Spin-Orbit Coupling and Circular Dichroism in Twisted-Light Absorption by Atoms

Andrei Afanasev[1], C.E. Carlson[2], and Maria Solyanik[1]
[1]The George Washington University, Washington, DC 20052, USA
[2] College of William and Mary in Virginia, Williamsburg, VA 23187, USA
afanas@gwu.edu

We consider effects of spin-orbit coupling and predict circular dichroism (CD) and spin-dependent rates for absorption of the twisted photons, or optical vortices, by single atoms and ions. We demonstrate that although for electric dipole transitions the atomic excitation rates depend on the relative orientation of photon spin and orbital angular momentum (OAM), the resulting CD is zero. However, CD is nonzero for atomic transitions of higher multipolarity, peaking in the optical vortex center.

CD is defined as differential absorption of left and right circularly polarized photons. Twisted photons, or optical vortices, carry OAM along their direction of propagation, and therefore their states with opposite spins but fixed OAM are not mirror images of each other. It results in the predictions for spin dependence of twisted light absorption by atomic and ion targets presented in this report. Similarly, the photo-absorption depends on OAM sign for the fixed circular polarization.

We define the twisted-photon states as non-paraxial Bessel beams formed by superposition of plane-wave photons with well-defined (spin) helicity Λ that form a cone in momentum space with half-opening angle θ_k. In this case the total angular momentum projection on the propagation direction is defined as $m_\gamma \equiv \overline{m}_\gamma + \Lambda$, see Ref.[1, 2] for the details of theoretical formalism. The quantity $\overline{m}_\gamma$ coincides with a topological charge in a paraxial approximation. Due to the property of plane-wave factorization of twisted-light absorption amplitudes in a linear regime, the predictions for CD (Fig.1) for the excitation of a state with a given OAM do not depend on the details of atomic wavefunctions.

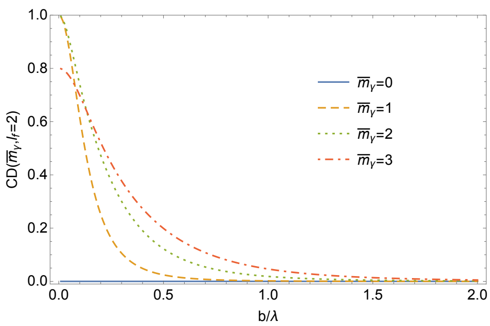


Figure 1: Circular dichroism as a function of atom's position b (in units of photon wavelength λ) w.r.t. the vortex center for different values of $\overline{m}_\gamma$ for excitation of the atomic states from ground state to the state with OAM l_f=2; the angle θ_k=0.1 rad. The curve styles are: $\overline{m}_\gamma = 0$ is the blue solid curve, $\overline{m}_\gamma = 1$ is orange and dashed, $\overline{m}_\gamma = 2$ is green and dotted, $\overline{m}_\gamma = 3$ is red and dot-dashed. CD is zero for the beams with $\overline{m}_\gamma$=0.

Predictions for spin-dependent relative strengths of transition amplitudes for $^{40}Ca^+$ ion excitations under experimental setup of Ref.[2] will be presented.

References

[1] Andrei Afanasev, C.E. Carlson, A. Mukherjee, J. Opt. **18**, 074013 (2016).

[2] Andrei Afanasev, C.E. Carlson, Maria Solyanik, *Circular Dichroism of Twisted Photons in the Non-Chiral Atomic Matter*, e-print ArXiv:1704.07495.

[3] Christian T. Schmiegelow *et al.*, Nature Comm. **7**, 12998 (2016).

Optical Wings that Rock, Roll, and Orbit

Alexandra B. Artusio-Glimpse
National Institute for Standards and Technology,
325 Broadway, Boulder CO 80305, USA
artusio.glimpse@gmail.com

Optical lift, the transverse force on asymmetric wing-like optical elements, and the accompanying optical torque, which varies with object orientation, influence the motion of simple rod-shaped objects in uniform beams of light. Like foils in laminar fluid flows, "optical wings" in collimated laser beams are an approachable framework for understanding complex dynamics between optical design, illumination, and environment for engineered optical micromanipulation.

Through the study of representative designs, optical wings are observed to exhibit a variety of dynamic behaviors. For example, when constrained to two-dimensional motion, optical wings rotate about the rod axis with multiple zero-torque orientations [1]. Both the number of and the angle of these stable orientations depend on tunable parameters, like refractive index and wing geometry, with variations in torsional stiffness and optical force magnitude.

Rocking on a flat, nonslip surface, an illuminated optical wing exhibits an intensity-dependent rocking frequency with bistable orientations above a critical intensity [2]. Under conditions when the optical forces and torque are well known, this behavior may be exploited to measure interaction forces between the wing and the adjoining surface.

Hemispherical wings with six degrees of freedom demonstrate similar behavior to spinning tops, but, unlike the pivot point of spinning tops, the pivot point of these wings moves through space. This results in orbital motion in the plane of the incident wavefront of a plane wave beam. Perturbations to pure orbital motion arise when the initial angle of attack of the wing is not equal to its stable orientation, and these perturbations decay with small damping.

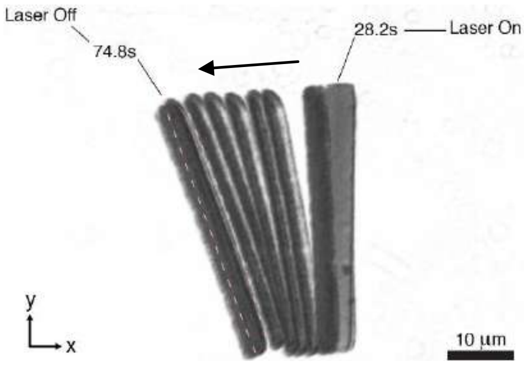


Figure 1: A semicylindrical optical wing rotates into a stable orientation and travels to the left across the profile of a 470 µm diameter laser while the laser is on.

This talk will present a sampling of complex dynamics that characterize optical wings as predicted by ray-based models. In these models, optical forces are isolated from compounding forces like stiction, drag, and convection. To support the numerical predictions, I will also present experimental results, where microscopic semicylindrical wings stably orient at a glass-water boundary under low-intensity (2 $\mu W/\mu m^2$), weakly-focused illumination (see Fig. 1). I will further show the detection of oscillations purportedly due to optical torque on semicylindrical wings affixed to glass torsion oscillators in vacuum.

References

[1] Artusio-Glimpse A., Peterson T., and Swartzlander G., Refractive optical wing oscillators with one reflective surface, Optics Letters 38, pp. 935-937, 2013.

[2] Artusio-Glimpse A., Schuster D., Gomes M., and Swartzlander G., Rocking motion of an optical wing: Theory, Applied Optics 53, pp. I1-I9, 2014.

A Measure of Flow Vorticity with Helically Phased Light

A. Belmonte[1], C. Rosales-Guzmán[2,*], and J. P. Torres[1,2]

(1) Universitat Politècnica de Catalunya, BarcelonaTech, Dep. Signal Theory and Communications, 08034 Barcelona, Spain
(2) ICFO-Institut de Ciencies Fotoniques, Mediterranean Technology Park, 08860 Castelldefels, Barcelona, Spain
belmonte@tsc.upc.edu

The measurement of vorticity, which provides local measurements of fluid rotation at every point in a flow, is of paramount importance in research fields as diverse as biology microfluidics, complex motions in the oceanic and atmospheric boundary layers, and wake turbulence on fluid aerodynamics.

However, the precise measurement of flow vorticity is difficult. Here, we propose and demonstrate a technique that uses Laguerre-Gauss (LG) beams, characterized by a ring–like intensity distribution and an azimuthal phase variation, to sense fluid rotation at every point in a flow. The key point is to make use of the transversal Doppler effect [1-3] of the returned signal that depends only on the azimuthal component of the flow velocity along the ring-shaped observation beam. We found from a detailed analysis of the experimental method that probing the fluid with LG beams is an effective and simple sensing technique capable of producing accurate estimates of flow vorticity [4].

The measurement determines the vorticity ω from the estimation of the transversal Doppler frequency centroid $\langle f_{\perp} \rangle$ of the signal backscattered by the flow when illuminated by a LG beam with azimuthal index m and radial index $p = 0$:

$$\omega = 4\pi/m \ \langle f_{\perp} \rangle$$

The frequency centroid $\langle f_{\perp} \rangle$ estimation is typically based on the observation and analysis of the spectrum of the return backscattered signal –a compound of signals with different frequency Doppler shift triggered by the multiple components of velocity along the annular illumination beam. The characteristic return Doppler spectrum is a histogram of Doppler frequency components describing the spectral content of the returned signal and it can be used to calculate the frequency centroid $\langle f_{\perp} \rangle$ as the average of the frequencies present in the signal.

We verify the working principle of the technique with numerical and lab experiments. A heterodyne receiver based on a modified Mach-Zehnder interferometer was used for experiments. By using measurement data, we assess the feasibility of the sensing technique and identify the accuracy of vorticity measurements from return signals affected by target speckle and receiver noise. We should also notice that later experiments have used the idea to measure vorticity in other fluid systems [5].

Details of our analysis, along with experimental results on the measurement of flow vorticity, will be presented at the meeting.

References

[1] A. Belmonte and J. P. Torres, Opt. Lett. **36**, 4437 (2011).
[2] M. P. J. Lavery, F. C. Speirits, S. M. Barnet, and M. J. Padgett, Science **341**, 537 (2013).
[3]. C. Rosales-Guzmán, N. Hermosa, A. Belmonte, and J. P. Torres, Sci. Rep**. 36**, 2815 (2013).
[4] A. Belmonte, C. Rosales-Guzmán, and J. P. Torres, Optica **2**, 1002 (2015).
[5] A. Ryabtsev, S. Pouya, A. Safaripour, M. Koochesfahani, and M. Dantus, Opt. Express **24**, 11762 (2016).

**CRG is currently a postdoctoral research fellow at the School of Physics in the University of the Witwatersrand, South Africa.*

Session 3. "Electrons & Other Particles"

Measuring orbital angular momentum spectrum of electron beams

Ebrahim Karimi
Department of Physics, University of Ottawa, 25 Templeton St., Ottawa, Ontario, K1N 6N5 Canada
Department of Physics, Institute for Advanced Studies in Basic Sciences, 45137-66731 Zanjan, Iran
ekarimi@uottawa.ca

Quantum complementarity states that particles, e.g. electrons, can exhibit wave-like properties such as diffraction and interference upon propagation. Electron waves with a helical wavefront, referred to as twisted electrons, possess an azimuthal quantized current density. Such an azimuthal current density induces a quantized and unbounded magnetic dipole moment parallel to the electrons' propagation direction [1]. When interacting with magnetic materials, the wavefunctions of twisted electrons are inherently modified. Such variations therefore motivate the need to analyse electron wavefunctions, especially their wavefronts, in order to obtain information regarding the material's structure.

We recently propose, design, and demonstrate the performance of a device for measuring an electron's azimuthal wavefunction, i.e. its orbital angular momentum (OAM) content [2]. Our device consists of nanoscale kinoforms designed to introduce astigmatism onto the electron wavefunctions and spatially separate its orbital angular momentum components. We sort pure and superposition OAM states of electrons ranging within OAM values of -10 and 10. Finally, we employ our device to analyse the OAM spectrum of electrons having been affected by a micron-scale magnetic dipole, thus establishing that, with a midfield optical configuration, our sorter can be an instrument for nanoscale magnetic spectroscopy.

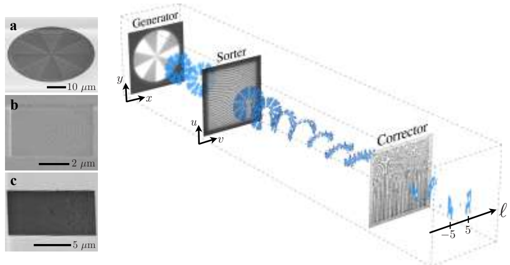


Figure 1: Schematics of the electron sorter depicting Transmission Electron Microscopy (TEM) images of the phase holograms.

References

[1] Bliokh, K. Y., Bliokh, Y. P., Savel'ev, S., Nori, F. Semiclassical dynamics of electron wave packet states with phase vortices. Physical Review Letters 99, 190404 2007.

[2] Grillo, V., Tavabi, A. H., Venturi, F., Larocque, H., Balboni, R., Gazzadi, G. C., Frabboni, S., Lu, P.-H, Mafakheri, E., Bouchard, F., Dunin-Borkowski, R. E., Boyd, R. W., Lavery, M. P. J., Padgett, M. J., Karimi, E., arXiv:1609.09129 [quant-ph].

Generating twisted electron beams with arbitrary topological charge

A. H. Tavabi[1,2], P. Lu[1,2], M. Duchamp[3], R. E. Dunin-Borkowski[1,2] and G. Pozzi[1,4]

1. Ernst Ruska-Centre for Microscopy and Spectroscopy with Electrons, Forschungzentrum Jülich, 52425 Jülich, Germany
2. Peter Grünberg Institute, Forschungszentrum Jülich, 52425 Jülich, Germany
3. Nanyang Technological University, School of Materials Science and Engineering, 50 Nanyang Ave, Singapore 637371
4. Department of Physics and Astronomy, University of Bologna, Viale B. Pichat 6/2, 40127 Bologna, Italy

a.tavabi@fz-juelich.de

Twisted electron beams possess one or more phase singularities at the center of their helical wavefront and are an eigenstate of the component of orbital angular momentum (OAM) along their propagation direction with eigenvalue $\ell\hbar$, making them an ideal probe for measuring the electronic and magnetic properties of materials. The ability to form electron vortex beams (EVBs) has been demonstrated using helical phase plates [1], computer generated holograms [2] and magnetic monopoles [3]. By taking advantage of their magnetic moment and angular momentum, EVBs have been applied to the measurement of magnetic and shape dichroism, to chiral crystal structure characterization and to nanoparticle manipulation. However, all of the methods that have been proposed to generate EVBs are limited by a constant value of OAM.

Here, we present a new concept for a helical phase plate for creating EVBs based on the electrostatic counterpart of the Aharonov-Bohm effect. We show theoretically and experimentally that the phase plate is able to generate EVBs with any desirable value of OAM as a tunable and rapidly switchable device.

The new device creates an electrostatic monopole field, which can be realized using two narrow metallic parallel wires, to which an external voltage is applied to generate a potential difference. A device was fabricated using a combined procedure involving electron beam lithography and focused ion beam milling. Details of its fabrication, performance in an electron optical set-up and possible applications will be discussed.

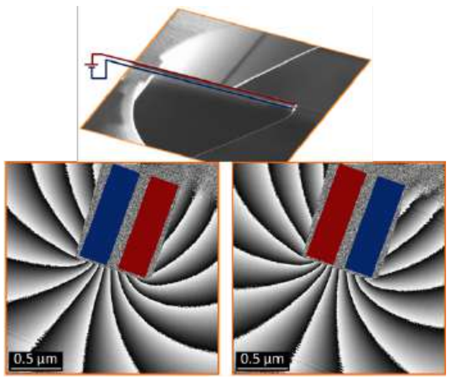


Figure 1: Secondary electron image of a tunable EVB generator fabricated from oppositely charged metallic nanorods, which are marked by red and blue lines (top). Reconstructed phase images (1× amplification) of the vacuum region around the ends of nanorods recorded using off-axis electron holography for applied voltages of -5 V (bottom left) and +5 V (bottom right).

References

[1] M. Uchida, A. Tonomura, Nature 464, 737 (2010).
[2] J. Verbeeck, H. Tian, P. Schattschneider, Nature 467, 301 (2010).
[3] A. Béché, R. Van Boxem, G. Van Tendeloo, J. Verbeeck, Nature Physics 10, 26 (2014).

Orbital angular momentum mode selection using rotationally symmetric superposition of chiral states with application to vortex generation in matter waves

Y. Yang[1,2], M. Mousley[1], G. Thirunavukkarasu[1], M. Babiker[1] and J. Yuan[1]
[1]Department of Physics, University of York, Heslington, York YO10 5DD, UK
[2]School of Astronautics & Aeronautics, University of
Electronic Science and Technology of China, Chengdu 611731, China
jun.yuan@york.ac.uk

Vortex beams are structured travelling waves endowed with orbital angular momentum (OAM) about the propagation direction. Typical descriptions of vortex beam production methods focus on the replication of precise vortex beam wavefunctions. Here we offer an alternative new perspective of the conversion process by focusing on the rotational symmetry characteristics of the vortex beams. This gives rise to a new design principle for OAM convertors based on the superposition of rotationally symmetric chiral motifs. We show that the order of the rotational symmetry determines the OAM of the vortex beams generated, while the chiral symmetry determines their helicity. The principle not only explains the operation of existing mode convertors such as holographic spiral phase gratings, but it also enables the evaluation of the vortex generation potential based on naturally patterned surfaces such as that of a sunflower head.

Our understanding of the OAM state selection principle is valid for structured quantum waves in general, but here we demonstrate by experiment two practical applications of this new principle in convertor design and relate our experimental results to theoretical predictions. We first focus on the generation of electron vortex beams using rotationally symmetric binary amplitude sieve masks [1]. Such a mask (see Fig. 1 for an example) involves sets of rotationally symmetric units of spiral pinhole arrays which convert an incident plane wave into vortex beams with well-defined OAM contents. We show that the number of holes in each unit can be designed to consist of several co-existing different spirals, leading to an electron sieve mask capable of producing nested compound electron vortex beams characterized by concentric bright rings associated with different OAM modes. Furthermore we show how to apply the same principle to the design of chiral plasmonic nanostructures by introducing rotationally symmetric spiral boundary conditions to selectively generate chiral breathing surface plasmon modes. These vortex states have potential applications in chiral molecular sensing and nanoscale mixers in liquid cells.

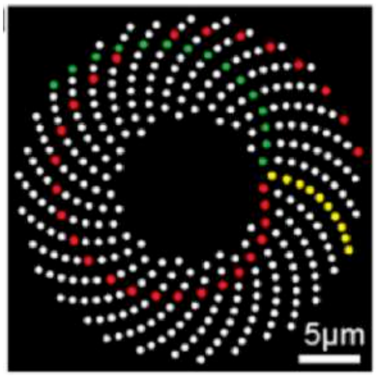


Figure 1: Different spiral arrangements of holes in an electron sieve mask for generating OAM vortex beams.

References

[1] Yuanjie Yang, G. Thirunavukkarasu, M. Babiker, Jun Yuan, Orbital angular momentum mode selection by rotationally symmetric superposition of chiral states with application to electron vortex beams, https://arxiv.org/abs/1701.03973

Large electron vortex beams interacting with vertical magnetic fields: a "vertical" Aharonov-Bohm experiment?

V. Grillo[1], T.R. Harvey[2], F. Venturi[1, 3], J. S. Pierce[2], R. Balboni[4], F. Bouchard[5], G.C. Gazzadi[1], S. Frabboni[1,3], A.H. Tavabi[6], Z.A. Li[6,7], R.E. Dunin-Borkowski[6], R.W. Boyd[5,8], B. J. McMorran[2] and E. Karimi[5,9]

[1] CNR-Istituto Nanoscienze, Centro S3, Via G Campi 213/a, I-41125 Modena, Italy
[2] Department of Physics, University of Oregon, Eugene, 97403-1274 Oregon, USA
[3] FIM, Universitá di Modena e Reggio Emilia,Via G. Campi 213/a, 41125 Modena, Italy
[4] CNR-IMM Bologna, Via P. Gobetti 101, 40129 Bologna, Italy
[5] Department of Physics, University of Ottawa, Ottawa, Ontario, K1N 6N5 Canada
[6] Ernst Ruska-Centre for Microscopy and Spectroscopy with Electrons and Peter Grünberg Institute, Forschungszentrum Jülich, 52425 Jülich, Germany
7Institute of Physics, Chinese Academy of Sciences (CAS),100190 Beijing, China
[8] Institute of Optics, University of Rochester, Rochester, New York, 14627, USA
[9] Department of Physics, Institute for Advanced Studies in Basic Sciences, 45137-66731 Zanjan, Iran
vincenzo.grillo@unimore.it

One of the largest differences between optical and electron vortex beams lies in the fact that electrons are charged. This means that an electron vortex beam is endowed with a magnetic dipole moment and is therefore an ideal instrument to probe a vertical magnetic field. It is easy to demonstrate that a vortex in a constant vertical magnetic field B acquires a global phase $\varphi = \frac{e\ell B \Delta z \lambda}{2h}$ that can be measured in an interferential setup. The measured phase is proportional to the magnetic field and the topological charge ℓ of the beam, providing a motivation for the use of a larger OAM quantum number. Here, we report the experimental use of a vortex beam with an OAM of 200 ħ and an interferential geometry for measuring a vertical magnetic field. Instead of a constant magnetic field, we study a more complicated situation where the field originates from a magnetic pillar, which produces a local approximation of an Aharonov-Bohm field. We analyze the extent to which this configuration can be modeled as two magnetic monopoles and the consequences of this topology on the phase for different pillar geometries.

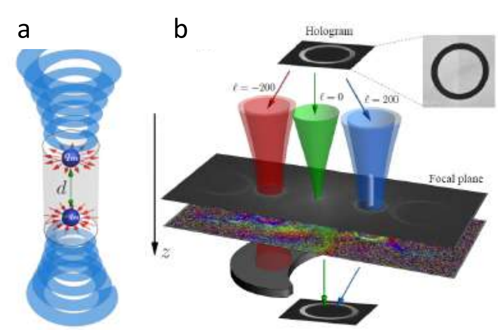


Figure 1: Schematic diagrams of (a) the effect of a magnetic pillar (modeled as two magnetic monopoles) on an electron vortex beam and (b) the experimental setup for interferential measurement of the phase associated with its magnetic field.

Exploring the inelastic interaction between phase-shaped electron beams and plasmonics resonances

G. Guzzinati (1), A. Béché (1), H. Lourenço-Martins (2), J. Martin (3), M. Kociak (2) and J. Verbeeck (1)
(1) EMAT, University of Antwerp, Antwerpen, Belgium.
(2) Laboratoire de Physique des Solides, Universite de Paris-Sud, Orsay, France
(3) Institut Charles Delaunay , Universite de Technologie de Troyes, France
giulio.guzzinati@uantwerpen.be

Electronic spectroscopies are important in the study of localised surface plasmon resonances of metallic nanostructures, allowing to detect and image the strong spatial variations in the electrical field of the induced resonances of a single nanoparticle. These techniques do however present some drawback when compared to their optical counterparts. While optical spectroscopies can make use of polarisation to directionally probe the response of a nanoparticle, an electronic beam can't discriminate between energy-degenerate eigenmodes and is also blind to optical activity and dichroism.

As we show here, designing the wavefunction of the electron beam by manipulating its phase allows to circumvent this [1], allowing to measure previously inaccessible properties. We show theoretically and experimentally how the phase in the electron beam's wave function couples to the electric potential of the plasmonic resonance, allowing to selectively detect localised plasmonic excitations that possess the same symmetry as the electron probe [2]. A successful experimental demonstration of this method will be shown, the selective detection of the dipolar mode of a Al nanorod with an HG-like beam, which we successfully generate in a TEM by applying state of the art phase manipulation techniques. This demonstrates the viability of this new approach and opens the way to a variety of new plasmon-oriented experiments base on the control of the electron's wave function.

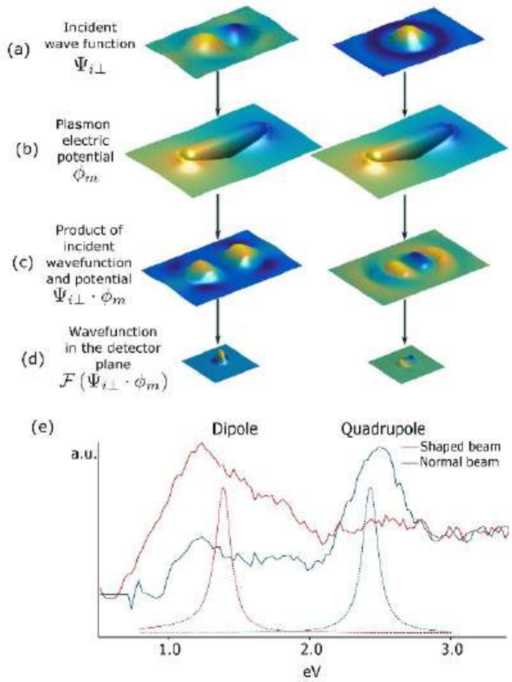


Figure 1: A schematic representation of the interaction. A conventional or modified electron beam (a) interacts with the potential of a plasmon resonance (b). This interaction results in partial inelastic exit wave, whose form depends on both the incident beam, and plasmon potential (c). This information is then carried to the detection plane where a selection becomes possible (d) as shown in numerical and experimental realisations of this setup (e).

References

[1] G. Guzzinati et al., Ultramicroscopy 151, 85 (2015).
[2] Guzzinati et al., Nature Comms 8, 14999 (2017)

Holography of Twisted Neutron Waves and their Spin-Orbit Coupling

D.A. Pushin,
Institute for Quantum Computing,
University of Waterloo,
Waterloo, ON, N2L 3G1, Canada
dmitry.pushin@uwaterloo.ca

Most waves encountered in nature can be given a "twist", so that their phase winds around an axis parallel to the direction of wave propagation. Such waves are said to possess orbital angular momentum (OAM). For quantum particles such as photons, atoms, and electrons, this corresponds to the particle wavefunction having angular momentum of $L\hbar$ along its propagation axis.

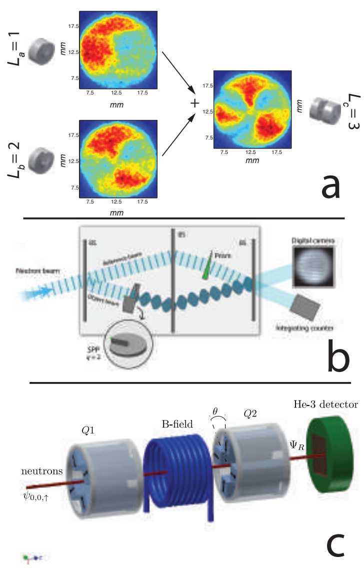


Figure 1: a) Addition of angular momenta along the direction of propagation accomplished by two spiral phase plates. Interferograms represent neutron phase profile after passage through the spiral phase plates [1]; b) Illustration of neutron holography experiment [2] c) Schematic of a spin-orbit Ramsey fringe experiment [3].

Here I discuss the first demonstration of OAM control of neutrons [1]. Neutron interferometry with a spatially incoherent input beam, it has been used to show the addition and conservation of OAM (Fig. 1a) and entanglement between quantum path and OAM degrees of freedom. A spiral phase plate used in these experiments has been holographically imaged using a neutron interferometer [2]. The resulting hologram is a fork dislocation image (Fig. 1b), consistent with the predictions of [4]. Neutrons have an intrinsic spin, and here we suggest a means of coupling neutron spin and OAM to obtain an entangled spin-orbit state [3]. A Ramsey-fringe-type measurement is suggested as a means of verifying the spin-orbit correlations (Fig. 1c).

Neutron-based quantum information science heretofore limited to spin, path, and energy degrees of freedom, now has access to another quantized variable, and OAM modalities of light, x-ray, and electron beams are extended to a massive, penetrating neutral particle. The methods of neutron phase imprinting demonstrated here expand the toolbox available for development of phase-sensitive techniques of neutron imaging.

References

[1] Clark C.W., et.al., Controlling neutron orbital angular momentum, Nature 525, pp. 504-506, 2015.

[2] Sarenac D., et.al., Holography with a neutron interferometer, Optics Express 24, pp. 22528-22535, 2016.

[3] Nsofini J., et.al., Spin orbit states of neutron wavepackets, Phys. Rev. A 94, p. 013605, 2016.

[4] Bazhenov, V. I., et al., Laser beams with wave front screw dislocations, Pisma v ZETF 52, 1037-1039, 1990.

Generation of gamma-ray vortex beams using inverse Compton scattering

Yoshitaka Taira[1,3], Shukui Zhang[2], Joseph Grames[2], Dave Gaskell[2], Matthew Poelker[2]
Dipangkar Dutta[3], Benjamin McMorran[4]
1: National Institute of Advanced Industrial Science and Technology (AIST), Japan
2: Thomas Jefferson National Accelerator Facility, USA
3: Mississippi State University, USA
4: University of Oregon, USA
yoshitaka-taira@aist.go.jp

After remarkable work conducted by L. Allen et al., which revealed that a Laguerre Gaussian (LG) laser mode carries $m\hbar$ orbital angular momentum (OAM) per photon [1], research on optical vortices using visible wavelength lasers has thrived and resulted in successful applications in various research fields. Moreover, vortex beams are not limited to visible light but have been generated in 10 keV X-rays, terahertz/radio waves, sub-MeV electron beams and cold neutrons.

Gamma-rays are an important tool for various research fields including solid-state physics using magnetic Compton scattering, positron production via pair production for a linear collider, nuclear physics, medical diagnostics and therapy, non-destructive inspection for industrial products and homeland security, and astrophysics. At Jefferson Lab, we aim to generate a gamma-ray vortex with energy in the MeV and GeV energy range, and to explore the application of gamma-ray vortices for nuclear physics research. If the OAM of gamma-rays is transfered to the angular momentum of quarks and gluons inside a proton, it may be a strong tool to measure the spin configuration of protons.

In this research, inverse Compton scattering (ICS) will be used to generate gamma-ray vortices. Figure 1 shows a schematic illustration of ICS. In ICS, the laser photon is backscattered by the relativistic electron and its energy is increased to a high energy region. The maximum gamma-ray energy scattered onto the center axis is described as $E_\gamma = 4\gamma^2 E_L/(1+4\gamma E_L/m_e c^2)$, where γ is the Lorentz factor of an electron, E_L is the energy of incident laser, and $m_e c^2 = 0.511$ MeV is the electron rest energy. Gamma-rays with energy of tens of MeV can be generated by using a 1 GeV electron beam, and ~ GeV gamma-rays can be produced by a 10 GeV electron beam.

The first theoretical paper [2] describing OAM conservation of incident vortex laser light revealed that OAM was preserved at a small scattering angles $\theta < 1/\gamma^2$. In this work, we present the OAM characteristics and the spatial intensity distribution of gamma-ray vortex beams generated by ICS. We also describe an experimental plan to be conducted at Jefferson Lab.

Figure 1: Schematic illustration of ICS.

References

[1] L. Allen, et al., “Orbital angular momentum of light and the transformation of Laguerre-Gaussian laser modes”, Phys. Rev. A 45 8185-8189, 1992.
[2] U. D. Jentschura and V. G. Serbo, “Generation of High-Energy Photons with Large Orbital Angular Momentum by Compton Backscattering”, Phys. Rev. Lett. 106 013001, 2011.

Vortex transmutations in polariton fluids

Lorenzo Dominici,[1,*] Antonio Gianfrate,[1] David Colas,[2] Amir Rahmani,[2]
Carlos Sánchez Muñoz,[2] Dario Ballarini,[1] Milena De Giorgi,[1]
Giuseppe Gigli,[1] Fabrice P. Laussy,[2] and Daniele Sanvitto[1]
[1] CNR NANOTEC, Istituto di Nanotecnologia, Via Monteroni, 73100 Lecce, Italy
[2] Dept. de Física Teórica de la Materia Condensada, UAM, 28049 Madrid, Spain
*lorenzo.dominici@gmail.com

In this work we experimentally and theoretically describe three different kinds of quantum vortex transmutation that can be achieved thanks to 2D microcavity polariton fluids. Such bosonic quasiparticles are made of strongly coupled excitons and photons fields [1]. Their assets comprise high coherence properties, spinorial nature, photonic in- and out-coupling, sub-ps Rabi oscillations (due to normal modes splitting), and strong nonlinearities.

A first approach of vortex trasmutation consists in initializing the polariton fluid with resonant structured beams, such as baby-skyrmions (*aka* full Poincaré beams in space) or spin vortices (such as radial or hyperbolic polarization textures). Based on the *xy* linear polarization anisotropy of polaritons, the initial patterns are twisted along the Poincaré sphere of polarizations, also leading to the reversal of the initial topology. The transformation is *continouos* in time, on the scale of tens of ps. Conformal mapping reveals that, e.g., a baby-skyrmion becomes a full Poincaré beam *both* in space and time.

In the second approach, we exploit Rabi oscillations, and double-pulse coherent control to shape an ultrafast space-swirling vortex. This results from the induced splitting of the original vortex between the two normal modes of polaritons. A continouos exchange of energy and OAM happens between the coupled fields of excitons and photons. We focus on the phase singularities, and their 2D+t vortex lines (or topological strings), showing that the emitted photonic packets are characterized by one or more inner vortex tubes which spiral around the axis of propagation. Yet, the surrounding polarization space texture undergoes ultrafast rotations around the Poincaré sphere.

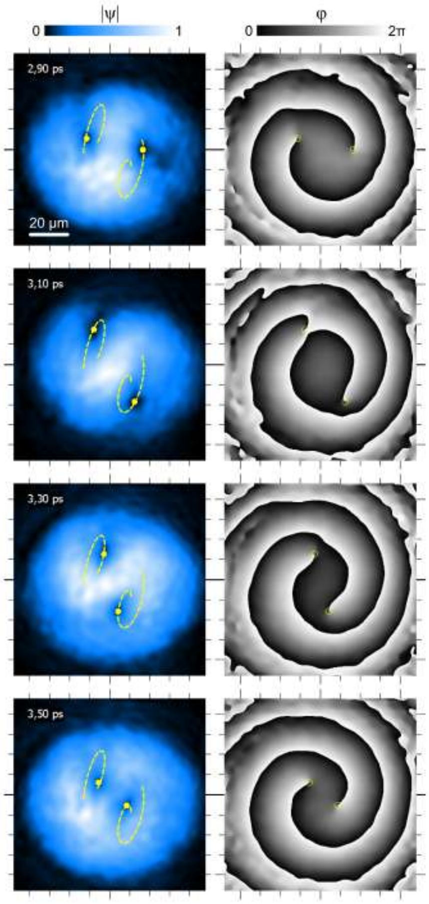


Figure 1: Rabi double vortex. Polariton density and phase, highlighting the sub-ps orbiting of the phase singularities.

Finally, we exploit the nonlinear interactions of polaritons. Upon activating the mutal rotations of a couple of cowinding vortices, it is possible to induce, e.g., the decomposition of an initial couple of spin vortices into their four component baby-skyrmions.

References

[1] Dominici *et al.*, Pulse, polarization and topology shaping of polariton fluids, Proc. SPIE 10120, 101200E (2017)

Taming Orbital Angular Momentum Entanglement with Mutually Unbiased Measurements

Mehul Malik
Institute for Quantum Optics and Quantum Information (IQOQI), Vienna
Austrian Academy of Sciences, Boltzmanngasse 3, 1090 Vienna, Austria
mehul.malik@univie.ac.at

The orbital angular momentum (OAM) modes of a photon have emerged as an ideal testbed for the rapidly advancing field of high-dimensional quantum information. The use of multiple quantum levels offers several advantages, from increasing the capacity in quantum communication systems to increasing the noise robustness in fundamental tests of quantum mechanics. However, the verification of high-dimensional entanglement is notoriously difficult. Complete tomographic reconstruction of a high-dimensional quantum state requires one to make at least as many measurements as density matrix elements in the state, which can be staggeringly large even for states with a modest dimensionality.

A solution is found in entanglement dimension witnesses, which allow one to verify the presence of high-dimensional entanglement with a significantly fewer number of measurements than tomography. Several such witnesses have been developed and used for quantifying OAM entanglement, with the most recent example being a Fidelity witness that bounds the dimensionality of a measured entangled state by calculating its overlap with an ideal target state [1]. While being quite robust against noise, this method still requires one to make $\mathscr{O}(d^4)$ single-outcome measurements of OAM for a $d \times d$ dimensional entangled state.

A recent theoretical technique quantified the entanglement of formation (EoF) of a high-dimensional state via measurements in only two mutually unbiased bases (MUBs) [2]. While drastically reducing the number of measurements to $\mathscr{O}(d^2)$, this method was extremely sensitive to any noise in the state. Here, we introduce and experimentally demonstrate a new, noise-resistant method for quantifying entanglement in a high-dimensional OAM-entangled state that uses measurements in up to $d+1$ carefully constructed MUBs (Fig. 1). Our technique adapts to the noise present in the state by optimizing the number of measurement bases used, while maximizing its entanglement dimensionality. We test our method with a high-dimensional OAM-entangled state of two photons under realistic noise conditions, thus demonstrating its applicability for efficient, noise-resistant tests of high-dimensional entanglement in a diverse range of physical systems beyond just OAM.

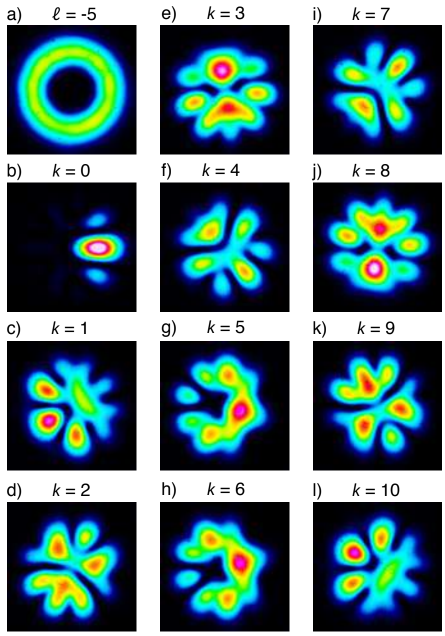


Figure 1: CCD images showing states in twelve different mutually unbiased bases (k) corresponding to $d = 11$ ($\ell = -5 \ldots 5$).

References

[1] Malik M. et al, Nat. Photonics 10, 248, 2016.

[2] Erker P. et al, arXiv:1512.05315, 2015.

Session 4. "Spin-orbit & Quantum"

Session 5. "Quantum"

Photonic quantum information processing with orbital angular momentum

Xi-Lin Wang*, Chao-Yang Lu and Jian-Wei Pan
University of Science and Technology of China,
Hefei, Anhui 230026, China
*Email: xlwang12@ustc.edu.cn

Orbital angular momentum (OAM) arising from the helical phase structure of a photon could be used to encode a qubit or a qudit. It plays an important role for the photonic quantum information processing since it could result in some unique functions. We have developed some OAM manipulation technologies with high efficiency, together with previous multi-photon technology to control spin angular momentum (SAM), we successfully implemented the first quantum teleportation [1] of the spin and orbital angular momentum of a photon for the first time as shown in Fig. 1. This work has been awarded as the *Physics World* 2015 Breakthrough of the Year [2].

Quantum teleportation provides a "disembodied" way to transfer quantum states from one object to another at a distant location, assisted by previously shared entangled states and a classical communication channel. In addition to its fundamental interest, teleportation has been recognized as an important element in long-distance quantum communication, distributed quantum networks and measurement-based quantum computation. There have been numerous demonstrations of teleportation in different physical systems. Yet, all the previous experiments were limited to teleportation of one degree of freedom (DoF) only. A fundamental open challenge is to simultaneously teleport multiple DoFs, which is necessary to fully describe a quantum particle, thereby truly teleporting it intactly. Here, we demonstrate quantum teleportation of the composite quantum states of a single photon encoded in both the spin and orbital angular momentum [1]. Our work moves a step toward teleportation of more complex quantum systems, and demonstrates an enhanced capability for scalable quantum technologies.

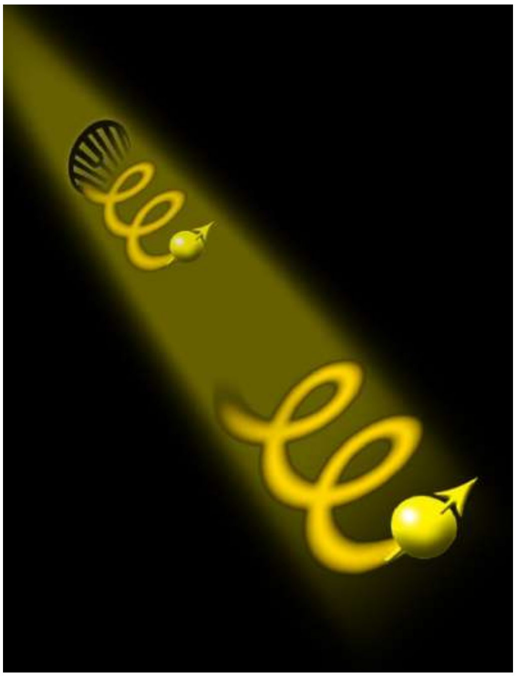


Figure 1: We have teleported the spin and orbital angular momentum of a photon for the first time.

Now, together with the production technology of new entanglement photon source developed in our recent work of ten-photon entanglement [2], we are striving hard to generate the six-photon eighteen-qubit entanglement with three degrees of freedom of a photon including SAM, OAM and path.

References

[1] X.-L. Wang et al., Nature 518, 516-519, (2015).
[2] http://physicsworld.com/cws/article/news/2015/dec/11/double-quantum-teleportation-milestone-is-physics-world-2015-breakthrough-of-the-year
[3] X.-L. Wang et al., Phys. Rev. Lett. 117, 210502 (2016).

Simultaneous entanglement swapping of multiple orbital angular momentum states of light

Megan Agnew[1], Yingwen Zhang[2],Thomas Roger[1], Filippus S. Roux[2,3], Thomas Konrad[4,5], Daniele Faccio[1], Andrew Forbes[2,3], Jonathan Leach[1]

[1]IPaQS, SUPA, Heriot-Watt, Edinburgh EH14 4AS, United Kingdom
[2]CSIR National Laser Centre, PO Box 395, Pretoria 0001, South Africa
[3]School of Physics, University of Witwatersrand, Johannesburg 2000, South Africa
[4]School of Chemistry and Physics, University of KwaZulu-Natal, Private Bag X54001, Durban 4000, South Africa
[5]National Institute of Theoretical Physics, University of KwaZulu-Natal, Private Bag X54001, Durban 4000, South Africa
j.leach@hw.ac.uk

Entanglement swapping generates remote quantum correlations between particles that have not interacted and is the cornerstone of long-distance quantum communication, quantum networks, and fundamental tests of quantum science. In the context of spatial modes of light, high-dimensional entanglement provides an avenue to increase the bandwidth of quantum communications and provides more stringent limits for tests of quantum foundations. Here we simultaneously swap the entanglement of multiple orbital angular momentum states of light. The system is based on a degenerate filter that cannot distinguish between different anti-symmetric states, and thus entanglement swapping occurs for several thousand pairs of spatial light modes simultaneously.

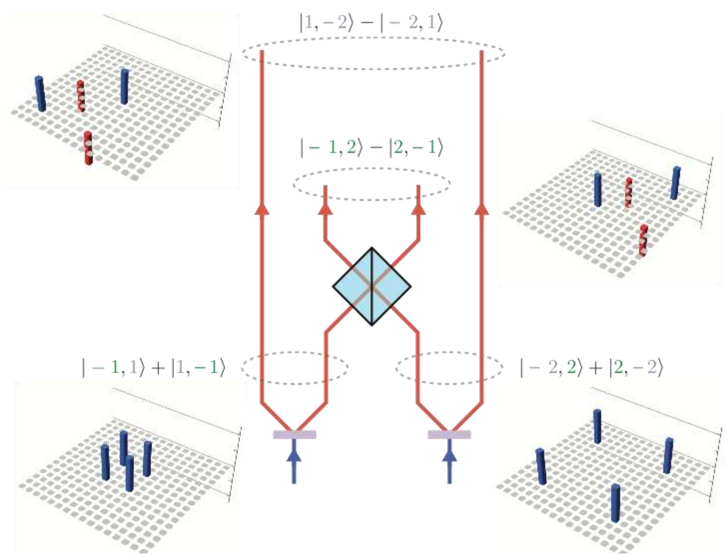


Figure 1: Schematic of entanglement swapping for orbital angular momentum states of light.

On computer-designed Quantum Experiments

Mario Krenn, Armin Hochrainer, Mayukh Lahiri,
Robert Fickler, Mehul Malik, Radek Lapkiewicz, Anton Zeilinger

Vienna Center for Quantum Science & Technology (VCQ), Faculty of Physics,
University of Vienna, Boltzmanngasse 5, 1090 Vienna, Austria.
Institute for Quantum Optics and Quantum Information (IQOQI),
Austrian Academy of Sciences, Boltzmanngasse 3, 1090 Vienna, Austria.

Designing experimental setups for high-dimensional multipartite entangled states is a notoriously difficult feat. For that reason, we have developed the computer algorithm MELVIN which is able to find new experimental implementations for the creation and manipulation of complex quantum states [1]. The discovered experiments extensively use unfamiliar and asymmetric techniques which are challenging to understand intuitively. MELVIN autonomously learns from solutions for simpler systems, which significantly speeds up the discovery rate of more complex experiments. Several of the computer-designed experiments have already been successfully implemented in our laboratories [2, 3, 4].

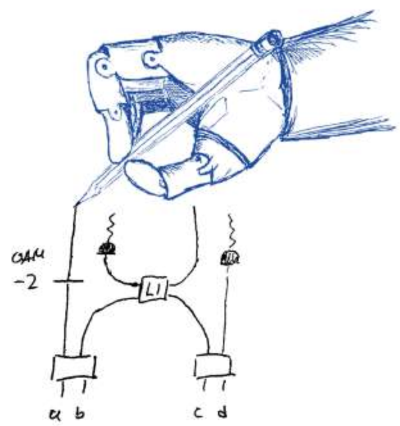


Figure 1: Designing an experiment for the 3-dimensional Greenberger-Horne-Zeilinger state (Image by Robert Fickler).

By analysing MELVIN's proposal for an unexpected quantum state, we discovered a novel technique. It allows for well controlled generation of entanglement based on a technique introduced by the group of Leonard Mandel in 1991 [5]. Surprisingly, this technique only uses elements which were available already for 25 years, but it has been discovered only now by a computer algorithm. This shows that computer designed quantum experiments can be inspirations for new techniques [6].

References

[1] M. Krenn, M. Malik, R. Fickler, R. Lapkiewicz and A. Zeilinger, Automated search for new quantum experiments. *Physical review letters* **116**, 090405 (2016).

[2] M. Malik, M. Erhard, M. Huber, M. Krenn, R. Fickler and A. Zeilinger, Multi-photon entanglement in high dimensions. *Nature Photonics* **10**, 248-252 (2016).

[3] F. Schlederer, M. Krenn, R. Fickler, M. Malik and A. Zeilinger, Cyclic transformation of orbital angular momentum modes. *New Journal of Physics* **18**, 043019 (2016).

[4] A. Babazadeh, M. Erhard, F. Wang, M. Malik, R. Nouroozi, M. Krenn and A. Zeilinger, High-Dimensional Single-Photon Quantum Gates: Concepts and Experiments. *arXiv:1702.07299* (2017).

[5] X. Zou, L. Wang and L. Mandel, Induced coherence and indistinguishability in optical interference. *Physical review letters* **67**, 318 (1991).

[6] M. Krenn, A. Hochrainer, M. Lahiri and A. Zeilinger, Entanglement by Path Identity. *Physical review letters* **118**, 080401 (2017).

Tomography of a quantum channel with classical light

B. Ndagano[1], B. Perez-Garcia, F. S. Roux, M. McLaren, C. Rosales-Guzmán, Y. Zhang, O. Mouane, R. I. Hernandez-Aranda, T. Konrad, A. Forbes

[1]School of Physics, University of the Witwatersrand, Johannesburg, South Africa.

nibienvenu@gmail.com

The notion of entanglement in classical light fields is hotly debated [1], the main argument against stemming from the fact that the entangled parties, the degrees of freedom, do not exhibit non-locality, a salient feature of quantum entanglement. However, non-locality is not the linchpin of classical entanglement; the notion holds physical significance that can be of great importance to understand and characterize the dynamics of quantum entanglement. Here, we demonstrate a physical setup in which the dynamics of classical and quantum entanglement are indistinguishable from each other. We study the decay of correlation of an entangled pair of photon, in which one of the photon is subjected to in atmospheric turbulence. We show that the observed decay of quantum entanglement is identical to that measured for the classically equivalent system (see Fig. 1) in which only one degree of freedom, the orbital angular momentum of a vector vortex beam, is perturbed by the same levels of turbulence [2]. This provide further physical significance to the notion of classical entanglement, beyond the mathematical similarities to the quantum entangled state. It is from the equivalence in entanglement decay between the two systems that we propose and demonstrate a scheme to mitigate the effect of turbulence on the quantum states, whereby the measurements on the classically entangled vector vortex beam are used to recover the initially entangled quantum state, resulting in a conversion from noise – which affect the degree of entanglement – to photon loss.

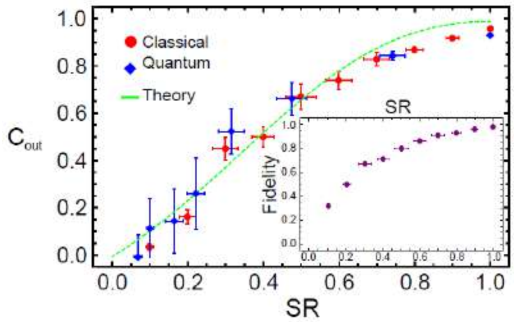


Figure 1: Decay of classical and quantum entanglement in turbulence, increasing in strength from right to left.

References

[1] Karimi, E., and Boyd, R. W., Classical entanglement?, Science 350, 1172–1173 (2015)

[2] Ndagano, B., Perez-Garcia, B., Roux, F.S., McLaren, M., Rosales-Guzman, C., Zhang, Y., Mouane, O., Hernandez-Aranda, R.I., Konrad, T., and Forbes, A., Characterizing quantum channels with non-separable states of classical light, Nature Physics 13, 397–402 (2017).

Entanglement with Quantum Numbers up to 10010 and Controlled Scattering for Spatial Mode Sorting

R.Fickler[1], M.Ginoya[1], G.Campbell[2], B.Buchler[2], P.K.Lam[2], A.Zeilinger[3,4], R.W.Boyd[1,5]
[1]Department of Physics, University of Ottawa, Ottawa, ON, K1N 6N5, Canada
[2]Research School of Physics & Engineering, ANU, Canberra, ACT 2601, Australia
[3]IQOQI, Austrian Academy of Sciences, 1090 Vienna, Austria
[4]Faculty of Physics, University of Vienna, 1090 Vienna, Austria
[5]Institute of Optics, University of Rochester, Rochester, New York 14620, USA
rfickler@uottawa.ca

Advanced techniques to control the transverse phase front of light enable tasks to investigate fundamental questions and develop novel tools for enhanced mode transformations. We present two recent results, in which we investigate entangled bi-photon states with quantum numbers up to 10010 [1] and we demonstrate a novel transformation scheme by shaping the wave front prior to transmission though strongly scattering media [2].

Photons with a twisted phase front carry a quantized, in principle unbounded, amount of orbital angular momentum (OAM). Hence, photonic states can be used to test quantum mechanical prediction for large quantum numbers. We use spiral phase mirrors, which can imprint unprecedentedly large OAM values onto light, to generate entangled bi-photon quantum states with quantum numbers up to 10010.

We start by investigating the transformation of a Gaussian laser beam to modes with large OAM. By analyzing the intensity structure of superpositions, we are able to verify modes with OAM values up to 10010 (see Fig.1a). We then use the developed transfer scheme to generate hybrid-entangled photon pairs, where the polarization of one photon is entangled with a large OAM quantum number of its partner. Our results demonstrate that single photons can have OAM quantum numbers of 10010 and might be beneficially applied to boost the sensitivity in angular sensing or the transfer of angular momentum.

In a second experiment, we investigate recently developed techniques in wave front shaping to control the strong scattering of light and develop applications based on this ability. The high degree of control along with the complex coupling within the scattering media enables complex mode transformation, a task for which only a few limited techniques are known.

As a first demonstration, we implement a programmable mode-sorting scheme. Specifically, any input mode family can be custom-tailored to map onto a broad range of possible output channel arrangements (see Fig.1b). Our method enables full access to all of the information encoded in the transverse structure and points towards promising applications in future mode transformation tasks.

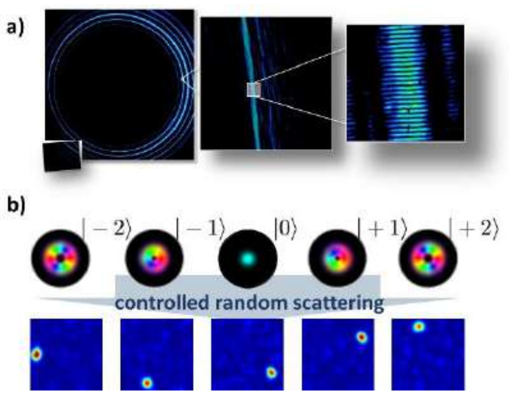


Figure 1: a) Recorded intensity of a superposition of ±10010 OAM. b) Sorting of five OAM modes (-2,-1…,+2) by controlling a random scattering process.

References

[1] R. Fickler, G.T. Campbell, B.C. Buchler, P.K. Lam, A. Zeilinger *PNAS* **113**, 13642 (2016)

[2] R. Fickler, M. Ginoya, R.W. Boyd *Physical Review B* **95**, 161108(R) (2017)

Quantum Causality

J Romero[1,*], C Giarmatzi[1], F Costa[1], M Rambach[1], T Weinhold[1], C Branciard[2], AG White[1]
[1]School of Mathematics and Physics, University of Queensland, St Lucia, QLD, Australia
[2]Institut Néel, CNRS/UJF, Grenoble, France
*jacq.romero@gmail.com

Causality is an underpinning concept in science – scientists identify causes and effects. In the same way that quantum physics has challenged our notion of reality, it also challenges our notion of causality. Recent developments in theory [1] and experiment [2] have brought at least some aspects of causality into experimentally testable territory. For example, we are used to thinking of space and time as a physical "stage" in which events, e.g. Alice receiving a message from Bob (event A) or Bob receiving a message from Alice (event B), take place. We show that this notion of a "stage" may not be a necessarily fundamental ingredient of nature. We show that it is possible for different orders of events to exist in superposition, i.e. that A is before B and that B is before A can both be simultaneously true -- thereby demonstrating an indefinite causal order.

We implement the quantum switch proposed in [1], and measure a "causality witness", which signals indefinite causal order in the same way that an entanglement witness signals entanglement. The experiment is possible because of our capacity to control the various degrees of freedom of light such as polarisation and transverse spatial mode (orbital angular momentum and their superposition). We use polarisation as the control which determines whether operation A is before operation B or, vice versa. We use the superposition of polarisation states to obtain a superposition of the order in which processes A and B (i.e. the Pauli transformations in Fig 1) act on the transverse spatial mode of photons. More interestingly, the availability of polarisation entanglement points to the possibility of experimentally realising entanglement of the causal order of processes.

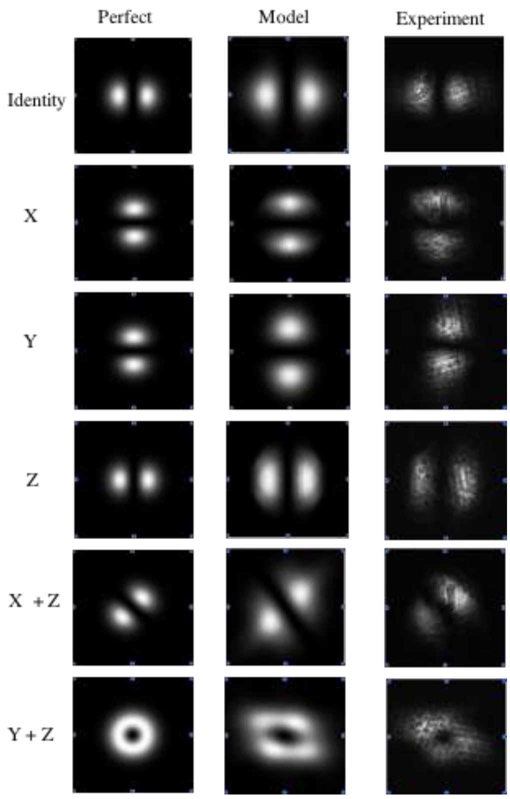


Figure 1: Our causal witness is based on perfect Pauli transformations. For an input first-order Hermite-Gaussian mode, we show the corresponding intensity profiles for the ideal transformation (perfect), what we expect from our setup (model), and we get from the experiment (experiment).

References

[1] G Chiribella, GM D'Ariano, P Perinotti, B Valiron, Quantum computations without definite causal structure, Physical Review A 88 (2), 022318 (2013)
[2] G Rubino, LA Rozema, A Feix, M Araújo, JM Zeuner, LM Procopio, Č Brukner, P Walther, Experimental verification of an indefinite causal order, arXiv:1608.01683 (2016)

Spatial Bell-State Generation without Transverse Mode Subspace Postselection

E.V. Kovlakov, I.B. Bobrov, S.S. Straupe, S.P. Kulik
Faculty of Physics, M. V. Lomonosov Moscow State University,
Leninskie Gory 1, 119992 Moscow, Russia
ekovlakov@gmail.com

Over the last decade, two-photon entanglement in transverse momentum (spatial mode) became a powerful tool for quantum engineering of hyperentangled photon states in addition to polarization and energy-time degrees of freedom. Special attention is paid to maximally entangled Bell-type states which play a crucial role in both fundamental tests of quantum mechanics and practical applications, such as entanglement-based and device-independent quantum cryptography protocols.

The process of spontaneous parametric down-conversion (SPDC) in nonlinear crystals is well suited for the generation of photon pairs spatially entangled in the bases of Hermite-Gaussian (HG) or Laguerre-Gaussian modes. At present, the common way to generate spatial Bell states is to filter a number of specific spatial modes from the whole SPDC transverse mode spectrum [1]. Due to the fact, that usually this spectrum contains a significant number of modes, such "postselection" leads to inevitable loss.

For this reason we provide a spatial Bell-state generation method, which does not require any spatial filtration of the SPDC transverse mode spectrum [2]. By changing the divergence of the Gaussian pump beam, we reach a regime of down-conversion close to single-spatial-mode one (with spatial Schmidt number close to unity). Next, using the spatial light modulator (SLM), we transform the pump beam into the first HG mode so the spatial mode content of generated SPDC radiation is limited to the subspace, containing the zero- and first-order HG modes only [3]. High fidelity of the generated states with ideal Bell states is confirmed by full state tomography and significant violation of Clauser-Horne-Shimony-Holt inequality The postselection-free character of the method allows for creation of high-brightness sources of spatial Bell states, while their well-defined and low-order mode content would facilitate their use in free-space and few-mode fiber communication channels.

In addition, we study a number of interesting states, generated by transforming the spatial mode of the pump beam to low-order HG modes, demonstrating vast abilities in engineering the spatial quantum state of photon pairs. An adaptive optics control of the pump beam profile of phase and amplitude allowed us to improve the quality of generated states by using iterative optimization technique based on simultaneous perturbation stochastic approximation.

References

[1] B. Jack et al., Entanglement of arbitrary superpositions of modes within two-dimensional orbital angular momentum state spaces, Phys. Rev. A 81, 043844, 2010.

[2] Kovlakov E.V. et al., Spatial Bell-State Generation without Transverse Mode Subspace Postselection, Phys. Rev. Lett. 118.3, 030503, 2017.

[3] Walborn S.P. and Pimentel A.H., Generalized Hermite-Gauss decomposition of the two-photon state produced by spontaneous parametric down conversion, J. Phys. B 45, 165502, 2012.

Session 6.
"Nonlinear, Ultrafast & Propagation"

Synthesis, Characterization and Control of extreme ultraviolet attosecond light springs

A. Camper, R. Géneaux, C. Chappuis, T. Auguste, O. Gobert, J. Caillat, R. Taïeb & T. Ruchon.
LIDYL, CEA, CNRS, Université Paris-Saclay, CEA Saclay, 91191 Gif-sur-Yvette, France
Sorbonne Universités, Laboratoire de Chimie Physique-Matière et Rayonnement (UMR 7614), UPMC Univ Paris 06, 11 rue Pierre et Marie Curie, 75005 Paris, France.
thierry.ruchon@cea.fr

The generation of beams carrying orbital angular momentum (OAM) has recently been extended to the extreme ultra violet (XUV) range [1]. In practice, an intense infrared femtosecond beam carrying OAM is focused into a gas target to drive photon up-conversion in the XUV through high harmonic generation (HHG). Here, we report on HHG driven with an 800 nm beam carrying 1 to 3 units of OAM in different targets (Argon, Neon).

In the far-field, we observe that the harmonic beam profile is donut-shaped and that the radius of the ring does not depend on the harmonic order. We show that this is consistent with a linear increase of the OAM with harmonic order, using an analytical analysis and a full 4-dimensional numerical experiment simulating HHG.

We also measure the attosecond synchronization of the HHG comb implementing the RABBITT [1] technique for the first time with XUV beams carrying OAM. By matching the phase fronts of the harmonics and the dressing field, we demonstrate in an original way that there is a difference of two units in the OAM carried by two consecutive odd harmonic orders. This confirms the linear increase of OAM with harmonic order, the slope being determined by the OAM of the driver. Additionally, this measurement allows us to reconstruct the attosecond shape of the emission, as shown in Figure 1.

We then demonstrate control over the OAM in the XUV by setting the OAM of the driving IR field to 2 and 3. The ring radius of the XUV beam is still constant with harmonic order but increases with the driver topological charge.

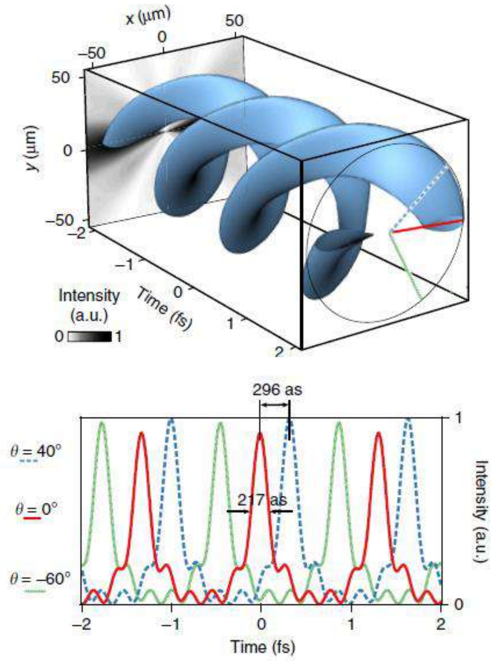


Figure 1: Reconstruction of the attosecond structure resulting from the coherent superposition of high harmonic orders carrying a topological charge linearly increasing with harmonic order.

Our results open new perspectives for the synthesis of attosecond electronic springs through photoionization.

References

[1] Géneaux, R., Camper, A., Auguste, T., Gobert, O., Caillat, J., Taïeb, R., Ruchon, T., Synthesis and characterization of attosecond light vortices in the extreme ultraviolet, Nature Communications 7, 12583, 2016.

Optical vortices at ultra-high intensity

A. Denoeud, L. Chopineau, A. Leblanc, G. Mennerat, Ph. Martin, F. Quéré
Laboratoire Interactions, Dynamiques et Lasers (LIDYL)
CEA, CNRS, Université Paris-Saclay, 91191 Gif-sur-Yvette, France
adrien.denoeud@cea.fr

Laser beams carrying orbital angular momentum (OAM) have found major applications in a variety of scientific fields, and their potential for ultrahigh-intensity (UHI) laser-matter interactions has since recently been considered theoretically, up to the relativistic regime [1, 2]. Indeed, the remarkable phase and intensity properties of these vortex beams could provide a new way to control UHI interactions as well as new properties for the resulting particles and XUV sources. Despite a large number of theoretical studies done on this topic until recently, no experiment had demonstrated such effects, espacially because of the difficulty to induce helical wavefronts in large and intense laser beams.

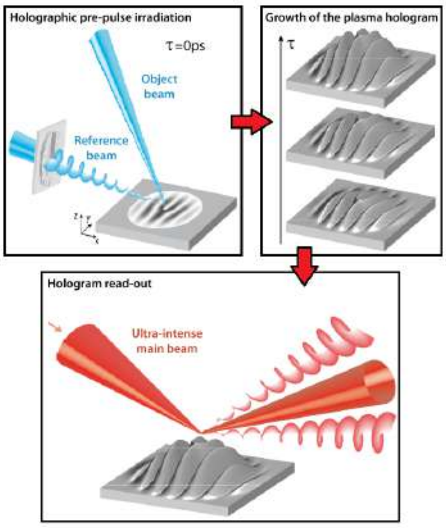


Figure 1: Experimental holographic set up used to create a transient plasma fork-grating and to generate laser and XUV vortex beams in the diffracted orders of an ultra-intense laser beam [6].

We show for the first time the possibility to induce OAM on such intense laser beams, as well as to transfer it to relativistic XUV harmonic beams, which are generated on solid targets at intensities higher than $10^{19}\ W/cm^2$ [3]. This was done on the UHI100 facility thanks to a spiral phase plate and the physical effects determining the field mode content of the twisted harmonic beams were elucidated. Moreover, thanks to an interformetric technique using a fork-shape binary transmission grating, we measure the helical phase of each harmonic beam and we validate the conservation of OAM in highly non-linear optical processes at extreme laser intensities, which was challenged in gases [4, 5].

Finally, we introduce a new holographic method, called plasma holograms (see. Fig.1), based on the controlled extension of structured plasma on the surface of the solid target to induce an optical vortex on the ultra-high intense laser beam as well as on its high-order harmonics [6]. In particular, this all-optical technic should be very interesting to manipulate Petawatt lasers.

References

[1] J. Vieira and J. T. Mendonca, Phys. Rev. Lett. **112**, 215001 (2014).

[2] X. Zhang *et al.*, Phys. Rev. Lett. **114**, 173901 (2015).

[3] A. Denoeud, L. Chopineau, A. Leblanc, and F. Quéré, Phys. Rev. Lett. **118**, 033902 (2017).

[4] M. Zürch *et al.*, Nat. Phys. **8**, 743 (2012).

[5] G. Gariepy *et al.*, Phys. Rev. Lett. **113**, 153901 (2014).

[6] A. Leblanc, A. Denoeud, L. Chopineau, G. Mennerat, Ph. Martin and F. Quéré, Nat. Phys., published online (2017).

Control of nonlinear beam propagation using fully-structured light

C. J. Gibson, P. Bevington, G.-L. Oppo, A. M. Yao
SUPA and Department of Physics, University of Strathclyde,
Glasgow, G4 0NG, Scotland, U.K. alison.yao@strath.ac.uk

Fully-structured light – light that has non-uniform intensity, phase and polarisation – lies at the heart of an emerging and extremely promising field of research, with applications in high-resolution imaging, optical communications, and trapping and manipulation of nanoparticles. By tailoring the spatial structure of the polarization, the effects of propagation in a self-focusing nonlinear medium can be effectively controlled and, in particular, fragmentation of the beams can be inhibited [1]. Here we demonstrate that the polarisation structure can additionally be used to control the amount of polarisation rotation of the beams, both linearly and non-linearly. These findings provide a novel approach to transport high-power light beams in nonlinear media with controllable distortions to their spatial structure and polarization properties.

Fully structured light beams may be constructed from a superposition of two Laguerre-Gaussian (LG) modes with orthogonal circular polarizations $(\vec{e}_l, \vec{e}_r)$:

$$\begin{aligned}\vec{E}(r,\phi,z) &= E_L(\rho,\phi,z)\vec{e}_l + E_R(\rho,\phi,z)\vec{e}_r, \\ &= \cos(\gamma) LG_L\, \vec{e}_l + e^{i\beta}\sin(\gamma) LG_R\, \vec{e}_r \quad (1)\end{aligned}$$

where γ and β give the relative amplitudes and phase, respectively, of the two modes with orbital angular momentum (OAM) of ℓ_L, ℓ_R.

We show analytically that for linear propagation the amount of polarisation rotation, $\Delta\psi$, depends only on the difference in Gouy phase between the modes. We then numerically model nonlinear propagation using two coupled nonlinear Schrödinger equations that provide excellent agreement with experimental results [1] and show that nonlinearity not only changes the amount of polarisation rotation for beams with a net OAM, but that it can also induce a rotation in beams with zero net OAM if there is an amplitude difference between the two modes.

Additionally, we investigate the fragmentation of fully structured beams during nonlinear propagation. Scalar LG modes fragment into solitons, with the number of solitons equal to twice the OAM of the beam [2]. Here we show instead that the fragmentation of fully structured beams can be inhibited, while nonlinear confinement, self-focusing, and polarization distributions are not altered for specific cases of nonuniform spatial polarization, both with and without net OAM. Our results are in excellent agreement with experiments of nonlinear propagation in Rubidium gas, and suggest that the spatial structure of the polarization plays an important role in beam fragmentation [1].

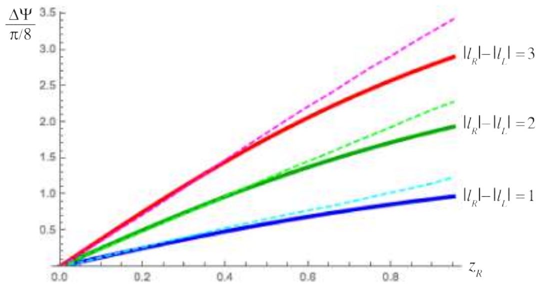


Figure 1: Linear (blue, green, red) and nonlinear (cyan, light green, magenta) rotation for fully structured beams with $\ell_L = 0, \ell_R = 1,2,3$ over one Rayleigh range.

References

[1] F. Bouchard et al., "Polarization Shaping for Control of Nonlinear Propagation", Phys. Rev. Lett. 117, 233903 (2016).

[2] W. J. Firth and D. Skryabin, "Optical Solitons Carrying Orbital Angular Momentum", Phys. Rev. Lett. 79, 2450 (1997).

Hanbury Brown and Twiss interferometry with twisted light

Robert W. Boyd
Department of Physics, University of Ottawa, Canada
The Institute of Optics, University of Rochester, USA
Department of Physics and Astronomy, University of Glasgow, UK
boydrw@mac.com

The Hanbury Brown-Twiss effect marks the beginning of modern quantum optics. Furthermore, it has been recognized that optical vortices are ubiquitous in random light and that the phase distribution around these optical singularities imprints a spectrum of orbital angular momentum onto a light field. We demonstrate [1] that random fluctuations of intensity give rise to the formation of correlations in the orbital angular momentum components and angular positions of pseudothermal light. The presence of these correlations is manifested through distinct interference structures in the orbital angular momentum–mode distribution of random light. These novel forms of interference correspond to the azimuthal analog of the Hanbury Brown and Twiss effect. This family of effects can be of fundamental importance in applications where entanglement is not required and where correlations in angular position and orbital angular momentum suffice. We also suggest some applications of the azimuthal Hanbury Brown and Twiss effect.

[1] Hanbury Brown and Twiss interferometry with twisted light, O.S. Magaña-Loaiza, M. Mirhosseini, R.M. Cross, S. M. Hashemi Rafsanjani, and R. W. Boyd, Sci. Adv. 2:e1501143 (2016).

Spatio-temporal Optical Vortices

N. Jhajj, G.A. Hine, I.L. Larkin, E.W. Rosenthal, S. Zahedpour, J.K. Wahlstrand, and H.M. Milchberg
Department of Physics
University of Maryland, College Park MD 20742, USA
njhajj@gmail.com, milch@umd.edu

In recent experiments, we discovered robust self-generation of a previously unobserved type of optical vortex: the spatiotemporal optical vortex (STOV). Such vortices have phase and energy circulation in a spatiotemporal plane and appear to be a universal phenomenon accompanying electromagnetic wave collapse induced by self-focusing in nonlinear propagation. Our initial experiments centered on measurements of STOVs accompanying filaments in air, but we also see evidence of STOV generation in relativistic self-focusing in plasmas and linear propagation scenarios.

When a high intensity pulse propagates through a medium, it experiences an intensity dependent self-lens resulting from nonlinearity in the polarization response of the medium's electrons. Above a critical power P_{cr}, the self-lens overcomes diffraction and begins to shrink the pulse in transverse size. As the pulse increases in intensity, the self-lens becomes increasingly dominant, resulting in the runaway process of optical collapse.

Optical collapse is invariably mitigated by an arrest mechanism, which becomes important to propagation as the pulse becomes increasingly singular. Collapse arrest mechanisms include refraction from plasma generated by field ionization, dispersive pulse lengthening, and electron cavitation in the relativistic propagation regime in plasmas [2]. Following collapse arrest, the pulse begins to "filament" or self-guide, leading to extended propagation of a high intensity core over many Rayleigh lengths.

We establish experimentally, and with theory and simulation, that during collapse arrest, pairs of STOVs are generated with opposite topological charges. Simulations of both air and relativistic filamentation show that the positively charged STOV settles down to propagate with the self-guided pulse and facilitates the global flow of energy. Further into propagation, the complex evolution of the field is determined by the movement, creation and destruction of STOVs.

We will present a review of our measurements and simulations leading to the detection of STOVs and then show recent results on STOV generation over a wide range of electromagnetic intensity.

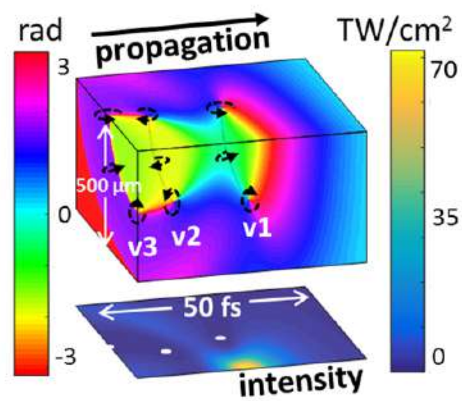


Figure 1: Simulation of phase (top) and intensity (bottom) of air filament. Three toroidal STOVs are present, labelled v1, v2, and v3.

References

[1] N. Jhajj, I. Larkin, E.W. Rosenthal, S. Zahedpour, J. K. Wahlstrand, and H. M. Milchberg, *Spatiotemporal Optical Vortices*, Physical Review X **6**, 031037 (2016).

[2] G.A. Hine, N. Jhajj, and H.M. Milchberg, submitted for publication

Orbital angular momentum mixing in type II second harmonic generation

L J. Pereira, W. T. Buono, D. S. Tasca, K. Dechoum, A. Z. Khoury
Instituto de Física - Universidade Federal Fluminense
Av. Gal. Milton Tavares de Souza s/n, 24210-346, Niterói - RJ, Brazil
khoury@if.uff.br

The ability to control different degrees of freedom of a light beam is essential for both quantum and classical communication protocols. In this context, orbital angular momentum (OAM) has proved to be a potentially useful tool. Its exchange in nonlinear interactions has been extensively studied and is still a fruitful field of investigation. OAM exchange has already been investigated in second harmonic generation [1, 2], parametric up conversion [3] and optical parametric oscillation [4]. In this work we consider type II second harmonic generation in collinear configuration with orthogonally polarized incoming beams carrying arbitrary topological charges. The multimode nonlinear dynamics is described by a set of coupled equations for the Laguerre-Gaussian mode amplitudes. We assume the crystal is pumped by two vortices with arbitrary topological charges l', l'' and radial indices equal to zero $p' = p'' = 0$. For the case where both input topological charges have the same sign ($l'l'' \geq 0$), the two input modes couple to a single second harmonic one carrying the added topological charge $l = l' + l''$ (OAM conservation) and having zero radial order $p = 0$.

A less intuitive situation is produced when the input modes carry topological charges with opposite signs. Here we also have the expected OAM conservation condition $l = l' + l''$, however the appearance of other radial orders can be seen in the second harmonic field. Therefore, the nonlinear mixing of opposite helicities implies a more complex dynamics with more transverse modes taking part in the nonlinear interaction. In order to evidence the generation of higher radial orders experimentally, we performed intensity measurements on the second harmonic beam both in the near and far field regions. The corresponding images are displayed in Fig. (1). The far field intensity patterns for second harmonic generation exhibit the external rings characteristic of higher radial orders.

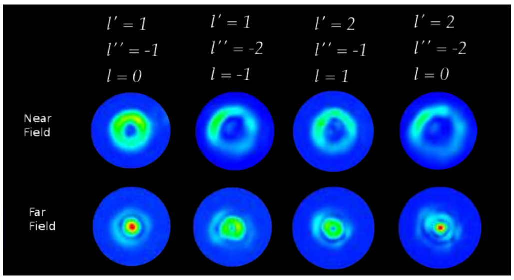


Figure 1: Experimental near and far field images for second harmonic generation of counter-rotating vortices.

References

[1] J. Courtial, K. Dholakia, L. Allen, and M. J. Padgett, Phys. Rev. A **56**, 4193-4196 (1997).

[2] W. T. Buono, L. F. C. Moraes, J. A. O. Huguenin, C. E. R. Souza, and A. Z. Khoury, New J. of Phys. **16**, 093041 (2014).

[3] A. Berzanskis, A. Matijosius, A. Piskarskas, V. Smilgevicius and A. Stabinis, Opt. Commun. **150**, 372-380 (1998).

[4] M. Martinelli, J. A. O. Huguenin, P. Nussenzveig, and A. Z. Khoury, Phys. Rev. A **70**, 013812 (2004).

Session 7.
"Technology, Communication & OAM Generation"

On-chip noninterference angular momentum multiplexing of broadband light

Min Gu
Laboratory of Artificial Intelligence Nanophotonics and Centre for Ultrahigh Bandwidth Devices for Optical Systems (CUDOS), School of Science, RMIT University, Melbourne, Victoria 3000, Australia
min.gu@rmit.edu.au

The primary properties of optical beams are brightness, propagation direction, wavelength, polarisation, and angular momentum. The possibility of manipulation of optical angular momentum at the nanoscale is of crucial importance for both fundamental research and many emerging applications. However, it is still fundamentally challenging to achieving on-chip angular momentum multiplexing due to the extrinsic nature of orbital angular momentum associated with a helical wavefront. Here we present an entirely new concept of nanoplasmonic multiplexing of angular momentum through the nonresonant angular momentum mode-sorting sensitivity by nanoring slit waveguides on tightly-confined plasmonic angular momentum modes, leading to on-chip angular momentum multiplexing of ultra-broadband light.

Biography: Professor Gu is Distinguished Professor and Associate Deputy Vice-Chancellor at RMIT University and was a Laureate Fellow of the Australian Research Council. He is a sole author of two standard reference books and has over 450 publications in nano/biophotonics. He is an elected Fellow of the Australian Academy of Science as well as the Australian Academy of Technological Sciences and Engineering. He is also an elected fellow of the AIP, the OSA, the SPIE, the InstP, and the IEEE. He was President of the International Society of Optics within Life Sciences, Vice President of the Bureau of the International Commission for Optics (ICO) (Chair of the ICO Prize Committee) and a Director of the Board of the Optical Society of America (Chair of the International Council). He was awarded the Einstein Professorship (Chinese Academy of Science, 2010), the W. H. (Beattie) Steel Medal of the Australian Optical Society (2011), the Ian Wark Medal and Lecture of the Australian Academy of Science (2014), the Boas Medal of the AIP (2015) and the Victoria Prize of the Victorian Government (2016).

Orbital Angular Momentum Microlaser

N. M. Litchinitser,[1] J. Sun,[1] P. Miao,[1] Z. Zhang,[1] W. Walasik,[1] S. Longhi,[2] Liang Feng[1]
1: Department of Electrical Engineering,
The State University of New York at Buffalo,
Buffalo, NY 14260, USA
2: Dipartimento di Fisica, Politecnico di Milano
and Istituto di Fotonica e Nanotecnologie del Consiglio Nazionale delle Ricerche, Piazza L. da Vinci 32,
Milano I-20133, Italy

natashal@buffalo.edu

Structured light and structured matter are two fascinating branches of modern optics that recently started having a significant impact on each other. The synergy of complex beams, such as the beams carrying an orbital angular momentum (OAM), with nanostructured engineered media is likely to bring new dimensions to the science and applications of structured light, ranging from fundamentally new regimes of spin-orbit interaction to novel ways of information encoding for the future optical communication systems.

We will discuss fundamental optical phenomena at the interface of singular and nonlinear optics in engineered optical media and show that the unique optical properties of optical nanostructures open unlimited prospects to "engineer" light itself. We demonstrate a microring OAM laser producing an optical vortex beam with an on demand topological charge and vector polarization states. This is enabled through combined index and gain/loss modulations at an exceptional, which breaks the mirror symmetry in the lasing generation dynamics and facilitates the unidirectional power oscillation.

We show that the polarization associated with OAM lasing can be further manipulated, creating a radially polarized vortex emission. Such OAM vector laser beams might offer novel degrees of freedom for the next generation of optical communications in both classical and quantum regimes.

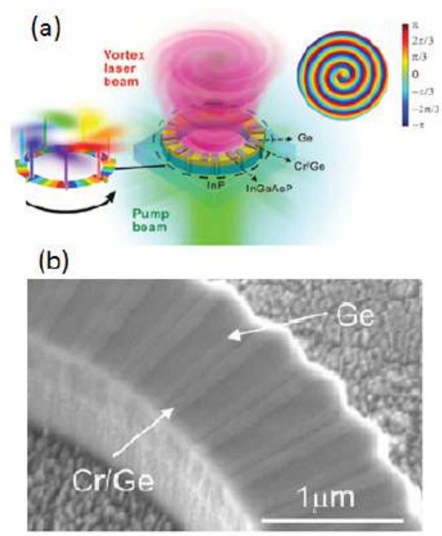


Figure 1: (a) Schematic of the OAM microlaser on an InP substrate. (b) Scanning electron microscope images of OAM microlaser. The OAM microlaser was fabricated on the InGaAsP/InP platform. Alternating Cr/Ge bilayer and Ge single-layer structures were periodically implemented in the azimuthal direction on top of the microring, presenting, respectively, the gain/loss and index modulations required for unidirectional power circulation.

References

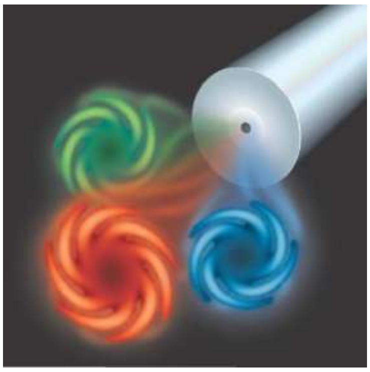
[1] P. Miao, Z. Zhang, J. Sun, W. Walasik, S. Longhi, N. M. Litchinitser, L. Feng, Orbital Angular Momentum Laser, Science 353, 464-467 (2016).

OAM in Optical Fibers:
similarities with, and differences from, OAM in free space

Siddharth Ramachandran
Boston University,
8 Saint Mary's Street, Boston, MA 02215, USA
sidr@bu.edu

Orbital angular momentum (OAM) carrying light states are natural eigensolutions of a circularly symmetric waveguide such as optical fibers. Nevertheless, for many years, they weren't thought to be especially stable in fibers because they are higher order eigenstates that are almost degenerate with several other, parasitic, higher order eigenstates. As such, small bend and birefringence induced perturbations would couple them and result in an output much like a speckle pattern normally observed from multimode fibers. A new class of optical fiber designs, where the guiding high-refractive-index region is an annular ring rather than a conventional step-index has been shown address this long-standing stability problem and OAM states in optical fibers have been propagated as long as 13 km without appreciable mixing, to date.

We will describe this class of optical fibers, and experiments conducted with them since their demonstration in 2013. As expected, OAM states in fibers share several attributes with their counterparts in free space. Likewise, they have spawned a multitude of applications ranging from information capacity scaling in tele-communications networks to fiber-based super-resolution microscopy. However, perhaps more interestingly, there are several attributes of OAM in optical fibers not observed in in free-space – these include angular momentum conservation laws leading to forbidden transitions between degenerate states, the ability to tailor the group-velocity dispersion of the states (thereby leading to interesting nonlinear optical interactions), and the ability, in contrast to free-space systems, to transmit propagation invariant non-integer OAM eigenstates.



This talk will elucidate the physics of these and other peculiarities of stably propagating twisted light in optical fibers, and discuss the applications they enable.

References

[1] N. Bozinovic et al, "Terabit-Scale Orbital Angular Momentum Mode Division Multiplexing in Fibers," Science vol. 340 (6140), p. 1545, 2013.

[2] S. Ramachandran et al, "Optical vortices in fiber," J. Nanophotonics vol. 2, p. 455, 2013.

[3] P. Gregg et al, "Conservation of orbital angular momentum in air-core optical fibers," Optica vol. 2, p. 267, 2015.

[4] P. Gregg et al, "13.4km OAM state propagation by recirculating fiber loop," Opt. Express vol. 24, 18938 (2016).

[5] P. Gregg et al, "Spin-Orbit Coupled, Non-Integer OAM Fibers: Unlocking a New Eigenbasis for Transmitting 24 Uncoupled Modes," Post-deadline, CLEO-2016.

[6] L. Yan et al, "All-fiber STED microscopy illumination system," SM4P.3, CLEO-2016.

[7] G. Prabhakar et al, "In-Fiber Monomode Octave-Spanning OAM Supercontinuum," AM4J.3, CLEO-2016.

Session 8. "Spin-orbit"

Classification of the known effects of the spin-orbit interactions of light and prediction of new effects

N.D. Kundikova
Institute of Electrophysics of UD RAS, 106 Amundsen St., Yekaterinburg, Russia
South Ural State University, 76 Lenin Av., Chelyabinsk, Russia;
kundikovand@susu.ru

Light beams can carry three types of angular momentum. The spin angular momentum is associated with polarization [1], the extrinsic orbital angular momentum is determined by the propagation path of the light beam [2], and the intrinsic orbital angular momentum is determined by the structure of the light field of the beam [3, 4]. The effect of one of the angular momenta on another angular momentum leads to the spin-orbit interactions of light [5].

The effects of the spin-orbit interactions of light can be divided into six types in the following way: 1) the spin angular momentum affects the extrinsic orbital angular momentum; 2) the extrinsic orbital angular momentum affects the spin angular momentum; 3) the intrinsic orbital angular momentum affects the extrinsic orbital angular momentum; 4) the extrinsic orbital angular momentum affects the intrinsic orbital angular momentum; 5) the spin angular momentum affects the intrinsic orbital angular momentum; 6) the intrinsic orbital angular momentum affects the spin angular momentum. These effects can be observed under reflection and refraction of light beams, in focused light beams, under light propagation in anisotropic inhomogeneous medium and in optical fibers.

The influence of two types of angular momentum on the third one suggests the existence of three new effects [5]: 1) the joint influence of the spin angular momentum and the extrinsic orbital angular momentum on the intrinsic orbital angular momentum; 2) the joint influence of the spin angular momentum and the intrinsic orbital angular momentum on the extrinsic orbital angular momentum; 3) the joint influence of the extrinsic orbital angular momentum and the intrinsic orbital angular momentum on the spin angular momentum.

One of these effects, namely, the joint influence of the spin angular momentum and the extrinsic orbital angular momentum on the intrinsic orbital angular momentum can be experimentally observed under light propagation through a multimode optical fiber coiled into a helix.

This work was partly carried out within the scope of the topic of State Assignment No. 0389- 2014-0030.

References

[1] Beth, R.A., Mechanical detection and measurement of the angular momentum of light, Phys. Rev. 50, 115-125, 1936.

[2] Landau, L.D., Lifshitz, E.M., Berestetskii, V.B., Pitaevskii, L.P., Course of theoretical physics. 4: Quantum electrodynamics, Pergamon Press, 1982.

[3] Allen, L., Beijersbergen, M.W.R., Spreeuw, J.C., Woerdman,J.P., Orbital angular momentum of light and the transformation of Laguerre-Gaussian laser modes, Phys. Rev. A 45, 8185-8189, 1992.

[4] Bliokh, K., Geometrical optics of beams with vortices: Berry phase and orbital angular momentum Hall effect, Phys. Rev. Lett. 97, 043901, 2006.

[5] Abdulkareem, S., Kundikova, N., Joint effect of polarization and the propagation path of a light beam on its intrinsic structure, Opt. Express 24, 19157-19166, 2016.

Transverse spin of light and nanoscopic position sensing

Peter Banzer
Max Planck Institute for the Science of Light, Staudtstr. 2, and Institute of Optics, Information and Photonics, Friedrich-Alexander-University Erlangen-Nuremberg, Staudtstr. 7/B2, D-91058 Erlangen, Germany
peter.banzer@mpl.mpg.de

Polarization is one of the most interesting and powerful properties of light beams or electromagnetic fields, also enabling countless applications. For a single plane wave, the purely transverse electromagnetic field can, for instance, spin around the propagation axis of the beam as a result of a phase-shift between orthogonal field components. In analogy to mechanical systems, this wave then carries a spin angular momentum related to the elliptical or circular polarization state, which in the aforementioned setting is oriented parallel or anti-parallel to the linear momentum or *k*-vector.

For realistic beam scenarios however, it is well-known that within a fully vectorial non-paraxial treatment of propagating light beams in general or upon strong spatial confinement in particular, resulting, e.g., from tight focusing, longitudinal electric and/or magnetic field components appear [1]. Especially in the latter case of tight focusing, these components can be very strong and locally also de-phased with respect to their transverse counterparts [1-5]. At such points where the electric (or magnetic) field is then consequently elliptically or circularly polarized, the spinning axis having an orthogonal component (or being fully perpendicular) with respect to the local *k*-vector, the spin angular momentum (SAM) density has transverse components or is purely transverse (see [4] for a recent review). It was shown that electromagnetic fields exhibiting transverse SAM (densities) enable a wide range of different applications [2-5]. In addition, the topical area of transverse AM is also of fundamental interest and importance [4].

In this presentation we will introduce the concept of transverse SAM in general and discuss it also in the context of a selected and very intriguing application, i.e., the localization of sub-wavelength-sized particles with Angstrom or even sub-Angstrom spatial localization accuracies [5]. The underlying principle not only allows for very high spatial but also extraordinarily high temporal resolution. This application of nanoscopic position sensing is based on the polarization-dependent excitation of the nanoparticle to be tracked and its directional emission across interfaces [4,5]. Related phenomena will be discussed in the talk as well.

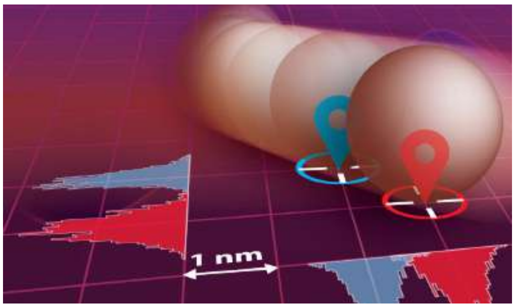


Figure 1: Schematic representation of nanoscopic particle tracking.

References

[1] B. Richards & E. Wolf, Proc. R. Soc. Lond. A 253, 358–379 (1959).
[2] P. Banzer, M. Neugebauer, A. Aiello, C. Marquardt, N. Lindlein, T. Bauer, G. Leuchs, J. Europ. Opt. Soc. Rap. Public. 8, 13032 (2013).
[3] M. Neugebauer, T. Bauer, P. Banzer and G. Leuchs, Nano Letters 14, 2546 - 2551 (2014).
[4] A. Aiello, P. Banzer, M. Neugebauer and G. Leuchs, Nat. Photon. 9, 789-795 (2015).
[5] M. Neugebauer, P. Wozniak, A. Bag, G. Leuchs, P. Banzer, Nat. Commun. 7, Article number: 11286 (2016).

High-order Poincaré Sphere Beams from the Source

D. Naidoo[1,2], F. S. Roux[2], A. Dudley[1,2], I. Litvin[1], B. Piccirillo[3], L. Marrucci[3] and A. Forbes[2]
[1] CSIR National Laser Centre, P.O. Box 395,Pretoria 0001, South Africa
[2]School of Physics, University of the Witwatersrand,Private Bag 3, Johannesburg 2050, South Africa
[3]Dipartimento di Fisica, Università di Napoli Federico II, Complesso Universitario di Monte Sant'Angelo, via Cintia, 80126 Napoli, Italy
dnaidoo3@csir.co.za

The intra-cavity selection of $LG_{0\ell}$ modes carrying OAM has proven to be non trivial as superpositions of these modes with opposite handedness often occur owing to the degeneracy in the handedness of azimuthal modes. We demonstrate the controlled intra-cavity selection of pure OAM $LG_{0\ell}$ modes of opposite handedness by implementing spin angular momentum (SAM) to OAM coupling [1]. With this we also present a direct approach to realise arbitrary vectorial vortex fields that may be described through a higher-order Poincaré sphere [2].

The excitation of pure $LG_{0\ell}$ modes is accomplished by coupling SAM to OAM by controlling the state of polarization incident on a q-plate inside a laser resonator. This is achieved by transmitting a single-mode light beam that is linearly polarized through a rotated quarter-wave plate (QWP). We implement this experimentally in a 3-mirror solid-state laser cavity where the laser cavity was constructed in a V-shape. The q-plate ($q = 1/2$) was positioned at the apex of the V with the QWP positioned to transmit both arms of the cavity.

We analysed the output of the cavity by varying the angle of rotation, β of the QWP, and the output was consistently a well-defined annular shaped beam (see Fig. 1) independent of the angle. The output polarization state was sampled from the transmitted intensity from a diffractive polarization grating (PG) and we evolve from a pure SAM state of left handedness ($\beta = -45$) to a pure SAM state of right handedness ($\beta = +45$). The selective excitation of higher-order Poincaré sphere beams is achieved by controlling the input polarization state on the q-plate ($-45 < \beta < +45$) as in Fig. 1 and through the rotation angle of the q-plate [3].

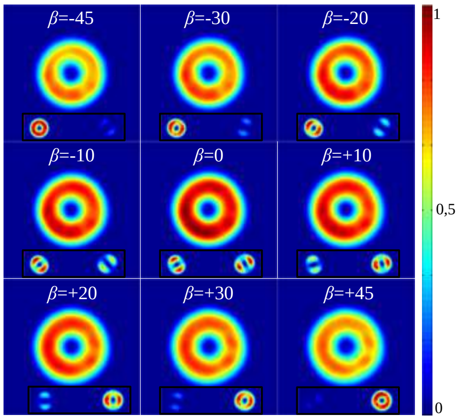


Figure 1: Higher-order Poincaré sphere beams at the output of a laser.

References

[1] Marucci, L., Manzo, C., Paparo, D., Optical spin-to-orbital angular momentum conversion in inhomogeneous anisotropic media, Phys. Rev. Lett. 96, 163905, 2006.

[2] Milione, G., Sztul, H.I., Nolan, D.A., Alfano, R.R., Higher-order Poincaré sphere, Stokes parameters, and the angular momentum of light, Phys. Rev. Lett. 107, 053601, 2011.

[3] Naidoo, D., Roux, F.S., Dudley, A., Litvin, I., Piccirillo, B., Marucci, L., Forbes, A., Controlled generation of higher-order Poincare sphere beams from a laser, Nat. Photon. 10, 327-332, 2016.

Focussing of vector vortex beams from Fresnel cones

Neal Radwell, Adam Selyem and Sonja Franke-Arnold
School of Physics and Astronomy, University of Glasgow,
G12 8QQ Glasgow, Scotland, UK
Sonja.Franke-Arnold@glasgow.ac.uk

Here we investigate the focussing properties of vector vortex beams generated by Fresnel cones, and find that they are capable of producing focal spots below the conventional diffraction limit. Furthermore, azimuthally polarised beams generated by the cones are shown to outperform traditional 'symmetric' radially polarised beams.

Vector vortex beams, containing both polarisation and phase singularities are interesting for their ability to mimic quantum states, or to produce fields beyond the scope of uniformly polarised beams. These beams can be generated by a number of methods, including the generation of arbitrary patterns using an SLM or DMD. While flexible, such systems are typically optically complex and restricted to operation at a single wavelength. More specific beams may be generated by fixed optical components such as q-plates as well as achromatic OAM generators [1, 2].

Here we discuss recent developments of our Fresnel cones [1], demonstrating a new design developed together with Gooch and Housego, nominally capable of 100% efficient generation of broadband radially and azimuthally polarised light. One of the benefits of vector vortex beams is the fact that under tight focussing they can produce focal spots below the conventional diffraction limit. Here we investigate the focussing properties of light generated with a Fresnel cone which has a net angular momentum of $\pm\hbar$ and find that the tightest focussing occurs for azimuthally polarised beams [3], with spot sizes that (slightly) outperform conventional radially polarised beams for all focussing strengths. We demonstrate this numerically using a Richards and Wolf model of strong focussing and compare a range of standard and vector vortex beams in terms of their focal spot areas and volumes (see figure 1 for an example focal volume).

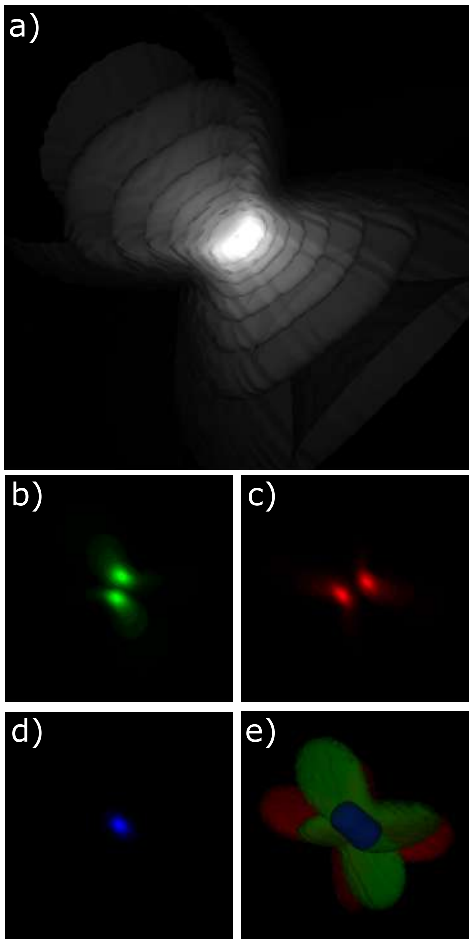


Figure 1: 3D representation of a strongly focussed radially polarised light beam. a) Total intensity. b) E_x intensity. c) E_y intensity. d) E_z intensity. e) Superposition of the E_x, E_y and E_z intensity.

References

[1] N. Radwell, R.D. Hawley, J.B. Götte and S. Franke-Arnold, Nat. Comms**7** (2016)

[2] F. Bouchard, H. Mand, M. Mirhosseini, E. Karimi and R.W. Boyd. N.J. Phys **16**(12) (2014)

[3] X. Li, P. Venugopalan, H. Ren, M. Hong

Lateral optical and Casimir forces enabled by spin-orbit locking

Francisco J. Rodríguez-Fortuño
Department of Physics, King's College London
Strand, London, WC2R 2LS, United Kingdom
francisco.rodriguez_fortuno@kcl.ac.uk

Spin-orbit locking in evanescent waves is a fundamental consequence of Maxwell's equations: the polarization of the evanescent tails of an electromagnetic waveguide mode will be elliptically polarized (transverse spin) with a handedness that depends on the propagation direction. This enables a robust example of spin-orbit interactions of light: using circularly polarized light to illuminate a small particle near a waveguide causes the particle to become circularly polarized. The scattering of the particle can then be modeled as a circularly polarized dipole source, which will therefore match and excite the electric field of the waveguide mode propagating predominantly in one direction, but not in the opposite one, depending on the illuminating polarization (Fig. 1). This constitutes a broadband and robust polarization-dependent light nano-router.

Following conservation of momentum, the lateral scattering of light into a waveguided mode is necessarily accompanied by a recoil mechanical momentum acting back on the particle, thus enabling lateral optical forces controlled with light polarization [1]. Additionally, even in the absence of illumination, we show how a small particle rotating near a surface will experience a lateral Casimir force. This is caused by an imbalance in the right-handed and left-handed polarizabilities of rotating particles. According to fluctuation electrodynamics, this implies a corresponding imbalance in right handed and left handed dipole thermal and quantum fluctuations, responsible for lateral Casimir forces acting on the rotating particle [2]. Casimir forces between spherical particles and smooth surfaces had always been considered as acting exclusively in a direction perpendicular to the surface.

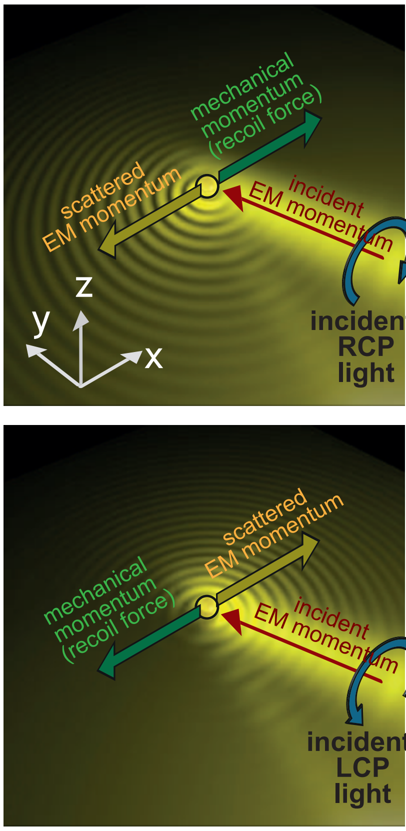


Figure 1: Polarization dependent directional scattering of an illuminated particle, and the associated lateral optical force.

References

[1] Rodriguez-Fortuno F. J. et al., *Lateral forces on circularly polarizable particles near a surface*, Nature Communications **6**, 8799, 2015.

[2] Manjavacas A. et al., *Lateral Casimir Force on a Rotating Particle near a Planar Surface*, Physical Review Letters, **118**, 133605, 2017.

Macroscopic observation of helicity-controlled lateral optical forces

H. Magallanes and E. Brasselet
Univ. Bordeaux, CNRS, LOMA, UMR 5798, F-33400 France
hernano.magallanes@u-bordeaux.fr

Optical forces driven by light-matter exchanges of linear momentum are nowadays a common tool in many areas of science to manipulate microscopic object. In general, at given light-matter interaction geometry, the magnitude of the optical force is driven by the incident photon flux and its direction may depend on the incident polarization state. In the recent years, a particular interest has been devoted to situations where the photon helicity is used as a control parameter to monitor the direction of the optical force. In particular, an intriguing situation corresponds to lateral forces (i.e., forces directed in a direction perpendicular to the average photon flux) controlled by the photon helicity.

To date, only a few experimental demonstrations of helicity-controlled lateral optical forces have been reported. This has been realized at the microscopic scale and involve force magnitudes of the order of ~10 fN [1] to ~1 pN [2]. Here we report on the direct observation of lateral forces of the order of 1 nN that induces the displacement of a solid-state macroscopic object (dimensions of several mm).

The experiment is achieved by using a structured anisotropic dielectric material enabling helicity-dependent redirection of the optical linear momentum. The sample is placed at a curved liquid-air interface that behaves as a stable capillary trap. A typical measurement is illustrated in Figure 1 where is reported the dynamics of the lateral displacement of a macroscopic parallelepiped ($0.1\times1\times6$ mm^3) illuminated by a right-handed or left-handed circularly polarized Gaussian beam with optical power is in the range 0.1 to 1 W. The relaxation of the object as the laser is switched off is also presented. Experimental data is quantitatively analyzed by a simple model.

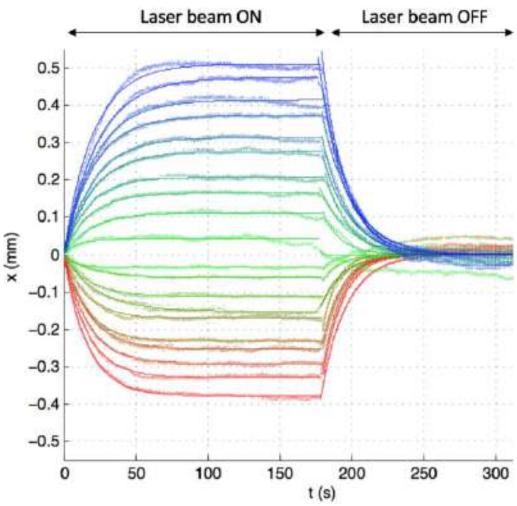


Figure 1: Lateral displacement x as a function of time of structured dielectric parallelepiped placed at a fluid interface under the influence of circularly polarized light beam of increasing incident optical power with positive (green-to-blue) and negative (green-to-red) helicity. Markers: experimental data. Curves: simulations.

These results extend previous works on unconventional optomechanics driven by the photon helicity to the macroscopic scale and extension to helicity-controlled push/pull optical forces will also be discussed. Our approach thus offer an original platform for naked eyes observation of optomechanical effects that are were restricted so far to subtle and highly demanding instrumentation.

References

[1] Sukhov S. et al., Dynamic consequences of optical spin–orbit interaction, Nature Photonics 9, 809, 2015.
[2] Antognozzi M. et al., Direct measurements of the extraordinary optical momentum and transverse spin-dependent force using a nano-cantilever, Nature Physics 12, 731, 2016.

Session 9. "Spin-Orbit & OAM Generation"

Cholesteric liquid crystal diffractive optical elements for optical vortex generation

Hiroyuki Yoshida, Junji Kobashi, Masanori Ozaki
Division of Electrical, Electronic, and Information Engineering, Osaka University
2-1 Yamadaoka, Suita, Osaka, 565-0871 Japan
yoshida@eei.eng.osaka-u.ac.jp

Optical vortices carrying orbital angular momenta have attracted great interest in the past two decades owing to their unique properties and application potential. Various methods of optical vortex generation have been proposed, such as the use of spiral phase plates, forked gratings and spatial light modulators. However, most passive methods are based on wave propagation and thus are optimized for use at a single wavelength.

We have recently proposed a new family of reflective diffractive optical elements (DOEs) based on cholesteric liquid crystals (ChLCs): a LC phase in which the constituent molecules spontaneously form a helical structure [1]. The helical modulation in the dielectric tensor gives rise to 'selective reflection', in which circularly polarized light with the same handedness as the ChLC is Bragg reflected over a wavelength range given by $n_o p - n_e p$, where n_o, n_e and p are the ordinary and extraordinary refractive indices, and helical pitch, respectively. Interestingly, changing the phase of the helical structure (helix phase) results in the phase of reflected light being modulated by twice the change in the helix phase. Because the effect occurs across the whole Bragg reflection band, efficient phase modulation can be achieved over a multiple wavelengths.

Despite the fact that the optical characteristics originates from the complex three-dimensional dielectric tensor distribution, the self-organizing nature of helix formation enables various kinds of DOEs to be fabricated by designing the two-dimensional orientational easy axis on the substrate with which the ChLC is in contact. Optical vortices can be generated from ChLCs by introducing a singular point in the helix phase distribution, as shown in Fig. 1(a). Upon observing the sample with an interference microscope (using a cylindrical reference wavefront), a helical wavefront is observed, with topological charges corresponding to the pattern on the substrate.

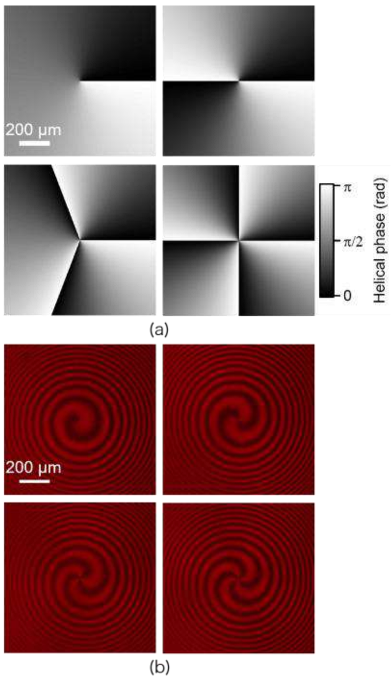


Figure 1: (a) Orientational easy axis distributions for optical vortex generation. (b) Reflection interference microscopy using a spherical reference wavefront confirms generation of optical vortices.

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References

[1] J. Kobashi, H. Yoshida, and M. Ozaki, Nat. Photonics **10**, 389 (2016).

Efficient vortex generation in sub-wavelength epsilon-near-zero slabs

A. Ciattoni[1], A. Marini[2], C. Rizza[1]
[1]Consiglio Nazionale delle Ricerche, CNR-SPIN,
Via Vetoio 10, 67100 L'Aquila, Italy,
[2]ICFO-Institut de Ciencies Fotoniques,
08860 Castelldefels (Barcelona), Spain

We show that a homogeneous, isotropic and ultra-thin (sub-wavelength thick) slab can support vortex generation [1]. We prove that such phenomenon is physically due to the mutual difference between the dynamics of transverse magnetic (TM) and transverse electric (TE) fields upon reflection and transmission. As the majority of radiation spin-orbit interaction phenomena [2], the slab vortex generation is mainly a nonparaxial effect. On the other hand, we prove that slab vortex generation in the epsilon near zero (ENZ) regime is remarkably efficient even for incident paraxial beams in spite of the very small slab thickness. Such phenomenology is unprecedent since, to the best of our knowledge, paraxial vortex generation in homogenous media (i.e. through lenses and uniaxial crystals) requires samples whose thickness is much larger than wavelength. Here, the crucial role is played by the physical ability of an ENZ slab to turn a paraxial wave, incoming from vacuum, into a nonparaxial one within the bulk, its nonparaxiality triggering the predicted slab vortex generation. The vortex generation method prosed in this letter can have important nanophotonic applications since, unlike the one based on metasurfaces, it does not require microfabrication (the ENZ slab is homogenous) and it is scalable down to very small wavelengths (exploiting the ultraviolet ENZ point of metals) where metamaterials are not available. It is also worth noting that our method, unlike the one based on inhomogeneous anisotropic media (q-plates), is based on a very simple setup that does require neither preparation nor external biasing by electric field, it operates in sub-wavelength thick slabs and it can be used even up to the ultraviolet frequencies.

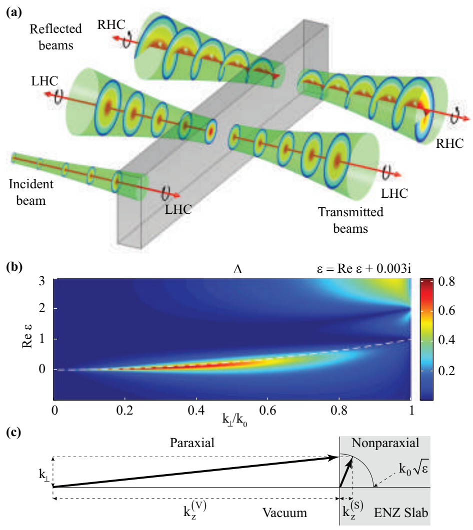

Figure 1: (a) Geometry of the vortex generation process. The incident beam is LHC polarized with no topological charge. Both the reflected and the transmitted beams have a LHC component with no topological charge and a RHC component containing a second-order vortex. (The beams in the figure are spatially separated for clarity purposes). (b) TM-TE transmissivity asymmetry $\Delta = |t_{TM} - t_{TE}|$ versus $k_\perp/k_0$ and $\mathrm{Re}\,\varepsilon$. The white dashed line is the curve $k_\perp = k_0\sqrt{\mathrm{Re}\,\varepsilon}$. (c) Excitation of nonparaxial waves within the ENZ slab by vacuum paraxial waves.

References

[1] A. Ciattoni, A. Marini and C. Rizza, Phys. Rev. Lett. 118, 104301, 2017.

[2] L. Marrucci, E. Karimi, S. Slussarenko, B. Piccirillo, E. Santamato, E. Nagali, and F. Sciarrino, J. Opt. 13, 064001 (2011).

Tailored singular vector beams in the paraxial and non-paraxial regime

E. Otte[1], K. Tekce[1], C. Alpmann[1], C. Denz[1]

[1]Institute of Applied Physics, University of Muenster, Corrensstr. 2/4, 48149 Münster, Germany
eileen.otte@uni-muenster.de

Singularities are a wide spread phenomenon whose properties are investigated and applied in various fields as astrophysics, material science, as well as in optics. In the latter, optical singularities facilitate a broad range of applications in e.g. super-resolution microscopy, data communication, material machining or optical manipulation [1]. Further, fundamental investigations on these singularities present a cutting-edge topic in the field of singular optics, which includes still a number of unsolved issues. Beside well studied scalar phase singularities, especially vectorial singularities in polarization structured light are discussed currently, wherefore advanced generation methods are required. Recently, e.g. holographic configurations have facilitated to access tailored polarization structures. However, in particular the analysis of complex, higher-order polarization structures and singularities [2], especially outside the paraxial regime, is still in its infancy, demanding further investigations.

With our contribution, we fill this gap by exemplarily investigating higher-order V-point singularities in singular vector fields in the paraxial as well as in the non-paraxial regime. First, we analyze V-points in tailored, paraxial vectorial structures, revealing the relation between singularity order and the light field's transverse shape. Following, we combine higher-order phase and polarization singularities to study their interaction upon propagation. For this purpose, we apply unfolding phase vortices to evoke striking propagation behavior of included V-points. We show experimentally as well as numerically that their evolution resembles singularity explosions, in which index conservation rule [3] is kept.

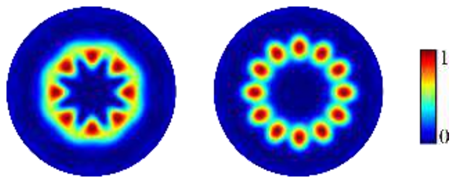

Figure 1: Examples of numerically calculated focal intensity landscapes of tightly focused vector fields of positive (left) and negative (right) order.

Beyond these investigations, we demonstrate numerically the application of higher-order vector beams for shaping focal intensity landscapes in the non-paraxial regime. By solving Richard and Wolf's integrals, we obtain three-dimensional polarization structures with a transverse total intensity that resembles dark stars or bright flowers [4] (see Fig. 1). Moreover, we find a relation between the order of the incident vectorial field and the resulting distribution of focal field components. Our findings facilitate shaping focal light fields for specific application as e.g. in advanced microscopy.

References

[1] Rubinsztein-Dunlop, H. *et al.*, Roadmap on structured light, J. Opt.19, 013001, 2017.
[2] Otte, E. *et al.*, Higher-order polarization singularitites in tailored vector beams, J. Opt. 18, 074012, 2016.
[3] Freund, I., Polarization singularity indices in Gaussian laser beams, Opt. Comm. 201, 251–270, 2002.
[4] Otte, E. *et al.*, Tailored intensity landscapes by tight focusing of singular vector beams, Opt. Express, accepted for publication, 2017.

Diffractive optics for OAM-mode division multiplexing

G. Ruffato, M. Massari, E. Gazzola and F. Romanato
Department of Physics and Astronomy 'G. Galilei',
Via Marzolo 8, 35131 Padova, Italy
Laboratory for Nanofabrication of Nanodevices (LaNN),
C.so Stati Uniti 4, 35127 Padova, Italy
gianluca.ruffato@unipd.it

The worldwide overwhelming traffic demand is fostering mode-division (MDM) as a novel multiplexing technique in order to increase the information bandwidth and prevent the menace of the so-called capacity crunch of today's optical networks. Recently, modes carrying orbital angular momentum (OAM) of light have been considered as a promising solution for MDM and orthogonal optical vortices have been demonstrated to support independent information channels both in free-space and in optical fibers. The design of next-generation optical transceivers requires the integration of novel optical elements for the generation, multiplexing and sorting of OAM channels.

Here we present a review of the several designs and configurations that we have recently conceived, fabricated and tested for the (de)multiplexing of optical vortices with integrated diffractive optics. Under the requirement of miniaturized, passive and efficient optics, two configurations have been considered: diffractive OAM-mode analyzers (Figure 1.a) [1] and diffractive *log-pol* transformation optics [2, 3] (Figure 1.b-c). While the first solution provides a degree of freedom in choosing the far-field channel constellation [1], the latter one exhibits higher efficiency values and its remarkable optical performance has been demonstrated for both the generation and sorting of OAM beams [3] (Figure 1.d-f). Samples have been designed with custom numerical codes and fabricated with 3D electron-beam lithography on PMMA resist layer over transparent glass substrate, exhibiting low roughness and high resolution. Optical characterization has been performed both in free-space and in commercial optical fibers, providing promising efficiency and cross-talk values (<-15 dB) for industrial applications in the telecom field.

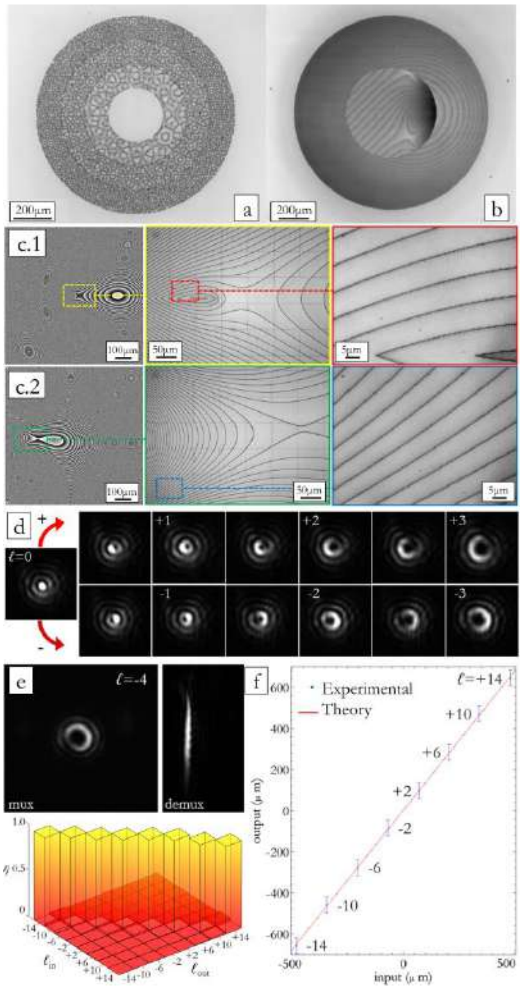

Figure 1: Different diffractive optics designs for (de)multiplexing of optical vortices: OAM-mode analyzer for combined OAM-mode and spatial- division multiplexing (a, [1]), elements for *log-pol* optical transformation: un-wrapper (c.1), phase-corrector (c.2), integrated version (b, [2]), 256 phase levels. Multiplexing (d) and sorting (e, f) experimental characterization.

References

[1] Ruffato, G., Massari, M., Romanato, F., *Sci. Rep.* **6**, 24760, 2016.
[2] Ruffato, G., Massari, M., Romanato, F., *Opt. Lett.* **42**, pp. 551-554, 2017.
[3] Ruffato, G., Massari, M., Parisi, G., Romanato, F., *Opt. Express* **25**, pp. 7859-7868, 2017.

Monstar Patterns of Spatially-Variable Polarization

E.J. Galvez,[1] B. Khajavi,[1,2] B.A. Cvarch,[1] J.A. Jones,[1] B. Piccirillo,[3] and L. Marrucci,[3]
[1]Colgate University, Hamilton, New York, USA,
[2]Florida Atlantic University, Boca Raton, Florida, USA
[3]Università di Napoli Federico II, Complesso di Monte S. Angelo, Napoli, Italy
egalvez@colgate.edu

We present our investigations of spatially-variable polarization of light that contain a rotational dislocation, or disclination. In particular we focus on a class of patterns known as monstars, which are asymmetric. We prepare these patterns by two means. One involves the superposition of three spatial modes, two with topological charges $+\ell_1$ and $-\ell_1$ in right circular polarization, and a third mode with ℓ_2 in left circular polarization. We do this experimentally using spatial-light modulators. We show that monstars can have a disclination index that can be positive negative or zero [1, 2].

More recently, we prepared monstar patterns in a different way: by passage of a circularly polarized Gaussian beam through one or more specially designed q-plates. These plates have a distribution of liquid-crystal directors that follow an elliptical symmetry[3]. Figure 1(a) shows the disclination pattern that was encoded onto the directors of the q-plate. The orientation is given by

$$\psi = \tan^{-1}(a \tan\phi), \tag{1}$$

where $q = 1/2$, a is an asymmetry, and ϕ is the angular coordinate.

By inputing circularly polarized light onto a q-plate with $a = 4$, the light acquired the disclination of the q-plate. Figures 1(c) and (d) show the modeling and measurements of the space-variant polarization pattern. The measured patterns were obtained by imaging polarimetry. Monstars have characteristic radial lines (shown in red in Fig. 1(a)), which appear when the orientation relative to the radial direction, as it decreases with angle, undergoes a non-monotonic inflexion. We confirmed that the measured patterns were indeed monstars by measuring this non-monotonic variation, as shown in Fig. 1(b).

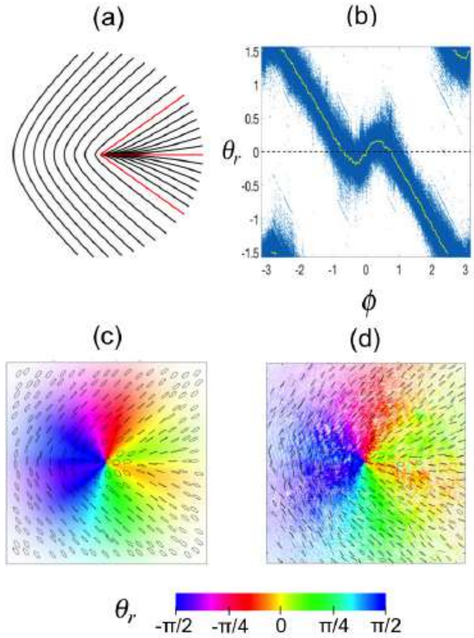

Figure 1: (a) Monstar pattern encoded in the directors of an elliptically symmetric q-plate; (b) radial orientation of measured points; (c) modeling of the pattern; and (d) measurements. Color coding denotes orientation of the polarization ellipse relative to the radial direction, with yellow denoting radial orientation.

This work was funded by NSF grant PHY-1506321.

References

[1] B. Khajavi and E.J. Galvez, J. Opt. **18**, 084003 (2016).

[2] E.J. Galvez and B. Khajavi, J. Opt. Soc. Am. A **34**, 568-575 (2017).

[3] B. Piccirillo, V. Kumar, L. Marrucci, and E. Santamato, Proc. SPIE **9379**, 937907 (2015).

Poster Session 1.

Visual Representations of the Polarization States of Photon Vortices

Dennis Afanasev, Andrei Afanasev
The George Washington University
Washington, D.C. 20052, USA
dennisafa@gwu.edu

Optical vortices may be characterized with very complicated polarization patterns [1]. Vectors can describe the polarization states of optical vortices in particular on higher order Poincare sphere [2].

In this work, we take advantage of stokes parameters and describe polarization of the optical vortex by a point on a tertiary (or Dalitz) plot.

Evolution of polarization is described by a trajectory on a tertiary plot. We also use one-to-one mapping of tertiary plot representation to color-coding (RGB) to present polarization states of the entire optical vortex wave front. We demonstrate this approach for the evolution of optical vortex polarizations during propagation in atomic matter, according to theoretical calculations of ref. [3]

Figure 1 shows the tertiary diagram used for color coding of the polarization states. Demonstrated, the upper corner corresponds to 100% circular polarization, while both lower corners describe linear polarizations. Figure 2 shows an area of circular polarization on the optical vortex wavefront developing from 100% linear polarized optical vortex.

We believe that the proposed color coding method will be useful to describe polarization evolution of optical vortices.

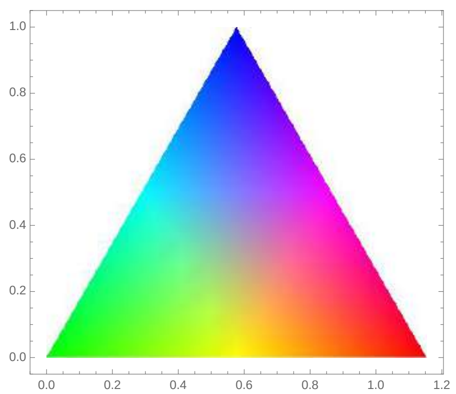

Figure 1. Polarization triangle for RGB color coding of polarization states

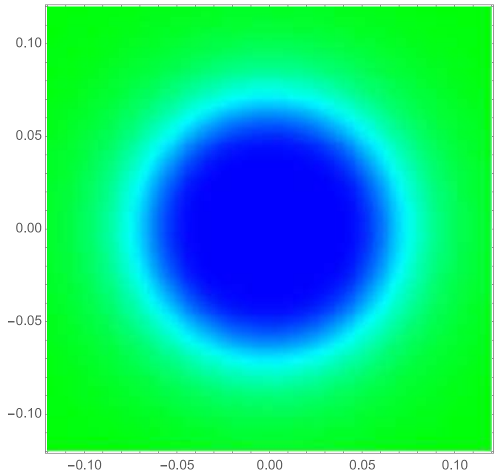

Figure 2. Evolution of optical vortex polarization as a result of propagation in atomic matter. The axes show the position on a transverse plane in units of wavelength.

References

[1] F. Cardano et al., Applied Optics **10**, C1 (2012).
[2] G. Milione et al., Phys. Rev. Lett. **107**, 053601 (2011).
[3] A. Afanasev, E. Carlson, M. Solyanik, *Circular Dichroism of Twisted Photons in the Non-Chiral Atomic Matter*, eprint arXiv: 1704.07495.

Ghost imaging using photons that have not interacted

M. Agnew[1,*], N. Bornman[2], D. Faccio[1], A. Forbes[2], J. Leach[1]
[1]Heriot-Watt University, Edinburgh, UK
[2]University of Witwatersrand, Johannesburg, South Africa
[*]ma1076@hw.ac.uk

Ghost imaging is a technique by which the image of an object is reconstructed using the combined information of two different detectors [1]. One is a bucket detector that detects the light that has interacted with the object. Simultaneously, correlated light that has not interacted with the object is detected using a spatially resolving sensor. Using the correlation of these two signals, the object can be reconstructed. The correlated light can come from a variety of sources, including a pair of entangled photons or classical light split with a beamsplitter.

Here we perform ghost imaging using two photons that have never interacted. We produce two pairs of entangled single photons, AB and CD, using spontaneous parametric downconversion (SPDC) in two β-barium borate (BBO) crystals (see Fig. 1). We combine photons B and C on a beamsplitter and observe Hong-Ou-Mandel interference with two multi-mode fibres (MMFs) connected to bucket detectors. This implements a projection onto all high-dimensional anti-symmetric states, thus correlating photons A and D [2].

Each of the remaining photons is then incident on a spatial light modulator (SLM). An SLM is composed of liquid crystals and can be used to change the phase and intensity of light. When combined with a single-mode fibre (SMF) and bucket detector, it can implement a spatial measurement of the incident light. In our experiment, we display a mask on SLM A, which serves as the object to recover. We cycle through different spatial measurements on SLM D, which serves as the spatially resolved detector.

We will discuss the theory, which predicts that the detected image in D is the contrast reversed image in A. We believe this effect

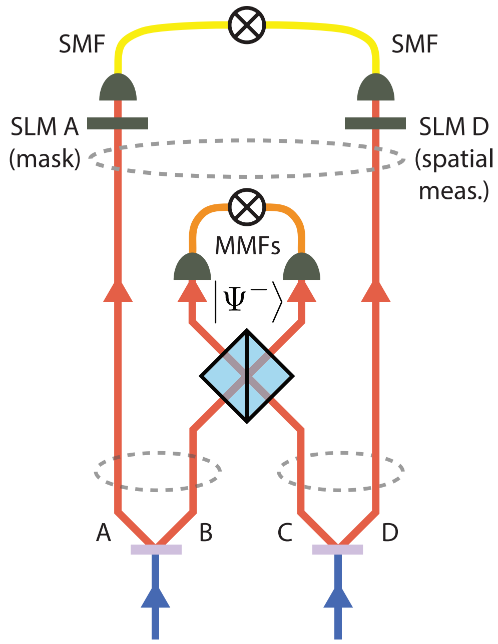

Figure 1: A simplified version of the experimental setup.

relies partially on quantum effects in that the use of two pairs of classically correlated beams in the same manner would seem to produce contrast reversal, though with lower contrast than the quantum case. We will also discuss the progress of the experimental realisation.

References

[1] D. V. Strekalov, A. V. Sergienko, D. N. Klyshko, and Y. H. Shih, “Observation of Two-Photon “Ghost” Interference and Diffraction,” *Physical Review Letters*, vol. 74, no. 18, p. 3600, 1995.

[2] Y. Zhang, F. S. Roux, T. Konrad, M. Agnew, J. Leach, and A. Forbes, “Engineering two-photon high-dimensional states through quantum interference,”

Science Advances, vol. 2, no. 2, p. e1501165, 2016.

Revealing pump amplitude in parametric down-converted photons

Ali Anwar[1], Pravin Vaity[1,2], Chithrabhanu P[1], R. P. Singh[1]
[1]Physical Research Laboratory, Ahmedabad, Gujarat - 380009, India.
[2]IMTEK, University of Freiburg, Germany.[†]
alianwar@prl.res.in

Spontaneous parametric down-conversion (SPDC) is a well-known process used to generate twin photons that are correlated in various degrees of freedom. It has been experimentally shown that the angular spectrum of the pump beam gets transferred to the twin photons generated in SPDC [1, 2] due to the spatial correlation between them. However, signal or idler part of parametric down-converted light is in general spatially incoherent. Although the modal signature of the pump is partially observed in the SPDC photon distribution [3], one cannot evidently confirm the modal distribution of pump in SPDC.

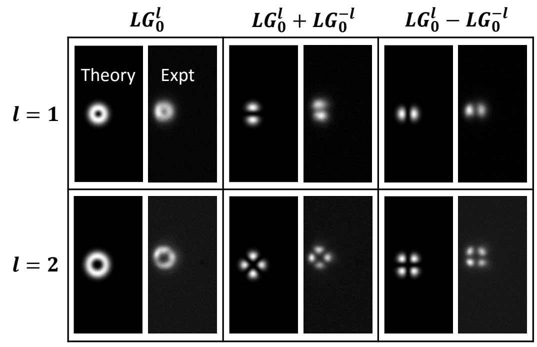

Figure 1: Angular spectrum of parametric down-converted photons at the Fourier plane of the closed-to-minimum aperture when the non-linear crystal is pumped with optical vortices of orders 1, 2 and their equal but oppositely charged coaxial superpositions.

Here, we show that the amplitude distribution of the pump beam is revealed in the Fourier plane of SPDC distribution restricted by an aperture. This distribution is observed at any part of the annular ring of SPDC. To verify the experiment with theory, we model the SPDC process for different pump modes with the Fourier imaging of SPDC restricted by the aperture. The model goes in good agreement with the experimental results. Phase measurements showed that the SPDC mode distribution does not contain the azimuthal phase corresponding to that of the pump mode. We also observe a considerable shift of the image plane from the actual Fourier plane, when the aperture is gradually opened. The shift of the Fourier image of down-converted photons affects the quality of spatial mode-based projection in various quantum correlation experiments with parametric down-converted photon pairs. The results may be useful in applications of SPDC in quantum imaging and quantum information.

References

[1] C. H. Monken, P. H. S. Ribeiro, and S. Pádua, Transfer of angular spectrum and image formation in spontaneous parametric down-conversion, Phys. Rev. A 57, 3123, 1998.

[2] Verónica Vicuña-Hernández, Héctor Cruz-Ramírez, Roberto Ramírez-Alarcón, Alfred B. U'Ren, Classical to quantum transfer of optical vortices, Opt. Exp. 22, 20027, 2014.

[3] S. Prabhakar and S. G. Reddy and A. Aadhi, A. Kumar, P. Chithrabhanu, G.K. Samanta and R.P. Singh, Spatial distribution of spontaneous parametric down-converted photons for higher order optical vortices, Opt. Commun 326, 64-69, 2014.

Spatially modulated thermal light in atomic medium for enhanced ghost imaging

Mingtao Cao[1,2], Jinwen Wang,[1] Hong Gao[1]
1. Laboratoire Kastler Brossel, UPMC-Sorbonne Universités, CNRS
ENS-PSL Research University, Collège de France, 4 place Jussieu, 75005 Paris, France
2. Key Laboratory of Quantum Information and Quantum Optoelectronic Devices
Shaanxi Province, Xi'an Jiaotong University, Xi'an 710049, China
honggao@xjtu.edu.cn

Recent years have seen vast progress in image modulation based on atomic medium, with potential applications in both classical optical imaging and quantum imaging region. However, there is rare evidence to show how thermal light images interact with electromagnetically induced transparency medium. In this work, we experimentally demonstrated the pseudo-thermal light modulation on coherent population trapping condition in ^{87}Rb vapour. By introducing the Laguerre-Gaussian (LG) beams as the control beam and encoding speckle as the probe beam, we obtained much shaper speckle patterns after the atom cell compared with that in free space. The spatially modulated thermal light was then used to enhance the image resolution in ghost imaging due to the sharper speckle, since the ghost image resolution is severely relied on speckle's transverse coherent length. Our results are very promising to have potential applications in high resolution ghost imaging and image metrology, image processing and biomedical imaging in the future.

In our previous work, we have already found that the compressed speckles from the atom cell pushed ghost imaging resolution better than that in free space [1]. In this work, we will report an even better experimental demonstration of speckle compression with different LG coupling beam in the EIT medium, which was expected to improve ghost imaging resolution more effectively. By coding different LG charges onto the control beam, then applying them to the atom vapor, we found that the speckle's profiles became much sharper. And it is impressive to find the resolution of ghost imaging was greatly enhanced, which is shown in Fig. 1. From Fig. 1(a)-(c), the resolution of GI became much better with the increment of the number l, that is because the control beam intensity profile was getting sharper with lager l number, which made the speckles compressed more and more.

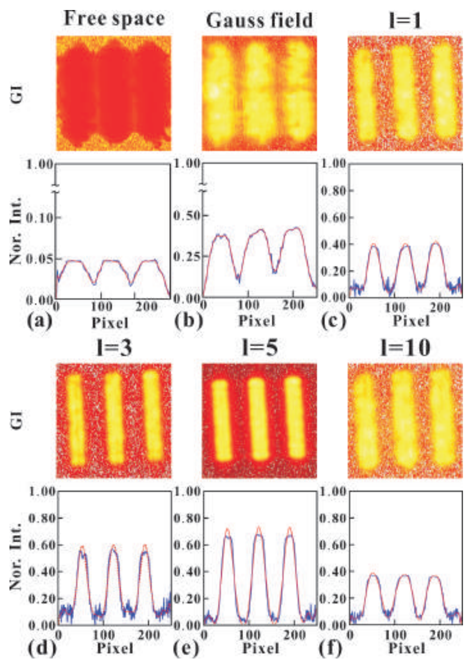

Figure 1: GI results with different control beam profile. (a)-(d) are the cases for control LG mode with $l = 1$, $l = 3$, $l = 5$ and $l = 10$, respectively.

References

[1] Cao, M., Yang, X., Wang, J., Qiu, S., Wei, D., Gao, H. & Li, F. Resolution enhancement of ghost imaging in atom vapor. Optics Letters. **41**(22), 5349-5352 (2016).

Exploring topological phases in quantum walks of twisted light

F. Cardano[1],*, A. D'Errico[1], A. Dauphin[2], M. Maffei1,[2], C. de Lisio[1], B. Piccirillo[1], G. De Filippis[1], V. Cataudella[1], E. Santamato[1], L. Marrucci[1], M. Lewenstein[2,3], P. Massignan[2]

[1]Dipartimento di Fisica, Università degli Studi di Napoli Federico II,
Complesso Universitario di Monte Sant'Angelo, Via Cintia, 80126, Napoli, Italy.
[2]ICFO-Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology, Av. Carl Friedrich Gauss 3, Castelldefels 08860, Spain.
[3]ICREA—Institucio´ Catalana de Recerca i Estudis Avanc¸ ats, Pg. Lluis Companys 23, Barcelona E-08010, Spain
*filippo.cardano2@unina.it

We present the realisation of a photonic quantum walk based on the Orbital Angular Momentum (OAM) of light [1,2], showing the topological phases that characterise periodically modulated 1D systems (Floquet topological insulators). These phases of matter are typically investigated through the analysis of protected edges states. Following a different approach, here we rather focus our attention to bulk observables. In particular, we find that important information about the system topology can be extracted from the statistical moments associated with photons OAM spectrum; while varying a control parameter that determines the value of the invariants, these show marked differences in distinct phases and exhibit abrupt variations at the transition points [2]. Quite remarkably, specific combinations of such moments (associated with orthogonal polarization components) are quantised and proportional to the topological invariants [3], hence can be used to detect topological phases. Such quantisation arises in absence of any external force, and it is robust to perturbations that preserve the system symmetries. We confirm experimentally these results in our photonic platform, and report the measurement of complete topological invariants characterising this class of systems [3,4]. We demonstrate that the method we propose is widely applicable in a variety of different 1D topological systems, and readily implementable in experimental platforms that are presently used to simulate these exotic phases.

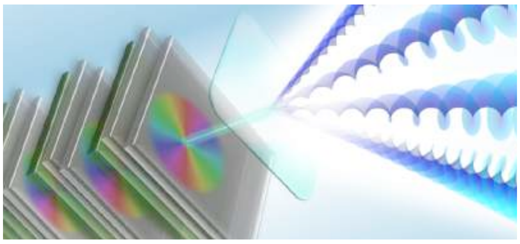

Figure 1: Pictorial representation of our photonic system. A collimated light beam passes through a sequence of optical elements; these are engineered so that they introduce the spin-orbit coupling giving rise to the quantum walk dynamics in the polarization-OAM space.

References

[1] Cardano F. et al., *Sci. Adv.* **1**, e1500087 (2015).

[2] Cardano F. et al., *Nat. Comm.* **7**, 11439 (2016).

[3] Cardano F. et al., *Nat. Comm.* **8**, 15516 (2017).

[4] Asboth J. K. and Obuse H. *Phys. Rev. B* **88**, 121406(R) (2013).

Unfolding Laguerre-Gaussian beams with OAM

A. Jaimes-Nájera[1], J. A. Ugalde-Ontiveros[1], J. Mendoza-Hernández[2], M. D. Iturbe-Castillo[1], S. Chávez-Cerda[1]
[1]Instituto Nacional de Astrofísica, Óptica y Electrónica
Luis E. Erro No.1, Tonantzintla, Puebla 72840, México
[2] FCFM, Benemérita Universidad Autónoma de Puebla, Puebla, 72570, México
sabino@inaoep.mx

The first laser and Laguerre-Gaussian beams (LGB) appeared in the same year 1960. They are intimately related as the latter can be the internal modes of a resonant laser cavity as well as the output beam of the same laser cavity allowing them to describe paraxial optical beams propagating in free space[1, 2].

In this sense, the LGB are found as the closed analytical solutions of the free space paraxial wave equation in cylindrical coordinates [3]. These beam are characterized by two eigenvalues, one associated to the radial coordinate and a second one to the azimuthal coordinate. The first one describe the transverse finite ringed structure of the beam while the second one their content of Orbital Angular Momentum (OAM).

In a recent publication it was demonstrated that, similar to Bessel beams, the multiringed LGB with OAM have the property of self-healing [4]. Nevertheless, an explanation on physical grounds of the observed phenomenon for LGB was not given.

It is now well known that the reason why a Bessel beam undergoes self-healing is in fact that they are the continuous superposition of two conical wavefields. This is, the the Bessel beam can be unfolded into outgoing and incoming wavefields [7, 6].

We demonstrate in this work that LGB with OAM can also be unfolded as Bessel beams do. Their wavefield components have conical features, see Fig.1, and such conical wavefields allow for a concise and physical explanation of the observed property of self-healing. We have obtained the closed analytical solutions that allow to explain this behavior and fully characterize the self-healing process. Our result also demonstrates that LGB have unknown and unexplored properties and that in some cases it is possible to fall into apparent inconsistencies but after a rigorous analysis we conclude that they are due to the paraxial approximation.

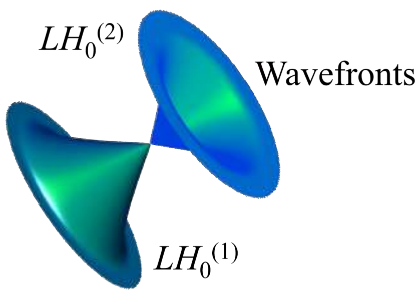

Figure 1: Wavefronts that on supersposition create the Laguerre-Gauss beams, case for OAM index $m = 0$.

References

[1] G. Goubau and F. Schwering, IRE Trans. Ant. and Prop. AP-9, 248-256 (1961).

[2] G.D. Boyd and H. Kogelnik, Bell Syst. Tech. J. 41, 1347-1369 (1962).

[3] A. E. Siegman, *Lasers* (University Science Books, 1986).

[4] J. Mendoza-Hernández, *et. al.*, Opt. Lett. 40, 3739-3742, 2015.

[5] Y. Cai, X. Lu and Q. Lin Opt. Lett. 28, 1084-1086 (2003).

[6] S. Chávez-Cerda, J. Mod. Opt. 46, 923-930, 1999.

[7] I. Litvin, M. McLaren, A. Forbes, Opt. Commun. 282, 1078-1082, 2009.

Talbot Effect in Optical Lattices with a Topological Charge

Caio V. C. Mendes[1], José S. Rodrigues[2], Eduardo J. S. Fonseca[1], Alcenísio J. Jesus-Silva[1]
Instituto de Física, Universidade Federal de Alagoas, Maceió, Alagoas 57061-970, Brazil
[2]Instituto Federal do Piauí, Piauí, Brazil
alcenisio@fis.ufal.br

The Talbot effect, also referred to as self-imaging, is of the phenomena manifested by a periodic repetition of planar field distributions in certain types of wave fields. This phenomenon has been demonstrated in areas such as acoustics, electron microscopy, plasmonics, x-ray, and atomic waves. In optics, long ago, it was proved that this phenomenon is a consequence of the diffraction with Talbot length expressed as $z_T = d^2/\lambda$. Here d and λ are the period of the structure and the wavelength of the incident light, respectively.

In fact, Talbot effect has been observed in many different types of apertures. Here we explored this effect using the superposition of Q-plane waves. This superposition results in an optical lattice. To control the Talbot effect we interfere two optical lattices with different modulus of the wave vectors and with different topological charge.

Following [1], the superposition of two Q-plane waves of different spatial frequencies can be described as:

$$f(x,y) = c\sum_{n=0}^{Q-1}\{\exp(i\theta_{1n})\exp[i2\pi\rho_1(x\cos(n\Delta\theta)+y\sin(n\Delta\theta))] + \exp(i\theta_{2n})\exp[i2\pi\rho_2(x\cos(n\Delta\theta)+y\sin(n\Delta\theta))]\}. \quad (1)$$

where r and θ are the radius and angle in cylindrical coordinates, respectively. $\rho_i = k_{T_i}/2\pi$ is the spatial frequency, $\theta_{ni} = p_i(n\Delta\theta)$, where $i = 1,2$ and $\Delta\theta = 2\pi/Q$. p is an integer number and represents the topological charge. The idea is to see the interferences along z-direction. Using the Fresnel diffraction theory, it is not difficult to show that the Talbot length is,

$$z_T = \frac{2m}{\lambda(\rho_2^2-\rho_1^2)}, \quad (2)$$

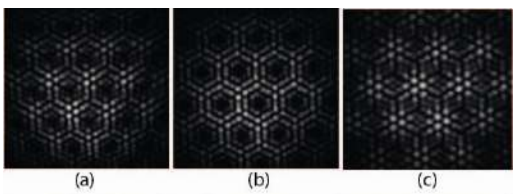

Figure 1. Experimental images showing the Talbot Effect. $Q=3$; $p_1=1$; $p_2=2$; $\lambda = 514nm$; (a)-(f) $\rho_1 = 1mm^{-1}$ and $\rho_2 = 1,5mm^{-1}$; (a), $z = 65$; (b) $z = 95$ mm; (c) $z = 109$ mm; (d) $z = 137$ mm; (e) $z = 159$ mm; (f) $z = 189$ mm.

where m is an integer number and λ is the wavelength.

Equation (2) shows that the Talbot length does not depend on the topological charge and it is inversely proportional to the difference of the squares of the spatial frequencies.

Figure 1 shows an optical lattice with the Talbot Length of $z_T = 42mm$. It is important to notice that the topological charge change the optical lattice but not the Talbot Length.

References

[1] Victor Arrizón, David Sánchez-de-la-Llave, Guadalupe Méndez, and Ulises Ruiz, Efficient generation of periodic and quasi-periodic non-diffractive optical fields with phase holograms, Optics Express, 19, 10553-10562, 2011.

Extreme ultraviolet vortices from a free electron laser

G. De Ninno
Sincrotrone Trieste, Italy
University of Nova Gorica, Slovenia
(*on behalf of the authors listed in [1]*)
giovanni.deninno@elettra.eu

Extreme-ultraviolet vortices may be exploited to steer the magnetic properties of nanoparticles, increase the resolution in microscopy, gain insight into local symmetry and chirality of a material, and might even be used to increase the bandwidth in long-distance space communications. However, in contrast to generation of vortex beams in the infrared and visible spectral regions, production of intense, extreme-ultraviolet and X-ray optical vortices still remains a challenge.

Here [1], we demonstrate two methods to produce intense femtosecond XUV vortex beams at a free-electron laser (FEL). One relies on the recently discovered mechanism that harmonics emitted by electrons in spiral motion carry OAM, while the other uses a spiral zone plate that simultaneously generates an optical vortex and focuses the beam (which is required for a number of applications). The latter method allows us to generate a micron-size optical vortex with a peak intensity approaching , paving the way to nonlinear optical experiments with vortex beams at short wavelengths.

The top panel of Fig. 1 shows the ring-like intensity distribution (characteristic of an optical vortex) of the 2nd harmonic emission (wavelength of 15.6 nm) produced by the FERMI FEL. In the bottom panel the ring-like mode was made to interfere with a "standard" Gaussian beam, producing a spiral intensity pattern, confirming the vortex nature of the beam shown in the top panel.

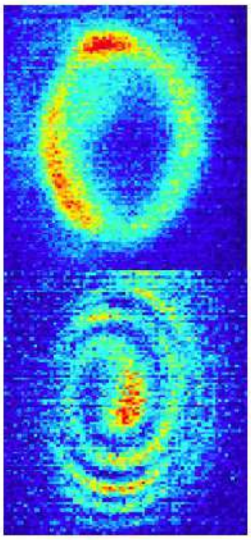

Figure 1: Generation of an XUV OAM beam at the FERMI FEL at the 2nd harmonic. Top: intensity, bottom: spiral pattern due to interference with a Gaussian beam.

The results we present constitute the first experimental demonstration of FEL vortex beams in the XUV and have the potential to open new research directions in the field of light-matter interactions at short wavelengths under extreme conditions.

References

[1] P. R. Ribič, B. Rösner, D. Gauthier, E. Allaria, F. Döring, L. Foglia, L. Giannessi, N. Mahne, M. Manfredda, C. Masciovecchio, R. Mincigrucci, N. Mirian, E. Principi, E. Roussel, A. Simoncig, S. Spampinati, C. David, G. De Ninno, submitted.

Tunable orbital angular momentum in high-harmonic generation

G. De Ninno
University of Nova Gorica, Slovenia
Sincrotrone Trieste, Italy
(*on behalf of the authors listed in [1]*)
giovanni.de.ninno@ung.si

Optical vortices are currently one of the most intensively studied topics in optics. These light beams, which carry orbital angular momentum (OAM), have been successfully utilized in the visible and infrared in a wide variety of applications. Moving to shorter wavelengths may open up completely new research directions in the areas of optical physics and material characterization. Here [1], we report on the generation of extreme-ultraviolet optical vortices with femtosecond duration carrying a controllable amount of OAM. From a basic physics viewpoint, our results help to resolve key questions such as the conservation of angular momentum in highly nonlinear light–matter interactions, and the disentanglement and independent control of the intrinsic and extrinsic components of the photon's angular momentum at short-wavelengths. The methods developed here will allow testing some of the recently proposed concepts such as OAM-induced dichroism, magnetic switching in organic molecules and violation of dipolar selection rules in atoms.

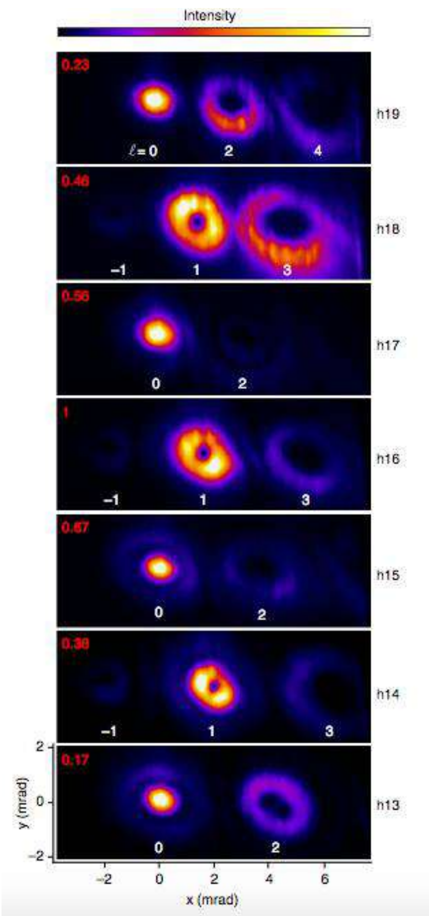

Figure 1: Single-shot images for different harmonic orders acquired using a CCD, in identical generating conditions. Each mode is labeled by its topological charge *l*. The number of photons incident on the CCD (after a metallic filter) for h16 was around $7x10^6$.

References

[1] D. Gauthier, P. Rebernik Ribic, G. Adhikary, A. Camper, C. Chappuis, R. Cucini, L.F. Di Mauro, G. Dovillaire, F. Frassetto, R.Geneaux, P. Miotti, L. Poletto, B. Ressel, C. Spezzani, M. Stupar, T. Ruchon, & G. De Ninno, Nat. Commun. 2017, 8, 14971

Measuring the complex Orbital Angular Momentum spectrum and spatial mode decomposition of structured light beams

Alessio D'Errico, Raffaele D'Amelio, Bruno Piccirillo, Filippo Cardano, Lorenzo Marrucci,

Dipartimento di Fisica, Università di Napoli Federico II, Complesso Universitario di Monte Sant'Angelo, Via Cintia, 80126 Napoli, Italy

derrico@fisica.unina.it

In general, a paraxial light beam can be decomposed in a complete set of helical modes (for example Laguerre-Gauss modes), which are eigenstates of the orbital angular momentum of light (OAM). Thus, a full characterization of the beam can be achieved by reconstructing both the OAM power spectrum and the radial profile of amplitude and phase of the single helical modes.

Here we propose, and experimentally validate [1], a simple technique based on the analysis of interference patterns obtained superimposing the unknown structured light beam with a known reference field (such as a Gaussian beam) that allows the full reconstruction of a structured light field. The analysis consists into recording the interference pattern and performing, at different radial positions, Fourier transform with respect to the azimuthal variable. The result gives some complex functions of the radial coordinate. Integration of the absolute square along the latter returns the full OAM power spectrum.

Moreover, the radial structure of the Fourier transform allows the reconstruction of radial amplitude and phase of the helical modes that are contained in the OAM spectrum.

The remarkable feature of this technique is that all the information of the light field is contained in a few images (at most four). This, together with the minimal equipment required, makes this new approach a valid tool for structured light characterization experiments [2].

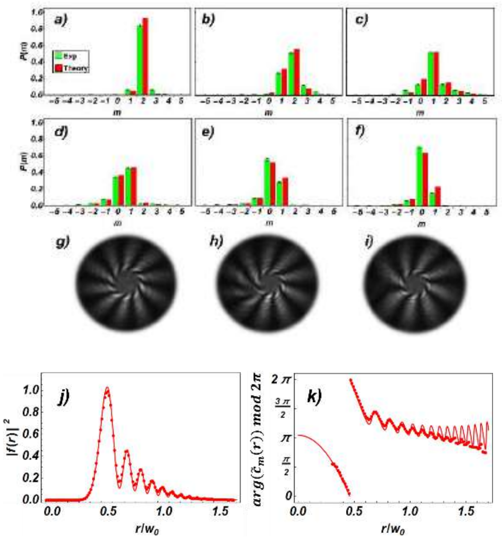

Figure 1: Characterization of a beam obtained displacing a q-plate with respect to an input plane wave. Panels a)-f) show the theoretical and experimental OAM distributions obtained from interference patterns as the ones shown in panels g)-i). Panels j) and k) are, respectively, the experimentally reconstructed amplitude and phase of an OAM eigenmode (red dots) compared with a Hypergeometric-Gaussian beam (red lines).

References

[1] A.D'Errico; R. D'Amelio; B. Piccirillo; F.Cardano; L.Marrucci, , arXiv:1706.04788 [physics.optics]

[2] H. Rubinsztein-Dunlop, A. Forbes, M. Berry, M. Dennis, D. L. Andrews, M. Mansuripur, C. Denz, C. Alpmann, P. Banzer, and T. Bauer *et al.*, J. Opt. **19**, 013001 (2016).

Experimental Generation of a three-dimensional Greenberger-Horne-Zeilinger State with OAM of Light

Manuel Erhard, Mehul Malik, Mario Krenn and Anton Zeilinger
Institute for Quantum Optics and Quantum Information,
Boltzmanngasse 3, 1090 Vienna, Austria
manuel.erhard@univie.ac.at, anton.zeilinger@univie.ac.at

Since the discovery of the Greenberger-Horne-Zeilinger argument in 1989, the so-called GHZ states have been investigated heavily on the experimental and theoretical side. These states play an essential role in the classification of entanglement, communication-complexity problems, quantum-error-correction schemes for quantum computation, as well as enabling novel experimental tests of quantum mechanics (QM) versus local-realistic (LR) theories. While most of these efforts focused onto two-dimensional systems (qubits), our work presented here focuses on three-dimensional systems. For example, in the case of the 2-dimensional contradiction between QM and LR theories, there are several properties of the measurements which have been considered essential. Remarkably, however, it has not yet been possible to transfer all these properties into the higher-dimensional case.

The experimental creation of GHZ states is a challenging task. Recently, the creation of a 10-photon GHZ state in two-dimensions (using the polarization degree of freedom) has been demonstrated. While the creation of two-dimensional N-partite GHZ states is a technically demanding task, the underlying physical principle is known. However, for three-dimensional systems the situation is quite different. While it seems to be a simple step to go from two to three dimensional systems, an experimental approach was just recently proposed by a computer algorithm, called MELVIN.

In this talk we present the actual experimental realization of the proposed three-dimensional GHZ state with three photons. As a physical carrier of the quantum information we employ the orbital-angular-momentum of light. It turns out that the transformations and resources for this degree-of-freedom available in the lab are sufficient to create such higher-dimensional GHZ states. The experimentally achieved fidelity of $75.2\% \pm 2.9\%$ with an ideal three-dimensional GHZ state verifies with three standard deviations that we indeed created such a genuinely high-dimensional multi-photon state. In addition, we elaborate a three-dimensional multi-setting "all-or-nothing" test of local-realism that can be implemented with our entangled state.

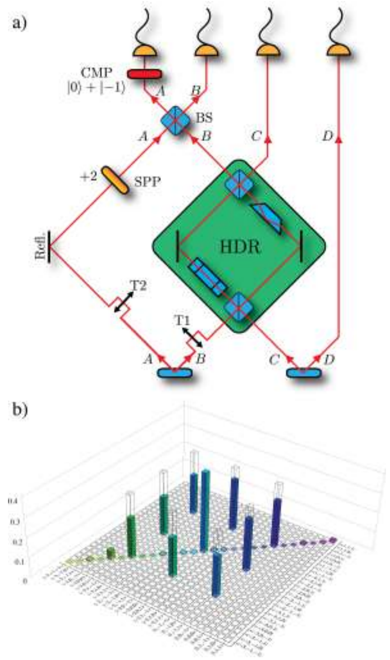

Figure 1: **a)** Experimental Scheme how to generate a three-dimensional GHZ state in the OAM degree-of-freedom. **b)** Experimentally measured density matrix. Note that only colored bars have actually been measured.

Spin and Orbital Angular Momentum Effects of Guided Ultrathin Optical Fiber Modes on a Dielectric Particle

Cindy Liza C. Esporlas, Aili Maimaiti, Viet Giang Truong, Sile Nic Chormaic
Light-Matter Interactions Unit,
Okinawa Institute of Science and Technology Graduate University,
1919-1 Tancha, Onna Village, Kunigami, Okinawa Prefecture, 904-0495 Japan
cindy.esporlas@oist.jp

The transfer of momentum arising from light-matter interactions is the core mechanism behind optical manipulation and control of micro- and nanoparticles. Field-enhancing structures such as ultrathin optical fibers transform coupled light resulting to strong and tightly-confined evanescent fields carrying bulk of the propagating power with steep intensity gradients. In addition, higher-order modes of such fields can also carry complex polarization patterns and other unique properties making ultrathin optical fibers a promising tool for high-precision optical manipulation and control experiments involving atoms, molecules, and micro- and nanoparticles.

Considering light confined in a quasi-circularly polarized fundamental mode propagating in a water-clad ultrathin optical fiber, the effects of the spin and orbital components of the optical angular momentum on dielectric microspheres immersed in water was investigated. Such light beams carry linear momentum along the propagation direction and spin and orbital angular momentum along the axial and azimuthal components of the Poynting vector which result to net translational force and rotational torque on polystyrene microspheres trapped near the ultrathin fiber surface [1,2]. It was analytically and numerically shown before by Fam et al. [1] that a significant orbital component arises when the fiber radius is within an intermediate range with respect to the propagating wavelength. The smaller core-cladding refractive index ratio result to a smaller magnitude of force compared to a higher expected magnitude for vacuum- or air-clad ultrathin fibers.

This work demonstrates the propulsion and rotation of individual polystyrene microspheres immersed in water and trapped near the surface of a 2-μm ultrathin optical fibre guiding two counter-propagating quasi-circularly polarized fundamental modes of fiber-coupled laser light with a wavelength of 1064nm. Optical manipulation and control of the particle's translational motion is done by adjusting the power of each beam whereas the phase and direction difference of the circular polarizations are used to control the particle's rotational motion. Measurements of the translational and rotational motion from microsphere trajectories were obtained from video recordings as well as quadrant position detector readings. The effects of the first-group of higher-order ultrathin fibre modes were also briefly investigated.

References

[1] Fam L.K., Rauschenbeutel A., Negative azimuthal force of nanofiber-guided light on a particle, Physical Review A **88**, 063845, 2013.
[2] Maimaiti A., Truong V.G., Sergides M., Gusaschenko I., Nic Chormaic S., Higher order microfibre modes for dielectric particle trapping and propulsion, Physical Review A **5**, 9077, 2015.

Three-dimensional Patterns of Spatially-Variable Polarization

E.J. Galvez,[1] I. Dutta,[1] K. Beach,[1] J.J. Zeosky, [1] B. Khajavi,[1,2] and J.A. Jones
[1]Colgate University, Hamilton, New York, USA,
[2]Florida Atlantic University, Boca Raton, Florida, USA
egalvez@colgate.edu

We present our investigations of spatially-variable polarization of light in three dimensions. We investigated the patterns of polarization when two optical beams, one a gaussian and another carrying an optical vortex, both in opposite states of circular polarization, formed an angle relative to each other. It has been predicted that in this situation, depending on the topological charge of the component beams, the polarization ellipse describes either Möbius strips or twisted ribbons along a closed path that encloses the central singular line [1].

When the angle between the two beams is increased, a polarization fringe pattern appears, but it contains a fork dislocation due to the optical vortex in one of the component beams. In the transverse plane, the polarization ellipse rotates along a circular path. The z-component of the field also oscillates with the fringes, with the net effect being a rotation of the polarization ellipse about the axis of the path [2]. Depending on the topological charge of the vortex, the polarization ellipse exhibits either Mobius strips or twisted ribbons when following a closed path that encloses the central singular line [1].

We measured this phenomenon with the crossing of paraxial light beams. They were prepared with a Mach-Zehnder-type interferometer that used a spatial light modulator to encode the spatial modes. The second beam splitter of the interferometer was used to control the relative angle between the two beams. The light was analyzed with a wire-grid polarizer and digital camera. Although the a polarizer cannot isolate the z-component of the field, recently we developed a method of extracting the polarization ellipse for this situation, using only polarization projections [3]. Figure 1 shows the results one of the cases when two beams form an angle of 1.9 arcmin relative to the normal to the observation plane. The results confirm the predictions and agree with the modelings.

This work was funded by NSF grant PHY-1506321.

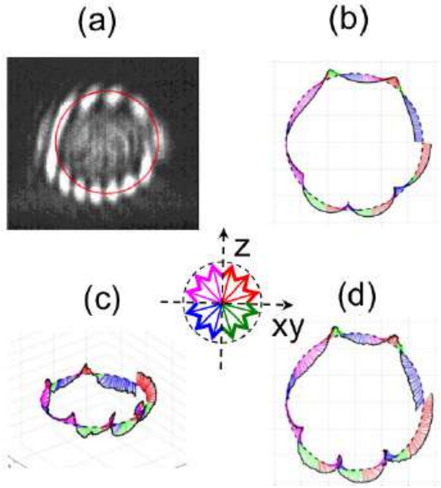

Figure 1: (a) Projection of the measured pattern with a vertical polarizer. A circle denotes the path. (b) Modeling of the semi-major axis of the polarization ellipse predicting 5-1/2 Möbius strip; (c) and (d) show respective 3-d and 2d projections of the semi-major axis extracted from the data. Color coding denotes the orientation of the axis relative to the center of the circle.

References

[1] I Freund Opt. Lett, **35** 148-150 (2011).

[2] E.J. Galvez, K. Beach, J.J. Zeosky, and B. Khajavi, Proc. SPIE **9379**, 93790A (2015).

[3] E.J. Galvez and I. Dutta, Proc. SPIE **10120**, 101200B (2017).

Optical vortices and polarization Möbius strips on all-dielectric optical antennas

Aitzol Garcia-Etxarri
Donostia International Physics Center (DIPC)
Paseo Manuel de Lardizabal 4, 20018, Donostia-San Sebastian, Spain
aitzolgarcia@dipc.org

The study of the optical response of high refractive index nano-particles has revealed that these resonant structures are capable of controlling different degrees of freedom of light fields with unprecedented versatility [1]. The ability of these particles to control the intensity, phase and polarization of light has unveiled a plethora of new physical effects. To mention a few, these particles have allowed controlling the directionality of optical antennas in an unprecedented manner, they have shown promise in enhancing chiro-optical spectroscopic techniques [2] and they have led to a generalized Brewster's condition to achieve full polarization of light.

In this talk, we unveil a two new phenomena that to the best of our knowledge were not reported up to date; the natural generation of an optical vortex in the back scattering of Silicon nanospheres and the emergence of a Möbius strip structure in the main axis of the polarization ellipse around lines where the scattered light is circularly polarized.

Firstly, based on singular optics arguments [3], we deduce the emergence of the vortex for a high index nano-particle Illuminated by circularly polarized light at the first Kerker condition. Using the recently developed helicity and angular momentum conservation framework, we prove that the modulus of the topological charge of the vortex has to be equal to 2. Lastly, we verify our predictions through analytic and numerical calculations (Figure 1a).

Secondly, we analize the emergence of polarization singularities (C lines and L surfaces) in the scattering of optical resonators excited by linearly polarized light. We demonstrate both analytically and numerically that high refractive index spherical resonators present such topologically protected features and calculating the polarization structure of light around the generated C lines, we unveil a Möbius strip structure in the main axis of the polarization ellipse when calculated on a closed path around the C line (Figure 1b).

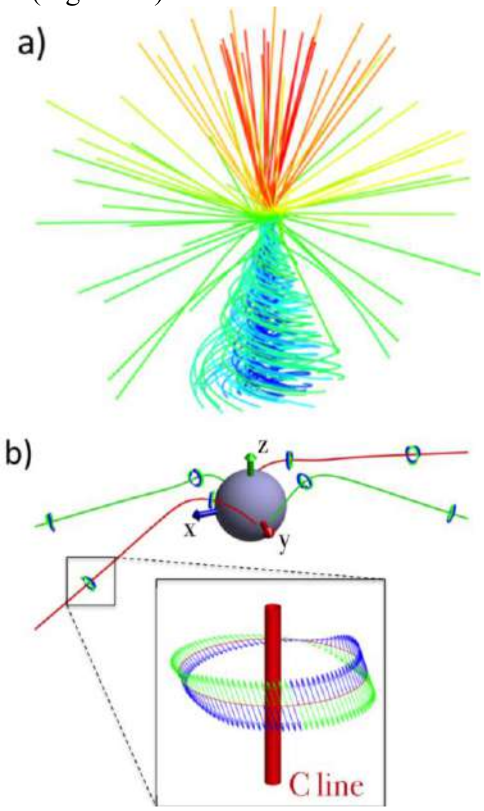

Figure 1: a) Poynting vector streamlines for the scattering of an all-dielectric scatterer illuminated by circularly polarized light when excited at the first Kerker condition of anomalous scattering. b) C lines around the Si nanoparticle. Green and red lines are the left and right handed C lines respectively. The inset is a zoom of Möbius strip polarization structure around one particular C line.

References

[1] A. García-Etxarri, et. al. Optics express 19, 4815-4826 (2011)
[2] A. García-Etxarri, and J. A. Dionne. Physical Review B 87.23, 235409 (2013)
[3] A. Garcia-Etxarri. ACS Phot. (2017)

Angular momentum transformation in three- and four-wave mixing processes in isotropic medium

I.A. Perezhogin, K.S. Grigoriev, N.N. Potravkin, V.A. Makarov
Lomonosov Moscow State University,
Leninskie Gory 1, Moscow, Russian Federation
ksgrigoriev@ilc.edu.ru

Light beams, carrying both orbital and spin angular momentum (OAM ans SAM) are not distorted when propagating in isotropic media, such as gases, plasma, liquid solutions and fused materials. Nonlinear optical mixing of these beams can lead to conversion between spin and orbital angular momenta (SAM and OAM) of the fundamental and signal photons. Three classical problems of nonlinear optics were studied analytically and numerically, namely the second harmonic generation (SHG), the sum-frequency generation (SFG) and the third harmonic generation (THG) in isotropic chiral medium.

Second harmonic generation can be realized even in centrosymmetric media in the case if they exhibit strong spatial nonlocality. We analytically demonstrate that only heterogeneously polarized superposition of LG pulses generates the signal at doubled frequency [1]. For this reason, the photons involved in nonlinear mixing must have opposite spins, which cancel each other, while the OAM of the fundamental beam is fully converted converted to SAM of the signal one.

The effective SFG can be achieved even via the local quadratic response of the medium [2]. We consider collinear geometry of beam interaction, in which the free-propagating wave can be still generated in the bulk of the medium due to diffraction divergence of the beam. In such case, even the homogeneously polarized Gaussian fundamental beams produce the nonlinear signal. The SAM of two photons of these beams is fully transferred to a photon at the sum-frequency, however, it is redistributed between both spin and orbital AM of the signal beam (fig. 1).

Third harmonic generation is also effective in isotropic medium with local cubic response. The only restriction is that the fundamental beam must not be circularly polarized. Then, three photons with different spins are mixed and generate a photon of the signal beam. In this process the SAM-OAM conversion does not happen and the spin and orbital parts of AM of the fundamental photons are fully transferred to corresponding parts of the signal photon.

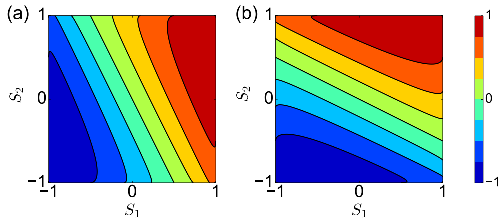

Figure 1: The dependency of average OAM (a) and SAM (b) of the photon at the sum-frequency on the average SAM of the photons of the fundamental beams.

For any type of the fundamental beams total AM of photons is conserved in each considered nonlinear process. However, in some processes it can be converted from spin part to orbital and backwards. Moreover, one needs to use heterogeneously polarized light beams, because in certain processes only the photons with opposite spins can interact.

References

[1] K. S. Grigoriev, N. Yu. Kuznetsov, E. B. Cherepetskaya, and V. A. Makarov, Opt. Express, 25, 6253, 2017.

[2] K. S. Grigoriev, V. A. Makarov, and I. A. Perezhogin, Phys. Rev. A, 92, 023814, 2015.

Fundamentals and Applications of an Optical Theorem for Chiral Optical Fields

Philipp Gutsche[1,2], Sven Burger[2], Manuel Nieto-Vesperinas[3]
[1]Freie Universität Berlin, Math. Institute, Arnimallee 6, 14195 Berlin, GER
[2]Zuse Institute Berlin, Takustr. 7, 14195 Berlin, GER
[3]Instituto de Ciencia de Materiales de Madrid, Consejo Superior de Investigaciones Cientificas, Campus de Cantoblanco, Madrid 28049, ESP
gutsche@zib.de

The helicity of light is of great interest in both fundamental research and in applications such as dichroism spectroscopy. Its time-harmonic formulation is directly proportional to the density of optical chirality. Recently, both an helicity optical theorem (HOT) [1] and a chirality conservation law (CCL) [2] have been formulated for arbitrary scatterers taking into account an underlying continuity equation of this quantity [3]. We summarize these two equivalent fundamental laws and analyze their potential applications.

Extinction measurements are a standard tool for the analysis of optical properties of individual scatterers or material distributions (Fig. 1). Such setups are described by the extinction of energy as the sum of scattering and absorption processes. Employing the HOT and CCL, we extract consequences in the study of the extinction of helicity [1]. The latter quantity consists of one part related to the chirality of the scattered field and a term associated with the conversion of chirality [2].

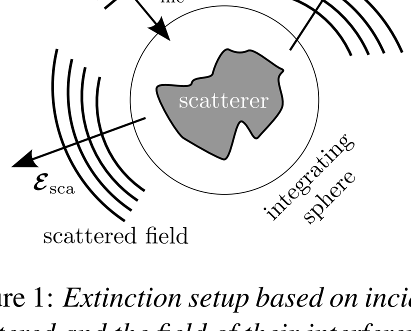

Figure 1: *Extinction setup based on incident, scattered and the field of their interference.*

We illustrate the formalisms with non-Rayleigh dipolar scatterers, arbitrary current densities, plane waves and illuminating complex light. The far- and near-field response of nanoparticles (specially those with magnetodielectric properties that attract recent research [4]) are studied, as well as the use of 3D polarized light such as Bessel beams.

Our analysis paves the way for figures of merit based on the extinction of chirality established by both the HOT and the CCL. They span from a generalized g-factor of dichroism measurements to a chiral analogue of the Purcell factor. This framework for the description of chiral optical fields can be employed in numerical simulations as well as in experimental studies.

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References

[1] M. Nieto-Vesperinas, Phys. Rev. A 92, 023813, 2015. M. Nieto-Vesperinas, Journal of Optics 19(6), 065402, 2017.

[2] P. Gutsche, L.V. Poulikakos, M. Hammerschmidt, S. Burger, F. Schmidt, Proc. SPIE 9756X, 2016.

[3] D.M. Lipkin, J. Math. Phys. 5, 696, 1964. R.P. Cameron, S.M. Barnett, A.M. Yao, N. J. Phys.14, 053050, 2012

[4] A.I. Iuznetsov, et al., Optically resonant dielectric nanostructures, Science 354(6314), 2016.

Spin-Orbit Coupling in the Neutron Regime

M. G. Huber[1], C. W. Clark[1,2], M. Arif[1], W. C. Chen[1,3], D. Sarenac[4,5]
J. Nsofini[4,5], I. Hincks[4,6], D. G. Cory[4,7,8,9], D. A. Pushin[4,5]
[1]National Institute of Standards and Technology, Gaithersburg, USA
[2]Joint Quantum Institute, College Park, USA
[3]University of Maryland, College Park, USA
[4]Institute for Quantum Computing, University of Waterloo, Waterloo, Canada
[5]Department of Physics, University of Waterloo, Waterloo, Canada
[6]Department of Applied Math, University of Waterloo, Waterloo, Canada
[7]Department of Chemistry, University of Waterloo, Waterloo, Canada
[8]Perimeter Institute for Theoretical Physics, Waterloo, Canada
[9]Canadian Institute for Advanced Research, Toronto, Canada
Michael.Huber@nist.gov

Historically, neutron scattering instruments such as Small Angle Neutrons Scattering (SANS), reflectometers, and spin-echo have been successful in using the unique properties of neutron-waves in order to probe the structure of matter. An important property for these techniques is the neutron's intrinsic spin of $\hbar/2$. This allows for spin-polarized neutron beams; a process that can be accomplished via a variety of different means; Bragg scattering, spin-dependent absorption, and multilayer films.

It has recently been shown that the orbital angular momentum (OAM) of a neutron wavepacket can be manipulated and controlled [1]. This was accomplished using simple, macroscopic spiral-phase-plates (SPPs) and resolved using a neutron interferometer. That work opens up the possibility for studying other previously unexplored neutron couplings. One of these is a spin-orbit coupling [2] that entangles the neutron's spin with that of its OAM state creating in effect a spin vortex. The proposed spin-obit coupling is generated by passing a well-collimated neutron beam through a gradient magnetic field such as those provided by a quadrupole magnet. This method is analogous to those used in optics to generate OAM based on Pancharatnam-Berry geometrical phases [3], and for generating OAM with electrons through a type of Wien filter [4]. We will discuss a means of coupling the neutron's spin and OAM to prepare an entangled spin-orbit state of the neutron wavepacket. This spin-orbit state could in principle be used for quantum metrology applications, such as probing chiral and helical materials.

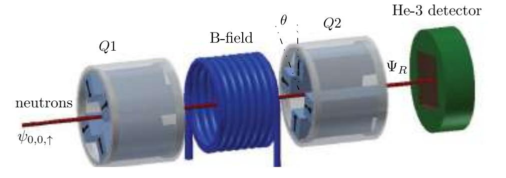

Figure 1: A proposed Ramsey scheme for creating and measuring spin-orbit neutron states using quadrupole magnets.

References

[1] Clark, C. W., *et al.*, Controlling Neutron Orbital Angular Momentum, Nature 525, 504-506, 2015

[2] Nsofini, J., *et al.*, Spin-orbit States of Neutron Wave Packets, Physical Review A, 94, 013605, 2016

[3] Liberman, V. S. and Zeldovich, B. Y. , Physical Review A, Spin-orbit Interaction of a Photon in an Inhomogeneous Medium, 46, 5199, 1992

[4] Grillo, V. *et al.*, Quantum Simulation of a Spin Polarization Device in an Electron Microscope, New Journal Physics, 15, 093026 (2013).

Elegant Laguerre-Gaussian beams with OAM as structured wavefields

A. Jaimes-Nájera, J. A. Ugalde-Ontiveros, S. Chávez-Cerda
Instituto Nacional de Astrofísica, Óptica y Electrónica
Luis E. Erro No.1, Tonantzintla, Puebla 72840, Mexico
ajaimes@inaoep.mx

It is well known that the standard Laguerre-Gaussian beams (LGB) as well as the standard Hermite-Gauss beams (HGB) are structurally stable maintaining their shape on propagation. A variant of these beams are the so called elegant Hermite-Gauss beams (eHGB) and elegant Laguerre-Gauss beams (eLGB) [1, 2].

The referred elegance is associated to the symmetry between the argument of the Gaussian envelope and that of the Hermite and Laguerre functions respectively. This symmetry makes the Gaussian envelope of the eLGB narrower than that of the standard LGB. As a result the eHGB and eLGB are not any longer structurally stable on propagation. These elegant beams can be relevant for communications as it has been shown for the case of eLGB that have robust propagation properties in turbulent media [3].

Not long ago it has been shown that the multiringed LGB with Orbital Angular Momentum (OAM) have the property of self-healing [4]. Nevertheless, a proper explanation on physical grounds of such phenomenon for LGB beams remains to be given.

We show in this work that eLGB with OAM belong to the families of structured wavefields, although they are not structurally stable during propagation. Moreover, in the far field they evolve into a ring shaped beam what is known as Hollow Gaussian Beam [5], see Fig.1. Using this fact we demonstrate that they must be similar to Bessel beams, whose spatial spectrum also lies on a ring, having the self-healing property and that this can be explained by traveling waves (that we call elegant Hankel-Laguerre waves, eLHW). The continuous superposition of the two kinds of these waves conform the propagated eLGB. In a similar way as for Hankel waves, associated to Bessel beams [6, 7], we show that the geometry of the wavefronts of the eLHW is quasiconical.

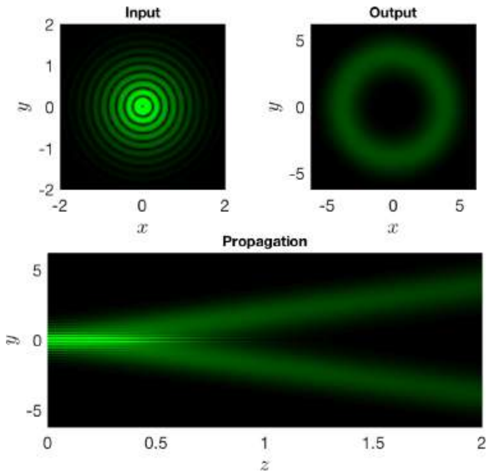

Figure 1: Whole propagation of an eLGB with radial index $n = 30$ and azimuthal or OAM index $m = 1$.

References

[1] A. E. Siegman, JOSA 63, 1093-1094, 1973.

[2] E. Zauderer, JOSA 3, 465-469, 1986.

[3] J. Qu *et. al.*, Opt. Commun. 283, 2772, 2010.

[4] J. Mendoza-Hernández, *et. al.*, Opt. Lett. 40, 3739-3742, 2015.

[5] Y. Cai, X. Lu and Q. Lin Opt. Lett. 28, 1084-1086 (2003).

[6] S. Chávez-Cerda, J. Mod. Opt. 46, 923-930, 1999.

[7] I. Litvin, M. McLaren, A. Forbes, Opt. Commun. 282, 1078-1082, 2009.

Multiple self-healing in partially coherent imaging systems

Danilo G. Pires, Artur F. Sonsin, José S. Rodrigues*, Alcenísio J. Jesus-Silva, and Eduardo J. S. Fonseca.
Instituto de Física, Universidade Federal de Alagoas, Maceió, Alagoas 57061-970, Brazil
* Instituto Federal do Piauí
eduardo@fis.ufal.br

Scattering light through a random media turns it into a speckle field. If, in the recent past, speckles were considered to be avoided, nowadays they have been considered an excellent light source for different applications. Although they emerge from a random interference, the optical information, scrambled by the random medium, is not lost. Additionally, the suppression and control of multiple light scattering events offer the possibility of optical focusing and imaging through thin or even heavily scattering medium. All these features contribute to new optical microscopy techniques. In this paper, based on self-reconstruction [1] using structured field, we show that is possible to image each layer independently one of the other. This allows for a simple and direct technique for imaging through scattering layers.

Recently, a study showed that a speckle pattern can also be reconstructed after being obstructed by an obstacle [1]. An object is placed on the path of the speckles and, after the reconfiguration length l, the signature of the object is completely washed out. The speckle pattern becomes homogeneous. In fact, if an opaque square was placed in the speckles path, after l its signature completely disappears. An interesting point thought is that, we can align as many objects as we want along the beam axis and separated by a distance l, and after l from each object, a homogeneous speckle pattern will be observed.

Now, if instead to worry about to erase the signature of the objects, we would focus to see the images of the objects. To do that, we aligned along of the speckle filed three opaque objects: circle, triangle, and square. The three objects were aligned distancing from each other of l. The plane of the first object, a dark circle, was projected by the imaging system into the CCD camera at position $z = 0$, consequently a dark circle was observed, as shown Figure 1. Interesting enough, when the CCD camera was moved of $z = l$, the second object, a dark triangle, is clearly observed without any signature of the first one. Similarly, we see a square, without any signature of the circle or triangle, if the detector is moved now by $2l$ from the initial position. Blurry images can be observed between the planes above mentioned.

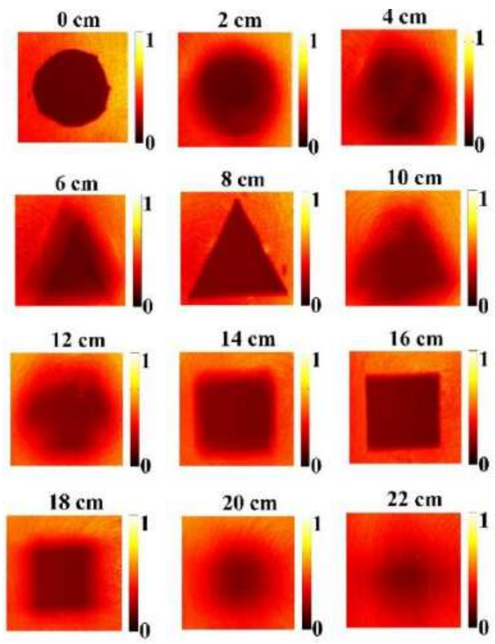

Figure 1: Intensity patterns measured by the CCD camera along different longitudinal positions shown on the top of the figures. The reconfiguration length was of $l = 8cm$

References

[1] Alves CR, Jesus-Silva AJ, Fonseca EJS, Self-reconfiguration of a speckle pattern, Opt Lett 39, 6320-6323 (2014)

Driving reflective particles by vortex beams to pump fluids efficiently

Jannis Köhler, Shuopeng Wang, Cemal Esen, and Andreas Ostendorf
Applied Laser Technologies,
Ruhr-Universität Bochum, Universitätsstr. 150, 44801 Bochum, Germany
koehler@lat.rub.de

In the field of microfluidics, fluid flow generation is an essential component. Therefore, rotational movements can be applied to generate a directed fluid flow and to pump liquids through microchannels. In recent years, the integration of optics and photonics into microfluidic devices, which is known as optofluidics, has been established as a versatile technology for the production of high-precision sensors and actuators. For instance, orbital angular momentum can be used for the rotation of multiple microparticles by ring-shaped vortex beams and the generation of fluid flow. Previous studies investigated the optimization of these beams and the rotation behavior as well as the hydrodynamic interactions of transparent particles.

In this study, a micropump based on the rotation of reflective particles by the transfer of orbital angular momentum is developed. Different approaches are investigated to enable stable rotation with high-order optical vortices despite strong repulsive forces acting on the reflective particles. As a result of the study, high rotational speeds can be achieved. By embedding the particles into a micropump (Fig.), a directed fluid flow is demonstrated experimentally. Thus, this pump is applicable for microfluidic systems.

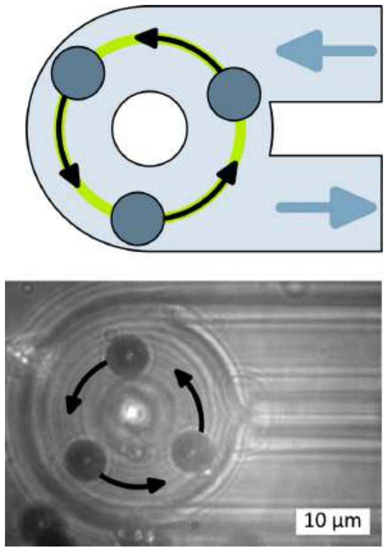

Figure 1: Rotation of reflective microparticles by vortex beam for directed fluid flow generation.

Polarization Correlation Singularities in Vector Speckle Field

Vijay Kumar[1], Bruno Piccirillo[2], S. G. Reddy[3], R. P. Singh[1]
[1]Physical Research Laboratory, Ahmedabad, Gujarat-380009, India
[2]Dipartimento di Fisica, Universiá di Napoli Federico II, Complesso Universitario di Monte Sant'Angelo, 80126 Napoli, Italy
[3]University of Electro-Communications, Chofugaoka, Chofu, Tokyo 1828585, Japan
vijaykumarsop@gmail.com

The correlation is a powerful tool to recover the information after the optical diffusion. Vector speckle field or polarization speckles is the field wherein local polarization is randomly varying. Here we are constructing a polarization related correlation function for the vector speckle field, formed due to the scattering of the vector beam.

Let us consider a superposition of orthogonal linearly polarized Gaussian and vortex beams,

$$\vec{E}_{PB} = \left(\hat{e}_x + re^{i|l|\theta}\hat{e}_y\right)e^{-\frac{r^2}{2w_0}} \qquad (1)$$

Here, l is the vortex charge. This superposition forms a special class of vector beam known as Poincaré beam [1]. If we scattered these vector beams using random media such as ground glass, will introduce spatially varying random phase $\phi_R(\vec{r})$. The scattered far-field is a vector speckle field ($\vec{E}_{Sc}$), given by the Fourier transform,

$$\vec{E}_{Sc}(\vec{r}) = \mathcal{F}\left(\vec{E}_{PB}e^{i\phi_R(\vec{r})}\right) = \vec{E}_{Sc(x)}(\vec{r}) + \vec{E}_{Sc(y)}(\vec{r}). \qquad (2)$$

One can define a polarization related complex correlation function (S_{xy}) for the vector speckle field [2],

$$S_{xy}(\vec{r}_1;\vec{r}_2) = \langle\{E^*_{Sc(x)}(\vec{r}_1)\}\{E_{Sc(y)}(\vec{r}_2)e^{i\Phi_{xy}(\vec{r}_2)}\}\rangle \quad (3)$$

where, $\Phi_{xy}(\vec{r}_2) = \phi_{Sc(y)}(\vec{r}_2) - \phi_{Sc(x)}(\vec{r}_2)$ gives the local phase difference between the $x(y)$ - polarized components of the vector speckle fields and $\langle\ldots\rangle$ represents the ensemble average. This correlation function contains singularity as shown in Fig. (1).

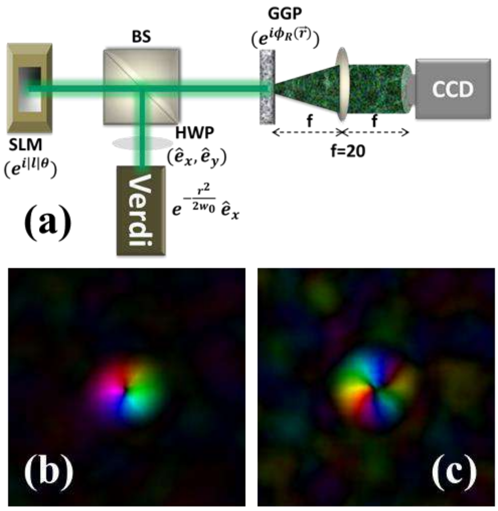

Figure 1: (a) Experimental setup for the realization of Polarization correlation singularities. Correlation singularities of vortex charge $l = -1$ (b), $l = -2$ (c). Here colors represent phase and amplitude by its saturation [2].

In conclusion, the experimental realization of amplitude and phase of the polarization correlation singularities is demonstrated as an application of Poincaré beam. The main advantage of this formalism is the simplicity and the use of the phase $\Phi_{xy}(\vec{r}_2)$, which contains all the necessary correlated information.

References

[1] V. Kumar and N. K. Viswanathan, Topological structures in vector-vortex beam fields, J. Opt. Soc. Am. B 31, A41-A-45, 2014.
[2] V. Kumar, B. Piccirillo, S. G. Reddy and R. P. Singh, Topological structures in vector speckle fields, Opt. Lett. 42, 466-469, 2017.

Superposition of integer and fractional optical vortices in a Michelson interferometer

C. Kusko[1,] R. Tudor[1,2], M. Kusko[1], M. Mihailescu[3]
[1]National Institute for Research and Development in Microtechnologies,
126A Erou Iancu Nicolae Str., 72996, Bucharest, Romania
[2]University of Bucharest, Department of Physics,
Atomistilor Street 405, 077125, Magurele, Romania
[3]Physics Department, Politehnica University of Bucharest,
313 Splaiul Independentei, Bucharest 060042, Romania
cristian.kusko@imt.ro

In this work we investigate experimentally and numerically the patterns obtained from the superposition of two co-propagating beams with helical wavefronts generated by integer and fractional spiral phase plates using an experimental set-up based on a Michelson interferometer.

For the superposition of two beams with helical wavefronts carrying integer values of orbital angular momentum we obtain bright and dark ring lattices [1]. These patterns can be rotated, the angle of rotation depending linearly on the optical path difference between the two arms of the interferometer. For the interference of two beams generated by the fractional spiral phase plate we obtain light configurations presenting off – axis phase singularities [2] and with a more complex dependence of the phase difference between them.

We compare the experimental interference patterns with the ones calculated numerically using the diffraction integral and we analyze the possibility to use this experimental set-up for sensing applications.

References

[1] S. Franke-Arnold, J. Leach, M. J. Padgett, V. E. Lembessis, D. Ellinas, A.J. Wright, J. M. Girkin, P. Ohberg, and A. S. Arnold, Optical ferris wheel for ultracold atoms, Opt. Express 15, 8619–8625, 2007.

[2] M. V. Berry, Optical vortices evolving from helicoidal integer and fractional phase steps, J. of Optics Pure and Appl. 6, 259, 2004.

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Observation of the full spiral spectrum of a light beam with single-pixel detection

Job Mendoza-Hernández[1], Luis José Salazar-Serrano[1] and Juan P. Torres[1]
[1] ICFO - The Institute of Photonic Sciences, the Barcelona Institute of Science and Technology
08860 Castelldefels (Barcelona), Spain
job.mendoza@icfo.eu

In the paraxial regime, the spatial shape Ψ of an arbitrary light beam can be decomposed as $\Psi(x,y) = \sum_m C_m \varphi_m(x,y)$, where $C_m = \int dxdy \Psi(x,y)\varphi^*(x,y)$, φ_m is the basis and the array $\{C_m\}$ is the set of complex numbers that uniquely describe Ψ. One such a basis is the set of Laguerre-Gauss modes, where modes are labeled by two indexes (l,p). The decomposition of Ψ into LG beams is the so-called spiral spectrum.

There is great interest in devising robust and efficient ways to measure C_m [1]. For instance, one can project the beam of interest Ψ into the set φ_m by impinging the beam into an spatial light modulator where the shapes of φ_m are written, and measuring the output power with a single-pixel detector. This procedure provides the value of $|C_m|^2$. However C_m is in general a complex number, so one needs to determine the real and imaginary parts of C_m.

Here we put forward and demonstrate a *simple* scheme to measure the full spiral spectrum. The idea is to generate a combined state of polarization and spatial shape of the form $\Theta = \Psi(x,y)\hat{h} + \varphi_m(x,y)\hat{v}$, where $\hat{h}$ and $\hat{v}$ designate horizontal and vertical polarizations, respectively. Notice the formal similarity of this classical state with a quantum two-photon state, where the degree of entanglement depends on the orthogonality between Ψ and φ_m.

The scheme is implemented experimentally by embedding the signal of interest Ψ with horizontal polarization and generating with an SLM the signal φ_m with the orthogonal polarization [2]. The real part of C_m is obtained by projecting the signal Θ into the diagonal and anti-diagonal polarizations states and substracting the intensitities measured. The imaginary part is obtained by similarly projecting into right-handed and left-handed circular polarizations.

In Fig. 1(a) we show the spiral spectrum of the engineered light beam $\Psi(x,y) \sim \varphi_{l=3}(x,y) + \exp(i\phi)\varphi_{l=-3}(x,y)$ when is projected into elements of the basis with $p = 0$. In (b) and (c) we consider projection into states $\varphi_{l=\pm 3}(x,y)\exp(i\delta)$ (δ from 0 to 2π) to demonstrate that our scheme measure the full spectrum (real and imaginary parts).

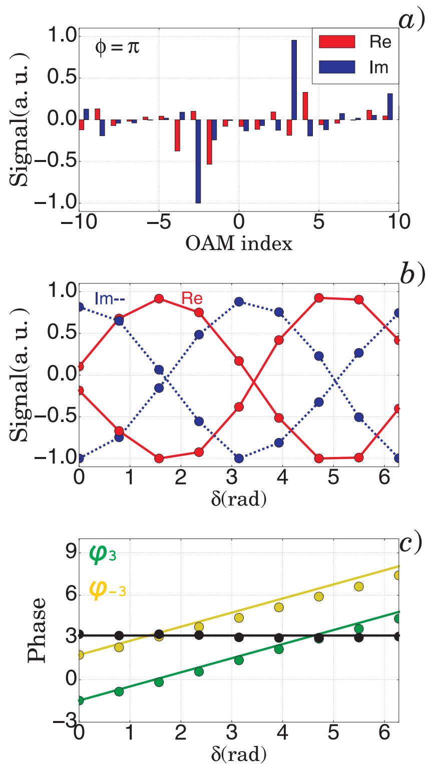


Figure 1: Full spiral spectrum of an engineered light beam.

References

[1] H. Rubinsztein-Dunlop, et al., , J. Opt. 19, 013001 (2017).

[2] L. J. Salazar-Serrano, et al., Rev. Sci. Instrumen. 86, 033109, (2015).

Inducing optical activity in single nano-structures using the angular momentum of light

Xavier Vidal[1], Xavier Zambraba-Puyalto[2], Gabriel Molina-Terriza[1]

[1]Department of Physics and Astronomy, Macquarie University, 2109 NSW, Australia

[2] Istituto Italiano di Tecnologia, Via Morego 30, 16136 Genova, Italy

xavier.vidal@mq.edu.au

We show that not only chiral but also non-chiral subwavelength single structures can produce circular dichroism when excited with non-paraxial vortex beams. It is shown that the chirality of the sample is induced by the angular momentum of light.

The simple measurement of the differential absorption between left (LCP) and right circular polarized (RCP) light, known as circular dichroism (CD), is a standard technique to know the 3-dimensional shape of any element at the nano and molecular scale. It is usually assumed that the only requirement to have non-zero CD is that the analyzed element must be chiral, i.e. elements whose mirror image cannot be superimposed with themselves. We will show examples where the analyzed element although being non-chiral, because the whole system is geometrically chiral shows CD. In order to do that, we use an internal degree of freedom of light: the angular momentum. The chirality arises from the light beam. The reason is that, in general, Laguerre-Gaussian beams with the same optical charge but opposite polarization are not mirror images of each other. In fact, $\ell = 0$ is the only exception.

In particular, we will present experimental results of CD through circular nano-apertures. Keeping the definition of CD, we have compared not only Gaussian beams but also optical vortices with optical charge, ℓ, equal to +1 and -1.

$$(1)\quad CD_\ell(\%) = \left(\frac{I_\ell^L - I_\ell^R}{I_\ell^L + I_\ell^R}\right) \cdot 100$$

Although the Gaussian beam, $\ell = 0$, does not present CD as expected, both optical vortices present CD. In fact, we will prove that:

$$(2)\quad CD_\ell = -CD_{-\ell}$$

We will show that the main actor is the total angular momentum of the light [1].

As expected, due to the fact that the circular nano-aperture is mirror symmetric and the incidence is normal, the CD is null for an incident Gaussian beam, $\ell = 0$. However, when vortex beams with $\ell = -1, 1$ are used the situation is very different. We obtain a considerable value for the CD, even though the incidence is normal and the nano-aperture is still mirror symmetric.

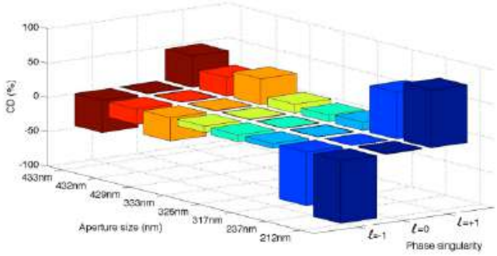


Figure 1: CD (%) for three different phase singularities ℓ for circular nano-apertures as a function of the diameter.

References

[1] Xavier Zambrana-Puyalto, Xavier Vidal, Gabriel Molina-Terriza, Angular momentum-induced circular dichroism in non-chiral nanostructures, Nat. Comm. **5**, 4922 (2014)

Generation of guided states for 4-dimensional quantum key distribution with structured photons

S. Faezeh Mousavi[1,*], Rahman Nouroozi[1], Giuseppe Vallone[2], and Paolo Villoresi[2]
[1] Institute for Advanced Studies in Basic Sciences, 45195-1159, Zanjan, Iran
[2] Universit‘a di Padova, I-35131 Padova, Italy
*mousavi.f@iasbs.ac.ir

Combining Orbital Angular Momentum (OAM) and Spin Angular Momentum (SAM) as two degrees of freedom for modulating structured photons in high dimensional Quantum Key Distribution (QKD) can enhance data transmission rate and security in communication systems [2]. High speed and high-frequency modulation of the beams encoded by OAM-SAM can provide their commercial applications in the compatible communication networks. Integrated optical devices are good miniaturized choices to manipulate the signals via electro-optical effects. Although integrated optically control of the optical signals with different OAM values are demonstrated [1], but non of them are performed for guided states.

This paper proposes a numerically verified integrated high-frequency electro-optical modulator for manipulation of guided modes encoded in OAM-SAM states. The $|+1\rangle|H\rangle$ state is assumed to be as the input of such modulator, and eight mutually unbiased bases ones ($|\psi\rangle^i$ and $|\phi\rangle^j$) for 4 dimensional QKD with structured photons encoded on two OAM ($|l=-1\rangle$ and $|l=1\rangle$) and SAM ($|H\rangle$ and $|V\rangle$) states are generated. As displayed in Fig. 1, the modulator is designed as an electro-optically active Y-cut Lithium Niobate (LN) on insulator (Silica) photonic wire configuration to exploit the electro-optical effects for manipulating the polarization and phase of SAM-OAM encoded optical states. The designed modulator operates as a switch by applying appropriate external electric field to the gold electrodes of its two successive parts: phase shifter (via V_1 voltage) and polarization converter with domain inverted structure (via V_2 and V_3 voltages). The switching operation of the proposed modulator is summarized in Table 1. In addition to QKD, the generated SAM-OAM encoded optical states can also be used in classical and quantum high-dimensional telecommunication networks.

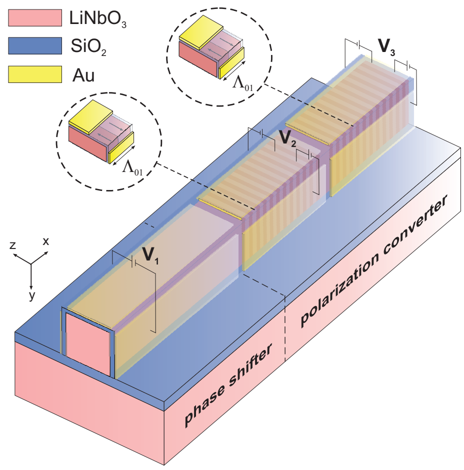


Figure 1: Schematic representation of the proposed modulator.

Table 1: Switching operation of the proposed modulator generating 4D QKD states

state	$\|\psi\rangle^1$	$\|\psi\rangle^2$	$\|\psi\rangle^3$	$\|\psi\rangle^4$	$\|\phi\rangle^1$	$\|\phi\rangle^2$	$\|\phi\rangle^3$	$\|\phi\rangle^4$
V_1	off	on	off	on	on	on	on	on
V_2	off	off	on	on	off	on	off	on
V_3	off	off	on	on	on	off	on	off

References

[1] A. Sit, et al., High-dimensional intra-city quantum cryptography with structured photons, http://www.arxiv.org/abs/1612.05195v1.

[2] X. Cai et al., Integrated compact optical vortex beam emitters, Science 338, 363 2012.

Towards orbital angular momentum transfer from light to cold atoms using selectively excited higher order modes of an optical nanofiber

T. Nieddu, J. Du, T. Ray S. Nic Chormaic
Light-Matter Interactions Unit, Okinawa Institute of Science and Technology Graduate School,
1919-1 Tancha, Onna-son, 904-0495 Okinawa, Japan
thomas.nieddu@oist.jp

Interfacing of ultrathin optical fibers and cold atoms has recently gained interest for the study of quantum systems [1]. These fibers feature a strong evanescent field at their waist, tightly-confined light over long distances, and allow for interactions between guided-light and atoms in their vicinity [2]. Such fibers are ideal for exploring nonlinear optical effects that usually require very high laser powers [3].

Most of the studies involving ultrathin optical fibers have focussed on the fundamental guided mode. Here, we exploit the first set of higher order modes (HOM) of an ultrathin optical fiber, namely TE_{01}, TM_{01} and HE_{21} modes (Fig.1), as they can lead to fiber-based atom traps with tunable geometries and increased control over the position of the trapping sites. In particular, combinations of the even and odd HE_{21} modes could be used to transfer orbital angular momentum (OAM) to ensembles of atoms surrounding the fiber. We are currently studying ways to transfer and store OAM to the motional state of the atoms[4].

The main challenge is to selectively excite these modes while limiting the cross-talk with the neighboring TE_{01} and TM_{01} modes of the fiber which do not carry OAM. We have addressed the issue by studying the influence of the input polarization on the modal excitation at the nanofiber-cold atoms interface via absorption data and comparison with the observed output profile. We have also calculated the ideal parameters required to drive a quadrupole allowed transition, and thus achieve OAM transfer to the atomic state, using guided-light in an ultrathin optical fiber.

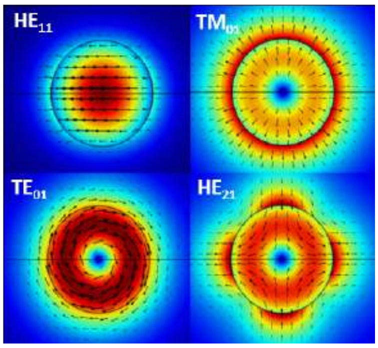


Figure 1: First four true-modes of the ultrathin optical fiber used in our experiment. An out-of-phase combination of HE_{21} modes in their *even* and *odd* configuration allows fiber guided-light to carry OAM.

References

[1] T. Nieddu *et al.*, Optical nanofibres and neutral atoms, J. Opt. 18, 053001, 2016.

[2] F. Le Kien and K. Hakuta, Scattering of an evanescent light field by a single cesium atom near a nanofiber, Phys. Rev. A. 73, 013819, 2006.

[3] R. Kumar *et al.*, Interaction of laser-cooled ^{87}Rb atoms with higher order modes of an optical nanofibre, New J. Phys. 17, 013026, 2015.

[4] G. Walker *et al.*, Trans-spectral orbital angular momentum transfer via four-wave mixing in Rb vapor, Phys. Rev. Lett. 108, 243601, 2012.

Biomedical applications of Mueller polarimetry

H. R. Lee[1], S. H. Yoo[1], T. Genova-Hristova[2], E. Garcia-Caurel[1], E. Borisova[2], R. Ossikovski[1], T. Novikova[1*]

[1]LPICM, CNRS, Ecole polytechnique, University Paris-Saclay,
Route de Saclay 91128 Palaiseau, France

[2]Institute of Electronics Bulgarian Academy of Science,
72, Tsarigradsko chaussee Blvd., 1784, Sofia, Bulgaria

*tatiana.novikova@polytechnique.edu

The use of polarized light for biomedical diagnostics has already a long history. Among all optical techniques Mueller polarimetry provides the most complete description of the interaction of polarized light with any type of sample in the absence of non-linear effects. Our prior studies showed the enhancement of contrast on tissue polarimetric images between cancerous and healthy zones [1, 2]. Lu-Chipman polar decomposition is commonly used to extract the diagnostic information from 16 elements of Mueller matrix Apart from conventional product decomposition of Mueller matrices the phenomenological theory of anisotropic scattering fluctuating medium based on differential Mueller matrix formalism [3] was explored for the definition of new optical biomarkers for the contrast enhancement.

The results of experimental, theoretical and numerical studies of anisotropic scattering media (tissue phantoms and human tissues) with our custom-built Mueller polarimetric microscope and Monte Carlo algorithm will be presented. The added value of using polarimetric parameters linked to spin angular momentum of light (circular depolarization) for the diagnostics of tissue will be also discussed.

References

[1] Novikova T. et *al*, Polarimetric Imaging for Cancer Diagnosis and Staging, Optics and Photonics News, 26-32, Oct. 2012.

[2] Rehbinder et *al*. Ex vivo Mueller polarimetric imaging of the uterine cervix: a first statistical evaluation, J. Biomed. Opt. 21(7), 071113, 2016

[3] Agarwal N. et *al*, Spatial evolution of depolarization in homogeneous turbid media within the differential Mueller matrix formalism, Opt. Lett, 40(23) 5634, 2015

Transport of classical entanglement in free space

E. Otte[1], C. Rosales-Guzmán[2], Bienvenu Ndagano[2], C. Denz[1], A. Forbes[2]

[1]Institute of Applied Physics, University of Muenster, Corrensstr. 2/4, 48149 Münster, Germany
[2]School of Physics, University of the Witwatersrand, Private Bag 3, Wits 2050, South Africa
eileen.otte@uni-muenster.de

Complex light fields, structured in the phase and polarization degrees of freedom, have attracted considerable attention within the last years [1] In particular, light fields, entangled or non-separable in its spatial and polarization degrees of freedom, had contributed to cutting-edge research at both the classical and quantum levels [2-4].

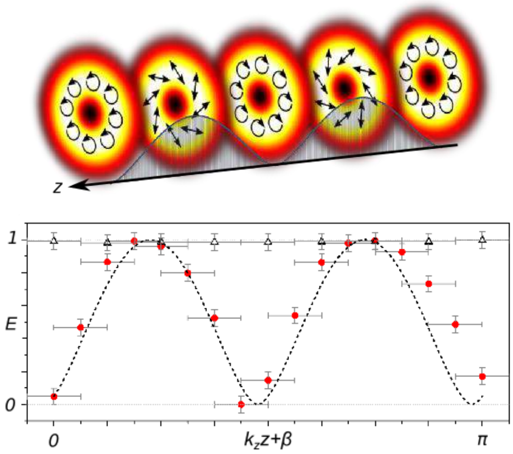


Figure 1: Top: Sketch of spatially varying degree of classical entanglement in free space. Bottom: Measured degree of entanglement E as a function of propagation distance z – red dots: superposition of vector modes, black triangles: pure vector beam, dotted line: simulation. (k_x, k_y, k_z): wave vector, β: phase shift.

It is known that entanglement is a property which stays unchanged under unitary transformation such as propagation in free space. By engineering propagation dependent polarization fields [5], we show theoretically and experimentally that under certain conditions this constrain can be removed. In particular we demonstrate the realization of a non-unitary evolution of classical entanglement in free space [6]. We experimentally generated classically entangled vector vortex beams, non-separable in polarization and orbital angular momentum, to produce a light field in which the degree of classical entanglement oscillates continuously upon propagation in free space (see Fig. 1, top). To quantify this oscillation, we evaluated the degree of entanglement of the generated vector field as a function of the propagation in free space (see Fig. 1, bottom). Furthermore, phase adjustment allows transporting the maximum degree of entanglement across chosen distances, similar to particle transport by tractor beams. At the receiver end, our approach facilitates the alternation of the degree of entanglement on demand which may pave the way to future developments in classical as well as quantum research fields.

References

[1] Rubinsztein-Dunlop, H. *et al.*, Roadmap on structured light, J. Opt.19, 013001, 2017.
[2] Vallone, G. *et al.*, Free-Space Quantum Key Distribution by Rotation-Invariant Twisted Photons, Phy. Rev. Lett. 113, 060503, 2014.
[3] Milione, G. *et al.*, 4 × 20 Gbit/s mode division multiplexing over free space using vector modes and a q-plate mode (de)multiplexer, Opt. Lett. 40, 1980–1983, 2015.
[4] Ndagano, B. *et al.*, Characterizing quantum channels with non-separable states of classical light, Nature Physics 13, 397–402, 2017.
[5] Vyas, S. *et al.*, Creation of polarization gradients from superpositions of counter propagating vector LG beams, Opt. Express 23, 33970–33979, 2015.
[6] Otte, E. *et al.*, Non-unitary evolution of classical entanglement in free space, under final revisions for soon submission.

Evanescent-Wave Driven Rotation of Plasmonic Nano-propeller

Daigo Oue, Satoshi Kawata
Department of Applied Physics, Graduate School of Engineering, Osaka University, Suita, Osaka 565-0871, Japan
oue@ap.eng.osaka-u.ac.jp

In 1909, J. Poynting predicted that circularly-polarized light beam has angular momentum, and rotate objects [1]. After 30 years, R. Beth experimentally demonstrated the rotation of objects by circularly-polarized light beam [2]. At that time, they used heated filaments as light source. Optical force exerted by that kind of light source were too small, so they need to employ vacuum chamber to confirm that small optical force experimentally. Thanks to the invention of laser, scientists could revolve micro-sized particles with circular polarization [3, 4]. After few years, rotation by optical vortex were also demonstrated [5, 6]. In 2010, linearly-polarized Gaussian light beam rotated plasmonic nano-propeller [7].

What will happen when we employ evanescent illumination? In this research, we discuss torque exerted on plasmonic nano-propeller with calculation using finite elementary method. The rotary drive is caused by optical radiation force. In this point of view, rotary driving force will increase as scattering cross section of particles become larger.

Metallic nano-particle has large scattering cross section in the condition of LSPR (localized surface plasmon resonance). For example, gold nano-propeller of diameter 37 [nm] has a resonance peak at excitation wavelength of 660 nm. Let the amplitude of the incident electric field, [V/m], and wave vector [/nm]. Then we can obtain the expression of evanescent wave as . In this case, -direction torque is [J].

This is about 100 times larger than -direction torque with wavelength of 488 [nm] excitation, which is [J]. The torque of [J] is larger than the energy of Brownian motion at 300 [K], [J].

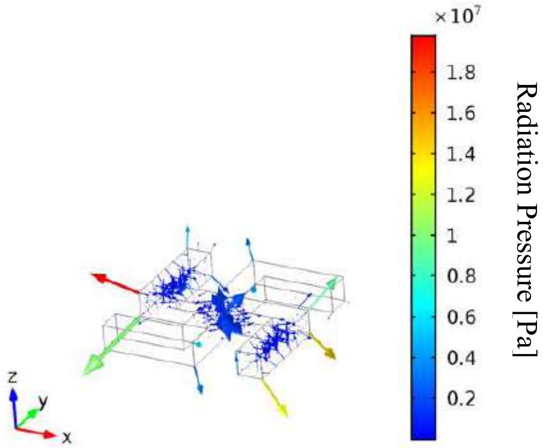


Figure 1: Mapping of Calculated Radiation Pressure on the Nano-propeller in Evanescent Wave (decay direction: +z, propagation direction: +y, polarization direction: +x)

References

[1] J. Poynting, *Proc. R. Soc. Lond. A* **82**, 560–567 (1909).
[2] R. Beth, *Phys. Rev.* **50**, 115–125 (1936).
[3] T. Sugiura *et.al.*, *J. Spectrosc. Soc. Jpn.* **39**, 342 (1990).
[4] M. Friese *et. al.*, *Nature* **394,** 348-350 (1998).
[5] M. Friese *et. al.*, *Phys. Rev. A* **54**, 1593-1596 (1996).
[6] N. Simpson *et. al.*, *J. Opt. Lett.* **22,** 52-54 (1997).
[7] M. Liu *et. al.*, *Nature Nanotech.* **5**, 570-573 (2010).

Detection of optical vortices with phase and polarization singularities by a triangular aperture

M. E. Pietrzyk, J. M. E. Glackin, G. A. Turnbull, K. Dholakia and I. D. W. Samuel
Organic Semiconductor Centre, SUPA, School of Physics and Astronomy,
University of St Andrews, St Andrews
mp212@st-andrews.ac.uk

We investigate the diffraction of optical vortex beams with superimposed phase and polarization singularities. Vortex beams with non-zero topological charge (TC) and the azimuthal polarization are generated using the distributed feedback organic laser. In order to generate optical vortices, the Bragg reflector has been designed in the form of a multi-armed Archimedean spiral. The diffraction patterns for azimuthally polarized vortices are different from those for linearly polarized vortices, they both allow to quantify the absolute value of TC of the vortex and its handedness. Fig. 1 shows numerical simulations of the Fraunhofer diffraction of the of Laguerre-Gaussian (LG) beam with topological charge with linear (Fig. 1a),

and azimuthal (Fig. 1b),

polarization.

To determine the topological charge of the linearly/azimuthally polarized vortex beam, one needs to calculate the number of bright/dark regions, which is equal to the absolute value of TC plus one, . On Fig. 1c we show the experimentally obtained diffraction patterns for the vortex beam with TC emitted from our vortex laser. There is a good agreement between the numerically and experimental obtained diffraction patterns.

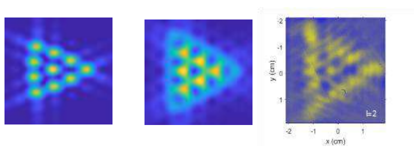
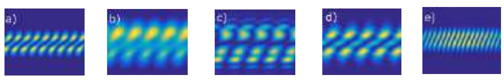


Fig. 1 a) b) c)

We also found that the use of the triangular aperture is a more reliable method of identifying and quantifying optical vortices than the double-slit aperture. This is confirmed by numerical simulations for the double-slit (Fig. 2) and triangular (Fig. 3) apertures for a vortex with TC . In the case of the double-slit aperture and the polarization component parallel to the slits there is a shift between the upper and lower parts of the interference fringes by the period of the fringes multiplied by TC. This method works quite well when the slits are symmetrically positioned with respect to the center of the vortex beam and when the distance between the slits and their length are properly selected (Fig. 2a). If these conditions are not satisfied one can run into misleading conclusion regarding the value of TC, as it is shown on Figs 2b, c, d, e, where misalignments are introduced. The situation is much different for the triangular aperture where, even if there is a misalignment of the aperture with respect to the vortex beam, one can still properly read out information about TC of the vortex.



ideal

Fig. 2

ideal

Fig. 3

$LG^{(2)}$ beam with TC width and central position . Parameter of the double-slit aperture: (separation between the slits), (length of the slits).

Parameters of the triangular aperture:
(length of the edges).

Manipulating Optical Vortices based on Convolution in Second Harmonic Generation

Xiaodong Qiu, Fangshu Li, and Lixiang Chen*
Department of Physics, College of Physical Science & Technology, Xiamen University, Xiamen, China 361005
*chenlx@xmu.edu.cn

Manipulating the optical vortex array is a meaningful yet challenging task. Here, by combining the optical Fourier transform (OFT) and second harmonic generation (SHG), we demonstrate a simple experiment to generate and manipulate optical vortices. In our scheme, a single spatial light modulator (SLM) is addressed to prepare one- or two-dimensional optical vortex arrays embedded in the 1064nm fundamental light. After placing the periodically poled lithium niobate (PPLN) crystal in the Fourier plane, serving as an optical frequency doubler, we perform the multiplication of the spatial frequency of the input vortex array, and thus, realizing the self- and cross-convolution between each constituent vortex. As a result, we succeed in generating a larger number of generated optical vortices in the image plane of OFT, e.g. with an output 3×3 array instead of the input 2×2 array. Additionally, the topological charges of vortices in the output array can be controlled precisely and neatly. The experimental results agree well with the numerical simulations. It is worth noting that our scheme could also act as a bridge between two OAM-based optical communication networks that employ different wavelengths. Besides, our method may find potential applications in optical trapping and optical imaging.

Generation of beams carrying OAM in an integrated optical circuit

R. Tudor[1,2], M. Kusko[1], C. Kusko[1]
[1]Institute for Microtechnology,
Erou Iancu Nicolae Street 126A, 077190, Bucharest, Romania
[2]University of Bucharest, Department of Physics,
Atomistilor Street 405, 077125, Magurele, Romania
rebeca.tudor@imt.ro

We numerically demonstrate the generation of beams presenting helical wavefronts carrying orbital angular momentum (OAM) $m=\pm1$ in an optical integrated circuit [1]. The generation of this class of beams is based on the coherent superposition of the first excited modes present in a waveguide with a rectangular cross section when the phase delay between them is $\pm\pi/2$.

We used the beam propagation method (BPM) in order to simulate the propagating fields in the optical circuit and to fine tune the geometrical parameters necessary to obtain beams with helical wavefronts presenting either transverse electric (TE) or transverse magnetic (TM) polarizations at the output of the optical circuit

Figure 1 illustrates the field amplitude at the output of the optical circuit for a beam with an OAM m=-1 and TM polarization.

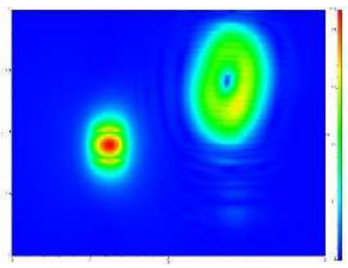


Figure 1: Field amplitude at the output of the optical integrated circuit; TM polarization with OAM m=-1.

References

[1] Tudor R., Kusko M., Kusko C., "Generation of optical vortices in an integrated optical circuit." Submitted to Journal of Optics.

Acknowledgement

The authors would like to acknowledge the support of the project "Secured high volume free space optical communications based on computer generated holograms", UEFISCDI, PN-II-PT-PCCA-2011-3.2-0862 Contract and IMT-Bucharest Core Programme "TEHNOSPEC" supported by MCI, project PN16320102.

Measuring the orbital angular momentum contribution to the velocity of photons

T. Roger (1), A. Lyons (1), C. Maitland (1), S. Vezzoli (1), N. Westerberg (1), J. Leach (1), M. Padgett (2), D. Faccio (1)
(1) School of Engineering and Physical Sciences, Heriot-Watt University, Scotland, UK
(2) School of Physics and Astronomy, University of Glasgow, Scotland, UK
t.w.roger@hw.ac.uk

The velocity of light in vacuum is known according to relativity to be constant. However, recent studies have shown that spatial structuring of light can lead to a deviation from this constant. For instance a Bessel beam, which has a constant and non-zero transverse wavevector, will have a longer transit time over a fixed distance than a non-structured (plane-wave) beam [1]. More complex structuring of the beam phase, for instance adding an azimuthal phase gradient inducing orbital angular momentum (OAM), a slowdown of the propagation speed of light has also been observed [2]. We will show that the true effect of adding OAM to the beam does not always lead to a slow down of the photon and depends specifically on the intensity distribution of the photon.

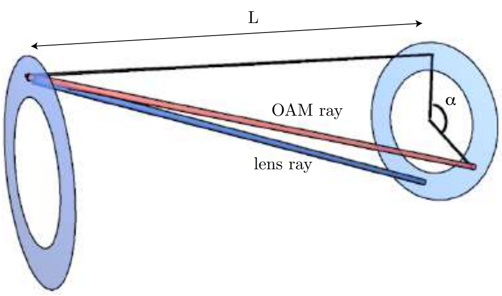


Figure 1: Ray tracing for beams carrying orbital angular momentum compared to a focussed plane wave.

We provide a simple ray-tracing description of how orbital angular momentum affects the propagation delay of photons. This simple theoretical prediction clearly indicates that, in the case of a focused beam, adding OAM while fixing the intensity distribution will reduce the photon delay i.e. speed the photon up. This result is not in contradiction with previous results where the photon spatial profile was allowed to vary in radius as OAM was added to the beam [3]. The aim of this study is to investigate the intrinsic OAM delay, rather than the overall effect which is in part due to reshaping of the beam. The reduction in delay (speed up of the photon) due to OAM can be understood within the framework of ray optics and is related to the fact that the longest path for a ray is given by paths that invert an image through a telescope. Beams with OAM will rotate an image by an certain angle that is always less than 180° and hence, light rays will propagate along shorter paths. We present a series of measurements based on a Hong-Ou-Mandel interferometer with which we verify our predictions and measure the OAM-induced speed-up of single photons.

References

[1] D. Giovanni, J. Romero, V. Potoček, G. Ferenczi, F. Speirits, S. M. Barnett, D. Faccio, M. J. Padgett, “Spatially structured photons that travel in free space slower than the speed of light" Science, E20, 857-860 (2015)

[2] F. Bouchard, J. Harris, H. Mand, R. Boyd, and E. Karimi, “Observation of subluminal twisted light in vacuum," Optica 3, 351-354 (2016).

[3] N. D. Bareza, and N. Hermosa, “Subluminal group velocity and dispersion of Laguerre Gauss beams in

free space." Sci. Rep. 6, 26842; doi: 10.1038/srep26842 (2016)

Orbital angular momentum entanglement in correlated quantum channels

Filippus S. Roux
National Metrology Institute of South Africa,
Meiring Naudé Road, Brummeria, Pretoria, South Africa

Orbital angular momentum (OAM) states of photons enable quantum communication within a larger Hilbert space; thus, leading to a higher information capacity and better security in quantum cryptography. However, the media through which these photons pass can introduce distortions to their spatial modes. In free-space channels, this distortion is caused by turbulence, which degrades the performance of free-space quantum communication system. In optical fibre, imperfections cause modal coupling, which also adversely affect the quantum communication process. For quantum key distribution protocols that are based on quantum entanglement, these distortions often lead to a loss in quantum entanglement.

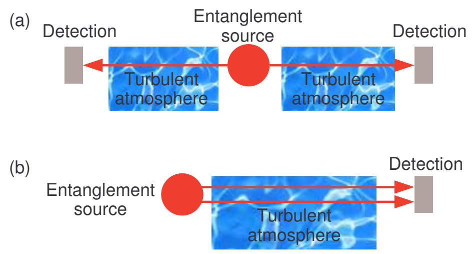


Figure 1: The two entangled photons propagate through (a) different regions of turbulence, and (b) the same turbulent medium.

Usually it is assumed that the different entangled photons pass through different uncorrelated channels. In Figure 1(a), such a scenario is shown for the case of two entangled photons propagating through different uncorrelated regions of turbulent atmosphere. However, in certain situations, the protocol may call for multiple entangled photons to be sent through the same channel. This is for instance the case in a recently proposed method to implement high-dimensional quantum teleportation [1]. Such a scenario is shown in Figure 1(b) where two entangled photons propagating through the same region of turbulent atmosphere. Since the medium that is seen by the different photons is the same, it gives rise to correlations in the effect of the medium on the photons, analogous to the quantum correlation that is seen in the Hong-Ou-Mandel effect.

Here, we investigate the effect of these correlations on the evolution of a bipartite OAM entangled photonic state when both photons propagate through the same channel. We'll focus on the case where the channel involves free-space propagation through a turbulent atmosphere. For this purpose, we use an infinitesimal propagation approach [2], which is a multiple phase screen analysis that is valid for all scintillation conditions and not only under weak scintillation.

What we find is that, while the propagation of photons through different turbulent channels causes the entanglement to become zero at a finite propagation distance, the entanglement for photons propagating through the same turbulent channel approaches zero asymptotically. This is true for qubits [3], as well as higher dimensional states.

References

[1] S. Goyal, P. E. Boukama-Dzoussi, S. Ghosh, F. S. Roux, and T. Konrad, "Qudit-Teleportation for photons with linear optics," Sci. Rep. 4, 4543 (2014).

[2] F. S. Roux, T. Wellens, and V. N. Shatokhin, "Entanglement evolution of twisted photons in strong atmospheric turbulence," Phys. Rev. A 92, 012326 (2015).

[3] F. S. Roux, "Biphoton states in correlated turbulence," Phys. Rev. A 95, 023809 (2017).

Generation of polarization entangled optical vortex lattice beams via pulse sequencing techniques

D. Sarenac[1,2], J. Nsofini[1,2], I. Hincks[2,3], P. Miguel[2,4], M. Arif[5], Charles W. Clark[6], D. G. Cory[2,4,7,8], M. G. Huber[5], D. A. Pushin[1,2]
[1]Department of Physics, University of Waterloo, Waterloo, ON, Canada, N2L3G1
[2]Institute for Quantum Computing, University of Waterloo, Waterloo, ON, Canada, N2L3G1
[3]Department of Applied Math, University of Waterloo, Waterloo, ON, Canada, N2L3G1
[4]Department of Chemistry, University of Waterloo, Waterloo, ON, Canada, N2L3G1
[5]National Institute of Standards and Technology, Gaithersburg, Maryland 20899, USA
[6]Joint Quantum Institute, National Institute of Standards and Technology and University of Maryland, College Park, Maryland 20742, USA
[7]Perimeter Institute for Theoretical Physics, Waterloo, ON, Canada, N2L2Y5
[8]Canadian Institute for Advanced Research, Toronto, Ontario, Canada, M5G 1Z8
dsarenac@uwaterloo.ca

It was demonstrated that neutron beams can carry orbital angular momentum (OAM), similar to beams of photons, atoms, and electrons. Recently we described a method for preparing neutron spin-orbit states where orbital angular momentum is induced via spin-orbit coupling. This is analogous to the use of q-plates for photons and Wien filters for electrons. It is important to recognize that the underlying principles of OAM manipulation in these different systems are related and that this allows for common preparation methods.

To enhance the expected signal of the neutron spin-orbit states, we have devised a parallel multiplexing technique that can produce a beam consisting of a lattice of coupled spin and angular momenta states. Our protocols are based on standard quantum information processing (QIP) pulse sequencing methods originally developed for applications in nuclear magnetic resonance.

Being based on a general model we can demonstrate the power of these protocols on photon beams, where we produce a lattice of polarization-orbit states. This can be achieved because there is an isomorphism between the Bloch sphere representing the spin states of fermions and that of the Poincare sphere representing the polarization states of light.

This technique provides a tool for diverse investigations, as polarization-orbit states have found applications in high resolution optical imaging, ultra-secure communication, and optical metrology. It may be possible to create a lattice of ring-shaped optical atomic traps, and one can also envisage arrays of tubular optical atomic traps.

Furthermore, this method is particularly useful for particle beams where the beam is generally an incoherent mixture of coherent wavepackets. Spin-orbit and orbit states may be generated where the OAM axis is specified along the coherent wavepacket rather than the beam axis. This opens the door for studies of chiral and topological materials via particle beams.

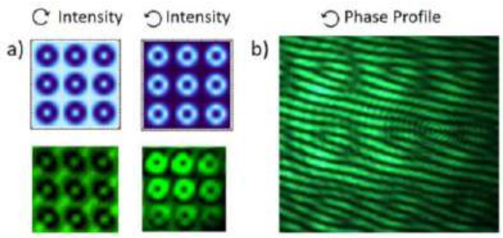


Figure 1: a) The simulated (top) and the observed (bottom) intensities of the polarization entangled optical vortex lattice beams, post-selected on the particular circular polarization. b) The phase profile of the beam obtained via an interferometric measurement where we post selected on the polarization which carries the OAM. We also induced a linear gradient inside the interferometer in order to obtain the well-known fork pattern.

Photonic orbital angular momentum entanglement past an obstruction

G. Sorelli, V. N. Shatokhin, A. Buchleitner
Physikalisches Institut, Albert-Ludwigs-Universität,
Hermann-Herder-Str. 3, D-79104, Freiburg i. Br., Germany
giacomo.sorelli@physik.uni-freiburg.de

It is well known that photonic orbital angular momentum (OAM) can be employed to increase channel capacity and security of quantum communication. On the downside, quantum entanglement between photon pairs, which is required for many quantum protocols, is fragile with respect to wavefront disturbances along the transmission path. In this contribution, we explore the robustness of biphoton entangled states upon transmission across a circular obstruction, for different spatial modes where OAM is inscribed in.

In particular, we focus on two widely studied sets of modes: Laguerre-Gaussian (LG) and Bessel-Gaussian (BG). Whereas LG modes are commonly used in experimental and theoretical studies of OAM entanglement, BG modes are famous in classical optics due to their self healing ability. In a recent experiment [1] it was shown that self healing makes OAM entanglement in the BG basis more robust against disturbances caused by an obstruction. However, a systematic analysis of how the transmission of OAM entanglement through obstructed paths is affected by properties of obstacles, as well as by the mode spatial structure, was missing.

We demonstrate that crosstalk between different OAM modes, which is the main cause of OAM entanglement degradation, is always weaker for BG modes than for LG modes. Using numerical Fourier optics simulations, we quantify how the size of the obstacle and its displacement with respect to the optical axis affect the strength of the crosstalk.

From an analysis of the crosstalk we present an interpretation of the behavior of the entanglement of the diffracted state under an increase of the obstacle's displacement with respect to the propagation axis. The entanglement transmission characteristics are illustrated in Fig. 1.

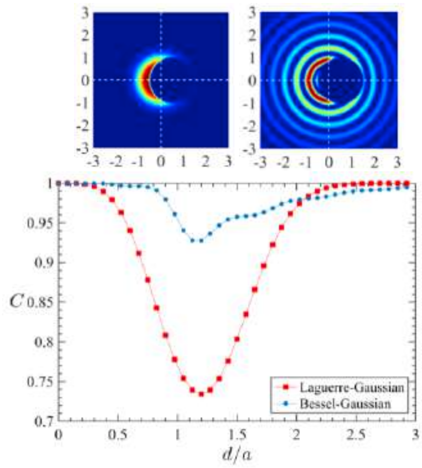


Figure 1: Top: Intensity distributions (linear colour code) of the OAM entangled state past the obstruction, for LG (left) and BG (right) modes, respectively. Bottom: Concurrence C of the maximally entangled qubit state with $l = \pm 1$ downstream the obstruction, for different obstacle displacement d (in units of the obstacle's radius a), for both, LG and BG modes.

Furthermore, we establish the relationship between the entanglement of LG modes, on one hand, and the ratio between obstacle size and phase-correlation length (introduced in [2]), on the other.

References

[1] M. McLaren, T. Mhlanga, M. J. Padgett, F. S. Roux, and A. Forbes, Nat. Commun. 5 (2014).

[2] N. D. Leonhard, V. N. Shatokhin, and A. Buchleitner, Phys. Rev. A 91, 012345 (2015).

Circularly Polarized White Light Optical Vortex Generation Using a Computer Generated Hologram with Structural Birefringence

Ryotaro Suzuki[1], Daisuke Barada[1,2],
Grad. Sch. Eng. Utsunomiya Univ.[1], CORE Utsunomiya Univ.[2],
mt166224@cc.utsunomiya-u.ac.jp

Circularly polarized optical vortices are known to possess spin and angular momenta dependent on the degree of circular polarization and topological charge[1]. In this study, a circularly polarized white light is generaged by using a computer generated hologram (CGH) and the interaction between the generated optical vortex and a matter is invesigated.

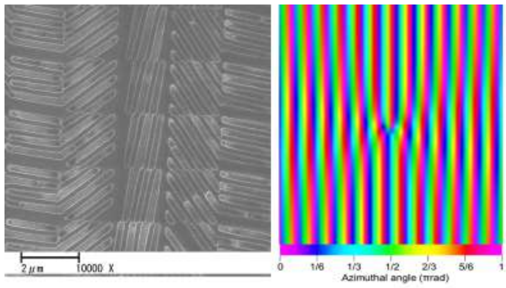
The time average of optical Lorentz force per unit volume is expressed by

$$\boldsymbol{F} = \frac{\omega\varepsilon_0}{2}\left[\chi_r \mathrm{Im}\left(\boldsymbol{E}\times\boldsymbol{B}^*\right) + \chi_i \mathrm{Re}\left(\boldsymbol{E}\times\boldsymbol{B}^*\right)\right], \qquad (1)$$

where $\boldsymbol{E}$, $\boldsymbol{B}$, ω, ε_0, χ_r and χ_i are electric field vector, magnetic flux density vector, the angular frequency of a monochromatic light, permittivity of vacuum, the real part and the imaginary part of the electric susceptibility of an irradiation target material, respectively. The second term means the force by momentum transfer from light to matter because χ_i becomes finite value by light absorption and $\mathrm{Re}\left(\boldsymbol{E}\times\boldsymbol{B}^*\right)$ is proportional to Poynting vector. The electric field of a monochromatic optical vortex beam with arbitrary polarization state is expressed by

$$\boldsymbol{E}(r,\varphi,z) = \boldsymbol{J}A_\ell\left(r,z\right)\exp\left(i\ell\varphi\right) \cdot \exp\left(-i\omega t\right), \qquad (2)$$

where $\boldsymbol{J}$, ℓ, and A_ℓ are a Jones vector, topoligical charge and the complex amplitude of incident light, respectively. By using Eq. (2), $\boldsymbol{B}$ is calculated by Faraday-Maxwell equation, and the rotational force is extracted from Eq. (1) as



(a) (b)

Figure 1: CGH pattern. (a)Partial SEM image. (b)Principal axis pattern of structural birefringence.

$$\boldsymbol{F}_\varphi = \frac{\varepsilon_0\chi_i}{4}\left[\left(\ell\frac{A_\ell^2}{r} - \frac{\sigma}{2}\frac{\partial A_\ell^2}{\partial r}\right)\boldsymbol{e}_\varphi\right], \qquad (3)$$

where $\sigma = 2\mathrm{Im}(J_x^* J_y)$ is the degree of polarization. As shown in Eq. (3), the direction of rotational force is not dependent on the frecuency of incident light. Therefore, the rotational force can be induced by whie light with common rotation axis.

In this study, in order to generate a white light optical vortex with circular polarization, a CGH with structural birefringence was fabricated by electron beam lithography (Fig. 1). The CGH exhibits a beam splitting property, in which arbitrary polarized light is split to a trasparent light and two diffracted beams with mutually opposite handedness. By extracting a diffracted beam, a circularly polarized whight light optical vortex beam was obtained.

References

[1] D. Barada , T. Omatsu et al., Appl. Phys. Lett., 108, 051108 (2016)

Angular Momentum Radio Communication Systems

Bo Thidé
Swedish Institute of Space Physics, Uppsala, Sweden
bt@irfu.se
Fabrizio Tamburini
ZKM, Centre for Art and Technologies for Media, Karlsruhe, Germany
fabrizio.tamburini@gmail.com

In order to use angular momentum radio in different radio communication scenarios, it is desirable to design systems that make full use of the physical properties of the EM angular momentum observable.

Starting from first principles, we have been able to show that angular momentum density beams can be shaped and focused precisely in the same way that conventional linear momentum density (Poynting vector) beams can. This make it possible to use standard antenna engineering techniques, developed over many decades, to generate, shape and focus angular momentum beams that have properties that can be adapted to a many different communication scenarios, significantly simplifying the design of angular momentum radio communication systems.

We also explain the difference between OAM radio and MIMO radio communication systems and show how the two methods can be combined into a super-MIMO technique.

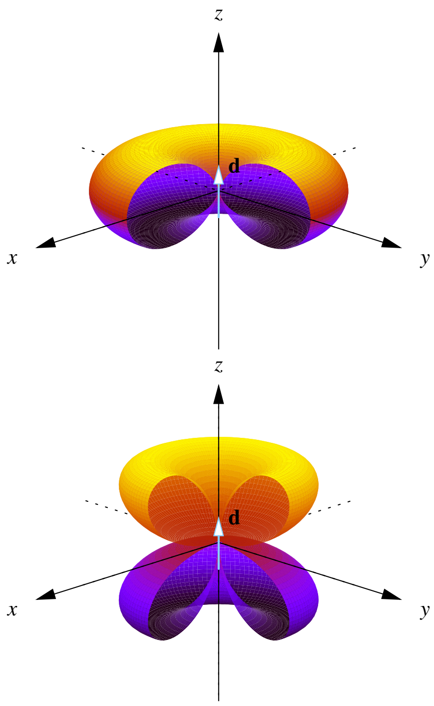


Figure 1: Distribution of the linear momentum density/Poynting vector (top) and the angular momentum density (bottom) emitted by a short, electric (Hertz) dipole **d** located at the origin.

Vortex rings on vortex lines in nonlocal nonlinear media

A.I. Yakimenko[1], V.M. Biloshytskyi[1], A.O. Oliynyk[1], A.S. Desyatnikov[2,3]
[1] Department of Physics, Taras Shevchenko National University of Kyiv, Ukraine
[2] Department of Physics, School of Science and Technology, Nazarbayev University, Kazakhstan
[3] Nonlinear Physics Centre, Research School of Physics and Engineering, The Australian National University, Canberrra, ACT 2601, Australia
alexander.yakimenko@gmail.com

Nonlocality is a key feature of many physical systems since it prevents a catastrophic collapse and a symmetry-breaking azimuthal instability of intense wave beams in a bulk self-focusing nonlinear media. This opens up an intriguing perspective for stabilization of complex topological structures such as vortex rings and vortex ring-on-line complexes.

Vortex rings are topological structures with a closed-loop core, which play a crucial role in the decay of superflow and in quantum turbulence in condensed matter physics. It was revealed in Ref. [1], that in self-saturating optical nonlinear media as a radially perturbed soliton propagates, vortex loops occur in the form of rings perpendicular to the propagation direction. This spontaneous vortex nucleation is a consequence of the nonlinear phase accumulation between the soliton's peak and its tail. Optical vortex rings (in contrast to vortex rings in fluids) are static in time and appear when nonlinear phase of the self-trapped light beam breaks the wave front into a sequence of optical vortex loops around the perturbed fundamental soliton ($m = 0$). In this work we demonstrate that vortex rings can be generated in nonlocal nonlinear media.

A vortex line is the singular wave beam with ringlike intensity distribution, with the dark hole at the center where the phase dislocation takes place: a phase circulation around the axis of propagation is equal to $2\pi m$. In contrast to fundamental soliton ($m = 0$), in a self-focusing nonlinear media the spinning solitons usually possess a strong azimuthal modulational instability. However nonlocality of the nonlinear response can suppress or completely eliminate the symmetry-breaking azimuthal instability [2, 3]. This opens up a perspective for stabilization also vortex soliton states with complex structure such as Hopfions. A Hopfion (or Hopf soliton) is a topological soliton with two independent winding numbers: the first, S, characterizes a horizontal circular vortex embedded into a three-dimensional soliton; and the second, m, corresponds to vorticity around the axis, perpendicular to this circle. Hopf solitons appear in many fields, including field theory, optics, ferromagnets, and semi- and superconductors. Multicharged ($m > 1$, $S > 1$) vortex structures have been demonstrated [4] to be unstable in optical media. In this work we demonstrate that radially perturbed vortex line soliton ($m \geq 1$) gains additional single-charged ($S = 1$) vortex rings. These vortex complexes represent the first examples of optical analog of Hopfions: vortex ring-on-line.

References

[1] A.S. Desyatnikov, D. Buccoliero, M.R. Dennis, and Yu.S. Kivshar Scientific Reports 2, p. 771, 2012

[2] A. I. Yakimenko, Yu. A. Zaliznyak, and Yu. Kivshar, Phys. Rev. E, 71, 065603(R) 2005.

[3] A. I. Yakimenko, V. M. Lashkin, and O. O. Prikhodko, Phys. Rev. E 73, 066605, 2006.

[4] M. V. Berry and M. R. Dennis, Proc. R. Soc. London A 457, 2251, 2001.

High-dimensional entanglement decay through atmospheric turbulence

Yingwen Zhang[1], Shashi Prabhakar[2,3], Alpha Hamadou Ibrahim[2], Filippus S. Roux[2,3], Andrew Forbes[2,3], Thomas Konrad[4,5]

[1]Department of Physics, University of Ottawa, 25 Templeton St., Ottawa, Ontario, K1N 6N5 Canada
[2]CSIR National Laser Centre, PO Box 395, Pretoria 0001, South Africa
[3]School of Physics, University of the Witwatersrand, Johannesburg 2000, South Africa
[4]University of Kwazulu-Natal, Private Bag X54001, Durban 4000, South Africa
[5]National Institute of Theoretical Physics, University of KwaZulu-Natal, Private Bag X54001, Durban 4000, South Africa

We study the effects of atmospheric turbulence on photon pairs entangled in high-dimensional Laguerre-Gaussian basis generated by spontaneous parametric down-conversion. One of the photons propagates through turbulence, while the other is left undisturbed. The atmospheric turbulence is simulated by a single phase screen based on the Kolmogorov theory of turbulence[1]. The output after turbulence is projected into a three-dimensional (qutrit) basis composed of specific Laguerre-Gaussian modes. Full state tomography is performed to determine the density matrix for each output quantum state. These density matrices are used to determine the amount of entanglement, quantified in terms of the negativity, as a function of the scintillation strength. We have found that the entanglement decay for larger orbital angular momentum (OAM) values is slightly slower than when smaller OAM values are used. However comparing our results to those that were previously obtained for the qubits [2] we see that the overall entanglement decays much faster for qutrits. Therefore the benefit of using high dimensional states (better security and higher information capacity) may be offset by a poorer performance in turbulence. This would play an important role in the design of a free-space QKD system.

References

[1] L. C. Andrews and R. L. Phillips, *Laser Beam Propagation Through Random Media*, SPIE, Washington, DC, 1998.

[2] A. Hamadou Ibrahim, Filippus S. Roux, Melanie McLaren, Thomas Konrad, and Andrew Forbes, Orbital-angular-momentum entanglement in turbulence, Physical Review A **88**, 012312, 2013

Poster Session 2.

Confined bases: from paraxial to electromagnetic

R. Gutiérrez-Cuevas and M.A. Alonso
The Institute of Optics and Center for Coherence and Quantum Optics,
University of Rochester, Rochester, New York 14627, USA
rgutier2@ur.rochester.edu

Most optical fields propagating through free space are not described by simple closed-form expressions. Instead, they are modeled through numerical evaluation of propagation integrals. For some paraxial beams, this numerical burden can be alleviated by expressing the field in terms of a discrete basis, such as the Hermite-Gauss or Laguerre-Gauss modes, which are simple to propagate and might posses properties similar to those of the original field (e. g. orbital angular momentum). These bases are composed of a polynomial, which gives the nodal/phase structure, *times* a Gaussian, limiting the spatial extent. The polynomial factors widen each element roughly proportionally to the square root of their order, so that the basis elements have very different width.

Here, we propose using a different approach: we build new bases by letting the Gaussian be the argument of the polynomials [1]. That is, instead of polynomials *times* a Gaussian, we consider polynomials *of* Gaussians [$u = \exp(-r^2) \in [0,1]$], multiplied by a simple vortex factor $r^{|m|}\exp(im\phi)$ to provide the azimuthal structure. Perhaps the main feature of the new bases is that all their elements have essentially equal effective width [Fig. 1(a)], which leads to a (roughly) truncation-independent transverse scaling parameter for fitting a well-localized beam. This is shown in Fig. 1(b) for the particular case of a circular simple vortex of the form $re^{i\phi}\mathrm{circ}(r)$. Furthermore, because they are combinations of Gaussians and simple vortices, the paraxial propagation of the elements is given in closed form.

These bases can be extended to the nonparaxial regime (scalar and vector) [2], where the elements are confined in direction space. They are given in terms of simple vortices (multipoles $l = |m|$) with their focus shifted to a complex point ($\mathbf{r} \to \mathbf{r} - \mathrm{i}nq\hat{\mathbf{z}}$). This allows a simple expression as well as

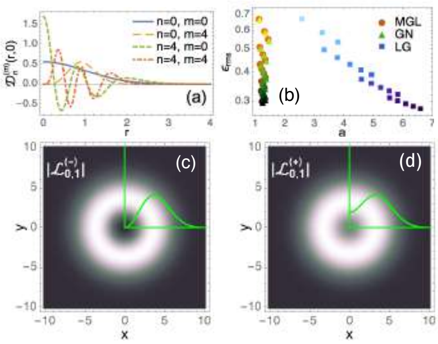


Figure 1: (a) Radial dependence of the new paraxial basis, (b) minimum truncation error as a function of scaling parameter a for orders 1 (lighter) through 18 (darker). (c-d) Transverse intensity for two orthogonal spin elements with same vorticity m.

the inclusion of the parameter q which controls the directionality of the elements. This parameter can be used to find the optimal fit of a given field and to study the transition from nonparaxial to paraxial fields. When using elements with definite helicity, this basis clearly shows the effect of nonparaxial spin-orbit coupling, as shown in Figs. 1(c) and (d): the radial profile depends on the relative sign between helicity and m.

References

[1] Gutiérrez-Cuevas, R., Alonso, M.A., Polynomials of Gaussians and vortex-Gaussian beams as complete, transversely confined bases, to appear in Opt. Lett., 2017.

[2] Gutiérrez-Cuevas, R., Alonso, M.A., Scalar and electromagnetic nonparaxial bases composed as superpositions of simple vortex fields with complex foci, submitted to Opt. Express, 2017.

Particle vortex waves – from electrons to other fundamental particles, atoms and big molecules

Mohamed Babiker
Department of Physics,
University of York, York, YO10 5DD, England, UK
m.babiker@york.ac.uk

The last few years have witnessed the prediction and subsequent creation of electron vortex waves in electron microscopes [1,2]. These electron waves represent the first matter vortex beam states bearing close similarities to but also crucial differences from optical vortex beams [3]. There is currently a growing activity and interest in electron vortex waves, but work is just beginning on other matter vortex waves: atoms, positrons, neutrons and neutrinos are among those currently being considered. Vortex beam research is now inter-disciplinary with their possible utility now contemplated in various areas, including biophysics and nuclear and particle physics. The issues here are: how successful is current work, what are the practical limitations i.e. the feasibility of experimental work in the respective type of matter waves; what new physics is expected in each category and what new applications are envisaged? There appears to be much scope for wide ranging variations in the scales and parameters as well as the physical principles involved in the vortex generation.

This talk will first discuss the general concepts underlying particle beam generation and the experimental evidence for quantum diffraction of particles. It then surveys the hierarchy of particles in nature, including the fundamental particles as well as composites such as neutral atoms, and small and large molecules which can be created in beam form and which can be subject to quantum diffraction. Fundamental vortex properties, namely linear and orbital angular momentum contents, spin and associated electromagnetic fields as well as mechanical and vortex multipolar interactions are discussed. Several features involving spin and orbital angular momentum exchange with matter are highlighted.

References

[1] S. M. Lloyd, M. Babiker, G. Thirunavukkarasu and J. Yuan, `Electron vortices – beams with orbital angular momentum', Review of Modern Physics (in press)
[2] K. Y. Bliokh, I. P. Ivanov , G. Guzzinati , L. Clarkd, R. Van Boxem , A. Beche , R. Juchtmans, M. A. Alonso, P. Schattschneider , F. Nori and J. Verbeeck ` Theory and applications of free-electron vortex states' arXiv:1703.06879v1 [quant-ph] 20 Mar 2017.
[3] D.L. Andrews and M. Babiker `The angular momentum of light' (Cambridge University press, 2012)

Anomalous time delays and quantum weak measurements in optical micro-resonators

K.Y. Bliokh, Y.P. Bliokh, A.G. Kofman, M. Asano, S.K. Özdemir,
R. Ikuta, T. Yamamoto, Y.S. Kivshar, L. Yang, N. Imoto, F. Nori

CEMS, RIKEN, Wako-shi, Saitama, Japan
Nonlinear Physics Centre, RSPE, The Australian National University, Canberra, Australia

k.bliokh@gmail.com

Quantum weak measurements, wavepacket shifts and optical vortices are universal wave phenomena, which originate from fine interference of multiple plane waves. These effects have attracted considerable attention in both classical and quantum wave systems. Here we report on a phenomenon that brings together all the above topics in a simple one-dimensional scalar wave system [1]. We consider inelastic scattering of Gaussian wave packets with parameters close to a zero of the complex scattering coefficient (Fig. 1). We demonstrate that the scattered wave packets experience anomalously large time and frequency shifts in such near-zero scattering. These shifts reveal close analogies with the Goos–Hänchen beam shifts and quantum weak measurements of the momentum in a vortex wavefunction. We verify our general theory by an optical experiment using the near-zero transmission (near-critical coupling) of Gaussian pulses propagating through a nano-fibre with a side-coupled toroidal micro-resonator. The measurements demonstrate the amplification of the time delays from the typical inverse-resonator-linewidth scale to the pulse-duration scale.

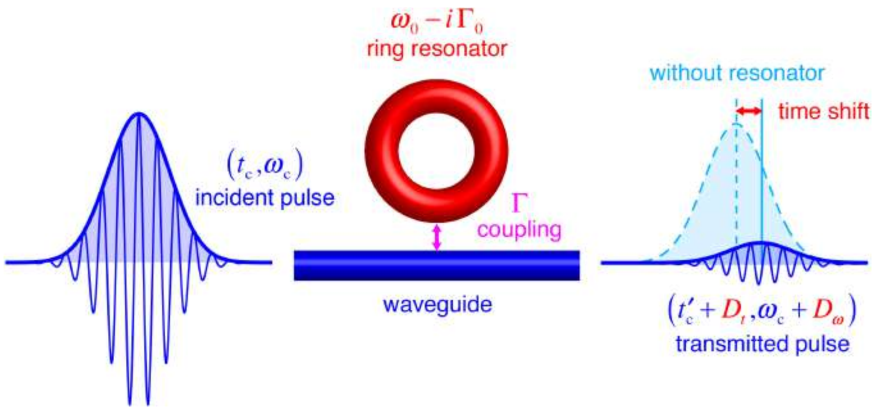


Figure 1: Time and frequency shifts of an optical pulse interacting with a waveguide-coupled resonator.

References

[1] M. Asano *et al*., Nature Commun. **7**, 13488 (2016)

High-dimensional quantum cloning of twisted photons

F. Bouchard, R. Fickler, R.W. Boyd, E. Karimi
Department of Physics, University of Ottawa, 25 Templeton St., Ottawa, K1N 6N5, Canada

fbouc052@uottawa.ca

In the classical world, information can be perfectly copied without any fundamental limitation. However, this is not the case in the quantum world due to the no-cloning theorem [1], a fundamental limitation of nature. The no-cloning theorem turns out to be necessary for quantum information to be consistent with many fundamental principles such as the no-signaling theorem and the uncertainty principle. Although perfect cloned copies of an unknown quantum system cannot be achieved, one may ask how good cloned copies are fundamentally allowed to be produced. Hence, quantum cloning machines may generate copies with some maximal fidelity, where the fidelity of the clone is defined as the overlap of the initial state that is to be cloned with the cloned copy. An expression for the optimal cloning fidelity of the 1 → 2 Universal Quantum Cloning Machine (UQCM) is given by $F=1/2+1/(1+d)$ [2], where d is the dimension of the Hilbert space of the quantum states. Orbital Angular Momentum (OAM) states of single photons, associated with twisted wavefronts, can serve as a physical realization of d-dimensional quantum states, referred to as qudits.

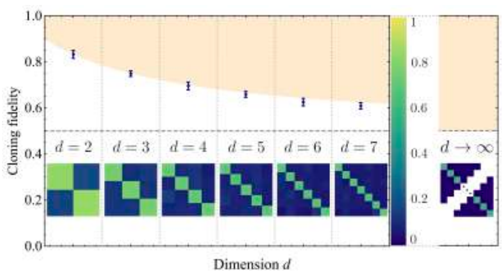


Figure 1: The average cloning fidelities are plotted along with amplitude probability matrices from which the fidelity values are extracted from. The shaded area corresponds to cloning fidelities not accessible by any optimal UQCM.

We use the symmetrization method to realize a universal optimal quantum cloning machine for high-dimensional OAM states [3]. Increasing the dimensionality of the input quantum states results in a decrease of the cloning fidelity. Interestingly, this behaviour can serve as an intuitive explanation of the superiority of high-dimensional quantum cryptography. In our experiment, we measure the cloning fidelity of the cloning machine for different input states belonging to the logical OAM basis of various dimensions, $d \in \{2, 3, 4, 5, 6, 7\}$. We find very good agreement of the experimentally evaluated cloning fidelities to the theoretical predictions of the high-dimensional $1 \to 2$ UQCM (see Fig. 1).

In conclusion, we have performed optimal quantum cloning of OAM qudits, using the symmetrization method. High dimensional quantum cloning has great fundamental importance in quantum information, quantum cryptography and quantum communication protocols.

References

[1] W. K. Wootters and W. H. Zurek, "A single quantum cannot be cloned", *Nature* **299**, 802 (1982).

[2] N. Gisin, G. Ribordy, W. Tittel, and H. Zbinden, "Quantum Cloning", *Reviews of Modern Physics* **74**, 145 (2002).

[3] F. Bouchard, R. Fickler, R. W. Boyd and E. Karimi, "High-dimensional quantum cloning and applications to quantum hacking", *Science Advances* **3**, e1601915 (2017).

Reflective spin-orbit photonics from chiral anisotropic media

M. Rafayelyan and E. Brasselet
Univ. Bordeaux, CNRS, LOMA, UMR 5798, F-33400 France
etienne.brasselet@u-bordeaux.fr

Liquid crystals are well-known for their exquisite sensitivity to external fields and their ability to tailor the amplitude, phase and polarization of light fields. The interplay between the topological features of liquid crystals and that of electromagnetic fields offers a playground for exploring various aspects of optical phenomena driven by the spin-orbit interaction of light. Here we report on highly reflective spin-orbit geometric phase optical elements based on a helicity preserving circular Bragg-reflection phenomenon [1,2].

We show that Berry phase associated with the circular Bragg reflection phenomenon in chiral anisotropic optical media (see Figure 1, left part) brings a novel paradigm to achieve wavelength-independent, pure spin-orbit topological shaping of light, from two- and three-dimensional "Bragg-Berry" mirrors (i) in the reflection mode, (ii) without need for any birefringent retardation requirement.

This is illustrated by the experimental realization of Bragg-Berry mirrors enabling the broadband generation of optical vortices upon reflection for both diffractive and non-diffractive light fields using spatially patterned chiral liquid crystal films (see Figure 1, right part).

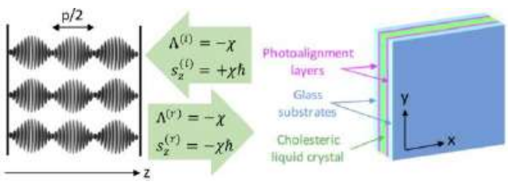


Figure 1: Left: illustration of the circular Bragg reflection main optical characteristics (helicity preservation, flipped spin angular momentum). Right: patterned chiral Bragg liquid crystal reflector acting as broadband optical vortex generator.

We also show that appropriate modulation of the chiral features of the liquid crystal supramolecular ordering allow the generation of vortex beams over the full visible spectrum (see Figure 2). This robust polychromatic behavior is also associated with a large acceptance angle, which supports further realization of spin-orbit devices with enhanced optical characteristics.

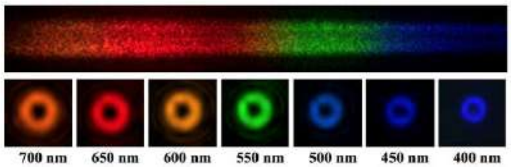


Figure 2: Broadband optical vortex generation from an azimuthally patterned Bragg-Berry mirror. Top: spectrally dispersed reflected vortex supercontinuum radiation. Bottom: far-field reflected vortex beams for 7 spectral bands.

Finally, we will also discuss how superposition of vortex beams can also be prepared from such Bragg-Berry mirrors.

References

[1] Rafayelyan M., Tkachenko G. and Brasselet E., Reflective spin-orbit geometric phase from chiral anisotropic optical media, Phys. Rev. Lett., 116, 253902, 2016.
[2] Rafayelyan M. and Brasselet E., Bragg-Berry mirrors: reflective broadband q-plates, Opt. Lett. 41, 3972 (2016).

Tunable two-photon quantum interference of polarization-structured light

Vincenzo D'Ambrosio[1], Gonzalo Carvacho[2], Iris Agresti[2], Lorenzo Marrucci[3], Fabio Sciarrino[2]

1-ICFO - Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology, E-08860 Castelldefels, Barcelona, Spain

2- Dipartimento di Fisica, Sapienza Universitá di Roma, I-00185 Roma, Italy

3- Dipartimento di Fisica, Universitá di Napoli Federico II, Complesso Universitario di Monte S. Angelo, 80126 Napoli, Italy

Hong-Ou-Mandel effect is a paradigmatic example of quantum interference between two photons entering a beam splitter [1][2]. When the time delay between the photons is set to zero they become completely indistinguishable and destructive quantum interference takes place, leading to a null probability of observing coincidence counts at the two output ports of the beam splitter. As well as being an intriguing topic for fundamental research (especially when multiple particle states are involved), this kind of interference lies nowadays at the basis of several quantum optics techniques and quantum information protocols.

A light beam can show a complex structure in terms of phase or polarization distribution along the beam profile. One example is given by the so called vector vortex beams which show an azimuthally varying polarization pattern surrounding an optical vortex [3]. One famous example of such beams is represented by radial and azimuthal polarized ones. These beams have interesting applications in a large variety of fields ranging from microscopy to quantum information.

Here we combine these two concepts by experimentally observing tunable quantum interference between two photons in structured light modes. More in detail we observe and control the photon bunching for two photons in radial and azimuthal polarization state respectively. The central device of the experiment is a q-plate [4] whose parameters can be easily tuned to control the strength of interference as well as the phase in the final two photon state. This scheme can be easily applied also to higher order vector beams and provides a new tool for fundamental research and quantum technologies based on structured light.

References

[1] C.K. Hong, Z.Y. Ou, L. Mandel, Phys. Rev. Lett. 59, 2044 (1987)

[2] J.W. Pan, et al., Rev. Mod. Phys. 84. 777-838 (2012)

[3] Q. Zhan, Adv.Opt. Phot. 1, 1-57 (2009)

[4] L. Marrucci, C. Manzo, D. Paparo, Phys. Rev. Lett. 96 (16), 163905 (2006)

High-dimensional quantum key distribution with OAM-fibre

D. Cozzolino*, D. Bacco**, K. Ingerslev, Y. Ding,
K. Dalgaard, K. Rottwitt, L.K. Oxenløwe
Department of Photonics Engineering, Technical University of Denmark
2800 Kgs. Lyngby, Denmark,
*dacoz@fotonik.dtu.dk, **dabac@fotonik.dtu.dk

Quantum Key Distribution (QKD) provides an efficient means to exchange information in an unconditionally secure way [1]. Traditional QKD is based on binary signal formats in which the information efficiency is limited to 1 bit/photon. Contrariwise, high-dimensional (HD) quantum states are suitable for longer transmission distance and higher secret key rate transmission, being more robust to noise level and allowing an higher channel capacity [2].

HD quantum states can be created by using different degrees of freedom, i.e. space, time, frequency and phase. In addition to that, a light wave is characterized by its orbital angular momentum (OAM) which corresponds to its helical wavefront. Here, we report the realization of a HD-QKD protocol based on the combination of OAM and polarization states. We combine the polarization states $|L\rangle$, $|R\rangle$, $|D\rangle$, $|A\rangle$ (L, left; R, right; D, diagonal; A, anti-diagonal) with OAM modes $\ell_1 = +6$ and $\ell_2 = +7$ creating two 4-dimensional mutually unbiased bases (MUBs) [3].

Alice, the transmitter, by using a FPGA randomly prepares one of the quantum states of the two MUBs. We utilize liquid crystal devices known as q-plates, which coherently couple optical spin angular momentum to OAM. The quantum states are sent through a 1.2km of OAM-maintaining fibre. At the fibre's output Bob, the receiver, divides the even from the odd OAM modes by using a mode-sorter interferometer. After the sorting process, the OAM states are reconverted to Gaussian mode by using symmetrical q-plates in order to project the quantum states into the correct bases. By combining OAM modes with polarization state of light, HD quantum states can be generated and sent through a OAM-fiber link.

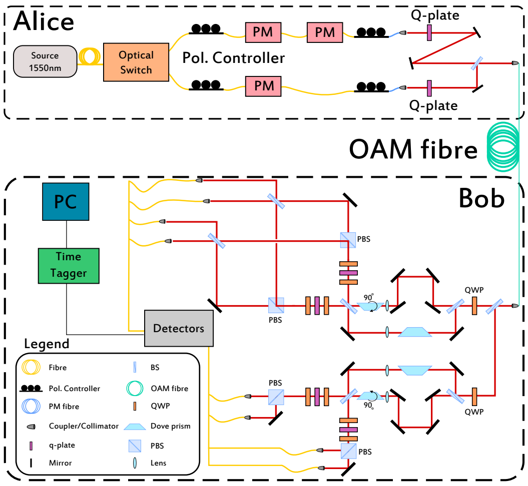


Figure 1: Experimental setup of the HD-QKD experiment.

References

[1] Lo, H. K., Chau, H. F., Unconditional Security of Quantum Key Distribution over Arbitrarily Long Distances, *Science* 283, 2050-2056 (1999).

[2] Ding, Yunhong, et al., High-Dimensional Quantum Key Distribution based on Multicore Fiber using Silicon Photonic Integrated Circuits, *npj Quantum Information* 10.1038/s41534-017-0026-2 (2017).

[3] Alicia Sit et al., High-Dimensional Intra-City Quantum Cryptography with Structured Photons, *arXiv:1612.05195* (2016).

A relativistic field theory description for optical and electron Bessel beams

T. Tijssen, M.R. Dennis
H H Wills Physics Laboratory
Tyndall Avenue, Bristol, BS8 1TL, United Kingdom
teuntje.tijssen@bristol.ac.uk

Bessel beams, cylindrically symmetric solutions of the Helmholtz equation, carry orbital angular momentum [1]. Optical Bessel beams and more recently electron Bessel beams have been created in experiments, showing similar characteristics; a density distribution described by Bessel functions and diffraction-free propagation. Using concepts from classical field theory, such as Noether's theorem and the energy-momentum tensor, we compare relativistic electron Bessel beams [2] with their optical counterparts. In principle, we could apply this to any field described in the Standard Model.

Formally, electrons are massive fermions described by the Dirac equation, whereas photons are massless spin-1 bosons described by Maxwell's equations. The similarities between optical and electron Bessel beams arise because photons, having zero mass, can only occupy two polarization states. This allows for a Dirac-like formulation of Maxwell's equations [3].

Several different representations of the Dirac equation exist, each favouring specific operators and corresponding eigenstates. Using the Riemann-Silberstein formalism we find parallels between the representations of the Dirac equation and the polarization states of the optical field; linearly or circularly polarized [4], or a helicity eigenstate [5]. This allows us to qualitatively identify the spin and mass effects of either the electrons or photons qualitatively.

The results show how various angular momentum-carrying beams can be unified in the formal framework of classical relativistic field theory which can be extended to other physical systems, and other separable beam families such as Mathieu or Weber beams.

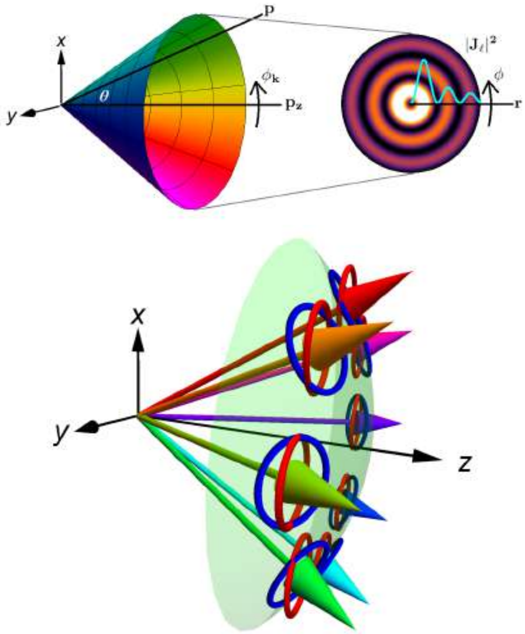


Figure 1: Top: The plane waves making up a Bessel beam lie on a cone making an angle θ with the propagation axis. Bottom: A Bessel beam is an helicity eigenstate if all plane waves are polarized the same (blue), if the beam is circularly polarized the plane waves are all polarized differently (red).

References

[1] Durnin, J, et al., Phys. Rev. Lett. **58**, 15, p.1499-1501 (1987)

[2] Bliokh, K.Y, et al., Phys. Rev. Lett. **107**, 174802 (2011)

[3] Barnett, S.M., New J. Phys. **16**, 093008 (2014)

[4] Bouchal, Z. and Olivík, M., J. of Mod. Opt. **42**, 8, p.1555-1566 (1995)

[5] Bliokh, K.Y, et al., Phys. Rev. A **82**, 063825 (2010)

Topological features of vector vortex beams perturbed with uniformly polarized light

Alessio D'Errico, Maria Maffei, Bruno Piccirillo, Corrado de Lisio, Filippo Cardano, Lorenzo Marrucci,

Dipartimento di Fisica, Universit`a di Napoli Federico II, Complesso Universitario di Monte Sant'Angelo, Via Cintia, 80126 Napoli, Italy

derrico@fisica.unina.it

Optical singularities appearing at the center of vector vortex beams are unstable, since their topological charge is higher than the lowest value permitted by Maxwell's equations.

Inspired by conceptually similar phenomena occurring in the polarization pattern characterizing the skylight, we show how perturbations that break the symmetry of radially symmetric vector beams lead to the formation of a pair of fundamental and stable singularities, i.e. points of circular polarization.

Using a liquid crystal device, called q-plate, we prepare a superposition of a radial (or azimuthal) vector beam and a uniformly linearly polarized Gaussian beam. Control of the optical retardation of the q-plate allows us to vary the relative amplitudes of the two fields. This leads to the formation of pairs of these singular points and to controlling of their spatial separation.

We complete this study by applying the same analysis to vector vortex beams with higher topological charges, and by investigating the features that arise when increasing the intensity of the Gaussian term. We carry this analysis on both Hypergeometric-Gaussian and Laguerre-Gaussian modes. In the case of the Hypergeometric-Gaussian modes the singularities present a peculiar behaviour in the near field that strongly resembles a topological phase transition.

Our results can find application in the context of singularimetry, where weak fields are measured by considering them as perturbations of unstable optical beams.

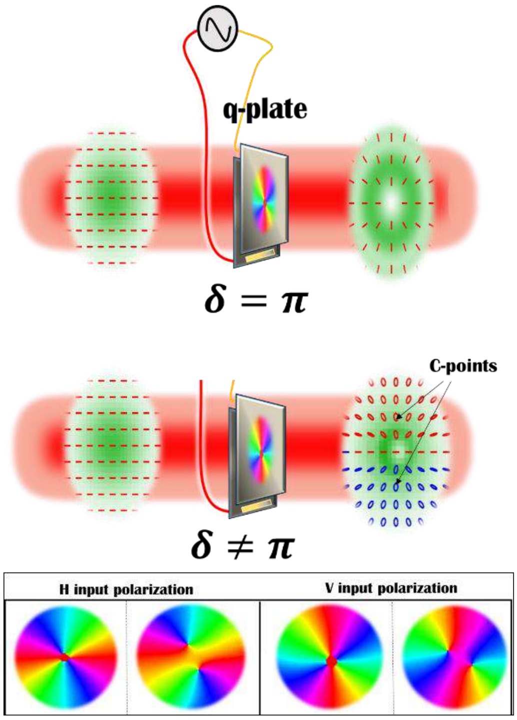


Figure 1: Top: schematics of the realization of singular beams using q-plates with different optical retardations δ. Bottom: examples of splitting of higher order singularities under the effect of a perturbation.

References

[1] A. D'Errico, M. Maffei, B. Piccirillo, C. de Lisio, F. Cardano, L. Marrucci, Topological features of vector vortex beams perturbed with uniformly polarized light- *Scientific Reports* **7**, Article number: 40195 (2017)

Coupling of light spin with plasmon orbital angular momentum investigated by ultrafast pump-probe measurements

T. Eul[1], G. Spektor[2], D. Kilbane[1,3], A.K. Mahro[1], M. Hartelt[1], E. Prinz[1], B. Frank[4], S. Ristok[4], L. Gal[2], P. Kahl[5], D. Podbiel[5], S. Mathias[1,6], H. Giessen[4], F.-J. Meyer zu Heringdorf[5], M. Aeschlimann[1], M. Orenstein[2]
[1]*Department of Physics and Research Center OPTIMAS, University of Kaiserslautern, Germany*
[2]*Department of Electrical Engineering, Technion-Israel Institute of Technology, 32000 Haifa, Israel*
[3]*School of Physics, University College Dublin, Belfield, Dublin 4, Ireland*
[4]*4th Physics Institute and Stuttgart Center of Photonics Engineering (SCoPE), University of Stuttgart, Germany*
[5]*Faculty of Physics and Center for Nanointegration Duisburg-Essen (CENIDE), University of Duisburg-Essen, Germany*
[6]*I. Physikalisches Institut, Georg-August-Universität Göttingen, Germany*

teul@rhrk.uni-kl.de

The ability of light to carry spin angular momentum (SAM), as well as optical angular momentum (OAM) offers a wide range of interaction mechanisms in physics. Using both physical properties, it was shown recently by means of time-resolved photoemission microscopy (TR-PEEM), that it is possible to observe interactions of light carrying SAM with surface plasmon polariton vortices carrying OAM[1]. By measuring the subfemtosecond angular velocity of the vortices the OAM magnitude of light could be directly accessed.

To further analyse the underlying physics of the observed interaction, different plasmonic vortex generators (PVG) consisting of m segments of an archimedes spiral were engraved in a gold surface. Here we show the influence on the vortex generation for different polarization states in our ultrafast pump-probe setup. Depending on the helicity of the generating light field $\sigma_{pump} = \pm 1$, the probing light field $\sigma_{probe} = \mp 1$ and the order of the spiral m, one can directly observe the signature of the angular momentum ℓ of the photoemitted vortex pattern with $\ell = (m + \sigma_{pump}) - \sigma_{probe}$.

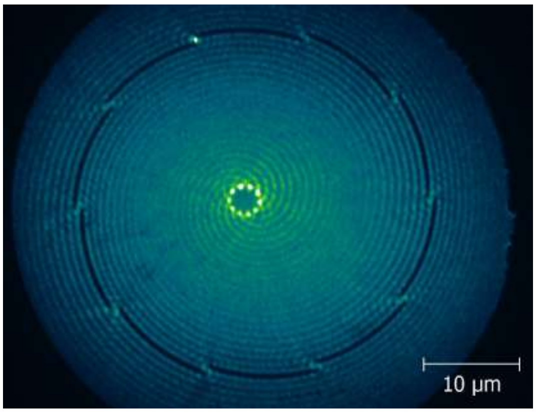


Figure 1: **Plasmonic vortex generation investigated with TR-PEEM.** Experimental TR-PEEM snapshot from a plasmonic-vortex generator with $m = 10$ segments upon right-handed circularly polarized light illumination. The snapshot illustrates the revolution stage of a plasmonic vortex at a pump-probe time delay $\Delta t = 55\,$fs between the fs pump and probe pulse.

References

[1] Spektor et. al. In: *Science* Vol. 355, Nr. 6330 (2017).

Agile spin-orbit shaping of polychromatic light

M. Ghadimi Nassiri and E. Brasselet
Univ. Bordeaux, CNRS, LOMA, UMR 5798, F-33400 France
mikael.ghadimi-nassiri@u-bordeaux.fr

The coupling between the polarization state of light and its spatial degrees of freedom (i.e., the spin-orbit optical interaction) is a rich and powerful tool to engineer the properties of light. A prototypical example is the generation of optical vortex beams that carry on-axis optical phase singularity. Many options based on optical spin-orbit coupling have been developed to generate vortex beams, the most popular being based on the use of inhomogeneous and anisotropic materials. Practical implementations have been realized using either artificial or natural birefringent materials, both options being nowadays available commercially.

However, such spin-orbit photonic devices are usually designed to operate at a given wavelength, which prevents the use of polychromatic light fields. Solutions have been proposed, which come at the expense of technologically demanding three-dimensional structuring of space-variant birefringent media [1]. Here we propose an alternative approach that consists in achieving broadband topological shaping of light by independent optimal spin-orbit processing for a finite set of spectral bands.

The proposed approach is based on the development of integrated spin-orbit optical couplers made of spontaneously formed liquid crystal topological defects under quasi-static electric fields. In practice, this is achieved by using patterned electrodes enabling the generation of arrays of spin-orbit micro-optical elements [2]. The initial approach has been optimized and now allows full control of the orbital angular momentum content of a polychromatic light field. Experiments are made using a supercontinuum laser source and recent demonstrations will be discussed. One example is illustrated in Figure 1 that shows spectrally distributed broadband optical vortex generation.

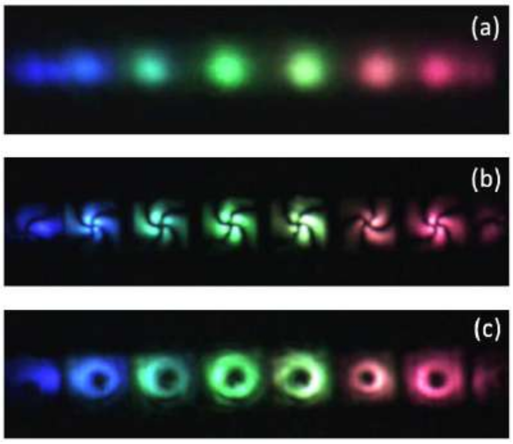


Figure 1: Illustration of the topological shaping of a supercontinuum light field owing to individual control of a discrete set of spectral bands. (a) Spectrum-to-space redistribution of an incident polychromatic field. (b) Visualization of the micro-array of liquid crystal topological defects between crossed linear polarizers. (c) Generated spectrally distributed vortex beams.

These results allow considering the elaboration of optical devices to modulate in an agile manner the spectral dependence of the orbital angular momentum content of broadband light sources.

References

[1] Li Y., Kim J. and Escuti M. J., Broadband orbital angular momentum manipulation using liquid crystal thin-films, Proc. of SPIE 8274, 827415, 2012.
[2] Loussert C., Kushnir K. and Brasselet E., Q-plates micro-arrays for parallel processing of the photon orbital angular momentum, Applied Physics Letters 105, 121108, 2014.

Fully structured light in a vectorial Kerr cavity

C. J. Gibson, G.-L. Oppo, A. M. Yao
SUPA and Department of Physics, University of Strathclyde,
Glasgow, G4 0NG, Scotland, E.U.
christopher.gibson.100@strath.ac.uk

Fully-structured light, where intensity, phase and polarisation are spatially varying [1], has received a great deal of interest in recent times in view of potential applications in optical communications, nanoscale optical imaging and micro-particle manipulation. With respect to scalar vortex beams (single Laguerre-Gaussian modes), beam fragmentation of such vector beams propagating in self-focusing nonlinear media can be suppressed [2] thus leading to extended durations of light-atom interaction.

Enhancement of the nonlinear response and further control can be obtained by using an optical cavity. Vector fields inside a nonlinear cavity have been shown to exhibit pattern formation (see left panel of Fig. 1) under the action of a linearly polarised plane wave input [3]. Bright spatial cavity solitons (CSs) have been demonstrated experimentally in Vertical-Cavity Surface-Emitting Lasers (VCSELs) [4] where the polarization of the CS's can be controlled by that of the injection, with potential application in polarisation multiplexing when using CSs as pixels.

Here we investigate the effect of using light carrying orbital angular momentum (OAM), and in particular fully-structured light, as the input field. We numerically study this using two coupled equations:

$$\frac{\partial E_{L,R}}{\partial t} = -(1+i\theta_{L,R})E_{L,R} + i\nabla^2 E_{L,R} + P_{L,R} + \frac{2i}{3}\left(|E_{L,R}|^2 + 2|E_{2,1}|^2\right)E_{L,R} \quad (1)$$

where $E_{L,R}$ are the circularly polarised fields inside the cavity, $\theta_{L,R}$ are the cavity detunings, ∇^2 is the transverse Laplacian operator and $P_{L,R}$ are the input beams carrying spatially varying intensity and phase. By choosing the OAM of P_1 and P_2 to be the same or different we can choose a pump with either homogeneous or inhomogeneous polarisation (i.e. *fully*-structured).

When the components of the pump have OAM we observe intensity peaks forming on a ring (Fig. 1, middle & right). At difference with the plane wave case each peak has a different phase and, if the pump has a net OAM, the peaks are seen to rotate. When the pump is fully structured (Fig. 1, right) more peaks are formed and there is no rotation. We study the effect of the interplay between the OAM and polarisation of the input beams for design, control and application of the output optical beam.

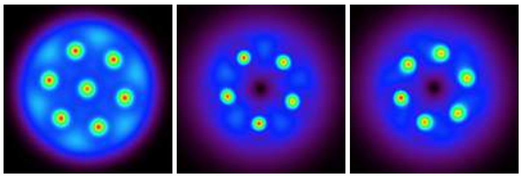


Figure 1: Simulations of Eq. (1). Left: Hexagonal pattern structure in the plane wave case. Middle: Ring pattern with two circularly polarised inputs of equal OAM. Right: Ring pattern with two circularly polarised inputs of equal but opposite OAM.

References

[1] A.M. Beckley, T.G. Brown, and M.A. Alonso, "Full Poincare beams", Opt. Express **18**, 10777-10785 (2010).

[2] F. Bouchard et al., "Polarization Shaping for Control of Nonlinear Propagation", Phys. Rev. Lett. **117**, 233903 (2016).

[3] J.B. Geddes et al., "Polarisation patters in a nonlinear cavity", Opt. Comm. **111**, 623-631 (1994)

[4] E. Averlant et al., "Vector cavity solitons in broad area Vertical-Cavity Surface-Emitting Lasers", Sci. Rep. **6**, 20428 (2016).

Proposal for an orbital angular momentum spectrometer for electrons

T.R. Harvey[1,2], B.J. McMorran[1], and V. Grillo[3]
[1] Department of Physics, University of Oregon,
1274 University of Oregon, Eugene, OR, USA 97405
[2] 4th Physical Institute, Solids and Nanostructures,
University of Göttingen, Göttingen 37077, Germany.
[3] CNR-Istituto Nanoscienze, Centro S3,
Via G Campi 213/a, I-41125 Modena, Italy
tyler.r.harvey@gmail.com

In order to probe the orbitals of atoms, molecules and crystals with electrons, one might want to postselect for final electron energy and orbital angular momentum (OAM) states after interaction with the specimen. If the incident electron has no orbital angular momentum, for example, postselection for final electrons with an energy loss and orbital angular momentum change matched to a particular atomic transition could reveal the shape of the core electron state involved in that transition. Currently, postselection for final energy states of electrons is routine at a wide range of energies. However, quantitative, non-interferometric postselection for final orbital angular momentum states is difficult.

We propose to use a Stern-Gerlach-like effect for electron orbital angular momentum measurement [1]. A spatially varying, cylindrically symmetric magnetic field forms an orbital angular momentum-dependent magnetic lens for electrons, where the longitudinal focal length of the lens is linear with incident orbital angular momentum. One can understand this effect in terms of the coupling of the magnetic dipole moment of an electron orbital angular momentum state with a magnetic field. A longitudinal magnetic field that decreases or increases in strength away from the optic axis forms an attractive or repulsive potential that depends on the strength of the dipole moment. Figure 1 illustrates a lens with this property.

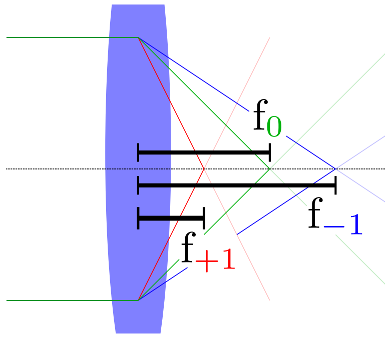


Figure 1: Ray diagrams for a lens (blue disk) with a strongly OAM-dependent focal length f m as given in (9). (red) rays for m = +1 electrons; (green) rays for m = 0 electrons; (blue) rays for m = -1 electrons.

For a standard round magnetic lens in an electron microscope, this effect is expected to be very small. Further exploration will be necessary to design a lens field to maximize the effect. If large enough, the effect could be employed in an orbital angular momentum spectrometer that magnifies electron orbital angular momentum states in proportion to their OAM. Or, one might place an aperture in the back focal plane for a single orbital angular momentum state to selectively pass that state into an energy spectrometer.

If successfully built and combined with already-existing energy spectrometers, such an electron orbital angular momentum spectrometer could allow new insights into the orbital states of atoms and materials.

References

[1] T.R. Harvey, V. Grillo and B.J. McMorran, *Phys. Rev. A* **95** 021801, 2017.

Raman Amplification of OAM Modes

K. Ingerslev[1], P. Gregg[2], M. Galili1, P. Kristensen[3], S. Ramachandran[2], K. Rottwitt[1], T. Morioka[1] and L. K. Oxenløwe[1]
1. SPOC, DTU Fotonik, Technical University of Denmark, DK-2800, Lyngby, Denmark
2. ECE Department, Boston University, 8 St Mary's St, Boston, MA, USA
3. OFS-Fitel, Priorparken 680, DK-2605, Broendby, Denmark
kaing@fotonik.dtu.dk

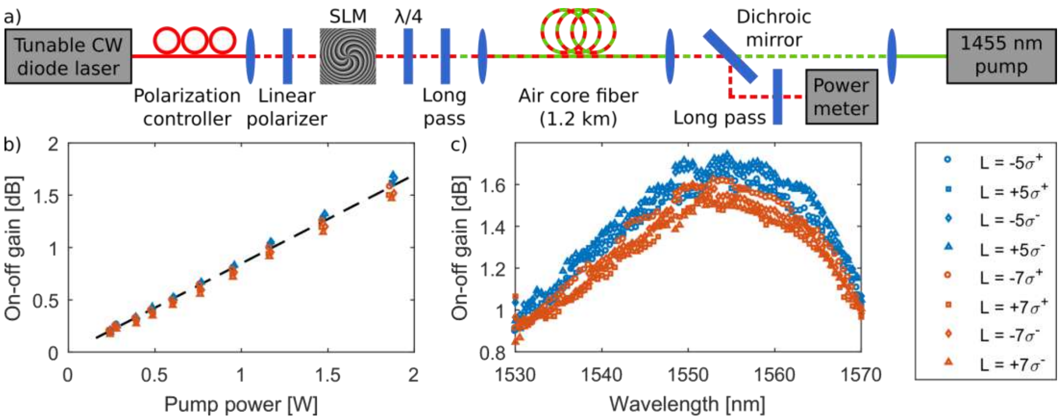


Fig. 1 a) Schematic of the experimental setup. b) Average gain from 1550 nm to 1560 nm as a function of pump power. The dashed line shows the theoretical gain. c) Gain as a function of wavelength with a pump power of 1.9 W, and a signal power of 0 dBm.

The set of fibre modes carrying orbital angular momentum (OAM) is a possible basis for mode division multiplexing. Fibres supporting OAM modes have been fabricated [1], and used for optical communication [2]. Here we demonstrate Raman amplification on OAM modes.

We demonstrate Raman amplification of 8 different OAM modes with $L=\pm 5$ and $L=\pm 7$, where L is the topological charge, and each mode has either a positive or a negative circular polarization, denoted $\sigma+$ or $\sigma-$, respectively. The experimental setup is sketched in Fig. 1 a). A tunable CW laser is launched into an air-core OAM fibre, [1], using a spatial light modulator (SLM) and a quarter-wave plate, thus exciting a single OAM mode with a purity of at least 18 dB, measured using time of flight. The fibre is backwards pumped, using a 1455 nm unpolarised CW laser, which is offset coupled. Thus the pump is coupled to a superposition of modes. The signal is separated from the pump using a dichroic mirror and a long pass filter, and the signal power is measured.

Raman gain depends mainly on the relative wavelengths, and intensity overlap of the signal and pump [3]. Since all the guided modes in the air-core fibre have nearly identical intensity distributions, the intensity overlap between any two modes is large. We measured a peak on-off gain of 1.7 dB at 1555 nm (Fig. 1 c), for the $L=+5$ σ- mode. Additionally we found that the $|L|=5$ modes on average across the C-band has a 0.1 dB larger gain than the $|L|=7$ modes. No consistent dependence of either polarization or L was observed. The gain was mainly limited by the available pump power, and the propagation loss in the fibre, which was measured to 6 dB/km for the pump, and 1 dB/km for the signal.

References

[1] P. Gregg *et al.*, *Optica*, **2**, 267 (2015).
[2] N. Bozinovic *et al.*, *Science*, **340**, 1545 (2013).
[3] J. Bromage, *J. Light. Technol.*, **22**, 79 (2004).

Experimental implementation of a polarisation-entangled photon source using a partial spatial coherent pump beam

Y. Ismail, S. Joshi, F. Petruccione
University of KwaZulu-Natal,
Private Bag X54001, 4000 Durban, South Africa
Ismaily@ukzn.ac.za

The generation of two photon fields, to date, has been implemented using a fully coherent pump beam through a process of spontaneous parametric down conversion (SPDC). Of recent, there have been numerous studies based on the temporal and spatial coherence properties of the twin beam state [1]. This is due to its probable applications in the field of quantum information processing and communication.

It has been shown that the spatial-spectral and spatial-temporal properties of the entangled photons are affected by crystal and pump beam parameters. Recently, spatial and spectral coherence of high intensity twin beam were studied by measuring intensity auto- and cross-correlation function for the near-field and far-field configurations [1]. Theoretically studies infer that the spatial coherence properties of the pump field is entirely transferred to the spatial coherence properties of the down-converted two-photon field [2]. Furthermore, studies show that the entanglement of a spatial two-qubit state is affected by the spatial coherence properties of the two photon field [3].

Here, we present the spatial coherence properties of the entangled-photon pairs produced by SPDC. The photon pairs are experimentally investigated in the polarisation degree of freedom by taking into consideration the partial spatial coherence of the pump beam as illustrated by the scheme in Fig. 1. For spatial correlation in SPDC, coincidence counts are recorded as a function of the detectors. It has been shown that partially spatially coherent beams are less affected by atmospheric turbulence. Hence, entangled photon fields produced by a partially coherent pump beam are a significant means to prepare two-qubit states for quantum communication.

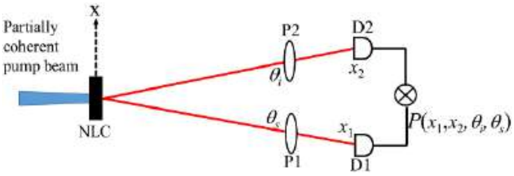


Figure 1: Schematic setup used to study the influence of the pump spatial coherence on the polarisation-entangled photons.

References

[1] Joobeur A, Saleh B. E. A., Teich M. C., Spatiotemporal coherence properties of entangled light beams generated by parametric down-conversion, Phys. Rev. A 50(4), 3349-3363, 1994.

[2] Jha K., Boyd R.W., Spatial two-photon coherence of the entangled field produced by down-conversion using a partially spatially coherent pump beam, Phys. Rev. A 81, 013828, 2012.

[3] Saleh E. A., Abouraddy A. F., Sergienko A. V., Teich M. C., Duality between partial coherence and partial entanglement, Phys. Rev. A 62, 043816, 2000.

Optical Phase Vortex Breakup in Turbulent Free-Space Propagation

Martin P.J. Lavery
School of Engineering, University of Glasgow, Glasgow, UK
martin.lavery@glasgow.ac.uk

The implementation of spatially structured optical field have resulted in wide array of scientific and technological advances [1,2]. Real world deployment of many optical metrology and communication systems will involved propagation through atmospheric turbulence [4]. Hence, an understanding of the propagation of spatially structured optical fields in free-space is important. The time-dependent and random variations in temperature and pressure of the atmosphere result in a change in the optical density of the atmosphere [5]. Current models for free-space transmission of optical fields are built on models developed for astronomical measurements, which generally assumed an input optical field with a flat wavefront [6]. These theories have been extended for use with spatially structured optical fields. However, these theories do not adequately predict the results acquired by free-space ranging experiments in urban environments [7].

This abstract presents a technique for modelling the expected modal degradation of a high-order spatial structured modes that carry orbital angular momentum through simulated point-to-point link atmospheric turbulence similar that experienced in an urban environment. This modelling confirms topological instability is a concern for point-to-point links. Vortex instability has been documented as a concern in the generation of beams that carry OAM, where a high order vortex breaks in the presence of weak non-cylindrically symmetric aberration, a high-order vortex of index will, upon propagation, break up to give individual vortices. Such a breakup in high order modes has not commonly been considered in the modelling of line-of-sight point-to-point links. A numerical modelling techniques is discussed, where the propagation is segmented into 150 short 10m propagation regions to simulate the effects of micro-scale atmospheric circulation effects. The accumulative affect of all short regions is designed to simulate a 1.5km free-space channel in an urban environment. The numerical model further considers the effective change in aperture as the optical mode increase in beam waist as it propagates over the link.

References

[1] M.P.J. Lavery *et. al*, Science 341, 537–540 (2013).
[2] D. J. Richardson *et. al*, Nat. Photon. 7, 354–362 (2013).
[3] G. R. Salla, C. Perumangattu, and S. Prabhakar, Applied Physics 5 (2015).
[4] AM Yao and MJ Padgett, Advances in Optics and Photonics 3 (2), 161-204, 2011.
[5] D. L. Fried, JOSA 55, 1427–1431 (1965).
[6] B. Rodenburg et. al, Optics Letters 37, 3736–3737 (2012).
[7] M. P. Lavery et. al, Lasers Congress, paper LTh3B.1 (2016).

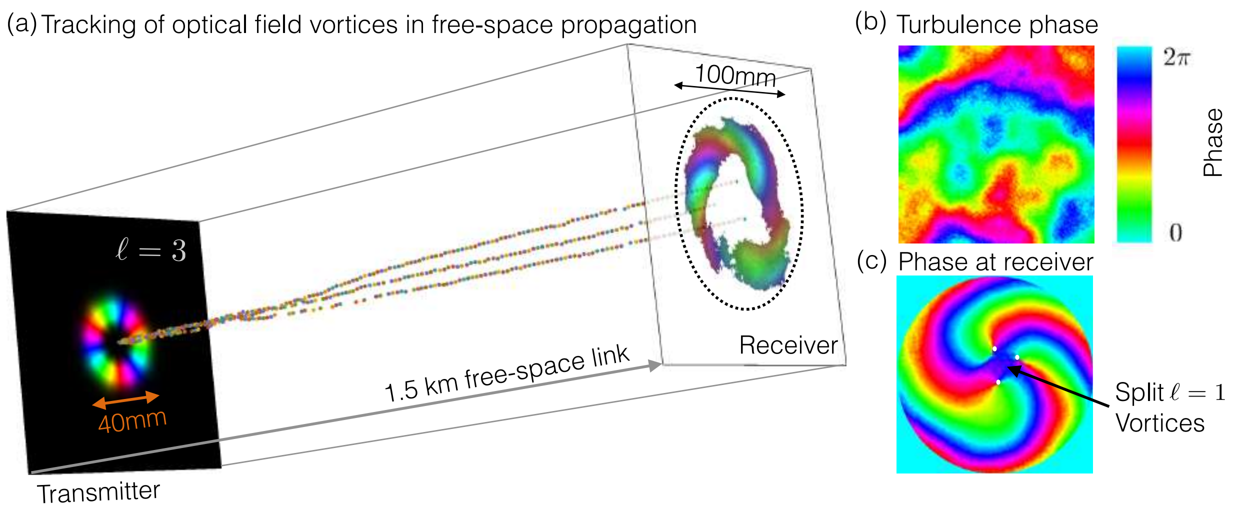


Figure 1. (a) A pure mode is generated at the transmitter, and propagated over a simulated free-space transmission channel of 1.5km, accumulative turbulence is approximately . The vortex position of the 3 split vortices are tracked after each 10m propagation length and plotted sequentially. (b) A cross sectional image of the accumulative aberration over the 1.5km link. (c) A cross sectional image of the phase profile of the received optical field, where each of the vortices are highlighted with an overlaid white circle.

Simulating Loschmidt Echo with a Photonic System

Zhao-Di Liu[1], Henri Lyyra [2], Yong-Nan Sun[1], Chuan-Feng Li [1,*] and Jyrki Piilo [2,†]
[1] CAS Key Laboratory of Quantum Information, University of Science and Technology of China, Hefei 230026, People's Republic of China
[2] Turku Centre for Quantum Physics, Department of Physics and Astronomy, University of Turku, FI-20014 Turun yliopisto, Finland,
* cfli@ustc.edu.cn, † jyrki.piilo@utu.fi

The process of decoherence is not only of paramount importance to understand the emergence of the classical world from the microscopic domain of quantum mechanics, but it also constitutes the fundamental obstacle for the design of reliable quantum technologies. The Loschmidt echo has been used extensively to explore decoherence dynamics for critical environments [1], where it has been shown that in the weak coupling regime, the decoherence rate is greatly enhanced.

The Loschmidt echo is intimately related to the information flowing out from and occasionally back into the system. This, in turn determines the non-Markovianity of the reduced dynamics. P. Haikka *et al.* show that the non-Markovianity measure of Breuer *et al.* can be used to pinpoint the critical value of the tranverse field [2].

Bi-Heng *et al.* reported an all-optical experiment which allows one to drive the open system from the Markovian to the non-Markovian regime, to control the information flow between the system and the environment, and to determine the degree of non-Markovianity by measurements on the open system [3]. As same as Bi-Heng *et al.*, in our experiment the open quantum system is also provided by the polarization degree of freedom of photons coupled to the frequency degree of freedom representing the environment. However, we use spatial light modulator (SLM) and gratings to control the frequency of photons. Because, we need to modulate both the probability amplitude and phase of frequency. The details of hologram used in our experiment can be seen in Fig. 1.

In our work, we first give an exact demonstration about the reasonable of simulating

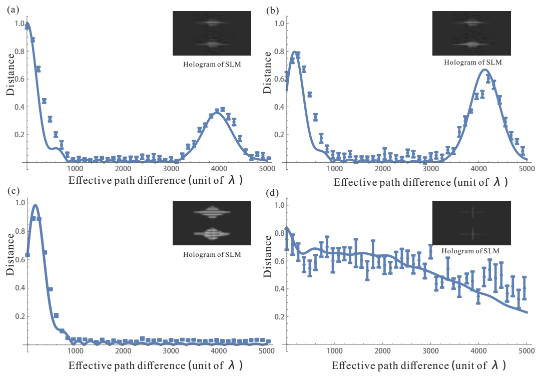


Figure 1: Experimental result. The Loschmidt echo flow induced by the coupling of a central spin to the transverse Ising model consisting of $N = 4000$ spins for three different values of the transverse field. We choose $J = 1$ and $\delta = 0.1$. (a) is the result of $\lambda^* = 0.01$ without phase. For (b) (c) and (d), λ^* is equal to 0.01, 0.9 and 1.8.

Loschmidt Echo with a photonic system. Then, SLM and gratings are used to achieve the complex environment needed in simulating Loschmidt Echo. Fig. 1 is our experimental result. we can see that the experimental data and theoretical simulation fit pretty well.

References

[1] H. T. Quan, Z. Song, X. F. Liu, P. Zanardi, and C. P. Sun, Phys.Rev. Lett. 96, 140604 (2006).

[2] P. Haikka, J. Goold, S. McEndoo, F. Plastina, and S. Maniscalco, Phys.Rev. A. 85, 060101(R) (2012).

[3] B-H. Liu et al., Nat. Phys. 7, 931 (2011).

Efficient sorting of free electron orbital angular momentum

Benjamin J. McMorran[1], Tyler R. Harvey[1], Martin P. Lavery[2]
[1] Department of Physics, University of Oregon, Eugene, Oregon, USA 97401-1274
[2] School of Engineering, University of Glasgow, Glasgow G12 8QQ, Scotland, UK
mcmorran@uoregon.edu

Here we describe a promising method for measuring and sorting orbital angular momentum (OAM) components of free electron wavefunctions [1]. Our proposed device is an electrostatic implementation of an optical OAM mode sorter developed for light optics [2]. Simple electrodes imprint the phase required to transform electron OAM modes into plane wave states.

A great variety of methods have recently been devised to produce phase vortices in electron wavefunctions such that each electron carries quantized OAM. Free electrons with OAM show great promise for probing chirality and magnetism at the nanoscale [3-5] by exchanging quantized OAM between the electron and the specimen. This process depends exquisitely on the relative size, alignment, and spatial coherence of an electron vortex probe and the system. To achieve this, several groups have devoted a great amount of effort developing ways to prepare electron OAM states with great precision, efficiency, and controllability. Yet despite the success of these efforts to produce high current, finely-focused, clean electron probes with prescribed OAM, experimental searches for a robust OAM-exchanging interaction are inconclusive. One major reason for this is an inability to *measure* the OAM distribution of scattered electrons. That is, to ensure that electron OAM has been exchanged with a system, one must also measure the OAM distribution of the incoherently scattered electrons.

To solve this problem, we propose an electron OAM sorter analogous to optical OAM mode sorters developed for light communications [2]. An optical OAM sorter consists of two custom elements – a phase unwrapper and phase corrector – and two lenses. Interestingly, the phase imprinted upon an electron wave as it propagates past a charged needle is exactly equivalent to the phase required for the unwrapper element. Furthermore, the field around alternating charged electrodes can be used to flatten or correct the phase of the unwrapped electron wavefunction. The electrostatic elements can be used with conventional electron lenses to provide the same orbital mode-sorting capability demonstrated for optical beams.

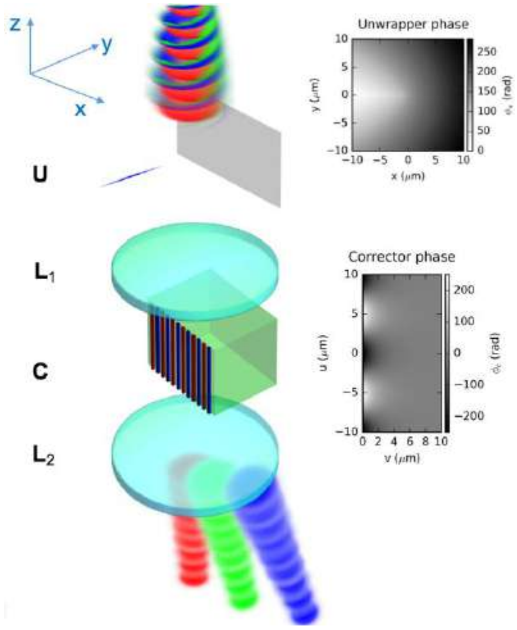


Figure 1 – Schematic of an electron OAM mode sorter based on electrostatic elements. A charged needle serves as a phase unwrapper element (U, phase distribution at right). Alternating strip lines serve as a phase flattener or corrector element (C, phase shown at right). Different OAM modes, shown in different colours at top, are sorted into different linear momentum states at bottom.

References

[1] McMorran, B.J., Harvey, T.R., Lavery, M.P., New J. Phys. 19, 23053, 2017
[2] Berkhout, G.C.G., Lavery, M.P.J., Courtial, J., Beijersbergen, M.W., Padgett, M.J., Phys. Rev. Lett. 105, 153601 (2010)
[3] Idrobo, J.C., Pennycook, S.J., J. Electron Microsc. 60, 295, 2011
[4] Lloyd, S., Babiker, M., Yuan, J., Phys. Rev. Lett. 108, 74802, 2012

[5] Schattschneider, P., Schaffer, B., Ennen, I., Verbeeck, J., Phys. Rev. B 85, 134422, 2012

Propagation of Laguerre-Gaussian laser beams in turbid tissue-like scattering medium

A. Bykov[1], N.O. Vera Paz, J.P. Staforelli[2], A. Doronin[3], I. Meglinski[1,*]
[1] Optoelectronics and Measurement Techniques, University of Oulu, Oulu, 90014 Finland
[2] Facultad de Ciencias Físicas y Matemáticas, University of Concepción, Concepción, Chile
[3] Department of Computer Science, Yale University, New Haven, CT 06520-8285, USA

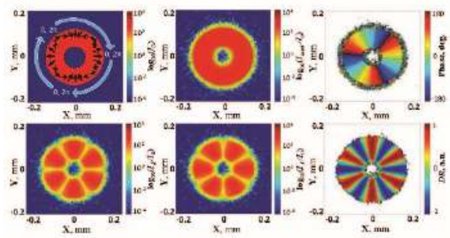
* Correspondence: igor.meglinski@oulu.fi

Polarization is the fundamental property of light that has been attracting great attention in various practical applications from space to modern biology and medicine. When the polarized light interacts with the matter its state of polarization is changed. The state of polarization of linearly, elliptically or circularly polarized light ("simple" light) has long been used to characterize material surfaces, thin films and transparent media. In fact, the structure of light can be more "complex", i.e. the light beams can be radially or azimuthally polarized and carry orbital angular momentum. The light with orbital momentum, Laguerre-Gaussian (LG) beams, plays an emerging role in both classical and quantum science, and offers fascinating opportunities for exploring new fundamental ideas, as well as for being used as a tool for practical applications.

We investigate (i) how the spin-orbit interaction leads to the mutual influence of the polarization and the trajectories of twisted photons propagating in turbid tissue-like scattering media, and (ii) how sensitive are the vector light beams to subtle alterations in the scattering medium. Thus, an overall aim is to investigate the potential applicability of LG laser beams for non-invasive tissue diagnosis (optical biopsy).

The results of propagation of LG laser beams in the scattering medium obtained by using specially developed Monte Carlo model are presented in comparison with the results of experimental studies (Fig.1).

(a)



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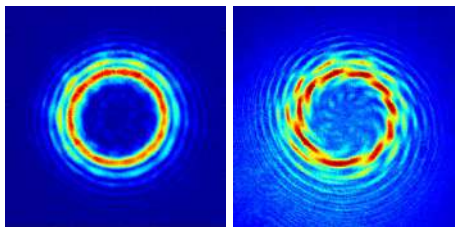


(c)

Figure 1: (a) Schematic presentation of the experimental system used to the studies of LG beams propagation through the turbid tissue-like scattering medium. (b) The results of Monte Carlo modeling of LG beam ($l = +3$, $\sigma = -1$) transmitted through the scattering medium ($g = 0.9$, $\mu_s = 100$ mm^{-1}). (c) – The experimental results of LG10 propagation through scattering medium.

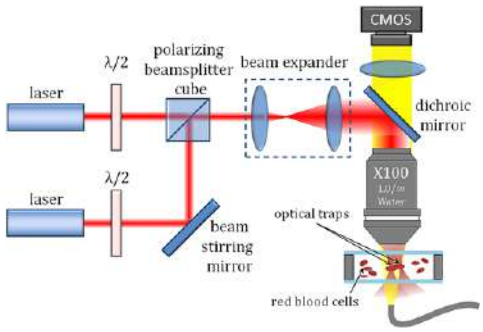
Influence of nano-particles on the interaction of red blood cells assessed by optical tweezers

A.P. Popov, A. Avsievich, A. Bykov, I. Meglinski
Optoelectronics and Measurement Techniques,
University of Oulu, P.O. Box 4500, Oulu, 90014 Finland
Correspondence: alexey.popov@oulu.fi and/or igor.meglinski@oulu.fi

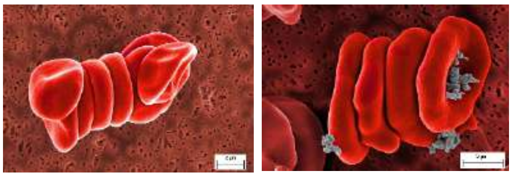
The red blood cell (RBC) aggregation is an intrinsic property of blood influencing significantly the blood microcirculation with a great potential in clinical applications. The ultimate understanding of the fundamental mechanism of the cells adhesion is essential for further proper applications. Presently there are two hypotheses of the 'cross-bridges' and 'depletion layer' to describe the cells interaction while either is still to be experimentally proven. Current study is aiming to obtain the experimental evidence toward the cells interaction mechanism. Optical tweezers were used to measure the RBC adhesion forces and energies, as presented in Figure 1-a.

The cells interaction was examined in different solutions, including plasma, serum and model solutions with dextran or proteins, and nanoparticles. The experimental results show that the cells adhesion forces get stronger as they are separated in all solutions except dextran. The adhesion energy is found to be increasing few times, while in dextran the adhesion force decreases as the cells are separated and corresponding adhesion energy is constant. The obtained results are clarifying the mechanism of the RBC adhesion, confirming the 'cross-bridge' migration model to describe properly the cells interaction.

In addition, the aggregation of RBCs were measured in presence of nanoparticles (NPs) of titanium dioxide (TiO_2), zinc oxide (ZnO) and nano-diamonds. To avoid the lysis of cell the concentration of NPs was chosen in a range of 0.1%. Optical microscopy was used as a reference modality to assess alteration of aggregation at the cell ensemble level. We have found that nano-diamonds and TiO_2 (RODI) NPs increase significantly (about twice) the aggregation of RBCs in comparison to the normal cells aggregation.



(a)



(b)

Figure 1: (a) – Schematic presentation of the two-channeled optical tweezers setup for measuring RBCs interaction (a). The laser beams from two Nd:YAG lasers are merged with polarizing beam splitter cube, and expanded with beam expander to achieve the most efficient optical trapping. Optical traps were formed with a water-immersion objective (×100, NA = 1.00). (b) – An example of RBCs aggregation without (left), and with the presence of ZnO NPs (right).

The understanding of NPs interaction with blood is essential for various applications in pharmacy and biomedicine. The optical tweezers approach shows a high potential for fast quantitative evaluation of RBCs aggregation in various conditions with and without presence of NPs. We anticipate that the presented approach will find the niche in design and testing of new NPs and nano-materials for biomedical applications.

Quantum eraser with hybrid entangled photons

B. Ndagano[1], I. Nape, A. Forbes

[1]School of Physics, University of the Witwatersrand, Johannesburg, South Africa.

nibienvenu@gmail.com

That light can behave as a wave or a particle is a fundamental concept of modern physics. At the single photon level, the distinguishability of photon paths can be used as a tuning parameter to control whether photons behave as wave or particles [1]. A classic example is the quantum version of Young's double slit experiment, where the polarization of the field traversing each slit is controlled in order to cause or prevent interference. In the language of quantum mechanics, the photon either goes through both slits at once (wave-like), or through one at the time (particle-like). However, the photon path need not to be a physical one. The photon paths can also be viewed as quantum states that can be made to interfere through a given projection measurement on the photon. To illustrate this concept, we introduce a new twist on the double slit experiment, replacing the physical path (slit) with an abstract one: an orbital angular momentum state (OAM). We prepared two photons, hybrid entangled in the OAM (our 'path') and polarization (our marker) – this is in essence a vector a vector vortex mode. We show that polarization projection of one the entangled photons, leads to OAM interference which manifests itself as fringes along the azimuthal direction, so long as the projection is not on an eigenstate of polarization (see Fig. 1(a)). Additionally, we show that the visibility of the interference produced can be tuned by controlling the rotation angle of the polarization projector as shown in Fig. 1(b).

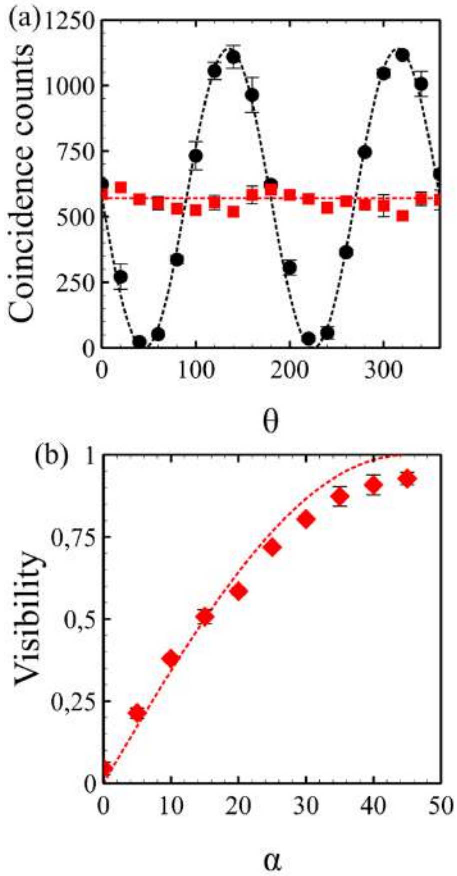


Figure 1: (a) Coincidence measurement for quantum eraser ON (black dots) and eraser OFF (red squares), as a function of the azimuthal angle (θ) in degrees. (b) Azimuthal fringe visibility as a function of the eraser state, parametrized by the angle α in degrees.

References

[1] Scully, M.O., Englert, B.G., Walther, H., Quantum optical tests of complementarity, Nature 351, 111-116, 1991.

A deterministic detector for high-dimensional communication with vector modes

B. Ndagano[1], I. Nape, B. Perez-Garcia, S. Scholes, R.I. Hernandez-Aranda, F.S. Roux, T. Konrad, A. Forbes

[1]School of Physics, University of the Witwatersrand, Johannesburg, South Africa.

nibienvenu@gmail.com

Of the many areas that have been invigorated by the rising interest in spatial modes of light, quantum communication is one that has certainly seen significant development. The theoretically infinite dimensions associated with the spatial degree of freedom does indeed offer the ability to pack more information into single photon, allowing for higher bit-rate quantum communication [1]. This is especially true in the world of quantum key distribution, where the increased dimensionality correlates with increased security. Despite the promise of increased information capacity, the detection of these high-dimensional spaces suffer from the lack of efficient detectors. It has become common practice to detect spatial modes of light using holographic filters, encoded in some instances on spatial light modulators. Such an approach, or any filter-based detection, is plagued by losses which, in a key distribution setup, translate in inefficient key generation and lower achievable key rates. A deterministic approach, using refractive optics, has been demonstrated to sort the spatial modes according to their orbital angular momentum (OAM) content. However, the above deterministic method is not applicable to vector vortex modes. Currently, only filter-based detection schemes for vector vortex modes have been demonstrated. These use geometric optics (q-plates) which, do not allow one to detect, simultaneously, all degenerate modes within a given subspace. Here, we present a deterministic scheme to sort all degenerate vector vortex modes within a given orbital angular momentum subspace. The technique uses a Mach-Zehnder interferometer to sort the vector modes according to their intra-modal phase, followed by OAM modes sorters. The result is a lossless mapping of vector modes to position in real space.

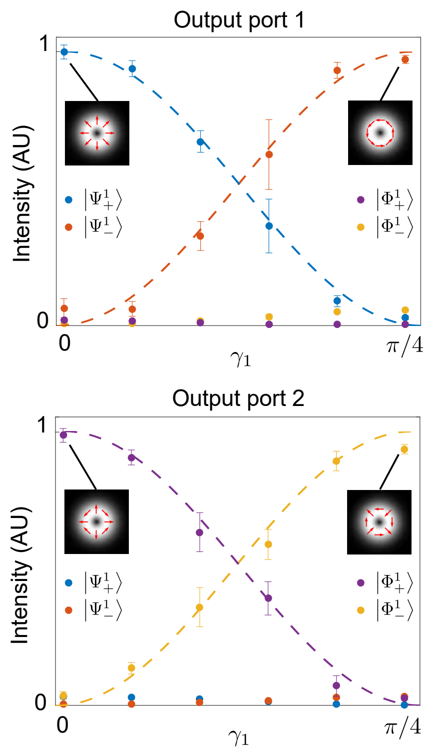


Figure 1: Sorting of vector modes as a function of the degree of non-separability, parametrized by the angle γ_1.

References

[1] Mirhosseini, M. *et al.*, High-dimensional quantum cryptography with twisted light, New Journal of Physics 17, 033033, 2015.

Encoding and Direct Detection of Continuous Variable Entanglement in Orbital Angular Momentum Space

A.Pecoraro[1,2] , F. Cardano[1], B.Piccirillo[1], L.Marrucci[1] and A.Porzio[2]

[1]Dipartimento di Scienze Fisiche, Università "Federico II" – Napoli, Complesso Univ. Monte Sant'Angelo, via Cintia, 80126, Napoli, Italy

[2]CNR –SPIN - Napoli, Complesso Univ. Monte Sant'Angelo, via Cintia, 80126, Napoli, Italy

Efficient optical generation of Continuous Variable (CV) entangled modes endowed with Orbital Angular Momentum (OAM), is becoming more and more challenging for many quantum protocols due to the increased information-carrying capacity. We demonstrate an innovative method capable of generating a bipartite CV state carrying OAM in which the two subsystems share non-classical correlations.

Our entanglement source is a triply resonant type- II Optical Parametric Oscillator (OPO) working below threshold. Such a device generates an entangled bipartite state consisting of collinear crossed polarized thermal states, with the same frequency. Once the bipartite entangled state is generated, entanglement previously encoded onto polarization acquires the OAM d.o.f. by means of a sequence of optical transformations that make the two entangled subsystems distinguishable by both polarization and OAM. These transformations are carried out by wave plates and a liquid crystal based optical device, the q-plate (qP), that plays a central role in such conversion because it transforms the two entangled TEM_{00} crossed polarized modes, produced by the OPO, into entangled helical beams carrying OAM $m=\pm\hbar$.

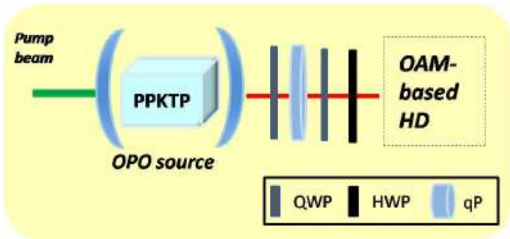


Figure 1: Experimental scheme constituted by quarter wave plates (QWP), half wave plates (HWP) and a qP, for OAM entangled modes generation.

Thermal states produced by OPO are a subclass of Gaussian states, i.e. states with a Gaussian Wigner distribution in optical phase space. This feature makes Gaussian states privileged since their quantum state can be completely characterized by their covariance matrix (CM).

Once the state is generated and provided with OAM its CM is reconstructed by directly homodyining the state in the OAM Hilbert space. This is possible thanks to a reconfigurable single Homodyne Detection (HD) scheme in which Local Oscillator (LO) swaps among the different OAM assuring the mode matching between the signal under scrutiny and the LO reference beam. After reconstructing the CM, we have witnessed the presence of entanglement between the vortex modes by applying suitable entanglement criteria to its elements.

Generalized directional evanescent coupling

Michela F. Picardi, Anatoly V. Zayats and Francisco J. Rodríguez-Fortuño
Department of Physics, King's College London
Strand, London, WC2R 2LS, United Kingdom
michela.picardi@kcl.ac.uk

The angular spectrum is a powerful tool to evaluate the radiation diagram of a dipole's far field emission. In addition, it can as well be used to determine the evanescent-wave coupling from dipole sources to nearby guided modes [1]. In this work we unify various phenomena for dipole directionality. We derive the condition under which any transverse angular component (p-polarized) can be arbitrarily canceled out (eq. 1):

$$[(\hat{\mathbf{z}} \times \hat{\mathbf{k}}) \times \hat{\mathbf{k}}] \cdot \mathbf{p} - (\hat{\mathbf{z}} \times \hat{\mathbf{k}}) \cdot \frac{\mathbf{m}}{c} = 0, \qquad (1)$$

where $\mathbf{p} = (p_x, p_y, p_z)$ is the electric dipole moment, $\mathbf{m}$ is the magnetic one, $\hat{\mathbf{k}} = \frac{\mathbf{k}}{k} = \frac{\mathbf{k}}{\omega\sqrt{\mu\varepsilon}}$ with $\mathbf{k}$ being the spectral component we want to make zero. An analogous condition can be found for the s-polarized spectrum. This condition accounts for spin-direction locking for circularly polarized electric dipoles [2] and, for linear dipoles having $\mathbf{p} = (0, 0, p_z)$ and $\mathbf{m} = (0, m_y, 0)$, it reduces to a generalization of Kerker's condition for Huygens' antennas, which are well known for their directional radiation diagram. It can as well be applied for any intermediate combination of $\mathbf{p}$ and $\mathbf{m}$. In figure 1 the Poynting vector of these two directional emitters over a waveguiding structure is plotted. We will show how this condition, analytically derived from the dipoles' angular spectra, is satisfied for directionality of evanescent-wave coupling.

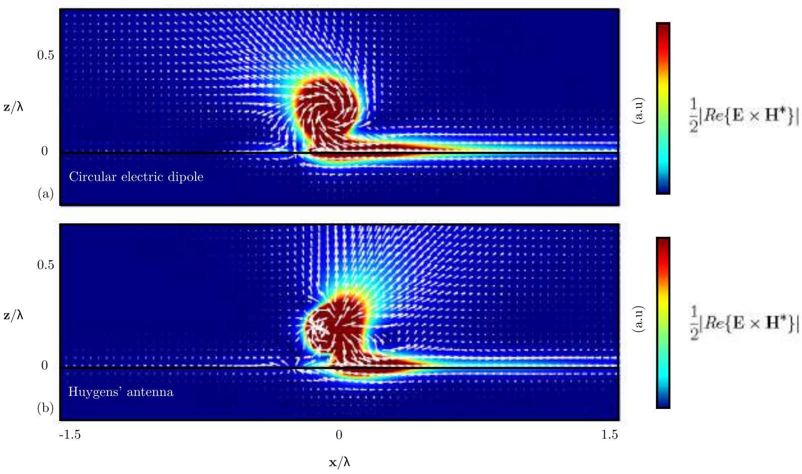


Figure 1: Power flow induced by (a) a circularly polarized electric dipole and (b) a Huygen's antenna in close proximity to an interface of a material with $\varepsilon = -1.5 + 0.2i$ and $\mu = 1$, calculated by integration of the angular spectra of the dipole field.

References

[1] Rodriguez-Fortuno F.J. *et al.*, Near-Field Interference for the Unidirectional Excitation of Electromagnetic Guided Modes, Science 340, 328-330, 2013.

[2] Picardi M.F. *et al.*, Unidirectional evanescent-wave coupling from circularly polarized electric and magnetic dipoles: an angular spectrum approach, Accepted for pubblication in Phys. Rev. B., 2017

Guiding light exploiting Pancharatnam-Berry geometric phases

Sergei Slussarenko,[1,2] Alessandro Alberucci,[3,4] Chandroth P. Jisha,[5] Bruno Piccirillo,[1] Enrico Santamato,[1] Gaetano Assanto,[3,4] and Lorenzo Marrucci[1,6]

[1]Dipartimento di Fisica, Università di Napoli Federico II, Napoli, Italy
[2]Centre for Quantum Dynamics and Centre for Quantum Computation and Communication Technology, Griffith University, Brisbane, Queensland 4111, Australia
[3]Nonlinear Optics and OptoElectronics Lab, University Roma Tre, I-00146 Rome, Italy
[4]Optics Lab, Department of Physics, Tampere University of Technology, FI-33101 Tampere, Finland
[5]Centro de Física do Porto, Faculdade de Ciências, Universidade do Porto, 4169-007 Porto, Portugal
[6]CNR-ISASI, Complesso Universitario di Monte S. Angelo, Napoli, Italy
bruno.piccirillo@unina.it

We present a novel approach to waveguiding light, based on geometric Pancharatnam-Berry phases and polarization states transformations. At variance with all the other cases up-to-now investigated, such mechanism does not rely on variations of the refractive index or, more generally, of the dielectric permittivity. We here demonstrate, in fact, the possibility for transverse trapping based on vectorial effects: the guided propagation of light can be achieved, in essence, by means of spin-orbit interactions between wave propagation and polarization states of light.

Specifically, we envisage an extended continuous medium supporting beam propagation over several Rayleigh distances, consisting of a uniaxial birefringent material whose optic axis is modulated in three-dimensions, i.e. both in the transverse plane *xy* and in the longitudinal coordinate *z* along the propagation direction.

The longitudinal modulation of the axis orientation $\theta(z)$ must be periodical to allow for a finite accumulation of the geometric phase along *z*. Besides, to achieve light confinement, the transverse modulation of the optic axis $\theta(x,y)$ must define the waveguide cross-section, since the phase retardation needs to be larger on the beam axis than in the outer regions (Figure 1, **c**) [1].

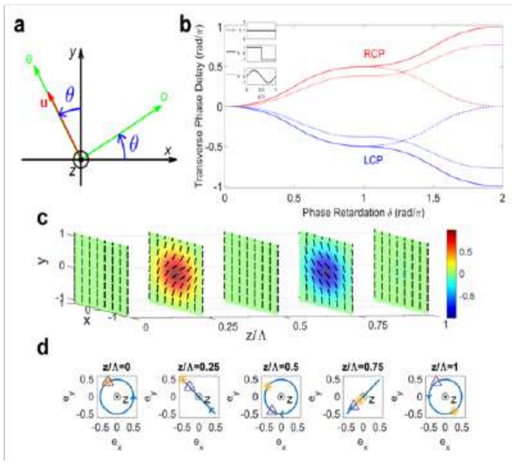


Figure 1: **a**, Orientation θ of the optic axis **u** and ordinary/extraordinary (*o*/*e*) fields. **b**, Geometric phase difference between two oppositely handed circularly polarized plane waves propagating in two transversely homogeneous media whose optic axes differ for a $\pi/4$ rotation. **c**, sketch of a continuously modulated Berry-phase waveguide. **d**, Polarization evolution of an input circular plane wave along the structure. Star and triangle show the geometric phase evolution of two points in the transverse plane (x_1, y_1, z) and (x_2, y_2, z) located so that $\theta_2 - \theta_1 = \pi/4$.

Source: Ref. [1]

References

[1] S. Slussarenko *et al*, Guiding light by geometric phases, Nature Photonics 10, 571-575, 2016.

Proposed optical realization of a two photon, four-qubit entangled χ state

Atirach Ritboon, Sarah Croke and Stephen M Barnett
School of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, UK
a.ritboon.1@research.gla.ac.uk

The four-qubit states $|\chi^{ij}\rangle$, exhibiting genuinely multi-partite entanglement have been shown to have many interesting properties and have been suggested for novel applications in quantum information processing. In this work we propose a simple quantum circuit and its corresponding optical embodiment with which to prepare photon pairs in the $|\chi^{ij}\rangle$ states.

Our approach uses hyper-entangled photon pairs, produced by the type-I spontaneous parametric down-conversion (SPDC) process in two contiguous nonlinear crystals [1], together with a set of simple linear-optical transformations which is illustrated in the figure 2. Our photon pairs are maximally hyper-entangled in both their polarisation and orbital angular momentum (OAM). After one of these daughter photons passes through our optical setup, we obtain photon pairs in the hyper-entangled state $|\chi^{00}\rangle$, and the $|\chi^{ij}\rangle$ states can be achieved by further simple transformations. A more complete account of this work may be found at [2]

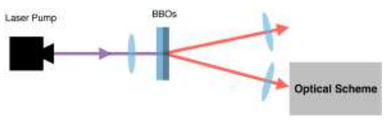


Figure 1: The optical alignment to create hyper-entangled photon pair by coherent sequential spontaneous parametric down-conversion. The crystals are aligned such that their optical axes are perpendicular to each other.

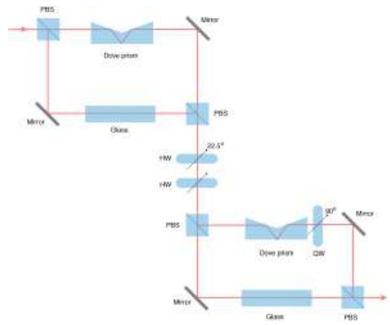


Figure 2: This figure shows our proposed optical system which is the detailed version of the grey box named optical scheme in the figure 1.

References

[1] Barreiro J T, Langford N K, Peters N A and Kwiat P G 2005 Generation of hyperentangled photon pairs *Phys. Rev. Lett.* **95** 260501.

[2] Ritboon A, Croke S and Barnett S M Proposed optical realization of a two photon, four-qubit entangled χ state *J. Opt.* (in press) (arXiv:1703.01965)

Mode division multiplexing beyond orbital angular momentum

Carmelo Rosales-Guzmán, Mitch Cox and Andrew Forbes
School of Physics, University of the Witwatersrand,
Private Bag 3, Wits 2050, South Africa
carmelo.rosalesguzman@wits.ac.za

Mode Division Multiplexing (MDM) has been mooted as a potential solution to eventually cope the increasing demand on bandwidth capacity of current communication systems. In particular, spatial modes of light endowed with Orbital Angular Momentum (OAM) have gained special interest due to their easiness of generation and detection[1]. The orthogonality nature of OAM modes has being widely exploited in MDM [2]. Despite the several achievements in MDM using OAM modes, its true capacity is still controversial[3]. Additionally, in long haul optical links, perturbations, as atmospheric turbulence, causes degradation of the modes, the spreading of power to neighboring modes and ultimately the mixing of information. In our contribution we will give an overview of our current work on MDM and some of the novel ideas we are implementing in an attempt to overcome some of the current limitations.

Indeed, OAM modes represents only a subset of spatial modes, while in general all transverse spatial modes require two degrees of freedom for a full description. In the case of Laguerre-Gaussian (LG_p^ℓ) modes, these are represented by an azimuthal (ℓ) and a radial (p) index, the former responsible for the OAM [see Fig. 1 (a) and (b)]. Remarkably, beams with the same mode index $M^2 = 2p + |\ell| + 1$ propagates in an identical manner. Hence, we can use both degrees of freedom to efficiently increase the number of information channels. This was recently demonstrated in a proof-of-principle experiment, where we used over 100 modes encoded on a spatial light modulator to transmit information [4].

We are also exploring diversity, a well-known technique to mitigate the effects of turbulence. Here, multiple dependent data

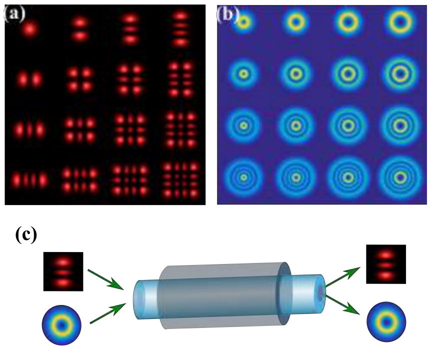


Figure 1: Transverse spatial modes require two degrees of freedom for a full description for example HG_{nm} (a) and LG_p^ℓ (b) modes. (c) Hybrid systems can be exploited to improve the bandwidth capacity.

streams, from separate emitters, are transmitted simultaneously along separate paths, experiencing different perturbations. A single detector recombines all the signals in a redundant way, producing an enhancement of the Signal to Noise Radio (SNR). This idea can be taken to the next level by using spatial modes with completely different shapes, for example LG and Hermite-Gaussian modes [see Fig. 1 (c)], which can travel along the same path. Enhancement of the SNR in this case will come from the difference in shape.

References

[1] A. Forbes , *et al.* Adv. Opt. Photonics, *8(2):200–227, 2016.*

[2] N. Bozinivic , et al. Science*, 340(1545-1548), 2013.*

[3] N. Zhao , et al. Nat Photon*, 9(12):822–826, December 2015.*

[4] T. Abderrahmen , et al. Sci. Rep.*, 6, 2016.*

Correlations in Stokes parameters of vector speckles

Salla Gangi Reddy[1], Vijay Kumar[2], Yoko Miyamito[1], and R. P. Singh[2]
[1] The University of Electro-Communiations, Chofu, Tokyo-1828585, Japan.
[2] Physical Research Laboratory, Navrangpura, Ahmedabad-380009, India.
sgreddy@uec.ac.jp, yoko.miyamoto@uec.ac.jp

The cylindrical vector beams are known for their non-separability in polarization and spatial mode as well as for spatially varying polarization states [1]. If the vectorial singularity coincides with optical phase singularity, then the beams are called vector vortex beams. These beams have ability to produce tighter focal spots and stronger longitudinal field gradients [2]. Recently, The speckles with spatially varying polarization i.e. polarization speckles, are getting a lot of attention in biomedical optics especially for distinguishing different types of skin cancers [4].

In this work, we generate a special class of vector vortex beams, Poincaré beams using polarization sensitive spatial light modulator (SLM). We incident the diagonally polarized light, having equal components of horizontal and vertical polarizations, on SLM displaying on-axis phase hologram corresponding to the optical vortices. The SLM converts the vertically polarized Gaussian beam into optical vortex beam in the central order and the horizontally polarized Gaussian beam will be unaffected by SLM. The output is the superposition of Gaussian and vortex beams with orthogonal polarizations that forms a vector vortex beam. This is the vector vortex beam in the linear polarization basis that contains two opposite C-singular points in its polarization profile. This beam can be converted to the vector vortex beam in circular polarization basis using a quarter wave plate (QWP) and it is an isolated C-singular point. The presence of polarization singularity has been confirmed using Stokes polarimetry.

After verifying the presence of a star pattern in the polarization profile of vector vortex beam using the polarimetry, we scatter these beams through a rough surface, the ground glass plate (GGP). This leads to the formation of speckles that have random polarization profile i.e. spatially varying random polarization. We have experimentally verified the presence of random polarization profile and measured the correlation in Stokes parameters for different indices of the Poincaré beam. Here we measure the widths of scalar as well as vector speckles using the Stokes correlation. It has been suggested that the width of auto-correlation function of Stokes parameter S_0 gives the scalar speckle size and the width of a function given by the sum of auto-correlation functions of remaining three Stokes parameters gives the size of vector speckles [6].

$$C_s = < S_0 S_0 > \quad (1)$$

$$C_p = < S_1 S_1 > + < S_2 S_2 > + < S_3 S_3 > \quad (2)$$

where C_p, C_s are the correlation function of polarization and scalar speckles, (S_0, S_1, S_2, S_3) are Stokes parameters. Figure 1 shows the correlation lengths corresponding to the Stokes parameters corresponding to different indices l=1-3. It is clear from the figure that the correlation length for S_0 is independent of index and the correlation lengths for the remaining three Stokes parameters decreases with the index. It is very interesting to see that the scalar speckle size is independent of index which is in contrast to the behaviour of speckles generated by the scalar vortex beams whose size decreases with the increase in order as discussed in ref.[5]. However size of polarization speckle is decreasing with the increase in index. This may find applications in imaging and communications as one can control the correlation in polarization by keeping the intensity correlation remains same.

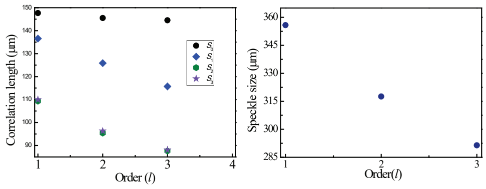


Figure 1: The variation of correlation lengths for the Stokes parameters (left) and the vector speckle size (right) with the index of Poincaré beam.

References

[1] Q. Zhan, Adv. Opt. Photon. **1**, 1-57 (2009).

[2] R. Dorn, S. Quabis, and G. Leuchs, Phys. Rev. Lett. **91**, 233901 (2003).

[3] F. toppel, A. Aiello, C. Marquardt, E. Giacobino, and G. Leuchs, New. J. Phys. **16**, 073019 (2014).

[4] L. Tchvialeva, G. Dhadwal, H. Lui, S. Kalia, H. Zeng, D. I. McLean, and T. K. Lee, J. Biomed. Opt. **18**,061211 (2012).

[5] S. G. Reddy, S. Prabhakar, A. Kumar, J. Banerji, and R. P. Singh, Opt. Lett. **39,** 4364 (2014).

[6] W. Wang S. G. Hanson, and M. Takeda, Proceedings of IX international conference on Correlation Optics, 738803 (2009).

Compact generation of arbitrary vectorial light fields

Adam Selyem, Max Derksen, Sonja Franke-Arnold, Neal Radwell
School of Physics and Astronomy, University of Glasgow,
G12 8QQ Glasgow, Scotland, UK
a.selyem.1@research.gla.ac.uk

We introduce a particularly compact digital micromirror device (DMD) based setup suitable to generate arbitrary vector beams at various wavelengths.

Light fields shaped in their transverse phase and amplitude are of interest in a wide variety of applications, such as microscopy, optical trapping and communication. The additional control of polarisation gives access to longitudinal fields when strongly focussed. Various methods have been developed to generate arbitrary vectorial light fields, including [1, 2, 3].

Our device uses a Wollaston prism to split a beam into two orthogonal polarisation components. Two multiplexed holograms displayed on a DMD provide both the complex field shaping of each component and their recombination. This allows a compact set-up based on less than five optical components after the prism, none of which are birefringent, allowing broadband operation with simple dispersion compensation. Furthermore, since the two polarisation components have almost identical optical path lengths, the device is suitable for beams with a small coherence length.

Here we present the design of our device and evaluate its performance by measuring the fidelity of various generated vector vortex beams, an example of which is shown in figure 1.

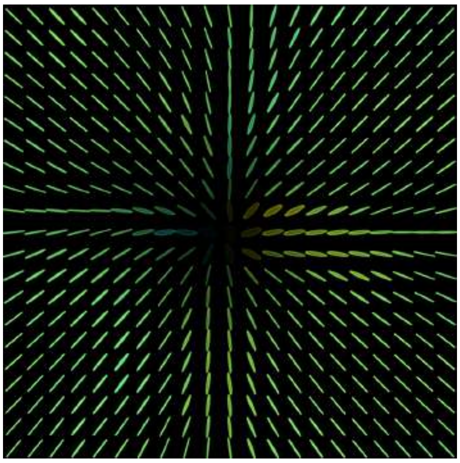


Figure 1: Measured polarisation structure of a radially polarised beam generated by our setup.

References

[1] C. Maurer, A. Jesacher, S. Fürhapter, S. Bernet and M. Ritsch-Marte, "Tailoring of arbitrary optical vector beams", New Journal of Physics, 9 (2007).

[2] F. Kenny, D. Lara, O. G. Rodríguez-Herrera and C. Dainty, "Complete polarization and phase control for focus-shaping in high-NA microscopy", Optics Express, 20, 14015-14029, (2012).

[3] K. J. Mitchell, S. Turtaev, M. J. Padgett, T. Čižmár and D. B. Phillips, "High-speed spatial control of the intensity, phase and polarisation of vector beams using a digital micro-mirror device", Optics Express, 25, 29269-29282 (2016).

3D control of atomic populations from structured light and darkness

Adam Selyem, Sylvain Fayard, Thomas W. Clark, Neal Radwell, Sonja Franke-Arnold
School of Physics and Astronomy, University of Glasgow,
G12 8QQ Glasgow, Scotland, UK
a.selyem.1@research.gla.ac.uk

We demonstrate the use of an atomic vapour to visualise 3D light structures, and in turn the use of 3D light structures to shape the local atomic population distributions.

Light that carries OAM, and more generally structured light, is often analysed in terms of its 2D beam profile. On propagation interesting 3D structures can be realised, including optical vortex knots, bottle beams and 3D lattices. We have developed a method to reconstruct the full 3D structure by measuring light scattered from an atomic vapour [1].

The structured light in [1], however, also affects the electronic levels of the atoms in the vapour. Atoms are pumped between electronic levels at rates dependent on the local light intensity, generating 3D population structures. We use structured laser beams shaped by a spatial light modulator to deplete a specific electronic level in rubidium 85. More specifically, we pump atoms out of an upper ground state via excitation of a short-lived excited state and subsequent spontaneous decay into the lower ground state. In dark regions of the beam, atoms remain in the upper ground state and we can probe this remaining population with an unshaped laser at a different frequency. We then tomographically reconstruct the 3D population pattern from the fluorescence of this probe laser [2]. Bright regions of the structured light beam coincide with suppressed fluorescence from the probe laser, as the upper ground state is depleted. The retrieved 3D fluorescence patterns are therefore complementary to each other as shown in Fig. 1.

Here we demonstrate the 3D structuring of atomic populations by measurement of 3D fluorescence distributions. We establish a link between fluorescence rates and populations using a spatially resolved rate equation model.

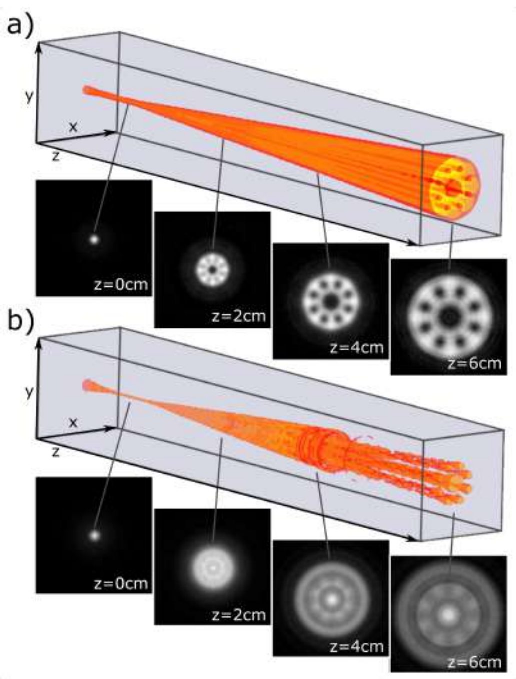


Figure 1: 3D reconstructions of fluorescence from a) a focussed structured light field with an 'optical ferris wheel' profile and b) the corresponding focussed probe laser. The boxes correspond to a physical volume of approximately 1x1x7 cm^3. The insets show the reconstructed cross-sections at various propagation distances from the focus.

References

[1] N. Radwell, M.A. Boukhet, S. Franke-Arnold, Optics Express, 21, 22215-22220, 2013

[2] A. Selyem, T.W. Clark, N. Radwell and S. Franke-Arnold, in preparation

High-dimensional Quantum Cryptography with Structured Photons across Ottawa

A. Sit,[1] F. Bouchard,[1] R. Fickler,[1] J. Gagnon-Bischoff,[1] H. Larocque,[1]
K. Heshami,[2] D. Elser,[3,4] C. Peuntinger,[3,4] K. Günthner,[3,4] B. Heim,[3,4]
C. Marquardt,[3,4] G. Leuchs,[1,3,4] R.W. Boyd,[1,5] E. Karimi[1]
[1]Physics Department, University of Ottawa, 25 Templeton, Ottawa, Canada, K1N 6N5
[2]National Research Council of Canada, 100 Sussex Drive, Ottawa, Canada, K1A 0R6
[3]Max-Planck-Institut für die Physik des Lichts,
Günther-Scharowsky-Straße 1, Bau 24, 91058 Erlangen, Germany
[4]Institut für Optik, Information und Photonik,
Universität Erlangen-Nürnberg, Staudtstraße 2, 91058 Erlangen, Germany
[5]Institute of Optics, University of Rochester, Rochester, New York, 14627, USA
asit089@uottawa.ca

Compared to classical encryption methods, which rely on the complexity of mathematics for security, quantum cryptography via quantum key distribution (QKD), such as the first protocol by Charles Bennett and Gilles Brassard in 1984 [1], promises secure communication based on the properties of quantum mechanics. The recent work on realizing a high-dimensional BB84 protocol with structured photons across an intra-city link is discussed, here [2]. Quantum states of light resulting from an arbitrary coherent superposition of different polarizations and spatial modes, e.g. orbital angular momentum (OAM) modes, are called structured photons. Structured photons allow for higher-dimensional states to be implemented in QKD protocol [3, 4]. The two mutually unbiased bases (MUBs) implemented in this protocol are consist of vector vortex beams with ± 2 units of OAM.

The experiment was performed between two campus building roof tops 300 m apart at the University of Ottawa. Alice, on the sender side, generates non-degenerate single photon pairs via spontaneous parametric downcoversion. She prepares the signal photon (850 nm) in one of the states from one of the MUBs with a sequence of waveplates and a q-plate [5]. Then she sends the encoded photon with its corresponding idler photon (775 nm) across the link to Bob at the receiver. Bob separates the photon pairs, projects the signal photon onto one of the states from one of the two MUBs, and then couples the photons to single mode fibers connected to detectors. The idler photon acts as a heralding trigger for the signal to record coinicidence rates, and as a 'target' to help correct for beam wandering to due turbulence.

A comparison of sent and measured photon states led to a quantum bit error rate of 11%, which is below the security threshold of 18% in dimension 4, yielding a secret key rate of 0.65 bits per sifted photon. Similar measurements with 2-dimensional structured states resulted in 0.43 bits per sifted photon from a 5% error rate. These results are promising for the development of future free-space intra-city quantum networks.

References

[1] C.H Bennett, G. Brassard. International Conference on Computer System and Signal Processing, IEEE, 175, 1984.

[2] A. Sit, *et al.* arXiv:1612.05195 (2016).

[3] G. Vallone, *et al.* Phys. Rev. Lett. 113, 060503 (2014).

[4] M. Mirhosseini, *et al.* New J. Phys. 17, 033033 (2015).

[5] H. Larocque, *et al.* J. Opt. 18, 124002 (2016).

Knotted hopfion in tightly focused light

Danica Sugic, Mark R. Dennis
University of Bristol,
H. H. Wills Physics Laboratory, Tyndall Avenue BS8 1TL, UK
danica.sugic@bristol.ac.uk

The discovery of novel topological objects is an intriguing task for scientists in several different research areas. It has been previously shown that optical vortices, that is, zero lines of complex amplitude in a propagating light field, can be shaped in the form of knots and links [1]. In this talk we present a novel type of volume filling configuration of polarization singularities, that has the form of a knotted hopfion embedded in a tightly focused eletromagnetic field [2].

It is known that non-paraxial electromagnetic waves can show three-dimensional patterns of polarization singularities, but knotted configurations have not previously been created, given that the design of holograms in vector optical fields is very challenging. We found that certain dark fields naturally manifest continuously knotted polarization structures, as illustrated in figure 1. A subwavelength knot is embedded in any transverse component of the beam, with the result of a surprising topological structure that looks like a hopfion.

So far, optical knots have just been created experimentally in paraxial light, where a computer-controlled hologram determined the complex amplitude of the beam [1]. The design of holograms for non-paraxial fields is not well understood yet, but we propose experiments for the realisation of knotted hopfions in tightly focused beams [3]. The subwavelength hopfion should yield optical knots suitable for embedding knotted defect structures in liquid crystals, photopolymers and Bose-Einstein condensates [4], where similar topologies have been investigated.

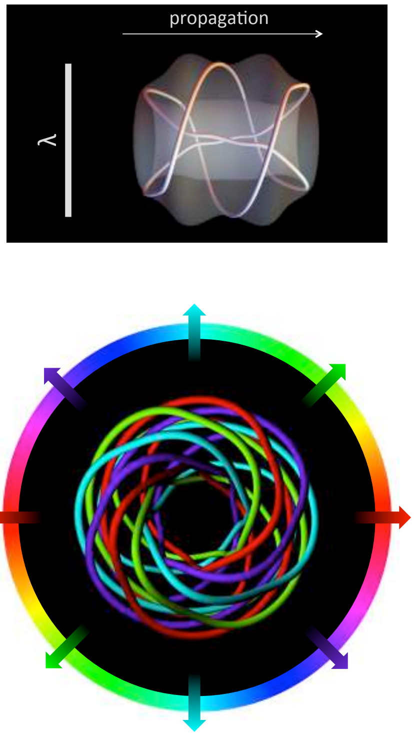


Figure 1: Representation of an optical hopfion in a dark tightly focused beam. The colours represent the different transverse linear polarization states, with repeated arrows for esthetic purposes. Each curve is a trefoil knot, and it includes points with the same transverse linear polarization, resulting in a topological structure that looks like a hopfion and where a torus surface is swept out.

References

[1] Dennis M.R, et al, Isolated optical vortex knots, Nat. Phys. 6, 118-121, 2010.

[2] Sugic D. & Dennis M.R, in preparation.

[3] Richards B. & Wolf E, Electromagnetic Diffraction in Optical Systems. II. Structure of the Image Field in an Aplanatic System, Proc. R. Soc. Lond. A 253, 358-379, 1959.

[4] Hall D.S, Ray M.W, et al, Tying quantum knots, Nat. Phys. 12, 478-483, (2015).

Experimental test of single-system steering and application to quantum communication

Zhao-Di Liu, Yong-Nan Sun†, Chuan-Feng Li *
1 CAS Key Laboratory of Quantum Information, University of Science and Technology of China, Hefei 230026, People's Republic of China
† synan@ustc.edu.cn, * cfli@ustc.edu.cn

In the view of a quantum information task, EPR steering can be regarded as the distribution of entanglement from an untrusted party, whereas entangled states need both parties to trust each other, and Bell nonlocality is presented on the premise that they distrust each other. EPR steering has been identified as a resource for one-sided device-independent quantum key distribution (QKD) [1].

In order to give a unified picture to connect quantum steering with generic quantum information task, such as quantum computation and quantum communication (for example QKD), Che-Ming Li *et al.* present a theoretical framework about quantum steering for single-system steering [2]. Based on a generic classical description of state preparation and transition, a condition is derived for SS steering, which not only enable unambiguously ruling out of generic classical means of mimicking steering, but also can prevent QKD using qudits from cloning-based individual attacks and coherent attacks. The steering condition also can be applied in quantum computation to serve as an efficient criterion for the evaluation of quantum logic gates of arbitrary size.

In this work, we use OAM of photons to produce high-dimensional quantum states with high fidelity. On the basis of this technique, we experimentally validate single-system steering, observing quantum effects beyond classical limits. At the same time, we study the application of single-system steering in quantum communication, and realize the information of each photon safely carrying 2.82 qubit information. The experimental results show that the proposed scheme can be widely used in quantum information tasks.

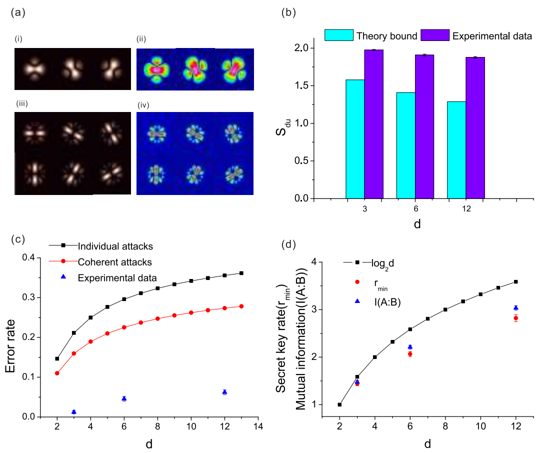


Figure 1: (a) (i) and (iii) are the theoretically calculated intensity profiles of the modes for qutrit and qusix quantum states. (ii) and (iv) are the experimentally produced intensity profiles. (b) Experimental result of the single system steering.(c) Error-bound for security.(d) The Shannon mutual information $I(A:B)$, the secret key rate r_{min} and the maximum information of a photon are plotted as a function of the dimension. The value of the secret key rate r_{min} is 1.44 ± 0.04, 2.06 ± 0.05 and 2.82 ± 0.07 for dimension 3, 6 and 12.

References

[1] C. Branciard, E. G. Cavalcanti, S. P. Walborn, V. Scarani, and H. M. Wiseman, Phys. Rev. A **85**, 010301(R) (2012).

[2] C.-M. Li, Y.-N. Chen, N. Lambert, C.-Y. Chiu, and F. Nori, Phys. Rev. A **92**, 062310 (2015).

Direct measurement of near field optical forces with femtonewton resolution

M. Antognozzi[1,2], S. Simpson[3], C. Bermingham[1,2],

M. Dennis[1], K. Bliokh[4], W.K. Szeremeta[1]

[1]H.H. Wills Physics Laboratory, University of Bristol, Bristol, UK
[2] Centre for Nanoscience and Quantum Information, University of Bristol, Bristol, UK
[3]Institute of Scientific Instruments of the ASCR, Brno, Czech Republic
[4]Center for Emergent Matter Science, RIKEN, Wako-shi, Saitama 351-0198, Japan
E-mail: ws12193@bristol.ac.uk

Optical forces in the near field display interesting and often unintuitive effects. Many such forces have been theoretically predicted but their measurement is challenging. We present the use of the Lateral Molecular Force Microscope (LMFM) to measure near field optical forces through the mechanical deflection of a highly compliant cantilever. In particular, we show the measurements of forces associated with the spin momentum of light.

The LMFM is a probe microscope that uses a vertically oriented cantilever (Fig. 1) which detects the lateral movement of the cantilever tip using an optical method [1][2]. The cantilever is highly compliant in one direction with femtonewton force sensitivity. It can be oriented in any direction in the sample plane allowing to isolate any individual optical force component.

We find that the response of the cantilever to light in the evanescent field is strongly dependent on the polarization state of the light and the cantilever orientation as well as its shape. Changes in the evanescent field due to the incident polarization state and the sample properties can therefore be measured by recording the deflection of the cantilever tip.

In the situation of total internal reflection of circularly polarized light, we have measured a force transverse to the propagation direction of the evanescent wave and shown that it is dependent on the spin handedness of the light [3]. We also show that this fN scale force is associated

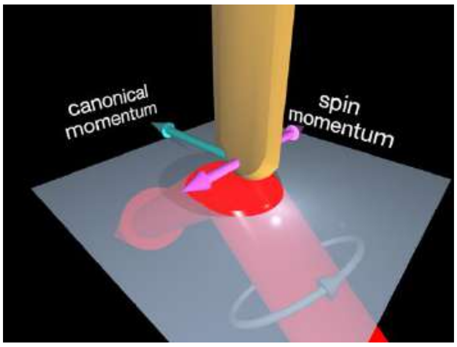


Figure1: The cantilever is deflected by the spin and canonical momentum of the circularly polarised evanescent field

with the theoretically predicted transverse spin momentum [4]. In conclusion, the results presented show how the LMFM provides a unique experimental tool to test and uncover new near-field optical effects.

References

[1] M.Antognozzi et al., Nonotechnology, **19**, 384002 (2008)
[2] J.Vicary et al., Ultramicroscopy, **111**, 1547 (2011)
[3] M.Antognozzi et al., Nature Physics, **12**, 731 (2016)
[4] K.Bliokh et al., Nature Communications, **5**, 3300 (2014)

Tunable hybrid states for quantum channel simulation and characterization

Adam Vallés[1,2], Juan P. Torres[2], Andrew Forbes[1]
[1]School of Physics, University of the Witwatersrand,
Private Bag 3, Wits 2050, South Africa
[2]ICFO—Institut de Ciències Fotòniques, Castelldefels, Barcelona, Spain
adam.vallesmari@wits.ac.za

We present two experimental schemes aimed at easing the simulation and characterization of quantum channels. The constant need for higher data transmission rates in fibre communications systems has ignited a new research field focused in employing the high-order spatial modes of optical fibres as new optical channels. More specifically, guided modes that posses orbital angular momentum (OAM). This is the spatial counterpart of the nowadays mature use of spectral multiplexing to enhance communication bit rates.

In the first scheme, we are able to simulate a real communication quantum channel by generating coherent and non-coherent correlations between two degrees of freedom in a single photon. We make use of the polarization and OAM modes of a single photon. The tuning of the correlations is analogous to the tuning of the purity (first-order coherence) of each of the photons forming part of a two-photon state. Therefore, well-known tools such as the Clauser-Horne-Shimony-Holt (CHSH) Bell-like inequality can be used to characterize entanglement between degrees of freedom [1], as can be seen in the results shown in Fig. 1.

In the second scheme we demonstrate a simple projective measurement based on the quantum eraser concept, that can be used to characterize the disturbances of any communication channel. Here we exploit the advantages of redefining the which-path information in terms of spatial modes, replacing physical paths with abstract paths of OAM modes. Remarkably, vector modes are the natural modes of optical fibres and are non-separable spin-orbit coupled states, equivalent to the description of two independently

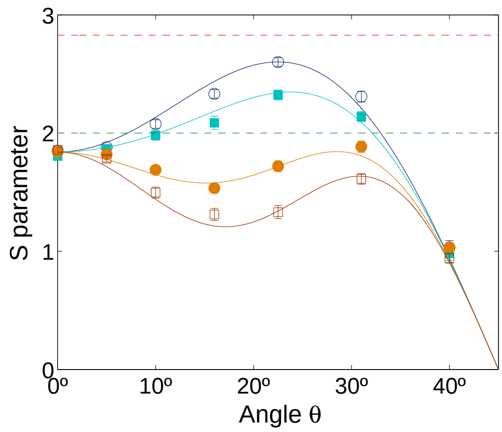


Figure 1: Values of the parameter S in a CHSH inequality, varying the purity of the quantum state as a function of the angle relation between measurement projections.

marked physical paths. We explore the effects of fibre perturbations by probing a step-index optical fibre [2].

The results presented here can be useful for analysing and characterizing multiplexing technology based on the use of high-order spatial modes of optical fibre communications, since we can simulate and probe quantum channels with different transmission properties.

References

[1] A. Vallés, V. D'Ambrosio, M. Hendrych, M. Mičuda, L. Marrucci, F. Sciarrino, and J. P. Torres, Phys. Rev. A 90, 052326, 2014.

[2] I. Nape, C. Kyeremah, A. Vallés, C. Rosales-Guzmán, P. K. Buah-Bassuah, and A. Forbes, arXiv preprint arXiv:1705.01276, 2017.

Scalable orbital-angular-momentum sorting without destroying photon states

F.X Wang, W. Chen, Z.Q. Yin, S. Wang, G.C. Guo, Z.F. Han
CAS Key Laboratory of Quantum Information, USTC, Hefei, China
fxwung@mail.ustc.edu.cn; weich@ustc.edu.cn

Single photons with orbital angular momentum (OAM) have attracted substantial attention from researchers. A single photon can carry infinite OAM values theoretically. Thus, OAM photon states have been widely used in quantum information and fundamental quantum mechanics. Although there have been many methods for sorting quantum states with different OAM values, the nondestructive and efficient sorter of high-dimensional OAM remains a fundamental challenge. Here, we propose a scalable OAM sorter which can categorize different OAM states simultaneously (Ref. [2] proposed a similar scheme), meanwhile, preserving both OAM and spin angular momentum. Fundamental elements of the sorter are composed of symmetric multiport beam splitters (BSs) and Dove prisms with cascading structure, which in principle can be flexibly and effectively combined to sort arbitrarily high-dimensional OAM photons. The scalable structures proposed here greatly reduce the number of BSs required for sorting high-dimensional OAM states. In view of the nondestructive and extensible features, the sorters can be used as fundamental devices not only for high-dimensional quantum information processing, but also for traditional optics.

It can be proven that the numbers of BSs necessary for different structures satisfy $d_N = \mathcal{O}(N^2 - N)$ (for a classical N-dimensional UT [1]), $d_N^{PCS} < \mathcal{O}((q+p/q)N)$ and $d_N^{TDCS} < \mathcal{O}((p/q+q/p)N)$ [3]. If the factors in the PMCS are all primes, then $d_N^{PMCS} < \mathcal{O}((p_k+4/3)N)$. The cascading structures greatly reduce the number of BSs. For example, when $N = 30$, $d_N = 870$, while $d_N^{PCS} = 150, d_N^{PMCS} = 80$ and $d_N^{TDCS} = 50$.

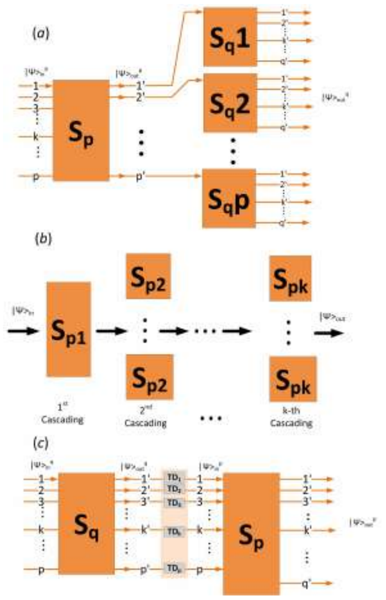


Figure 1: Cascading structure of the OAM sorter for $(p \cdot q)$-dimensional OAM states [3]. (a) Parallel cascading structure with one S_p and p S_q. (b) Parallel multi-cascading structure (PMCS). The number of S_{p_i} of the i-th cascading is $p_1 \cdot p_2 \cdots p_{i-1}$, where $i > 1$ and $p_1 > p_2 > \cdots p_k$. (c) Time-delay cascading structure (TDCS) with only one S_p and one S_q, where $p > q$. TD_k: time delay of Port-k.

References

[1] M. Reck, A. Zeilinger, H. J. Bernstein, and P. Bertani, Phys. Rev. Lett. 73, 58 (1994).

[2] R. Ionicioiu, Sci. Rep. 6, 25356 (2016).

[3] F.-X. Wang, W. Chen, Z.-Q. Yin, S. Wang, G.-C. Guo, and Z.-F. Han, Phys. Rev. A 94, 33847 (2016).

Controlled-phase manipulation module for orbital-angular-momentum photon states

F.X Wang, W. Chen, J. Wu, Z.Q. Yin, S. Wang, G.C. Guo, Z.F. Han
CAS Key Laboratory of Quantum Information, USTC, Hefei, China
fxwung@mail.ustc.edu.cn; weich@ustc.edu.cn

The phase manipulation of OAM is commonly accomplished by the Dove prism (DP). The DP rotating with an angle α at its longitudinal axis will introduce an OAM-dependent phase $e^{i2l\alpha}$ to the OAM state $|l\rangle$, where l is the order of the OAM mode. By utilizing this property, the Mach-Zehnder interferometer (MZI) with a DP in each arm can sort OAM photons [3]. In order to overcome the stable problem of the original MZI, the modified Sagnac interferometers have been introduced [1]. But the interferometer will also introduce an OAM-dependent global phase. For example, for an input state $|l\rangle + |-l\rangle$, the output state becomes $i(|l\rangle - |-l\rangle)$, which is orthogonal to the input one, if $\alpha = \pi/4$. Additionally, the DP rotates the linear polarization into elliptical polarization and decreases the visibility of the interferometer [2]. For hyper-entangled states, the shortcoming also decreases the purity of the states.

We implement a passive phase manipulation module (PMM) to sort OAM photons. The main component in the modified Sagnac interferometer is a sandwich-like structure with a DP stuck in the middle of two HWPs, as shown in Fig. 1(a). In direction a, the rotating angle of the DP is α, the angle between the fast axis of these two HWPs and the horizontal axis are $\theta_1 = \theta_2 = \alpha/2$ (Fig. 1(b)). Then, for the input state $\sum_l(|H\rangle + |V\rangle)|l\rangle$, the output state becomes $\sum_l \sqrt{t_{//}t_{\perp}} e^{i\Delta\varphi}(|H\rangle + e^{-i4l\alpha}|V\rangle)|l\rangle$, where $t_{//(\perp)}$ is the transmission coefficient of the DP for the polarized light that parallel (perpendicular) to the normal of the base $\mathbf{n}_{DP}$, and $\Delta\varphi$ is the relative phase shift between the two polarization components attributed to the total internal reflection inner the DP. The PMM compensates the polarization-dependent effect of the DP well and introduces an OAM-dependent phase

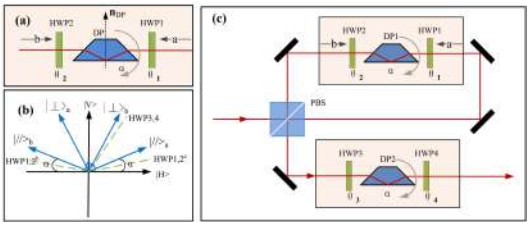


Figure 1: (a) The schematic diagram of the sandwich-like structure in the Sagnac loop. (b) The rotating angles of the DP and the HWPs. (c) The schematic setup of the PMM.

$e^{-i4l\alpha}$ to the photon only if the controlled qubit is $|V\rangle$. Thus, the PMM is a high-dimensional C-phase gate.

The PMM is a 2-dimensional controlled-NOT gate when $4\alpha = \pi$. The output state becomes $\sum_l(|H\rangle \mp |V\rangle)|l\rangle$. Thus, the PMM is also an OAM sorter. **The sorting fidelity of the PMM and the purity of the output photon state are high even when** $\alpha = \pi/4$. Although the DP with $\alpha = \pi/4$ decreases the fidelity by about only several percents in a classical single-path Sagnac interferometer, the error is intolerant in quantum cryptography. For a BB84 protocol quantum key distribution (QKD), the upper bound of tolerant bit error of the whole system is about 11%.

References

[1] J. Leach, M. J. Padgett, S. M. Barnett, S. Franke-Arnold, and J. Courtial, Phys. Rev. Lett. 88, 257901 (2002).

[2] S. Slussarenko, V. D'Ambrosio, B. Piccirillo, L. Marrucci, and E. Santamato, Opt. Express 18, 27205 (2010).

[3] M. J. Padgett and J. P. Lesso, J. Mod. Opt. 46, 175 (1999); I. Moreno, G. Paez, and M. Strojnik, Opt. Commun. 220, 257 (2003).

Non-radiating angularly accelerating electrons?

J. Webster[1,*], J. Pierce[2], B. McMorran[2], E. Karimi[3], A. Forbes[1]
[1]School of Physics, University of the Witwatersrand, Private Bag 3, Wits 2050, South Africa
[2]Department of Physics, University of Oregon, 1585 E 13th Avenue, Eugene, Oregon 97403, USA
[3]Department of Physics, University of Ottawa, 75 Laurier Ave E, Ottawa, ON K1N 6N5, Canada
[*]jasonrobwebster@gmail.com

Radiation due to the acceleration of charged particles is a well-known phenomenon in physics. Synchrotron radiation is an example of this, arising from an electron following a curved path. Such radiative models typically take the electron as a classical point charge in order to calculate its emission spectrum, while to a good approximation ignoring the wave-like behavior of the particle.

We demonstrate the construction of an angularly accelerating electron matter wave that possesses no radiation, and also analyze the EM field surrounding such a matter wave in regimes where a classical description does not fully suffice. To do this, we created a customized nano-fabricated SiN diffraction grating [1], manufactured such that an electron Bessel beam with a tunable angular acceleration is produced at the first diffraction order. This beam is chosen due to its non-linear propagation behavior, as has been demonstrated for the optical case [2], and is a characteristic that is due solely to the wave nature of the electron.

The electromagnetic field surrounding our beam was analyzed theoretically using a semi-classical approach. We predict a solenoidal magnetic field could arise in the center of the beam for the simplest non-accelerating case (pictured in Figure 1). We also deduced that for this simple non-accelerating case that no radiation should be emitted from our beam.

For the angularly accelerating case, we rely on a continuum argument based on the behaviour of the EM field at a large distance from our beam. From this we deduce that our accelerating beam does not radiate. We also report indirect measurements of this lack of radiation, confirming our hypothesis that we have indeed created a non-radiating accelerating electron beam.

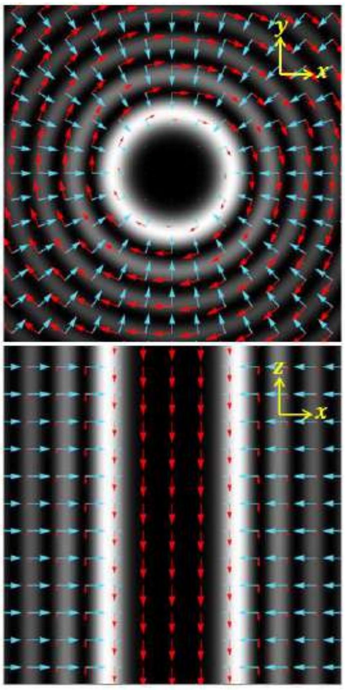


Figure 1: Electric (blue) and magnetic (red) field lines plotted with the electron probability intensity (grayscale) for a non-accelerating electron Bessel beam.

References

[1] Harvey, T.R., et al., 2014. Efficient diffractive phase optics for electrons. New Journal of Physics, 16(9), p.093039.
[2] Schulze, C., et al., 2015. Accelerated rotation with orbital angular momentum modes. Physical Review A, 91(4), p.043821.

Normal modes and mode transformation of bandwidth limited electron vortex beams

G. Thirunavukkarasu, M. Mousley, M. Babiker and J. Yuan
Department of Physics, University of York, Heslington, York YO10 5DD, UK
jun.yuan@york.ac.uk

Electron vortex beams constitute the first class of matter vortex beams which are currently routinely produced in the laboratory. Due to the limited spatial coherence of experimentally available electron sources, the electron vortex beams being created and studied so far have been mostly generated using a suitable plane wave mode convertor of a finite radius at the back-focal plane of an electron microscope lens. So these electron vortex beams, like most beams used in conventional electron microscopy, are, by definition, bandwidth limited. This distinguishes electron vortex beams from optical vortex beams which are characterized by much longer spatial and temporal coherence lengths. Here we put forward a complete natural quantum basis set (normal modes) for any such bandwidth limited vortex beams and apply this to generate pure electron vortex beams which are characterized not only by the topological charge l but also by the radial quantum number p [**?**], in analogy with the prominent roles Laguerre-Gaussian (LG) normal modes (also characterized by quantum number pairs, l and p) have played in optical vortex beam research [**?**].

The normal modes we put forward are truncated Bessel beams (TBBs) defined in the aperture plane, or the Fourier Transform of the transverse structure of the TBB (to be referred to as FT-TBBs) in the focal plane of a lens. The characteristics of the TBBs and FT-TBBs modes are described analytically, including the quantized orbital angular momentum (in terms of the topological charge l and the radial index p > 0). We present the experimental realization of such beams using computer-generated holograms and the mode analysis is carried out using astigmatic transformation optics. The experimental results of the FT-TBB beams and their mode transformation show close analogy with the LG beams and the astigmatic mode transformation resembles that between LG and Hermite-Gaussian beams, but with some subtle differences.

The set of complete orthonormal modes we have put forward offers an alternative basis for the quantum description any bandwidth limited electron waves when compared to the standard methods based on the plane wave sets as electron beam instruments are usually axial symmetric. Our modes are eigenfunctions of the axial orbital angular momentum operator, so they can provide a complete description of the two-dimensional transverse distribution of the wave function of any electron vortex beams. We expect these modes to play a fundamental role in electron vortex beams in a similar manner which LG wavefunctions play in the study of optical vortex beams. In particular, we show that the higher p vortex modes and their superposition allow us to study the control and manipulation of the radial structure of electron vortex beams, a hitherto neglected topic in electron vortex beam research, with implications for applications in super-resolution imaging.

References

[1] G. Thirunavukkarasu, M. Mousley, M. Babiker, and J. Yuan, Normal modes and mode transformation of pure electron vortex beams, Phil Trans R Soc A 375:20150438, 2017

[2] L. Allen, M. W. Beijersbergen, R. J. C. Spreeuw, J. P. Woerdman, Orbital anguar momentum of light and the transformation of Laguerre-Gaussian laser modes. Phys, Rev, A, 45, 8185-8189, 1992

Caustics in non-diffracting Bessel-lattice beams and beyond

A. Zannotti[1], E. Otte[1], D. Sugic[2], C. Denz[1], M. A. Alonso[3], M. R. Dennis[2]
1. Institute of Applied Physics, University of Muenster, 48149 Muenster, Germany
2. HH Wills Physics Laboratory, Tyndall Avenue, Bristol BS8 1TL, UK
3. The Institute of Optics, University of Rochester, Rochester, New York 14627, USA
a.zannotti@uni-muenster.de

Caustics in light naturally form as the envelope of a family of rays. They mark the discontinuous change of the number of crossing rays in each point of space, often accompanied by a remarkable increase of the field intensity in close vicinity to the caustic.

The individual geometric structures of caustics are described by the catastrophe theory and are hierarchically categorized into fold, cusp, swallowtail, butterfly, and further higher-order umbilic catastrophes. One possibility to map catastrophes as caustics in light is via the catastrophe diffraction integral [1]. This approach facilitated the realization of transverse invariant and accelerating Airy beams, form-invariant and autofocusing Pearcey beams, and swallowtail beams that dynamically transform to cusp and butterfly caustics [2]. This ray-based description of several upon propagation transverse invariant beams is far reaching and was shown to explain also many aspects of Hermite-, Laguerre-, and Hermite-Laguerre-Gaussian beams [3].

In our contribution, we demonstrate a new and generalized class of caustic beams that are created as eigenfunctions of the operator $\hat{L} + q\hat{M}^n$, where $\hat{L}$ is the orbital angular momentum operator and $\hat{M}$ is the linear momentum operator, taken to the power of a positive integer n. The eigenstates depend on the real number q and possess a quantized orbital angular momentum (OAM) l. We exemplary present a sub-class for $n = 1$ that forms structured light fields capable to interpolate between Bessel beams and discrete lattices in light, which we call Bessel-lattice beams. Examples of these beams that propagate with unchanged transverse intensity are shown in Fig. 1. An inner regular lattice is surrounded by concentric intensity rings (a). The corresponding rays are presented in (b), clearly showing the caustic. Increasing q and l, this beam becomes elliptic, the lattice structures vanishes, and the outer rings carry OAM (c, d). Following this approach, we will show higher-order $(n > 1)$ non-diffracting caustics in light.

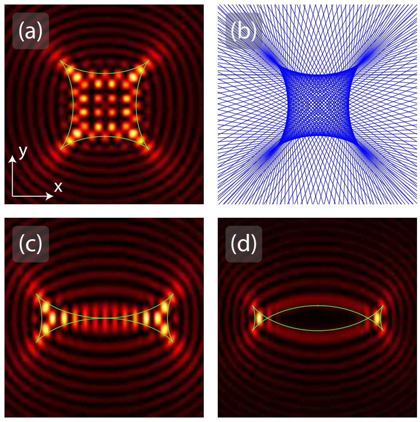


Figure 1: Bessel-lattice beams: (a) $q = 10, l = 0$, (b) $q = 10, l = 10$, (c) $q = 10, l = 15$. Ray picture of (a) is presented in (b). Caustics are indicated in green.

References

[1] Berry, M. V., Upstill, C., Catastrophe optics: Morphologies of caustics and their diffraction patterns, Prog. in Optics 18, 257-323, 1980.

[2] Zannotti, A., Denz, C. et al., Optical catastrophes of the swallowtail and butterfly beams, New J. Phys., doi:10.1088/1367-2630/aa6ecd, 2017.

[3] Alonso, M. A., Dennis, M. R., Ray-optical Poincaré sphere for structured Gaussian beams, Optica 4, 476-486, 2017.

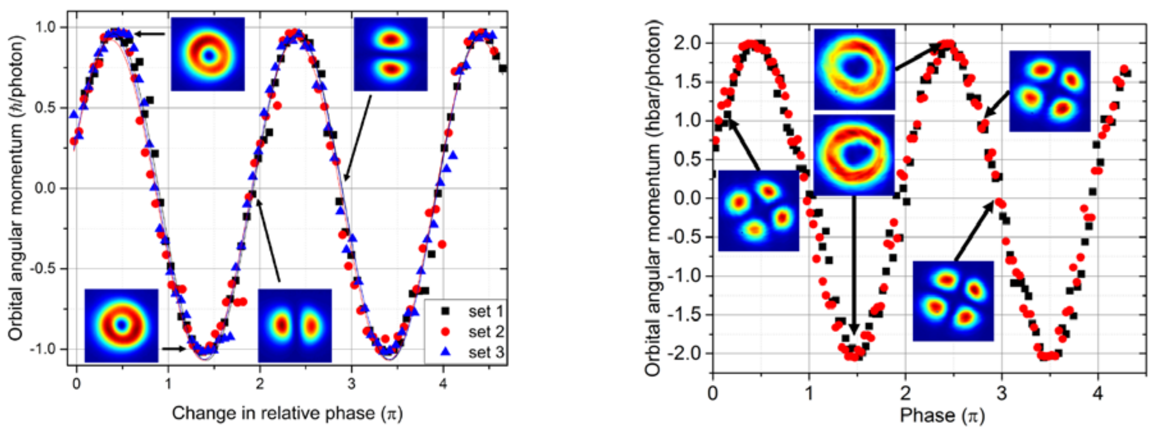
Generation and detection of tunable orbital angular momentum in optical fiber

Sam Alperin[1], Brendan Heffernan[2], Robert Niederriter[2], Mark Siemens[1], and Juliet T. Gopinath[2,3]

[1]*Department of Physics and Astronomy, University of Denver, Denver CO USA*
[2]*Department of Physics, University of Colorado Boulder, Boulder CO USA*
[3]*Department of Electrical, Computer and Energy Engineering, University of Colorado Boulder, Boulder CO USA*

In the past few years, twisted light, or light with orbital angular momentum (OAM) has captured interest for its diverse array of applications. It can be used to drive micromachines and in biophotonics. In quantum information science, OAM states can be entangled, which leads to surprising demonstrations of quantum mechanics and potentially new computational possibilities. OAM-enabled communications, of all the applications, has received the majority of the attention due to the potential increase in fiber optic bandwidth that would be realized in a move from a single photon channel to a classical or quantum mechanical-vast parameter space per photon provided by the integer OAM states.

Generation and delivery of OAM in optical fiber is an important goal for realizing OAM-enabled communications. To date, specialty fiber has been used to carry OAM. We have developed new methods for generating OAM light in commercially available polarization maintaining optical fiber. Specifically, we demonstrated generation of tunable OAM by launching and phase-controlling two higher order modes [1, 2]. Figure 1 shows an example of generation of OAM with l = +/-1 and l = +/- 2. In addition, we have studied and shown a new method for quantitative measurement of light's OAM and extensions of the technique [3]. Finally, we have determined a method to control independently, both the OAM and the spatial beam profile [4].



(a) (b)

Figure 1. (a) Tunable OAM from +/- 1, by varying the phase of the two higher order modes that add up coherently to produce OAM. We have plotted average OAM per photon vs. the change in relative phase [1]. (b). Tunable OAM from +/- 2 by varying phase of the two higher order modes that add up coherently to produce OAM. Note here that at an OAM of 1, we are looking at the case of imbalanced addition of l = +2 and -2. This is also the case at zero OAM [2].

References

1. R. D. Niederriter, M. E. Siemens, and J. T. Gopinath "Continuously tunable orbital angular momentum generation using polarization maintaining fiber," *Optics Letters* **41** 3213 - 3216(2016).
2. B. M. Heffernan, R. D. Niederriter, M. E. Siemens, and J. T. Gopinath, "Tunable higher-order orbital angular momentum using polarization-maintaining fiber," *Optics Letters* **42** , 2683-2686 (2017).
3. S. N. Alperin, R. D. Niederriter, J. T. Gopinath and M. E. Siemens, "Quantitative measurement of the orbital angular momentum of light with a single, stationary lens," *Optics Letters* **41** 5019 (2016).
4. R. D. Niederriter, M. E. Siemens, and J. T. Gopinath "Continuously tunable orbital angular momentum generation using polarization maintaining fiber," *Optics Letters* **41** 3213 - 3216(2016).