

8. Space-varying polarized fields: classical and quantum prospects – Ebrahim Karimi¹ and Lorenzo Marrucci²

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Status

In most optical experiments and applications, the polarization across the light beam is uniform or at least approximately so. The possibility of having a space-varying polarization across the beam was obviously there, but until the early 2000's there was no particular interest in such “exotic” beams. This has however changed when it was first realized that *radially and azimuthally polarized beams* exhibit very intriguing properties upon tight focusing [1]. In the focal region, they respectively generate “needle” electric and magnetic fields oriented along the beam longitudinal propagation direction and with a beam waist that is smaller than for a standard Gaussian beam. This important result is of obvious interest for applications such as optical nano-probing, nano-lithography or high-density optical memories. Radially and azimuthally polarized beams are specific examples of so-called *cylindrical vector (CV) beams*, i.e. beams having a cylindrically-symmetric polarization pattern, and of the even more general class of *vector vortex (VV) beams*, i.e. beams with an azimuthally-varying linear polarization surrounding an optical vortex located on the beam axis (see Fig. 1a-b) [2]. VV beams are the most general light beams having propagation-invariant transverse polarization patterns (except for diffraction-induced radial rescaling). They have attracted an increasing interest, recently, for various applications. For example, VV beams approximately match the higher-order eigenmodes of multimode optical fibers, currently considered for a possible “mode-division multiplexing” in future optical communication technology. Unlike standard polarized photons, photons of CV beams carry rotation-invariant qubits of quantum information, useful to establish a quantum-communication link between continuously-rotating or randomly-oriented parties, as for example in future satellite-based quantum networks or hand-held wireless quantum devices [3]. Conversely, high-order VV beams can have the property of being highly sensitive to rotations, and this in turn can be used to measure tiny mechanical rotations.

Another important family of light fields is that of the “Poincaré beams” [4], which are light beams exhibiting all possible polarization states in their cross-section and having a polarization singularity on their axis. This singularity is not an optical vortex in a standard sense, e.g., there is no vanishing of the fields at its core, although it is associated with a certain degree of

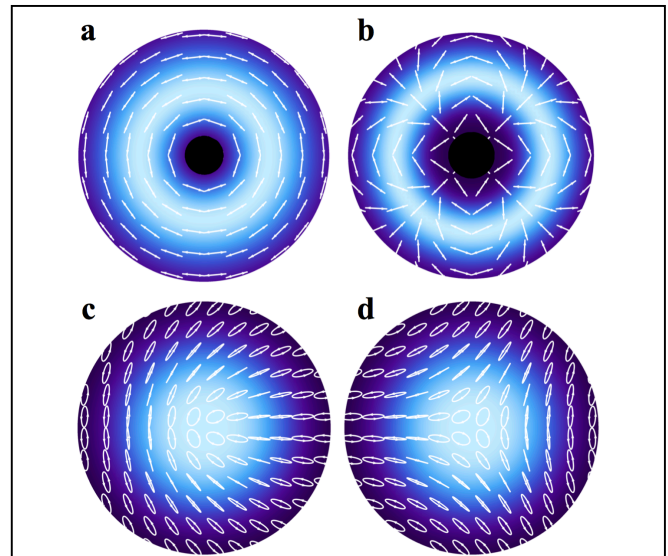


Figure 1 – **a** and **b** are examples of vector vortex beams; **a** in particular is an azimuthally polarized beam. **c** and **d** are Poincaré beams having “lemon” and “star” polarization topologies, respectively. Color brightness represents the intensity distribution, while the local polarization is depicted as small white ellipses or lines.

“vorticity”; in certain scientific communities, it is also named as “half-vortex”, because the optical phase changes by π when circling once around the singularity (but the wave remains continuous and single-valued thanks to the polarization variation). Polarization singularities [5], spontaneously arising in any pattern of light with random polarization, are points having circular polarization (C points) or linear polarization (L lines), surrounded by generic elliptical polarizations. The lowest-order C-point polarization singularities have been classified according to the topology of the surrounding polarization ellipse orientations (see, e.g., Fig. 1c-d). Unlike VV beams, the polarization pattern of Poincaré beams changes upon propagation, but following simple rules (e.g., it rotates around the beam axis).

In the quantum regime, photons with space-varying polarization can be also described as non-separable (“entangled”) quantum states of the polarization and spatial degrees of freedom. Such form of single-particle entanglement, although not challenging local realism, can still be used for certain quantum information protocols [6].

Current and Future Challenges

A major current challenge in this area is that of moving from two-dimensional (2D) field polarization structures to three-dimensional (3D) cases. 3D here means exploiting all three field components, rather than the sole transverse ones, but also being able to generate a field that is not only structured within the transverse plane but also along the longitudinal

coordinate, as in time-varying polarization pulses. Some first steps in creating complex 3D field structures in terms of field components have been taken recently. These relied on the fact that the longitudinal field component is non-negligible for a non-paraxial beam. In this generalized case, the polarization ellipse is not transverse and defines a plane of oscillation that is spatially varying in 3D. Isaac Freund first predicted the existence of 3D polarization topologies in the form of multi-twist Möbius strips and twisted ribbons for spatially structured optical beams [7]. And such 3D structures have recently been observed experimentally in the focal volume of a tightly focused Poincaré beam (see Fig. 2) [8]. However, these are just the first examples, and many other complex 3D polarization structures could be addressed in the future.

Pulsed vector fields having space-varying polarization along propagation have already been demonstrated, using Gouy phase effects, self-phase modulation and pulse “chirps”. However, combining such methods with a transverse patterning, so as to achieve a full 3D vector field structuring has not been attempted yet and is a major future challenge. Another possible important challenge is that of extending the polarization structuring ability to other spectral domains, such as terahertz or extreme ultraviolet.

In the quantum regime, the main current challenge is that of developing more efficient and controlled methods for generating and measuring complex entangled and hyper-entangled states involving multiple photons and using both polarization and spatial degrees of freedom for the entanglement. A more specific challenge is also that of using rotation-invariant photons for efficient quantum communication at long distances, against the limiting effects of air turbulence and beam divergence.

Advances in Science and Technology to Meet Challenges

The required technical advances concern of course the generation, but also the manipulation and characterization of the generated fields or photons. Current methods for generating standard 2D vector fields exploit holography (with spatial light modulators) or 2D-patterned anisotropic media (e.g., liquid crystal q -plates and plasmonic meta-surfaces) [9,10]. To add a longitudinal field component, one then sends the light through high numerical aperture (NA) optics, such as a microscope objective [8]. However, this approach is clearly limited in terms of possible outcomes. So, a more general non-paraxial optics will have to be developed in order to fully control the 3D field structures to be generated. For the generation of 3D pulsed vector light, a suitable combination of the

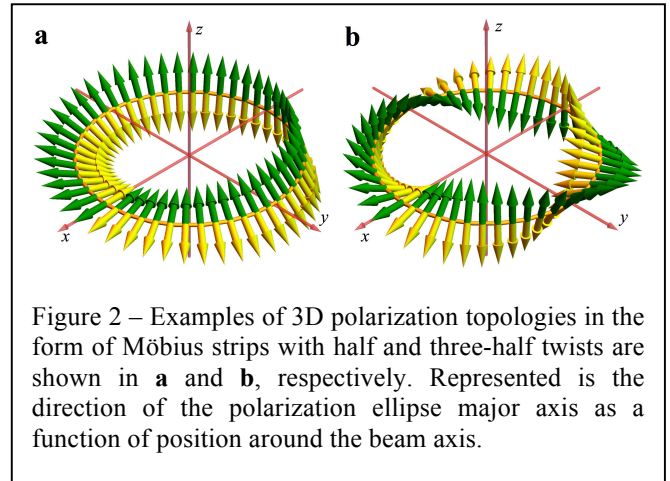


Figure 2 – Examples of 3D polarization topologies in the form of Möbius strips with half and three-half twists are shown in **a** and **b**, respectively. Represented is the direction of the polarization ellipse major axis as a function of position around the beam axis.

current 2D structuring techniques with the spectrally-resolved methods used to control the pulse shape will probably need to be developed.

The greatest technical problem in all cases will be that of proper characterization of the generated fields. For the 3D field structures obtained in the focus of high NA optics, a technique based on angle-resolved light scattering from a nanoparticle that is raster-scanned in the plane (or volume) of study has recently been developed to measure amplitude and phase of all three individual components of the electric field (see section 7 and ref. [8]). However, the need for other techniques, such as the equivalent of a 3D photo imaging, remains strong. More generally, there are calls for ultrafast, efficient and possibly miniaturized devices capable of generating and sorting structured beams for all possible applications. In the ongoing race to develop novel optical materials and systems, possible solutions could be based on patterned electro-optics and ultra-thin plasmonic devices, respectively capable of rendering fast-modulation and detection, as well as integration.

Concluding Remarks

The recent advances in the generation, manipulation, and reconstruction of optical fields with complex polarization topologies have allowed ideation and proof-of-principle demonstration of many interesting applications, such as high-resolution optical writing and reading, high-bandwidth or ultra-secure communication, and optical metrology. More potential applications will emerge if it will be possible to overcome the challenges discussed here. 3D-structured vector fields may for example provide an innovative platform for sub-wavelength lithography of complex structures or allow optimized coupling to specific material excitations having similar topologies. However, much remains to be done to acquire full control of the vectorial nature of light.

Acknowledgments

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References

- [1] Dorn R, Quabis S and Leuchs G 2003 Sharper focus for a radially polarized light beam *Phys. Rev. Lett.* **91** 233901
- [2] Zhan Q 2009 Cylindrical vector beams: from mathematical concepts to applications *Adv. Opt. Photon.* **1** 1-57
- [3] D'Ambrosio V, Nagali E, Walborn S P, Aolita L, Slussarenko S, Marrucci L and Sciarrino F 2012 Complete experimental toolbox for alignment-free quantum communication *Nat. Commun.* **3**, 961
- [4] Beckley A M, Brown T G, and Alonso M A 2010 Full Poincaré beams *Opt. Express* **18** 10777-10785
- [5] Dennis M R, O'Holleran K, and Padgett M J 2009 Optical vortices and polarization singularities *Prog. Opt.* **53** 293-363
- [6] Karimi E *et al.* 2010 Spin-orbit hybrid entanglement of photons and quantum contextuality *Phys. Rev. A* **82** 022115
- [7] Freund I 2005 Cones, spirals, and Möbius strips, in elliptically polarized light *Opt. Commun.* **249** 7-22.
- [8] Bauer T *et al.* 2015 Observation of optical polarization Möbius strips *Science* **347** 964-966
- [9] Galvez E J, Khadka S, Schubert W H, and Nomoto S 2012 Poincaré-beam patterns produced by nonseparable superpositions of Laguerre–Gauss and polarization modes of light *Appl. Opt.* **51** 2925-2934
- [10] Cardano F *et al.* 2012 Polarization pattern of vector vortex beams generated by q -plates with different topological charges *Appl. Opt.* **51** C1-C6