OPTIONAL SOURCES

A laser for complex spatial modes

A cavity design that makes it possible to directly generate Laguerre–Gaussian modes on demand looks set to benefit applications in microscopy and data communications.

Robert R. Alfano, Giovanni Milione, Enrique J. Galvez and Lingyan Shi

Lasers can be found in almost every academic and industrial setting, in tasks ranging from the simple, such as a pointing aid in a classroom presentation, to the complex, such as exciting electronic energy transitions in molecules. In most applications, the output beam of a laser system is a fundamental transverse spatial mode with a well-behaved Gaussian intensity profile. Writing in *Nature Photonics*, Andrew Forbes and collaborators now report a design of a laser cavity that allows for the generation of arbitrary higher-order spatial modes on demand[1]. The researchers achieved mode purities higher than 98%, while retaining cavity losses comparable to those of conventional laser sources.

Spatial modes of laser beams have recently received renewed interest from the research community. In optical communications, the use of specially designed fibres supporting numerous spatial modes has yielded a much needed new degree of freedom for multiplexing data transmission[2], making it possible to overcome the data capacity limits of single-mode optical fibres[3] and providing a potential solution to decrease the footprint of data centres[4].

Spatial modes can be defined as patterns of light that are solutions to the wave equation. A well-known example is given by Laguerre–Gaussian (LG) modes, which are solutions to the wave equation in cylindrical coordinates and are commonly labelled by a radial index p and an azimuthal index l. An LG mode with a central point of zero intensity is also referred to as a vortex beam with topological charge l, and can be visualized as a beam with a doughnut-shaped transverse intensity profile. Among LG spatial modes, scalar vortex beams and cylindrical vector beams have arguably received the most attention as their properties are proving useful for a range of applications.

Scalar vortex beams are important as they carry orbital angular momentum that is associated with an l-dependent azimuthally varying phase[5]. Light's orbital angular momentum is fundamentally different from its spin counterpart (which is associated with circular polarization), and it has recently sparked growing interest for its applications in free-space high-speed communications and secure quantum key distribution[6].

On the other hand, cylindrical vector beams are characterized by l-dependent azimuthally varying polarizations, such as radial and azimuthal polarizations, and do not carry orbital angular momentum[7]. When focused through a high-numerical-aperture lens, cylindrical vector beams produce strong polarization components along their direction of propagation; because of this property, they have found applications in single-molecule spectroscopy and laser-cutting techniques[7].

Scalar vortex beams and cylindrical vector beams are inherently related in that both can be represented on a higher-order Poincaré sphere[8] — a Bloch sphere for visualizing generalized polarization fields that incorporate both spin and orbital angular momentum (Fig. 1a). The well-known Poincaré sphere is a geometric representation of the polarization state of a light beam, with right- and left-circular polarizations given by the north and south poles, respectively, and arbitrary polarizations represented by points between the poles. Similarly, right- and left-handed circularly polarized scalar vortex beams (that is, with azimuthally varying phases that display opposite handedness) are given by the north and south poles of the higher-order Poincaré sphere, respectively. Arbitrary linear combinations of these states are found between the equator and the poles — for example, radially and azimuthally polarized cylindrical vector beams are located on the equator (Fig. 1a).

The interest in scalar vortex beams and cylindrical vector beams has been paralleled by the development of methods to produce them in the laboratory. In most cases, their generation takes place outside the laser cavity by optical elements that manipulate a fundamental Gaussian mode so that this mode acquires the required l-dependent azimuthally varying phase or polarization, but not the correct p index. Well-known methods to obtain scalar vortex beams include the use of fork-shaped diffraction gratings and spiral phase plates; the latter can be implemented by using liquid crystals on silicon spatial light modulators, for example[5]. To generate cylindrical vector beams, tested options include segmented half-wave plates and subwavelength diffraction gratings[7].

Far fewer approaches can produce scalar vortex beams and cylindrical vector beams directly inside a laser cavity. The reason for this is that a laser beam that is not a fundamental Gaussian mode is often unstable. This is because the gain and loss parameters of a laser cavity depend on the Gouy phase shifts that the spatial modes acquire as they focus and diverge; Gouy phases dramatically affect the interference phenomena inside a laser cavity that are responsible for the selection of the cavity's longitudinal mode, that is, the wavelength of the output beam. When spatial modes are degenerate, that is, their Gouy phase shifts are identical, the output field from a laser can be given by a superposition of LG modes with opposite handedness, as these modes suffer the same intracavity losses. As a result, methods to controllably generate spatial modes inside a laser cavity have so far remained elusive.

Forbes and co-workers present a method that addresses the degeneracy problem. The key to their solution lies in this idea: whereas spatial modes are degenerate inside a laser cavity, polarization states are not. Therefore, the degeneracy of the spatial modes can be broken by converting any polarization state on the well-known Poincaré sphere into a corresponding scalar vortex beam or cylindrical vector beam on the higher-order Poincaré sphere. To experimentally achieve this, the researchers modified a solid-state laser cavity that used a Nd:YAG crystal as the gain medium in a standard Fabry–Pérot geometry (Fig. 1b). If, for example, a polarizing beam splitter and a quarter-wave plate are added inside the cavity, the polarization of the laser output beam can be controlled through rotation of the quarter-wave plate. The slight modification considered by Forbes and collaborators was the further addition of an optical element referred to as a *q*-plate (Fig. 1b). A *q*-plate is made up of a thin layer of liquid-crystal molecules 'sandwiched' between two thin glass plates; the liquid-crystal molecules are patterned such that their preferred orientation azimuthally varies *q* times around the centre of the plate. When an external electric field is applied to a *q*-plate, it can be mathematically proven (thanks to the Jones matrix analysis) that the *q*-plate acts as a half-wave plate with an azimuthally varying fast axis. Consequently, for a given setting of the *q*-plate, any state of polarization on the Poincaré sphere can be converted into a scalar vortex beam or cylindrical vector beam on the higher-order Poincaré sphere by rotating the quarter-wave plate in the geometry discussed above.

This is not the first time that an optical element has been placed inside a lasing cavity to produce LG modes. Previously proposed methods have generated scalar vortex beams or cylindrical vector beams — not both. By contrast, Forbes and colleagues have realized a veritable 'higher-order Poincaré sphere laser' that can create any LG mode on the higher-order Poincaré sphere. The fundamental difference between the use of a *q*-plate and other optical elements, such as a tilted piece of glass or a spiral phase plate[9,10], is that the *q*-plate allows to set the correct azimuthally varying phase or polarization of a given spatial mode through control of the geometric phase. Notably, the Pancharatnam–Berry (or geometric) phase has not been used for spatial mode selection in a laser cavity before. This phase is acquired by a light ray depending on the 'geometry' of its polarization conversion: every light ray of a spatial mode in the laser cavity acquires a phase that depends on the azimuthal orientation of each liquid-crystal molecule in the *q*-plate. Conversely, a tilted piece of glass or a spiral phase plate set the correct azimuthally varying phase or polarization of a spatial mode by acting on the dynamic phase, which is a function of the path length that a light ray travels — making this approach more sensitive to misalignment. Ultimately, a *q*-plate requires no mechanical adjustments other than the rotation of the quarter-wave plate in the layout described above. As a result, the higher-order Poincaré sphere laser enables Forbes and co-workers to generate arbitrary scalar vortex beams and cylindrical vector beams in a stable, controllable manner inside a laser cavity. They found that less than 2% of the output power comes from spatial modes different from the intended LG mode (that is, having the correct *l* and *p* indices), which sets a clear benchmark for the performance of this laser source.

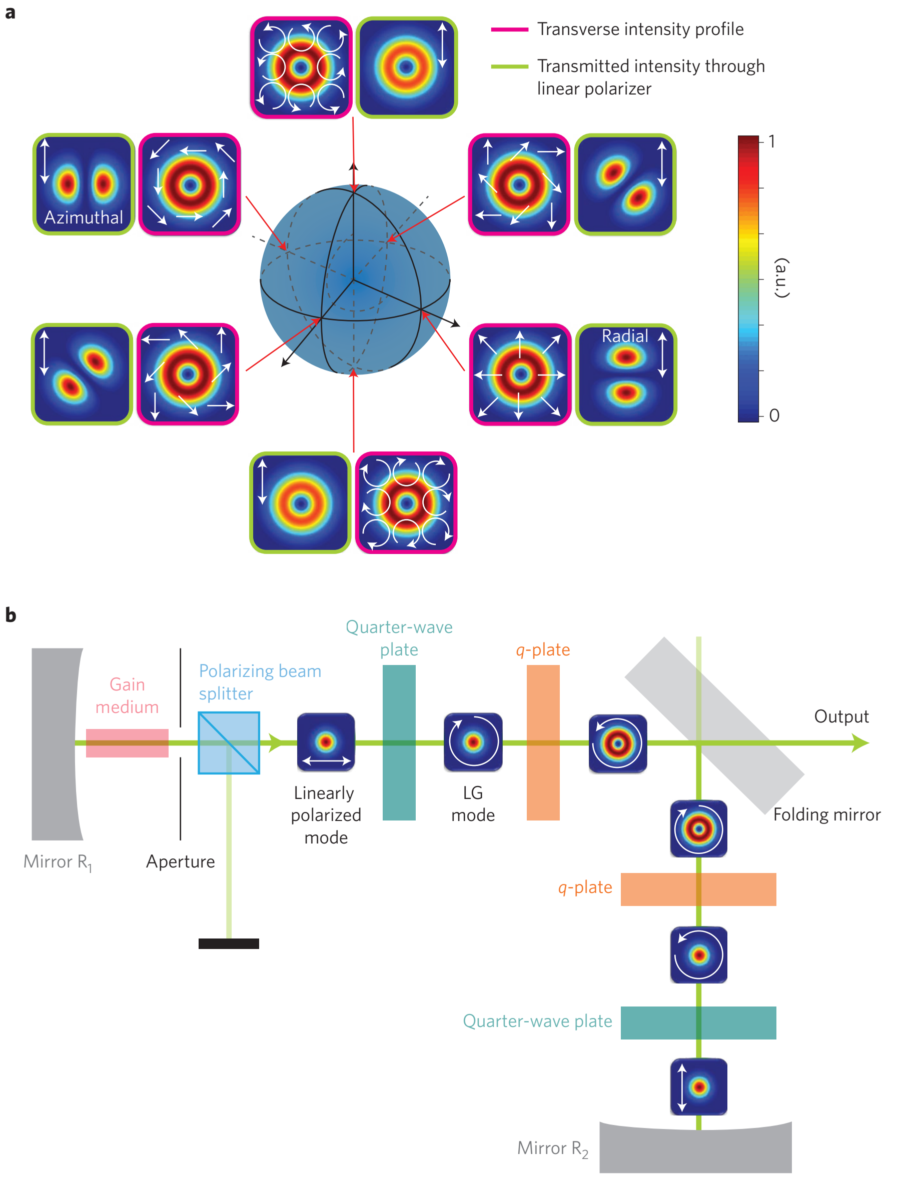

Figure 1 | Higher-order Poincaré sphere laser. **a**, The transverse profiles for distinct LG modes on the higher-order Poincaré sphere all display a central point of zero intensity (white arrows show each beam's polarization). A vertically oriented linear polarizer can be used to distinguish these states. Cylindrical vector beams with radial and azimuthal polarizations are located on the equator. **b**, Conceptual layout of the experiment where mirrors R_1 and R_2 identify the Fabry–Pérot lasing cavity. For a given setting of the *q*-plate, varying the angle of the first quarter-wave plate (QWP) yields different states on the higher-order Poincaré sphere. An additional QWP and a second *q*-plate are necessary to repeat the preparation of the polarization state and of the spatial mode over a cavity round trip. Figure adapted from ref. 1, Nature Publishing Group.

The novelty of the work by Forbes and collaborators is to harness the geometric phase to realize effective mode selection within a lasing cavity. The scheme's black-box nature and its ease of use are its key attractions, and are perhaps best illustrated by an example. In the early days of laser technology, if a physicist, chemist or biologist wanted to measure the fluorescence lifetime of a chemical substance they had to build a bespoke picosecond or femtosecond pulsed laser. Today, turn-key ultrafast laser systems are commercially ubiquitous. As interest in LG modes grows stronger, the higher-order Poincaré sphere laser realized by Forbes and co-workers will allow researchers to take advantage of the spatial degree of freedom of the electromagnetic radiation in a straightforward manner. A good example for these prospects is stimulated emission depletion (STED) microscopy, which relies on LG modes to achieve super-resolved imaging. In a typical commercial STED microscope, LG modes are generated with a spiral phase plate or a segmented half-wave plate that are not part of the light source. Now, the higher-order Poincaré sphere laser may facilitate the development of a more integrated STED solution and, through its access to scalar vortex beams as well as cylindrical vector beams, enable simultaneous STED microscopy and molecular orientation mapping[11].

Additionally, the higher-order Poincaré sphere laser might be applied in future free-space high-speed optical communication systems based on mode-division multiplexing, where multiple spatial modes carry independent data streams over a point-to-point link[6,12]. The direct generation of spatial modes from a single laser cavity could significantly reduce the form factors of such systems, which initially relied on the production and combination of spatial modes with external spatial light modulators and beam splitters. What may be challenging is to devise a strategy that makes it possible to directly modulate the spatial modes of the higher-order Poincaré sphere laser at bit rates comparable with those achieved by present commercial systems — for instance, state-of-the-art vertical-cavity surface-emitting lasers can modulate the intensity of a single spatial mode at 25 Gbit s^{-1}.

For future research, a logical next step might be to integrate a higher-order Poincaré sphere laser with mode-locked ultrafast laser technology. As Forbes and colleagues only slightly modified a standard Fabry–Pérot laser cavity geometry, it may be possible to add a mode-locking element, perhaps in the form of a nonlinear Kerr material that is typically used for picosecond and femtosecond pulsed lasers, near the cavity's back-reflector. This would, however, lead to inevitable chromatic dispersion due to the thickness of the *q*-plate, opening the way to further challenges and ingenious solutions. ❐

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X-RAY IMAGING

Perovskites target X-ray detection

Single crystals of perovskites are currently of interest to help fathom fundamental physical parameters limiting the performance of perovskite-based polycrystalline solar cells. Now, such perovskites offer a technology platform for optoelectronic devices, such as cheap and sensitive X-ray detectors.

Wolfgang Heiss and Christoph Brabec

In the last few years researchers have exploited polycrystalline organic–inorganic hybrid perovskite semiconductors to boost the efficiency of solution-processed thin-film solar cells to values[1,2] that are beaten only by elaborate devices based on single-crystal materials.

X-ray radiation is detected by the conversion of high-energy X-ray photons either into light, by making use of scintillating materials, or directly into an electrical signal, by making use of so-called direct converters. Both approaches have their limitations, at least in pixelated detector arrays. Scintillator-based detector arrays have a limited resolution due to a lateral spread of the scintillated light within the converting layer. In contrast, direct converters, which are generally amorphous or polycrystalline semiconductors, are limited in their time response, causing effects such as ghosting. Perfect direct converters would be single crystals, which are, however, expensive and cannot be grown in arbitrary sizes.

Writing in *Nature Photonics*, Haotong Wei *et al.* now describe the application of perovskite single crystals as X-ray detectors[3], with comparable or even superior properties than those obtained with the established high-vacuum crystal-growth techniques, such as CdZnTe. The high performance of the X-ray detectors is enabled by the recently developed simple and fast solution-based growth methods for perovskite single crystals[4], providing crystals with dimensions up to 2 inches (ref. 5), with extremely low defect densities[6], and long electron–hole diffusion lengths[7]. The methylammonium lead tribromide ($MAPbBr_3$) single-crystal X-ray detectors demonstrated by Wei *et al.* exhibit a record mobility-lifetime product of 1.2×10^{-2} cm^2 V^{-1} and a collection efficiency of 16.4% for irradiation from an X-ray source providing a continuum of photon energies up to 50 keV.

X-ray detectors find applications in various fields, such as medical diagnostics, non-destructive testing of industrial products, and security inspection. These applications rely on the partial transparency of the object of interest for electromagnetic radiation in the energy range between 1 and 120 keV. While the transmissibility in the X-ray spectral region is of utmost importance for all these applications, it represents a serious problem for radiation detection. Thus, X-ray detectors are either bulky in their dimensions, such as gas-chamber detectors, or should consist of materials containing heavy elements, because the X-ray absorbance is proportional to the atomic number of the element to the power of four. The latter condition is fulfilled by typical scintillator materials (for instance CsI and $CdWO_4$) and by polycrystalline