Radially polarized light beams are produced using liquid crystal devices, manipulated with half-waveplates, and detected by vortex sensing gratings.

A great deal of attention has recently been given to the fundamental properties and practical applications of cylindrical vector beams, which have a spatially variant axially symmetric state of polarization. Radial, azimuthal, and spiral polarized beams are particular cases: see Figure 1. Radial polarized beams can produce very small focal spots, or generate longitudinal electric field components upon focalization, and so are of particular interest. Small focal spots improve spatial resolution, for instance, in microscopy.

Radial polarization is the sum of two circularly polarized beams, the first with a left spiral phase pattern (known as a vortex beam of topological charge +1) and the second with the opposite, right, spiral phase pattern (i.e., topological charge -1). As a consequence, the constituent vortex beams generate a ‘singularity’ on the axis, causing the beam to appear dark in the center: see Figure 1. We have been studying how to produce, analyze, and detect such light beams.

A variety of techniques produce radial and azimuthal polarization, including interferometric systems, specially designed subwavelength structures, liquid crystal devices, and inhomogeneous birefringent elements named q-plates. Commercial solutions are available, such as a radial polarization converter and patterned polarizers. We have produced vortex beams using phase-only spatial light modulators, and radically polarized beams using other optical elements, such as radial polarizers and specially designed liquid crystal devices.

Waveplates alter the polarization state of light traveling through them, and we have recently devised some interesting ways to use different combinations of waveplates to manipulate the 2D polarization map of a radically polarized beam. Half-waveplates rotate the polarization plane of linearly polarized light, and we made a polarization rotator (PR) by combining two half-waveplates with an angle $\theta$ between their relative orientations. This combination of two half-waveplates rotates the polarization by $2\theta$, and we used this PR to transform radial polarization into azimuthal polarization (by rotating the polarization by $90^\circ$) or into spiral polarization (by rotating the polarization by $45^\circ$). Other general cylindrical vector beams are generated with other combinations of waveplates.

Radially polarized light is typically detected with a linear polarizer. A dark radial line appears in the azimuthal angle denoting the direction perpendicular to the transmission axis of the analyzer and rotates as the analyzer rotates. However, this simple technique does not detect any additional phase pattern that might destroy the properties of interest of a pure radially polarized beam.

We have proposed a ‘vortex sensing diffraction grating’ to identify the two constituent vortex beams of a radial polarization. The vortex sensing grating is obtained by adding a spiral phase pattern and the phase of a linear blazed grating: see Figure 2. The result is a forked-type phase grating. Next, this phase pattern is transformed to control the relative power of the different diffraction orders. For example, Figure 2 shows the case of a forked binary phase-only pattern quantized to binary values 0 and $\pi$ (black and white in the figure). Here the quantization follows the transition levels of a ‘Dammann’ grating, which is made up of alternating materials with different refraction indices or, as in this case, with a phase-only spatial light modulator with two voltage levels. It diffracts incident light into a field of orders. These transition levels indicate the phase values where the continuous phase pattern is forced to present a phase jump from 0 to $\pi$ radians (or vice versa) in the binary version of the phase mask. It is possible to numerically adjust these transition levels in the Dammann gratings to force a number of diffraction orders with equal intensity.
A bright spot corresponding to a delta function is recovered at the 0th diffraction order. Vortex beams are generated on the ±1st and ±2nd diffracted orders, with topological charges ±1 and ±2, respectively. The Fourier transform field is obtained at the back focal plane of a converging lens placed behind the grating. When focused in the Fourier plane, the vortex beams create doughnut focalizations, with increasing diameter as the absolute value of the topological charge increases. Figure 3 (top right) shows this result. If such a vortex grating is illuminated with a light beam carrying a topological charge, its value and sign are visualized in the Fourier transform plane as the diffraction order index where the bright spot is shifted.

In this way, such a vortex grating tests light beams for true radial polarization. Being the sum of vortex beams with topological charges +1 and −1, such a beam must provide bright spots on ±1 diffraction orders. To differentiate between the two circular polarization components, we used right and left circular polarizer films (RCP and LCP, respectively) placed in front of the detector. Figure 2 shows experimental results. It can be seen that the bright focalization has moved to the +1 diffraction order for one circular component, while it moves to the −1 order for the other component. This verifies that we have produced a pure radially polarized beam.

In conclusion, devices for the generation of radially polarized beams are commercially available. Used in combination with waveplates, they also generate other types of cylindrical vector beams by polarization transformation. We have developed techniques to generate and detect vortex beams, which are suitable for analyzing such vector beams. We believe this is a very promising and exciting field. Vortex beams’ special polarization symmetry gives rise to very interesting properties when focused with high numerical aperture objective lenses, with application in optical trapping and manipulation. Other potential applications include transfer of optical angular momentum, and additional ones are sure to emerge now that we can generate such polarized beams simply and efficiently. For example, we are currently developing image processing systems based on these concepts, to be incorporated into optical microscopes and optical imaging systems.

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**Figure 2.** Combining a spiral phase pattern with the phase of a linear blazed grating results in a forked grating that acts as a ‘vortex sensing diffraction grating’ to identify a radially polarized beam, which is the sum of two circular polarization components.

**Figure 3.** Left: A vortex sensing diffraction grating. Right: Its diffraction pattern under uniform polarization illumination. Black and white denote phases 0 and π, respectively. RCP and LCP denote the diffraction pattern for the right and left circular polarization components. The bright spots on the +1 and −1 orders, respectively, provide a positive detection of a radially polarized beam.
References


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