Azimuthally and radially polarized off-axis lasers

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A large-apex-angle intracavity axicon combined with control of the cavity length enabled production of both azimuthally and radially polarized beams.

Vector laser beams are characterized by having polarizations that vary spatially across the beam. In particular, cylindrical vector beams, in which the polarization has cylindrical symmetry and is singular on the beam axis, have attracted substantial attention because of their potential applications in electron acceleration, laser machining, remote sensing, and singular optics.1 Radially and azimuthally polarized beams are common cylindrical vector beams. The tight-focusing property of radially polarized beams is useful for high-resolution imaging.

Cylindrical vector beams can be generated either passively or actively. Passive methods involve varying the polarization outside the laser cavity, whereas active approaches involve directly producing a suitably polarized laser beam. Since 1972, the typical method for directly generating a radially polarized beam has been to place a Brewster-angle axicon inside a cavity,2 and numerous studies have evaluated this process.3, 4 (Recall, light reflected at Brewster’s angle is perfectly polarized.) Recently, Bisson and coworkers generated radially polarized off-axis laser beams by using an intracavity axicon similar to the Brewster-angle type, and proposed that such beams could provide high levels of energy transfer to metals and plasma heating.4

Brewster-angle axicons are typically unfavorable, however, for generating azimuthally polarized beams because such an axicon in combination with azimuthal polarization yields a reflective loss. By contrast, this Brewster-cut type of interface yields nearly no loss of radial polarization. A large-apex-angle axicon system can overcome the problem of azimuthal polarization being impaired. We propose that a large-apex-angle axicon can be used to attain an off-axis laser that demonstrates either radial or azimuthal polarization depending only on how the cavity length is configured.5 Moreover, the axicon apex can have an arbitrary angle in practice, which is convenient for implementing cylindrical vector beams.

![Figure 1. Geometrical ray-tracing diagram of the hemispherical cavity.](image)

The thicknesses of the axicon and crystal are enlarged to show the ray tracing. When the curved mirror is at position Z₀, the ordinary rays (o-rays) form an azimuthally polarized laser beam. With the mirror at Zₑ, the extraordinary rays (e-rays) form a radially polarized beam. α: Apex angle of the axicon.

To generate an off-axis laser, we chose a hemispherical cavity design from a report by Wu.6 In a typical hemispherical cavity, all oblique rays from the center of the hemisphere are normally incident to a curved mirror, and rays repeat the path after two round trips. Inserting an axicon into the cavity creates a unique oblique path for generating the laser (see Figure 1). Only at that specific oblique incidence at the surface of the axicon does the beam have normal incidence on the curved mirror and thereby satisfy the self-consistency condition of the laser cavity.

Use of a birefringent laser crystal induces distinct paths for the ordinary and extraordinary rays, and distinguishing these rays is the main mechanism by which radially and azimuthally polarized cylindrical vector beams are generated. When the ordinary rays satisfy the self-consistency condition, they form an azimuthally polarized beam as shown in Figure 1. When the curved mirror is tuned to point Zₑ, the extraordinary ray survives instead, forming a radially polarized beam. Thus, the

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large-apex-angle axicon characterizes and stabilizes the generation of off-axis patterns, distinguishing distinct paths between the ordinary and extraordinary rays and forming a specifically polarized beam.

The azimuthally polarized pattern of a c-cut neodymium-doped yttrium vanadate (Nd:YVO\(_4\)) laser under various polarization conditions is shown in Figure 2. In the absence of a polarizing filter, the laser had a multilobe ring pattern: see Figure 2(a). Adding the polarizer caused the part of the pattern parallel to the direction of the polarizer to disappear: see Figure 2(b–d). Consequently, the laser beam was azimuthally polarized. Tuning the output coupler to increase the cavity length caused the polarization to transform from azimuthal to radial. Figure 3 displays the radially polarized pattern, in which the part of the pattern in the direction perpendicular to the polarization angle disappears. The degree of polarization was measured to be 94% ± 3.7% and 95.4% ± 2.6% for the radially and azimuthally polarized beams, respectively. Moreover, when the axicon was moved toward the curved mirror (the output coupler), the pattern transformed from a ring to an arc. Azimuthally and radially polarized arc beams existed for specific cavity lengths. To summarize, the distance between the crystal and the axicon determined the pattern type (ring or arc), and the cavity length determined the type of polarization with these hemispherical cavity configurations.

In summary, radially and azimuthally polarized lasers that comprise off-axis modes can be achieved using a large-apex-angle intracavity axicon in a hemispherical configuration.
References


