The formation of laser beams with pure azimuthal or radial polarization

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Laser resonator configurations for obtaining pure azimuthal and radial polarized beams are presented. They involve the coherent summation, inside the laser resonator, of two orthogonally polarized TEM_{01} modes. Basic principles and experimental results with a Nd:YAG laser are presented. The results include a full space variant polarization measurement and show efficient formation of high-quality azimuthal and radial polarized beams. © *2000 American Institute of Physics.* [S0003-6951(00)01347-4]

The inherent complete symmetry of laser beams that are either azimuthally or radially polarized has lead to their exploitation for improving the trapping and accelerating of particles,[1] as well as material processing,[2] light propagation in hollow fibers,[3] and light focusing with high numerical aperture lenses.[4] Such polarizations have been obtained by combining two linearly polarized laser output beams interferometrically[5,6] or by transmitting a linear polarized laser beam through a twisted nematic liquid crystal.[7] Unfortunately, these methods have relatively low light throughput efficiency or are somewhat cumbersome.

Other methods for obtaining azimuthal or radial polarizations, that potentially could have higher efficiencies, involve the insertion of specially designed elements into the laser resonator. Some have been investigated in the past, but all had certain difficulties. For example, radially polarized beams were obtained with conical elements, that involved difficult, if not impractical, refractive index matching techniques.[8] Complex Brewster-type windows have been proposed for forming azimuthally polarized beams,[9] but such windows are difficult to realize in practice. Polarization selective mirrors were incorporated into high power lasers to form radially polarized beams,[10] but the polarization purity was relatively poor. Also, radially polarized beams were formed by combining a calcite crystal with a telescope configuration,[11] with these the laser had to operate near the instability region, limiting the output power.

Here we present a method for efficiently obtaining essentially pure either azimuthal or radial polarized beam directly from a laser. It is based on the selection and coherent summation of two linearly polarized transverse modes that exists inside the laser resonator; specifically, two orthogonally polarized TEM_{01} modes. The modes are selected by inserting phase elements, which allow for significant mode discrimination, into the laser resonator,[12] and properly combined. In the following we present the needed phase elements and laser resonator configurations, along with experimental results obtained with a Nd:YAG laser.

We begin by considering the scalar field distribution of two TEM_{01} Laguerre–Gaussian modes oriented along the x and y axis, respectively. In cylindrical coordinates, the field distributions of the $TEM_{01(x)}$ and $TEM_{01(y)}$ modes can be expressed by

$$E_{(x)}(r,\theta)=E_0\sqrt{\varrho}\ \exp(-\varrho/2)\cos(\theta),$$
$$E_{(y)}(r,\theta)=E_0\sqrt{\varrho}\ \exp(-\varrho/2)\sin(\theta), \tag{1}$$

where r and θ are the cylindrical coordinates, E_0 the magnitude of the field, $\varrho=2r^2/w^2$ with w as the waist of the Gaussian beam. The coherent summation of such $TEM_{01(x)}$ and $TEM_{01(y)}$ modes, having orthogonal linear polarizations, leads to the formation of either azimuthally or radially polarized mode, whose vectorial field distributions have the form

$$\begin{aligned}\mathbf{E}_{(\theta)}(r,\theta)&=\hat{y}E_{(x)}(r,\theta)-\hat{x}E_{(y)}(r,\theta)\\&=\hat{\theta}E_0\sqrt{\varrho}\exp(-\varrho/2),\\\mathbf{E}_{(r)}(r,\theta)&=\hat{x}E_{(x)}(r,\theta)+\hat{y}E_{(y)}(r,\theta)\\&=\hat{r}E_0\sqrt{\varrho}\ \exp(-\varrho/2),\end{aligned} \tag{2}$$

where $\hat{\theta}$ and $\hat{r}$ are unit vectors in the azimuthal and radial directions, respectively. This coherent summation is illustrated in Fig. 1. Figure 1(a) depicts an azimuthally polarized beam, obtained by a coherent summation of a $\hat{y}$ polarized $TEM_{01(x)}$ mode and an $\hat{x}$ polarized $TEM_{01(y)}$ mode, whereas Fig. 1(b) shows a radially polarized beam, obtained by a coherent summation of an $\hat{x}$ polarized $TEM_{01(x)}$ mode and a $\hat{y}$ polarized $TEM_{01(y)}$ mode.

The laser resonator configuration in which specific transverse modes are selected and coherently summed is schematically shown in Fig. 2. Here, the light propagating inside the laser is split and displaced by means of a birefringent beam displacer to obtain two separate paths whose light is orthogonally polarized with respect to each other. A differently oriented discontinuous phase element (DPE) is inserted in each path, adjacent to the back mirror, to select the TEM_{01} mode.[12] Specifically, we select one of these modes to be $TEM_{01(x)}$, and the other to be $TEM_{01(y)}$. In practice, the two DPEs can be fabricated on the same substrate. In order to add the two modes coherently with the appropriate phase be-

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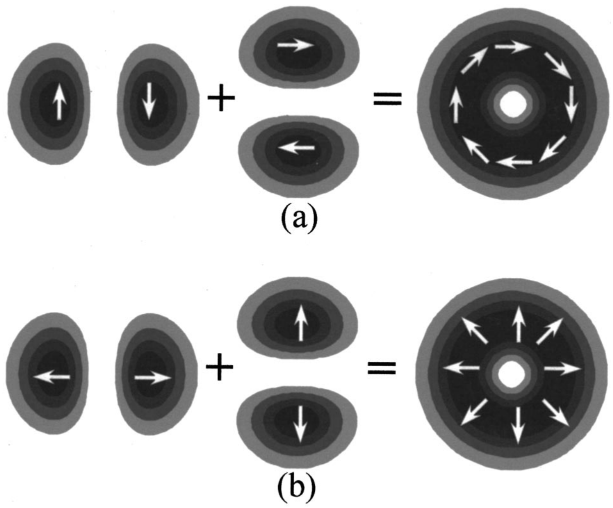

FIG. 1. Coherent superposition of two orthogonally polarized TEM_{01} modes to form azimuthally and radially polarized beams; (a) azimuthally (θ) polarized doughnut beam; (b) radially (r) polarized doughnut beam.

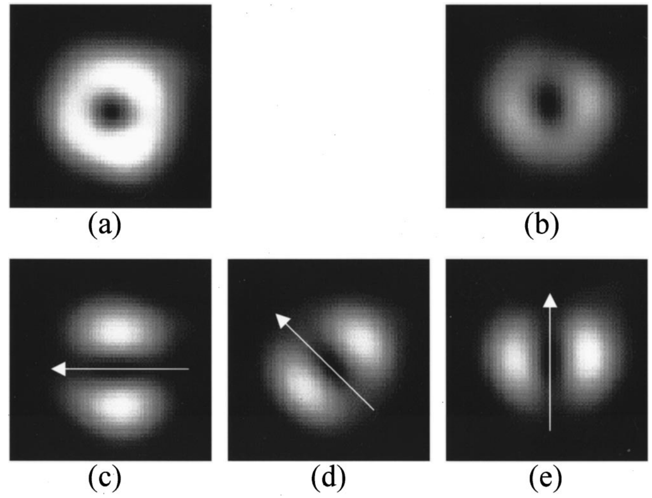

FIG. 3. Experimental intensity distributions of an azimuthally polarized beam that emerge from a Nd:YAG laser; (a) directly from the laser with no external elements; (b) after passing a horizontal $\lambda/4$ plate and a polarizer oriented at 45°; (c) after passing a polarizer oriented in the horizontal direction; (d) after passing a polarizer oriented at 45°; (e) after passing a polarizer oriented in the vertical direction.

tween them, we insert into one of the paths (at the region after separation) an additional aligning plate, so as to control the optical path by slightly tilting of the window. At the back mirror, two spatially separated TEM_{01} modes evolve each with a different linear polarization. However, as results from the coherent summation of these two modes, a circularly symmetric doughnut shaped beam emerges from the output coupler.

To verify our approach, we used a continuous wave lamp-pumped Nd:YAG laser in which we inserted a calcite crystal, as the birefringent beam displacer, two DPEs for selecting the orthogonally polarized TEM_{01} modes, and an alignment plate to adjust the phase between the two orthogonally polarized TEM_{01} modes. The calcite crystal was 4 cm long, so in our configuration the two orthogonally polarized light paths were displaced 4 mm apart. The DPEs were formed by reactive ion etching of fused silica substrates, so as to have phase discontinuities of π. We aligned the phase element to obtain two orthogonal TEM_{01} modes. The alignment plate was simply a flat fused silica window with antireflection layers on both faces. To ensure that the beam emerging from the laser is indeed azimuthally or radially polarized, we passed it through a linear polarizer at 45°, and tilted the alignment plate until the intensity distribution after the polarizer had two lobes perpendicular (for azimuthally polarized) or parallel (for radially polarized) to the polarization direction. This indicated that the orthogonal TEM_{01} modes add coherently.

The results are shown in Figs. 3–5. Figure 3 shows the intensity distributions, detected with a charge-coupled device camera, that emerge from a Nd:YAG laser which emits an azimuthally polarized beam. Figure 3(a) shows near-field intensity distributions of the azimuthally polarized beam, emerging directly from the laser. Here the doughnut shape is clearly evident. In order to determine the polarization of the output beam, we detected four additional intensity distributions, shown in Figs. 3(b)–3(e). Figure 3(b) shows the intensity distribution of the emerging beam after it passes through a quarter wave plate, whose main axis was oriented in the horizontal direction, and a polarizer oriented at 45°. Here, the nearly doughnut-shape intensity distribution (with approximately half the power) indicates that the polarization of the original beam is linear at each point. Figures 3(c)–3(e) show the intensity distributions of the emerging beam from the laser, after it passes a single linear polarizer oriented at different orientations. Figure 3(c) shows the intensity distribution when the polarizer was oriented in the horizontal di-

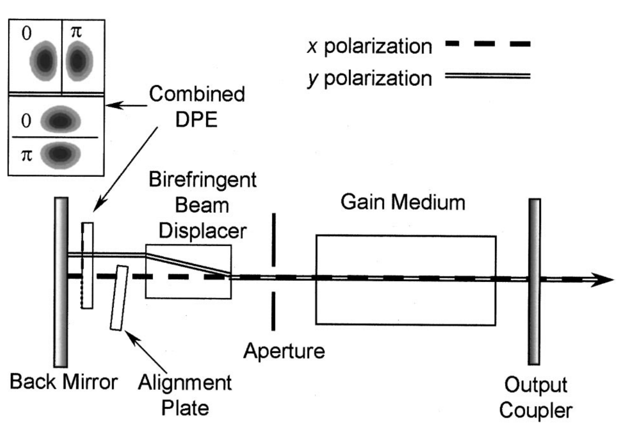

FIG. 2. Laser resonator configuration with a discontinuous phase element (DPE) for forming azimuthally or radially polarized beam.

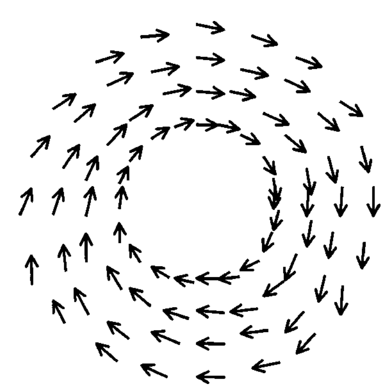

FIG. 4. Experimental plot of the space variant polarization directions of the emerging azimuthally polarized beam.

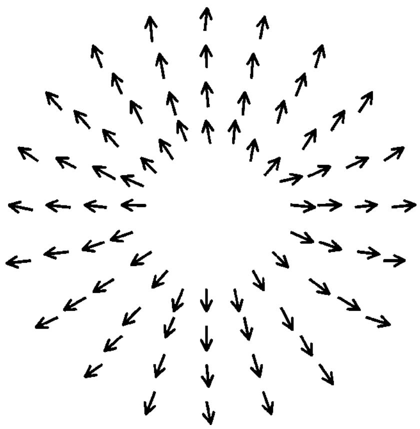

FIG. 5. Experimental plot of the space variant polarization directions of the emerging radially polarized beam.

rection, Fig. 3(d) in the diagonal (45°) direction, and Fig. 3(e) in the vertical direction. At these three orientations, the intensity distributions have two lobes, along a line perpendicular to the polarization direction, as expected for an azimuthally polarized beam.

By measuring the intensities at each point of the distributions in Figs. 3(b)–3(e), we calculated the Stokes parameters S_0, S_1, S_2, S_3 at each point of the beam, from which we deduced the polarization ellipse parameters at each point.[13] The results are presented in Figs. 4 and 5, where the arrows indicate the direction of the main axis of the local polarization ellipse (azimuthal angle ψ), calculated by $\frac{1}{2}\arctan(S_2/S_1)$. We also calculated the average ellipticity angle χ, by $\frac{1}{2}\arcsin(S_3/S_0)$, and the deviation from the desired direction of polarization. Figure 4 shows the experimental polarization orientations for an azimuthally polarized beam. The calculated deviation from the desired polarization orientation was 10°, and the average ellipticity angle was found to be 8°. The overall polarization purity (percentage of power which is azimuthally polarized) was determined to be 95%. As expected with a TEM_{01} mode operation, which exploits more of the laser gain medium than the fundamental Gaussian mode, the output power of our laser with azimuthal polarization was 5.2 W, which is higher by 50% than with the fundamental Gaussian mode. A similar procedure was used to obtain the radially polarized beam, after realigning the mode selecting phase elements. Again we measured the output beam intensity distributions after passing through the various polarizing elements, and obtained the polarization direction in each point. The results, shown in Fig. 5, had a similar polarization purity.

To conclude, we presented a method for efficiently forming azimuthally polarized and radially polarized laser beams, with high polarization purity. The polarization properties were verified with a complete space variant polarization measurement. The output powers of these beams were significantly higher than for a laser operating with the fundamental Gaussian mode. Finally, other polarization states can be obtained by applying higher order modes. These include high order rotational polarization by applying TEM_{0l} modes where $l \geqslant 2$, and azimuthally or radially polarized beams having a few concentric rings with TEM_{p1} modes where $p \geqslant 1$.

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