Laser operation with two orthogonally polarized transverse modes

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Laser resonator configurations, which enable laser operation with two orthogonally polarized transverse modes, are presented. The intensity distributions of these two modes can be chosen to be complementary, so the gain medium can be exploited more efficiently than with a single mode, leading to improved output power. Moreover, the two modes can be combined and efficiently transformed into a single high-quality beam. Basic principles and experimental results with Nd:YAG lasers are presented.

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1. Introduction

In a laser resonator operating with many transverse modes, the emerging output-beam quality is relatively poor. Researchers typically achieve improvement of the beam quality by inserting an aperture inside the resonator in order to reduce the effective radius of the gain medium, until only the fundamental mode of the Gaussian shape exists. Unfortunately, the introduction of the aperture results in a significant reduction of the output power, since only a small volume of the gain medium is exploited.

It is possible to obtain a high-output power together with a good beam quality by operating the laser with a single, high-order mode. Such a high-order mode exploits a relatively large volume of the gain medium, so the output power is relatively high. Moreover, the single high-order mode can be efficiently transformed into a nearly Gaussian beam.[1] Several methods for achieving a single high-order-mode operation have been investigated. These methods include the insertion of an absorbing wire grid or mask inside the laser resonator,[2] the insertion of phase shifting masks,[3] the use of conical resonator mirrors,[4] and phase elements.[5] With all of these methods, the intensity distribution of the single high-order mode inherently consists of some low-intensity regions, so that the utilization of the gain medium is still somewhat inefficient with respect to the multimode operation.

Here we present a novel laser-resonator configuration so the laser operates with two different specific transverse modes. Each of these modes has a different linear polarization and can be manipulated separately. The intensity distributions of the two modes can be chosen to be complementary, i.e. the peaks of the first mode fall on the valleys of the second mode. Thus the gain medium is exploited more efficiently, and the output beam can still be efficiently transformed into a nearly Gaussian beam.

2. Theory

We begin by considering the field distribution of a Laguerre–Gaussian TEM$_{pl}$ mode inside a laser resonator. In cylindrical coordinates, the normalized (e.g., $\iint |E^2(r, \theta)| r dr d\theta = 1$) field distribution $E_{pl}(r, \theta)$ can be expressed by[6]

$$E_{pl}(r, \theta) = \left[\frac{2p!}{\pi(p + l)!(1 + \delta_{0l})}\right]^{1/2} \rho^{l/2} L_p^l(\rho) \times \exp(-\rho/2)\cos(l\theta), \tag{1}$$

where r and θ are the cylindrical coordinates, $\rho = 2r^2/w^2$ with w as the waist of the Gaussian beam, L_p^l are the generalized Laguerre polynomials of order p and index l, and $\delta_{0l} = 1$ for $l = 0$ and $\delta_{0l} = 0$ otherwise. In order to evaluate the overlap between ev-

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Table 1. Mode Overlap Values for Various Laguerre–Gaussian Modes, According to Eq. (2)[a]

	TEM_{00}	TEM_{01}	TEM_{02}	TEM_{03}	TEM_{04}	TEM_{10}	TEM_{20}	TEM_{11}	TEM_{21}	TEM_{01^*}
TEM_{00}	100%	79.1%	63.1%	48.5%	36.8%	73.6%	62.1%	61.4%	53.7%	88.5%
TEM_{01}		63.1%	79.4%	64.5%	54.3%	71.8%	59.6%	48.2%	40.7%	89.8%
TEM_{02}			63.7%	76.6%	66.6%	76.0%	63.5%	67.4%	54.1%	83.7%
TEM_{03}				63.2%	78.3%	77.8%	67.3%	66.7%	57.9%	73.3%
TEM_{04}					62.0%	75.3%	70.5%	67.7%	59.4%	61.1%
TEM_{01^*}						79.9%	66.6%	68.7%	58.1%	100%

[a] Note that the overlap between two similar TEM_{0l} modes is obtained when they are rotated by $\pi/2l$ with respect to each other, so the peaks of one mode fall on the valleys of the other.

ery two modes, we introduce a mode-overlap value, between two modes $TEM_{p_1 l_1}$ and $TEM_{p_2 l_2}$, given by[7]

$$\text{Mode Overlap Value} = \iint |E_{p_1 l_1}(r, \theta) E_{p_2 l_2}(r, \theta)| r \mathrm{d}r \mathrm{d}\theta. \quad (2)$$

Note that the mode-overlap value equals 1 for two equal modes, and 0 for two modes that do not overlap at all. Thus it may be used as a measure to determine which modes are closer in their transverse field distribution. In principle, we would like to operate a laser with two modes that completely fill the gain medium but have the least overlap. Thus the gain medium would be exploited efficiently, with hardly any competition between the two modes. To find the most suitable modes, we calculated the mode-overlap value for various Laguerre–Gaussian modes. The results are summarized in Table 1. The results show that for two high-order TEM_{0l} modes, rotated by $\pi/2l$ with respect to each other (so the peaks of the first mode fall on the valleys of the second mode), the overlap is approximately 63% almost independent of l. A similar overlap value is obtained for the fundamental Gaussian mode and the TEM_{02} mode, whereas the overlap value for a Gaussian and higher-order modes (with $l > 2$), is even smaller.

3. Resonator Configuration

The laser resonator configuration in which two specific transverse modes are selected and how they are combined to form a single output beam is schematically shown in Fig. 1. Here, the resonator is Y-shaped, with an intracavity polarizing beam splitter (PBS) that separates the two orthogonal polarizations into two different paths. In our experiments we used an efficient thin-film polarizer. In each of these paths, there is a mode-selecting element, such as an aperture or a discontinuous phase element (DPE).[5] The two modes are emitted separately from the laser through two output couplers to form two orthogonally polarized output beams. Another, more-compact resonator configuration, in which a bi-

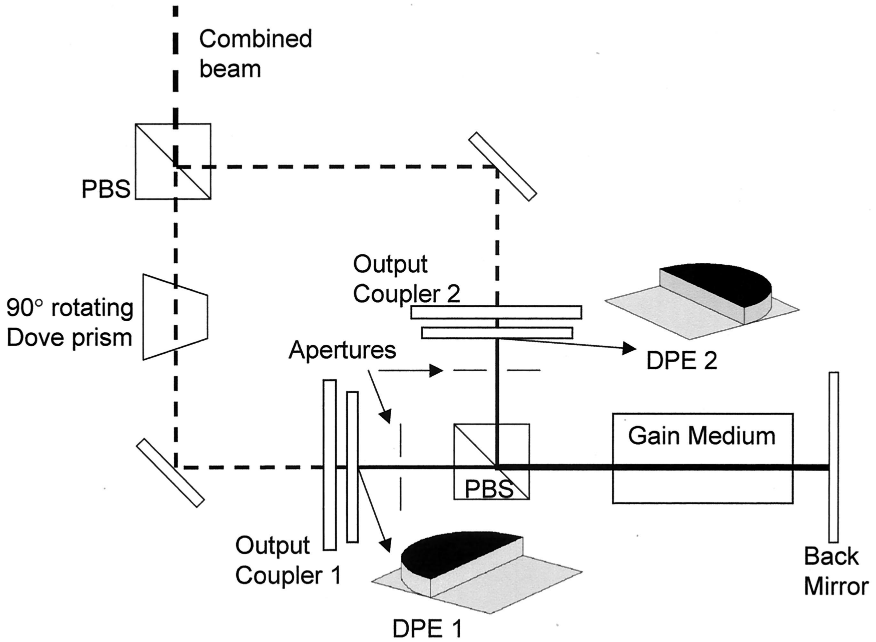

Fig. 1. Schematic resonator configuration for laser operation with two orthogonally polarized transverse modes and an external beam combiner. The modes are selected by intracavity discontinuous phase elements (DPEs) and combined after rotation with a prism. Note that the DPEs shown here are for selecting the $TEM_{01(x)}$ and $TEM_{01(y)}$ modes.

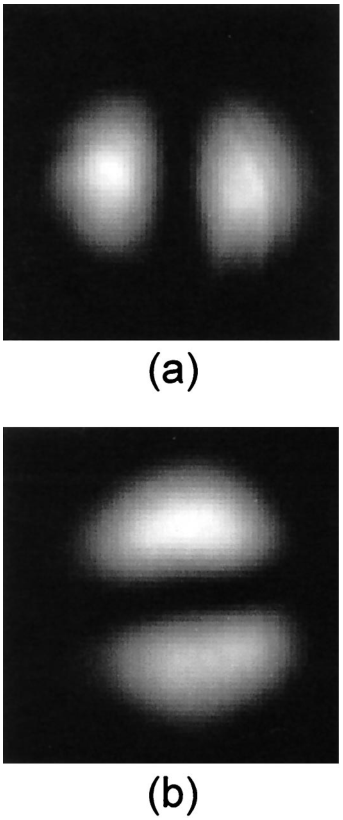

Fig. 2. Experimental near-field intensity distributions that emerge from a Nd:YAG laser in which two DPEs were incorporated to obtain two orthogonally polarized TEM_{01} modes. (a) Vertically polarized $\mathrm{TEM}_{01(x)}$ mode; (b) horizontally polarized $\mathrm{TEM}_{01(y)}$ mode.

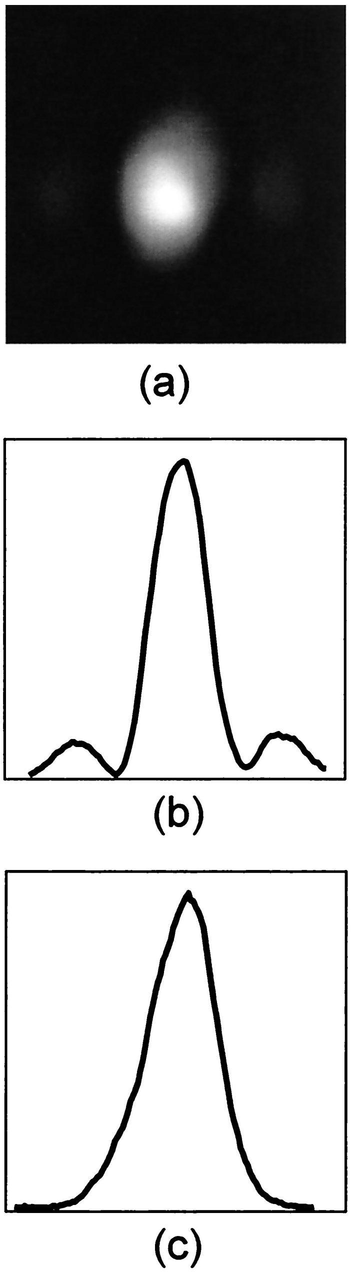

Fig. 3. Experimental intensity distribution and cross sections of the combined beam. (a) Intensity distribution; (b) x cross section; (c) y cross section.

refringent crystal was introduced instead of the polarizing beam splitter, was exploited. However, the manipulation of the intracavity and external beams was simpler with the PBS configuration than with the more-compact configuration. Similar resonator configurations, with different polarizations in different paths, were considered for the reduction of polarization effects and the improvement of the output power in solid-state lasers,[8,9] and for forming either azimuthally polarized or radially polarized laser output beams.[10] Outside the laser resonator, each of the two beams can be manipulated separately. For example, one of the two beams can be rotated to fit the intensity distribution of the other beam. The beams are then combined by another PBS to yield one output beam that is composed of the two orthogonally polarized and exactly overlapping beams.

4. Experimental Results

Using the configuration shown in Fig. 1 we performed two experiments, each with a different set of modes. We used a diode-pumped Nd:YAG gain module (Cutting Edge Optronics model RD-40). The Nd:YAG rod was 116 mm long, its diameter was 4 mm, and it was transversely pumped by five diode bars. The resonator length (from each of the output couplers to the back mirror) was 580 mm, whereas the gain medium was placed 240 mm from the back mirror, and the distances between each of the output couplers to the DPE, the aperture, and the PBS were 1, 60, and 120 mm, respectively. The reflectivity of the output couplers ranged between 85% and 90%.

In one experiment, two TEM_{01} modes, rotated by 90° with respect to each other [denoted $\mathrm{TEM}_{01(x)}$ and $\mathrm{TEM}_{01(y)}$], were selected by two separate DPEs, and their corresponding outputs were combined to form a single beam. This combination yielded an output power of 5.1 W. Here, there appeared to be some mode competition between the two TEM_{01} modes; however, the combined output power was stable up to

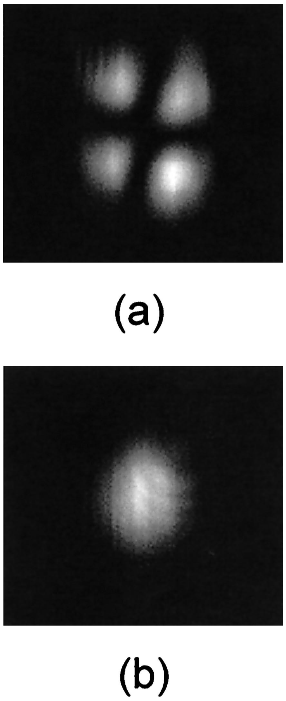

Fig. 4. Experimental near-field intensity distributions that emerge from a Nd:YAG laser in which a DPEs was incorporated in one path to obtain the TEM_{02} mode, and an aperture was inserted in the second path, to obtain the fundamental Gaussian TEM_{00} mode. (a) TEM_{02} mode; (b) TEM_{00} mode.

4%. This combined output power was higher by approximately 20% than a similar, but unpolarized laser, operating with a single TEM_{01} mode (having an output power of 4.3 W). As expected, when there was no rotation by 90°, there was no improvement in the output power, due to the resultant high overlap. The output intensity distributions were detected by means of a CCD camera, and the results are presented in Figs. 2 and 3. Figure 2 shows the near-field intensity distributions of the two TEM_{01} modes, emerging directly from the laser. Each mode has two main lobes, that are in phase,[5] so the resultant far-field intensity distribution should have a high central peak. After one of the output beams was rotated by 90°, by means of a dove prism so as to obtain exact overlap, the two beams were combined with the second PBS, to form a near-field intensity distribution of only two lobes. Finally, the far-field intensity distribution and x and y cross sections are shown in Fig. 3. Effectively, the combined laser output beam can be considered as a single high-order mode, and not as a mixture of two high-order modes (such a mixture exists, for example, in doughnut beams), so it can be efficiently transformed by means of a simple spatial filter, to yield a nearly Gaussian beam.[1]

In the other experiment, a DPE was inserted in one path to select the TEM_{02} mode and only an aperture in the other path to select the fundamental TEM_{00} Gaussian mode. The near-field intensity distributions of the two output beams, resulting from the two modes, are shown in Fig. 4. The combined output power from the laser operating with these two modes was 5.6 W, compared with 3.2 W from a laser operating with the single fundamental TEM_{00} mode and 4.7 W from one operating with the single high-order TEM_{02} mode.

5. Conclusions

We have shown that it is possible to operate a laser with two orthogonally polarized transverse modes so as to efficiently exploit the gain medium. One can select different single high-order modes can be selected by inserting appropriate phase elements into the laser resonator, and by ensuring that the overlap of their intensity distribution is low, it is possible for one to obtain a relatively high output power. Moreover, by manipulating the two beams emerging from the laser operating with two such modes, and properly combining them, one can obtain a single laser output beam that exhibits both high beam quality and high output power. In our experiments, this output power was higher by more than 70% than from a laser operating with a single Gaussian mode, and higher by about 20% than from a laser operating with a single high-order mode. In our experiments the combined output powers were probably limited by some birefringence of the gain medium, and resultant losses from polarization beam splitters. If such birefringence can be reduced, we expect that the combined output power would be increased further.

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