Elliptic-mode cavity for diode-pumped lasers

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A novel laser resonator capable of producing a strongly elliptic TEM_{00} mode in the gain medium is analyzed. Careful design results in an axially symmetric output beam, while the squeezed mode volume in the active medium allows an optimum exploitation of the inversion generated by end pumping the laser with a high-power laser-diode array. When a single array is used, the pump threshold can be typically reduced by an order of magnitude as compared with conventional (circular-mode) end-pumped systems without compromising any other laser characteristics. The combination of the presented cavity design with geometric multiplexing of diode arrays provides an efficient means for scaling end-pumped lasers to high powers.

The recent progress in diode-laser technology has greatly stimulated research efforts in diode-laser-pumped solid-state lasers.[1] End-pumped systems combine the advantages of an extremely compact optical setup with the highest efficiency at low and moderate powers.[2–7] Scaling end-pumped lasers to high powers calls for methods capable of matching the highly asymmetric emission geometry of multistripe diode arrays and bars to the circular mode of the solid-state laser. Line-to-circle converting fiber bundles[3,5] and geometric multiplexing of the astigmatic pump source[4] have been used to meet this requirement. Recently, an elliptic-mode cavity containing anamorphic prisms was constructed to match the cavity mode to the strongly asymmetric pump beam.[7] In this Letter we propose a new resontator design that leads to a strongly elliptic cavity mode in the gain medium without the need for any additional intracavity elements. A folded three-mirror resonator with a cylindrical center mirror has been devised and is shown to improve laser performance significantly compared with that of conventional resonators.

A schematic of our astigmatic cavity is shown in Fig. 1. A cylindrical folding mirror allows the cavity mode to be elliptic at mirror M3 while retaining cylindrical symmetry at the output coupler M1. This arrangement has several advantages over the technique that uses an anamorphic beam expander. First, elimination of intracavity elements considerably reduces cavity losses and results in a more compact optical setup. Second, exact cylindrical symmetry of the output beam and compensation of thermal lensing can be achieved by simply adjusting the length of the short cavity leg (M2–M3) within the stability range. Last, the absence of angular spreading of different wavelength components is an important condition for efficient operation in case the laser is to be mode locked, especially in the subpicosecond and femtosecond time domain.[8]

In an axially asymmetric laser cavity the beam characteristics have to be calculated separately in two orthogonal planes of propagation,[9] in our case the plane of the resonator axis (the y plane) and the folded plane perpendicular to this (the x plane). In a small-spot system of this type, the adjustment of the spacing d_1 between the focusing mirror M2 and the flat mirror M3 is critical, as the cavity is stable only over a small range of d_1 in the vicinity of $d_1 = f$, where f is the focal length of the cylindrical folding mirror.[10] It is therefore convenient to introduce an adjustment measure δ, which is defined by $d_1 = f + \delta$. The stability range[10] of the resonator in the x plane extends from a minimum adjustment value

$$\delta_{\min} = \frac{f^2}{d - R - f} \tag{1a}$$

to a maximum value

$$\delta_{\max} = \frac{f^2}{d - f}, \tag{1b}$$

where d is the spacing between M2 and the spherical output coupling mirror M1 and R is the radius of curvature of M1. The stability condition for the y plane can be written as

$$\delta < R - d - f. \tag{2}$$

Using the imaging rules of Kogelnik[10] and standard formulas for two-mirror cavities,[11] one can readily calculate the spot sizes at M3 (w_{0x}, w_{0y}) and M1 (w_{1x}, w_{1y}). We obtain

$$\frac{\pi w_{0x}^2}{\lambda} = \sqrt{(\delta_{\max} - \delta)(\delta - \delta_{\min})}, \tag{3}$$

$$\frac{\pi w_{0y}^2}{\lambda} = \sqrt{(d + f + \delta)(R - d - f - \delta)}, \tag{4}$$

and

$$\frac{\pi w_{1x}^2}{\lambda} = \frac{R(d - f)}{R - d + f}\sqrt{\frac{\delta_{\max} - \delta}{\delta - \delta_{\min}}}, \tag{5}$$

$$\frac{\pi w_{1y}^2}{\lambda} = R\sqrt{\frac{d + f + \delta}{R - d - f - \delta}}. \tag{6}$$

To achieve a small beam waist in the x plane, where the pump beam is usually diffraction limited, one

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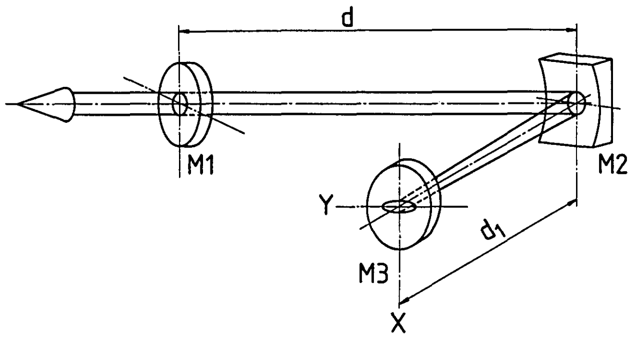

Fig. 1. Folded three-mirror cavity with a cylindrical focusing mirror producing an elliptic TEM_{00} mode at the flat end mirror M3. M1, spherical output coupling mirror with a radius of curvature R; M2, high-reflectivity cylindrical mirror with a focal length f; M3, high-reflectivity flat mirror. The active medium is to be inserted close to M3 in the cavity. A coated backface of the gain medium can replace M3 and result in a more compact optical setup.

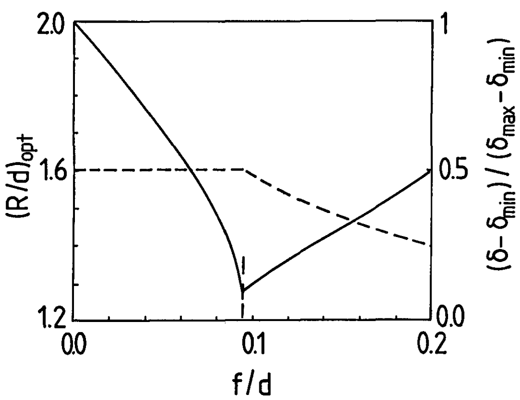

Fig. 2. Optimum value of R/d (solid curve) and the corresponding normalized adjustment parameter (dashed curve) versus f/d for simultaneous fulfillment of the requirements $w_{1x} = w_{1y}$ and $|\delta - \delta_0|$ = minimum.

designs the system with a large spacing $d \gg f$. In order to have an output beam free from astigmatism, we require that $w_{1x} = w_{1y}$. The stability of cavity mode parameters against small variations in d_1 (caused by mechanical perturbations) calls for an adjustment of δ to the middle of the stability range, $\delta = \delta_0$, where $\delta_0 = (\delta_{max} - \delta_{min})/2$. Equations (5) and (6) along with these conditions impose a constraint on the resonator parameters R, d, and f. This constraint leads to a relationship between R/d and f/d, if $\delta_{max} \ll R - d - f$, i.e., δ can be neglected in Eq. (6). The relationship yields the optimum ratio of the output coupler curvature R to the spacing d as a function of f/d, as shown in Fig. 2 (the solid curve). $(R/d)_{opt}$ ensures that the output beam is free from astigmatism when $\delta = \delta_0$. As an interesting feature, $f/d \to 0$ implies that $R/d \to 2$, i.e., optimum resonator design leads to a nearly hemiconfocal resonator in the y plane in case of tight focusing in the x plane. The discontinuity of the first derivative of $(R/d)_{opt}$ with respect to f/d is a consequence of the fact that for $f/d > 0.094$ circular output cannot be achieved with $\delta = \delta_0$. Thus $(R/d)_{opt}$ is obtained by minimizing $|\delta - \delta_0|$ for $f/d > 0.094$. The corresponding value of the normalized adjustment parameter $(\delta - \delta_{min})/(\delta_{max} - \delta_{min})$ is plotted in Fig. 2 (the dashed curve). The cavity tolerates deviations as large as 20% from $(R/d)_{opt}$ in the positive direction with only a small change in the adjustment parameter plotted in Fig. 2, whereas a comparatively small reduction of R/d (with respect to the optimum value) leads to the violation of the stability criterion [relation (2)] in the neighborhood of $f/d = 0.094$, where $(R/d)_{opt}$ is minimum.

It is noteworthy that this cavity design has the potential to reduce both thermal birefringence and thermal lensing, which may severely affect laser performance at high power levels in conventional end-pumped lasers.[12] A squeezed pump volume generally gives rise to a predominantly unidirectional heat flow and thus to an efficient reduction of thermally induced birefringence. Although the influences of thermal lensing on the output beam are generally different in the x and y planes, they can be balanced, i.e., the axial symmetry can be reconstructed by a slight readjustment of δ plotted in Fig. 2.

Figure 3 shows the ellipticity factor $\epsilon = w_{0y}/w_{0x}$ and the confocal parameter $b_x = 2\pi w_{0x}^2/\lambda$ of the cavity mode in the x plane normalized to f versus f/d. If one face of the laser rod is cut at Brewster's angle in the y plane,[7] the plotted values of ϵ are enhanced by a factor approximately equal to the refractive index of the gain medium. For minimum pump threshold, the minimum b_x should be found that still permits the pump beam to be within the cavity mode volume in the x plane. The ellipticity factor ϵ depends on the asymmetry in the beam quality of the diode laser used for pumping. Recently Fan and Sanchez discussed pump source requirements for end-pumped lasers.[13] They introduced an important characteristic of practical semiconductor pump sources, the asymmetry factor $Q = w_{0y}\theta_y/w_{0x}\theta_x$, where w_{0x} and w_{0y} are beam diameters at the diode facet and θ_x and θ_y are far-field divergence angles in the planes perpendicular and parallel to the junction, respectively. The poor spatial coherence of multistripe diode lasers in the plane of junction results in Q values much greater than 1. $Q > 1$ reduces the achievable gain in an end-pumped

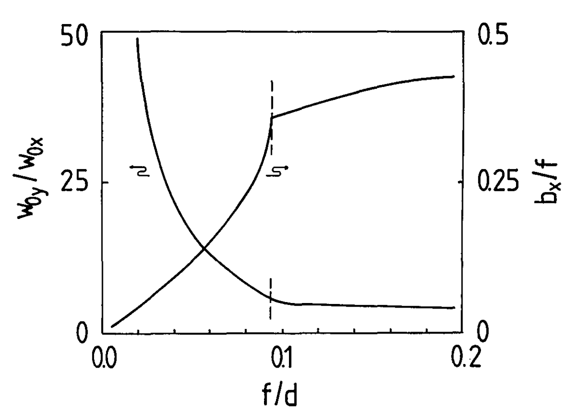

Fig. 3. Ellipticity factor w_{0y}/w_{0x} and normalized confocal b_x/f as a function of f/d.

laser circular cavity mode. To see whether an elliptic mode can improve laser performance, we generalized the results of Ref. 13 for the case of an elliptic cavity mode. The unsaturated single-pass gain takes the form

$$\Gamma \sim \frac{1}{L}\left(\frac{\epsilon^2}{Q}BP\right)^{1/2}, \qquad (7)$$

where $\epsilon^2 \leq Q$ is assumed. L represents the length of the active medium, and B and P are the brightness and the power of the pump source, respectively. For a circular mode ($\epsilon = 1$) the maximum gain attainable in a given end-pumped system is reduced by $\sqrt{Q}$ owing to the asymmetry in the beam quality of the pump source. Γ can be increased by suitable geometric multiplexing of the astigmatic pump source to yield $Q' = Q/N$, where N is the number of the pump lasers employed.[4,13] However, the use of high-power ($P > 1$ W) arrays with $Q > 100$ requires a large number of diodes for a complete compensation of beam asymmetry ($Q' = 1$), which would result in an extreme complexity. By contrast, the combination of the geometric multiplexing technique with the concept of an elliptic-mode cavity allows N to be a free parameter in the design of an end-pumped system, because the gain reduction due to the residual asymmetry of the pump beam can be fully compensated for by proper cavity design, i.e.,

$$\epsilon = \sqrt{Q/N}. \qquad (8)$$

The main steps of the design of such an elliptic-mode end-pumped system can be followed on a practical example. Let us take a 3-W monolithic diode array (Spectra Diode Laboratories SDL-2480) with an emission area of $w_{0x} \times w_{0y} = 1\ \mu m \times 500\ \mu m$ and a beam divergence of $\theta_x \times \theta_y = 20° \times 5°$ for pumping a laser material of 10-mm length. With $Q = 125$ and $N = 1$ we obtain from Eq. (8) $\epsilon = 11.2$. If we make use of Figs. 2 and 3, this implies that $f/d = 0.067$, $b_x/f = 0.17$, and $(R/d)_{opt} = 1.58$. Now we have to find the minimum value of b_x that still ensures that in the x plane the pump beam is inside the cavity mode volume in the active medium. The properly chosen ϵ [Eq. (8)] will then guarantee that this requirement is fulfilled in the y plane as well. In the special case of $N = 1$ the pump beam is diffraction limited in the x plane, and therefore b_x should be chosen such that the average cross-sectional area of the cavity mode is minimum in the laser medium. This is ensured by $b_x \approx L$. Using $b_x = 1$ cm, we obtain $f \approx 6$ cm, $d \approx 88$ cm, and $R \approx 1.4$ m. With this cavity design the unsaturated gain can be increased, and thus the pumping threshold can be reduced by a factor of $\epsilon \approx 11$ as compared with that of a conventional circular-mode laser pumped by the same diode. Note that relations (7) and (8) have been derived by using the same approximations as in Ref. 13, therefore the above numbers represent just a first-order estimate of the optimum resonator parameters. More precise values can be obtained by considering the exact intensity distribution of the pump beam in the laser medium instead of using Eq. (8).

Because of the small number of cavity components, the requirements of low threshold (minimum b_x), high slope efficiency (optimum mode matching by a suitable value of ϵ), and stability (minimum $|\delta - \delta_0|$) fix all the available free parameters. If another requirement constrains one of these parameters (e.g., $f + d$ in the case of mode locking), laser performance must be compromised, but it still may remain superior to that of a conventional resonator.

In conclusion, we have proposed and analyzed a new elliptic-mode laser cavity for solid-state lasers end pumped with diode arrays. We expect that the presented resonator design will result in a significant improvement of the performance of state-of-the-art high-power end-pumped systems.

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