High-Power Diode-Laser-Pumped CW Solid-State Lasers Using Stable–Unstable Resonators

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***Abstract*—We present a novel design for an efficient, high-power (>100 W), continuous-wave (CW) Nd:YAG laser with diffraction-limited performance. It uses a side-pumped, side-cooled, zigzag slab which is incorporated in a stable–unstable resonator that has a variable reflectivity output coupler. A geometric magnification of at least 1.3 in the unstable direction can be achieved. Modeled performance characteristics are presented.**

***Index Terms*—CW solid-state lasers, diode-pumping, single mode, unstable resonators.**

I. Introduction

THERE IS an urgent need for an efficient, high-power continuous-wave (CW), all solid-state laser with excellent beam quality. A particularly demanding application is the laser source for long-baseline gravitational wave interferometers, where single-frequency, single-mode laser power in excess of 100 W is required to be coupled efficiently to a high-finesse Fabry–Perot.

Significant recent improvements in diode-pumped solid-state lasers have been achieved due to a combination of crystal growth techniques, mirror technology, and the advent of high-power laser-diodes. Thus, an output power of 62 W in a single transverse mode (TEM_{00}) has recently been reported for a side-pumped, side-cooled solid-state rod laser using 370 W of pump power [1]. The same authors also reported that the TEM_{00} output power from this type of laser will probably be limited to between 100–150 W due to the strong thermal lensing and birefringence within the laser rod, and that efficiency will probably decrease with increasing output power.

Efficient operation of end-pumped, side-cooled rod lasers has been demonstrated by Tidwell *et al.* [2] who reported a near-diffraction-limited TEM_{00} output power of 60 W using a pump power of 235 W and two rods that were each pumped from both ends. While end-pumped lasers offer highly efficient energy extraction from the gain medium due to good spatial overlap between pump light and the fundamental mode volume, the maximum pump power per rod-end in realistic stable resonators is limited by the thermal fracture strength of the laser material to approximately 50–70 W [3].

Slab gain media can also be used for solid-state lasers. Shine *et al.* [4] employed a side-pumped, side-cooled zigzag slab laser to produce 40-W TEM_{00} output using 212 W of pump power. End pumping has been applied to a slab geometry by Neuenschwander *et al.* [5] who demonstrated operation of a multiple longitudinally pumped slab laser and produced an output of 4.5 W from 16-W pump power.

All of the above work has used stable resonator architectures. To obtain good dynamic stability, the mode size must be small [6]–[8] and the power must be extracted from a relatively small volume of gain medium. Thus, to produce high output powers one must intensely pump this small volume of gain medium and/or increase the length of the gain medium. However, in addition to the potential problem of crystal fracture, intense optical pumping will result in increased thermal birefringence, focusing, and distortion, which will decrease the efficiency and degrade beam quality. Increasing the length of the gain medium will increase the losses per round trip, thereby decreasing efficiency, and may compromise the spatial overlap of the laser mode and pumped region of the gain medium.

Many of the problems cited above can be avoided by changing from stable to unstable resonators. The useful properties of these resonators were first discussed by Siegman [9] in 1965. Since then, they have been used extensively in high-gain chemical and gas lasers [10]–[13], where it has been demonstrated that unstable resonators can simultaneously produce diffraction-limited beams and efficiently extract power from extended-gain media. It has also been shown that in an unstable resonator the beam quality is largely insensitive to changes in the refractive power of a thermal lens as compared to a stable resonator [14], [15]. There has also been considerable effort devoted to understanding the mode structures of these resonators [16], [17]. A particularly useful feature of unstable resonators is that the output coupling fraction depends only on the magnification of the resonator (to be discussed below) and thus the mode size can be adjusted to fill the gain medium by merely increasing the mirror size [18]. Thorough accounts of these resonators are presented by Chodzko *et al.* [19] and Oughstun [20].

Unstable resonators have been used to produce average kilowatt power, flash-lamp-pumped solid-state lasers that have beam–parameter products around 10 mm·mrad [8], [21]–[27]. To our knowledge, they have not been applied to CW solid-state lasers, probably because discrimination against higher order modes and obtaining good beam quality when using hard-edged output couplers, relies on the resonator having

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a large magnification. The gain of solid-state laser media, however, may not be high enough to support the large output coupling fraction associated with these geometric magnifications.

The advent of fiber-coupled high-power laser diodes and variable reflectivity mirrors (VRM's) has encouraged us to reconsider the application of unstable resonators to the production of high-power, diffraction-limited, CW solid-state lasers. The advantages of using laser diodes as pump sources to replace lamp-pumping are well known [28]–[30]—they minimize the heat deposited in the gain medium and thus allow an increase in the small-signal gain while remaining below the crystal fracture limit. Their well-controlled output also minimizes variations in the refractive power of the thermal lens. The slowly-varying reflectivity characteristic of a VRM output coupler avoids edge-diffraction encountered with hard-edged output couplers, hence the magnification needed to produce good mode discrimination and beam quality is reduced, and thus the gain–length product required for oscillation is decreased. Parent *et al.* [31] have demonstrated that the use of a VRM can significantly improve the far-field power density, particularly with low-magnification unstable resonators.

To define the spectral properties of the laser, we would injection lock it using a stable master oscillator [32]–[34]. Thus we choose to pursue a traveling-wave resonator design as this is more efficiently injection locked. Further, injection locking prevents the generation of excess noise associated with free-running unstable resonators [35]. Therefore, the output of the injection-locked high-power slave laser will be a unidirectional single-frequency single-transverse mode with low frequency and intensity noise.

II. Unstable Resonator Architecture

As indicated above, an unstable resonator which incorporates a VRM does not need to have a large magnification to be able to produce a good quality beam [36]. The magnification is instead determined by the required mode discrimination and misalignment sensitivity. Unstable resonators with larger magnifications are less sensitive to misalignment [18].

The power loss per round trip of a mode in an unstable resonator is given by $1 - |\gamma|^2$ where γ is the eigenvalue of the mode [18]. The eigenvalues of the modes in the geometric optical limit for resonators which have rectangular, cylindrical, and strip (unstable in one dimension) architectures are given by [16], [20]

$$\gamma_{mn,\text{rect.}} = \frac{1}{|M|^{n+m+1}}, \qquad m, n = 0, 1, 2, \cdots \tag{1}$$

$$\gamma_{pl,\text{cylind.}} = \frac{1}{|M|^{p+1}}, \qquad p = 0, 1, 2, \cdots \tag{2}$$

$$\gamma_{n,\text{strip}} = \frac{1}{|M|^{n+1/2}}, \qquad n = 0, 1, 2, \cdots \tag{3}$$

where M is the geometric magnification of the unstable resonator, m and n are Cartesian-mode indexes, and p and l are the radial and azimuthal mode indexes, respectively. Note that for a given magnification M, the eigenvalue of a strip resonator is greater than those of rectangular and cylindrical resonators, and thus the lowest loss mode in a strip unstable resonator will suffer less diffractive loss. Alternatively, since the mean reflectivity of the output coupler is given by $\bar{R} = R_0\gamma^2$ [18], where R_0 is the peak reflectivity of the VRM, the mean reflectivity for the lowest order mode in a one-dimensional (1-D) strip architecture is a factor of M larger than for the lowest order mode in a two-dimensional (2-D) architecture. A strip unstable resonator is, therefore, more appropriate for low-gain lasers. It should be noted that the ratio of the eigenvalues for a particular mode and the next higher order mode is equal to M for all architectures, and thus there is no mode discrimination penalty in using the lower loss strip resonator.

Other factors to consider in the choice of laser architecture are the effects of thermal gradients and stresses, the potential to scale the laser to high power, and limits imposed by the thermal-stress-fracture limit of the material. It is well known that the performance of side-pumped rod or cylindrical architectures is limited by thermal lensing, stress-induced biaxial focusing, and birefringence [1], [37]. These effects are much less significant when using a side-pumped slab architecture in which the mode zigzags in the plane of the thermal gradient [38], [39].

The slab architecture is also superior because it is simpler to scale to high powers. Since the width of the pumped gain medium (and thus the width of the mode) in the pump direction is determined by the absorption length for the pump light, the output power can only be increased by increasing the height of the mode, or by increasing the length of the gain medium as discussed earlier. Thus, side-pumped slab or tubular gain media are the preferred architectures for high-power lasers.

Eggleston *et al.* [39] have also shown that the ratio of thermal power per unit length which can be absorbed without fracture by a side-pumped, side-cooled slab to that which can be absorbed by a side-pumped, side-cooled rod is given by

$$\frac{(P_a/l)_{\text{slab}}}{(P_a/l)_{\text{rod}}} = \frac{3}{2\pi}\left(\frac{h}{w}\right) \tag{4}$$

where P_a is the thermal power absorbed by the gain medium, l is the length of the gain medium, and w and h are the width (in the pump direction) and height of the slab, respectively. They conclude that the power-handling capability of a slab is superior to that of a rod if the aspect ratio (h/w) is greater than two.

Thus, the preferred architecture for a scalable high-power CW solid-state laser is a side-pumped side-cooled slab incorporated in a strip unstable resonator. The mode should zigzag in the plane defined by the pump- and laser-mode propagation directions (we will refer to this as the horizontal plane). This will generally result in a laser mode that has a horizontal width comparable to a mode which might be produced in a stable resonator. Thus the resonator could be designed to be stable in the horizontal direction and unstable in the vertical direction. Such an architecture would allow the mode cross section to be scaled in the vertical direction. Since there will only be minimal thermal lensing in this direction, the height of the mode need not vary significantly as it propagates through the gain medium and should thus have good spatial overlap with a pumped gain region of constant height. Further increasing the mode height should not increase the refractive power of either the horizontal or vertical thermal lenses. These features should result in a laser which produces high beam quality and is relatively insensitive to thermal lens variations.

The output of an unstable resonator is affected by the reflectance profile of the VRM output coupler. Two reflectance profiles have been widely used: the super-Gaussian VRM and the parabolic VRM. The super-Gaussian [31], [40]–[42] has a reflectivity profile

$$R(r)_{sg} = R_0 \exp\left[-2\left(\frac{r}{w_m}\right)^n\right] \quad (5)$$

where R_0 is the peak (intensity) reflectivity and n is the order of the super-Gaussian (for $n = 2$ the super-Gaussian becomes a Gaussian, while as $n \rightarrow \infty$ it becomes a top-hat profile). The variable r denotes the radial distance from the center of the VRM and w_m is the characteristic half-width of the reflectivity profile.

The parabolic VRM [43] has a reflectivity profile

$$R(r)_{pa} = \begin{cases} R_0\left(1 - \left(\frac{r}{a_m}\right)^n\right), & -a_m \leq r \leq a_m \\ 0, & \text{elsewhere.} \end{cases} \quad (6)$$

where n is the order of the parabolic distribution and can be either two or four. As before, R_0 is the peak reflectivity of the mirror, r denotes the radial distance from the center of the VRM, and a_m is the characteristic half-width.

The peak reflectivity of a strip unstable resonator should be chosen so that it satisfies the "maximally flat" condition [18]

$$R_0 = \frac{1}{M^{n/2}} \quad (7)$$

so as to produce the most uniform near-field amplitude and the best far-field beam quality while reflecting enough light back into the resonator to sustain efficient oscillation.

For the lowest order mode in an unstable strip resonator, which has an order n super-Gaussian or parabolic VRM that satisfies the maximally flat condition

$$\bar{R} = \frac{R_0}{M} = \frac{1}{M^{\left(1+\frac{n}{2}\right)}}. \quad (8)$$

Equation (8) implies that for a given M, the gain–length product required to support lasing in an unstable strip resonator increases as the order of the VRM increases. That is, n should be small when using a low gain system, as this enables M to be maximized for the optimum $\bar{R}$.

III. Proposed Design

The gain medium is a side-pumped zigzag Nd:YAG slab in which the laser mode enters and exits at Brewster's angle (see Fig. 1) through the same end of the crystal, resulting in a compact laser [44]. This slab architecture has the advantage that it results in a mode that is narrower in the horizontal direction than that produced by conventional zigzag Nd:YAG slab lasers and, thus, has better dynamic stability while maintaining good slope efficiency. The laser in [44] used conductive cooling on the top and bottom of the slab and produced 6.4 W of CW power using 18.3 W of pump power in a standing-wave configuration with a beam quality parameter $M^2 = 1.2$. We have verified efficient operation of that laser in a stable ring resonator and observed that the multimode nature and intensity noise of the free-running laser are suppressed by injection locking [45]. We believe that the efficiency of that laser was limited by nonideal spatial overlap of the TEM_{00} mode and the pumped gain region in the vertical direction. The side-pumped, side-cooled stable–unstable resonator presented here should improve the overlap and thus improve the efficiency.

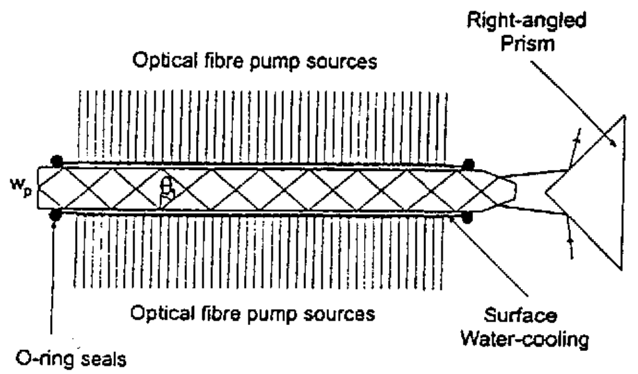

Fig. 1. Schematic diagram of the fiber-coupled laser-diode pumping scheme (top view) showing the zigzag path of the laser mode. w_p is the width of the crystal and θ_i is the TIR bounce angle.

The slab has a width w_p of 3.0 mm, parallel-side length of 32.2 mm, and a total length of 34.7 mm. The bounce angle is $\theta_1 = 50°$, giving 19 total internal reflections (TIR) as shown in Fig. 1. The pumped length l_p and height h_p are determined by the required pump density. The parallel sides of the crystal will be coated with a fluoropolymer, Teflon AF 1600, to prevent wavefront distortion by the cooling water and O-ring water seals [4].

The slab will be pumped from both sides using fiber-coupled laser diodes. Each diode bar is coupled to 24 multimode (275-μm outer diameter) step-index 0.1-NA fibers. Each fiber can supply 625 mW of pump power, giving a total of 15 W per bar. This pumping scheme allows us to arrange the pumping sources to produce a high pump density over an extended gain region without the need for complex focusing optics. In addition, it removes the laser diodes and their temperature control systems from the vicinity of the gain medium, and thus reduces the complexity of the laser *head* [30]. Scalability of this design can be achieved by simply stacking the layers of fibers as shown in Fig. 2. The scalability is predominantly limited by mechanical properties of the crystal and the maximum size of the large aspect ratio Nd:YAG slabs which can be grown and polished by conventional techniques [46] while maintaining low losses and wavefront distortion.

The combination of a small diameter core, low NA, and refraction as the pump light is transmitted through a protective window into the cooling water and then into the Nd:YAG crystal, results in a thin, almost collimated, slice of pumped gain medium being produced by each layer of fibers. If the pump beam passes through a 1-mm sapphire window and then

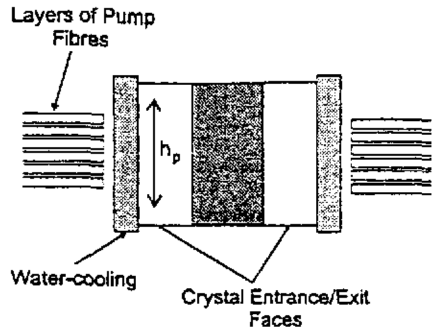

Fig. 2. End view of the pumped slab. h_p is the height of the pumped region in the slab.

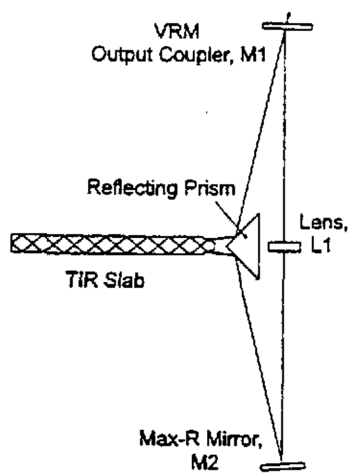

Fig. 3. Resonator configuration. M1 and M2 are separated by 11.5 cm and have radii of curvature of −76.9 and 100 cm, respectively.

2 mm of water, it will have a full width of 0.8 mm at the near face of the slab and 1.1 mm at the far face. The pump density can be adjusted by varying the packing density of the fibers.

To show that the proposed design can support an unstable strip resonator, we will consider a system which has 12 layers of fibers, each layer providing 45 W of pump power (3 bars per layer). If the fibers in each layer are laid side-by-side then $l_p = 20$ mm.

Assuming $M = 1.3$, then for an $n = 2$ super-Gaussian strip VRM output coupler that satisfies the maximally flat criterion, $\bar{R} = 0.59$. For this output coupler to be matched to the resonator, we require that [47]

$$T_{\rm opt} = (\gamma_0 l_g L)^{1/2} - L = 1 - \bar{R} \tag{9}$$

where $T_{\rm opt}$ is the optimum total out-coupling, $\gamma_0 l_g$ is the gain–length product, and L is the total resonator losses excluding output coupling. Assuming that $L = 5.6\%$ (due to the long path length in the gain medium and the 19 TIR's), the required gain–length product can be produced by stacking the layers of fibers so as to produce a pumped region of height $h_p = 3.3$ mm. This height is significantly larger than that produced if the fibers are hexagonally close packed and, as we will show below, larger than the minimum height at which the crystal would fracture.

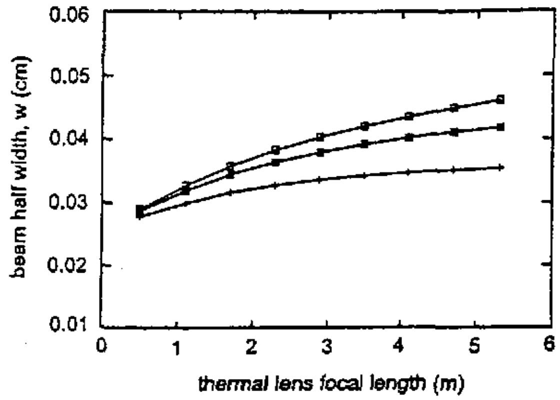

Fig. 4. Plot of dependence of beam half-width at the entrance and exit faces of the slab as a function of the focal length of the horizontal thermal lens for various focal lengths of the mode control lens L1 (mode control lens focal lengths of 0.8 m (+), 2.6 m (∗), and 15 m (□)).

The pump-power per unit length P_p/l_p, which would fracture the crystal is given by [39]

$$\frac{0.24 P_p}{l_p} = 12 R_s \left(\frac{h_p}{w_p}\right) \tag{10}$$

where $R_s = \sigma_{\max} M_s$ is the thermal shock resistance parameter, $\sigma_{\max}$ is the maximum surface stress at fracture, and M_s is a material constant composed of various thermal and elastic constants. Assuming $R_s = 790$ W·m^{-1} then $h_p = 2.0$ mm at the stress fracture limit.[1] Thus, the surface stress in this example is 60% of the stress-fracture limit.

The gain medium described above could be incorporated in either a standing-wave or traveling-wave unstable resonator. We will present here a design for a ring resonator as shown in Fig. 3. The beam leaving the gain medium is reflected by a prism toward the VRM output-coupler M1. The output coupler is a cylindrical convex mirror that has curvature in the vertical plane. Its reflectivity also varies in the vertical plane. The beam reflected from M1 passes through the cylindrical lens L1, which provides mode control in the horizontal (stable) plane. The beam is then recollimated in the vertical plane by mirror M2, a max-R cylindrical concave mirror. Mirrors M1 and M2 form a telescope which provides the required magnification in the vertical plane.

IV. Resonator Modes

A. Horizontal Plane

We have analyzed the proposed resonator to demonstrate that it can produce a stable mode in the horizontal plane which adequately fills the entrance and exit apertures of the Nd:YAG slab and, thus, efficiently couples to the gain medium. In addition to lens L1 there will be a residual horizontal thermal lens in the gain medium, which we model as a thin lens located at the end of the crystal opposite to the entrance and exit faces. Fig. 4 shows how the beam radius at the slab apertures depend on the focal lengths of the thermal lens and L1. As a general rule [48], the beam should fill 60% of the aperture

[1] Litton Airtron SYNOPTICS, Synthetic Crystals and Opt. Products Catalogue, Charlotte, NC: Nd:YAG specifications.

TABLE I
LIST OF PARAMETERS USED IN UNSTABLE RESONATOR CALCULATIONS

Total pump power (W)	540
Intra-cavity loss, L	5.6%
Pathlength in pumped region, l_g (mm)	52.2
Small-signal gain, γ_o (mm^{-1})	0.0743
Magnification, M	1.3
Super-Gaussian output coupler order	2
Optimal total output coupling, T_{opt}	0.41
Output coupler effective reflectivity, $\overline{R}$	0.59
Peak reflectivity, R_o	0.77
Output coupler characteristic half width, w_m (mm)	1.12
Near-field characteristic half width (mm)	1.15

to ensure sufficient discrimination against higher order modes, yet not limit the power in the lowest order mode. Thus, we require a horizontal beam half-width $w = 0.38$ mm, which can be achieved for a range of realistic thermal lenses, as demonstrated in Fig. 4.

B. Vertical Plane

We modeled the resonator using a Fox- and Li-type algorithm using a commercially available computer code which used physical optics within the paraxial approximation.[2] We considered an $n = 2$, $w_m = 1.12$-mm super-Gaussian strip unstable resonator with $M = 1.3$, which is pumped using 12 layers of fibers as discussed in Section III. The vertical magnification of the mode is provided by M1 and M2, which are arranged to produce a near-collimated mode within the gain medium. The magnification factor is 1.3. The characteristic half-width of the VRM was iteratively chosen to ensure the ratio of the characteristic widths of the intra-cavity mode just before the VRM to just after the VRM was equal to 1.3. The peak reflectivity of the VRM was chosen to satisfy the maximally flat condition. The total crystal height was 3.7 mm. The gain region was simulated using a $n = 12$, $w_m = 1.65$-mm super-Gaussian mask. Our model did not include gain saturation. For the readers convenience, we have summarized the salient parameters involved in these calculations in Table I. From this modeling example, we expect that an output power of about 100 W should be achievable.

Figs. 5 and 6 show the calculated near- and far-field intensity and phase profiles. The peak of the near-field intensity distribution is flatter than a Gaussian distribution due to the optimized choice of VRM peak reflectivity. The phase front near the center of the beam is reasonably constant, but starts to vary as the intensity decreases due to higher order modes. The far-field intensity distribution has a single peak as expected, demonstrating the advantage of the VRM compared with a hard-edged output coupler which would usually produce side lobes. Comparing the result in Fig. 6 to the distribution for a Gaussian TEM$_{00}$ mode using an overlap integral, we determined that 98.7% of the power could be coupled into a stable resonator, as used in long-baseline laser interferometric gravitational wave detectors.

[2]PARAXIA Resonator and Optics Programs version 2.0, distributed by SCIOPT Enterprises, San Jose, CA.

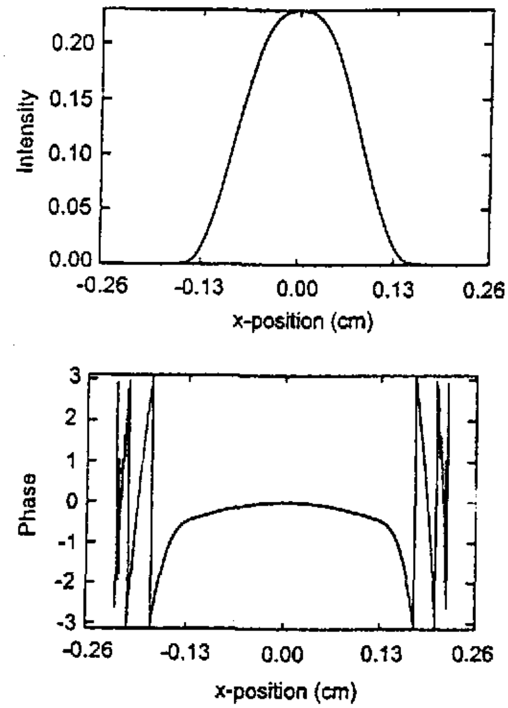

Fig. 5. Plots of near-field intensity and phase profiles (note that the fluctuations in phase near the edge of the profiles is a numerical artifact).

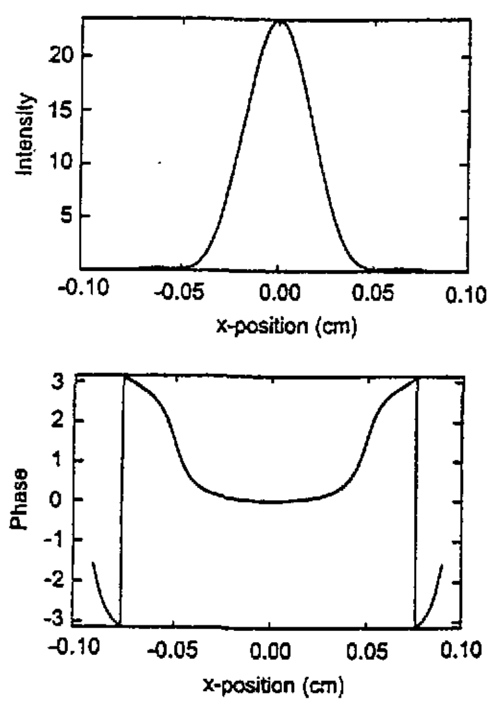

Fig. 6. Plots of far-field intensity and phase profiles.

The shape of the mode in the gain medium is similar to the reflectivity profile of the VRM. It has a characteristic half-width of 0.96 mm, approximately 60% of the height of the gain region. It is commonly believed that low-order VRM's result in poor extraction efficiency because the mode intensity is not