

## Confined propagation and near single-mode laser oscillation in a gain-guided, index antiguided optical fiber

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The authors report laser oscillation in what appears to be a single transverse mode with very large mode area in optical fibers having heavily Nd-doped 100  $\mu\text{m}$  diameter cores with refractive index significantly lower in the core than in the surrounding cladding. Since fibers of this type cannot support conventional index-guided modes, their results appear to confirm a recent analysis which predicts gain-guided single-mode propagation in index antiguided fibers, provided the gain coefficient in the core exceeds a threshold value. Fibers of this type may be of significant interest for amplifiers and oscillators having large power outputs and/or small nonlinear pulse distortion.

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Conventional index-guided optical fibers generally have a larger index of refraction within the core region than in the surrounding cladding, and this condition is generally viewed as essential for guided-wave propagation within such a fiber. The alternative concept of “gain guiding” (GG), either in combination with or as a substitute for “index guiding,” has also long been known in other structures, such as gain-guided stripes in semiconductor diodes and complex Gaussian or parabolic ducts.<sup>1,2</sup> The general case of a cylindrical step-profile optical fiber having both index steps (either positive or negative in sign) combined with a similar gain step across the fiber core was also recently analyzed by one of us, leading to the predictions summarized in Fig. 1.<sup>3</sup>

The presence of laser gain with a linear power gain coefficient  $g$  creates in effect an imaginary-valued refractive index component that must be added to the real refractive index step  $\Delta n$  within the core region of such a fiber. The real and imaginary parts of this complex-valued index step can then be expressed in the dimensionless forms

$$\Delta N \equiv (2\pi a/\lambda_0)^2 2n_0 \Delta n, \quad (1)$$

$$G \equiv (2\pi a/\lambda_0)^2 (n_0 \lambda_0 / 2\pi) g, \quad (2)$$

where  $2a$  is the diameter of the fiber core,  $\lambda_0$  is the free-space wavelength of the guided radiation, and  $n_0$  is the background refractive index of the core and cladding. With these definitions the conventional fiber  $V$  parameter takes on the complex-valued form<sup>4</sup>

$$\tilde{V}^2 = \Delta N + jG. \quad (3)$$

Figure 1 then indicates the regions in the  $(\Delta N, G)$  or complex  $\tilde{V}^2$  plane in which confined guided-wave propagation in the fiber can occur. Modes having LP01 or LP11 character but with complex-valued Bessel function arguments occur everywhere in the regions above the two solid boundary lines in the diagram. Conventional index-guided propagation without

gain occurs along the positive real axis, with LP01 mode propagation starting at the origin, joined by LP11 mode propagation beyond  $\Delta N \approx 5.78$ . Purely gain-guided propagation, with  $\Delta n$  and  $\Delta N = 0$ , occurs along the vertical axis, with an LP01-like mode occurring for  $G \geq 1.86$  and an LP11-like mode turning on at  $G \geq 5.19$ .

Of primary interest here is the region extending indefinitely to the left in the upper left quadrant of Fig. 1, in which the core index step is negative, i.e.,  $\Delta n$  and  $\Delta N < 0$ . The fiber is therefore index antiguiding (IAG) in this region, so that normal index-guided-wave propagation cannot occur. Figure 1 predicts, however, that if the parameter  $G$  becomes sufficiently positive, effective single-mode gain guiding can occur. The full analysis predicts that fibers falling in these propagation regions will support confined LP01- and LP11-like complex-Bessel-function propagating modes very similar to the index-guided modes in a conventional fiber, provided a sufficiently large gain coefficient  $g$  or a sufficiently large  $G$  value can be created in the core. Across this region such propagation turns on for values of  $G$  somewhat greater than  $\approx 2.5$  and then remains single mode, but with increasingly larger core filling factors as shown by the dashed lines

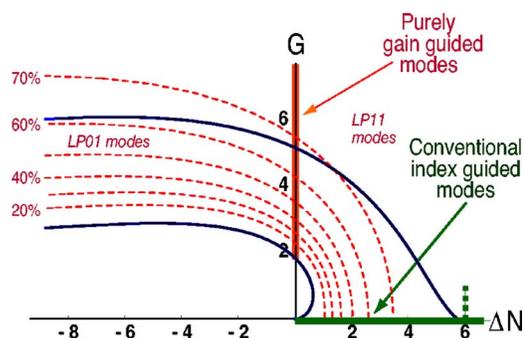


FIG. 1. (Color online) Propagation regions for the modes of an optical fiber in the complex  $V$ -squared plane. Modes of LP01 and LP11 characters exist everywhere above the two solid boundary lines in the figure. The dashed lines indicate contours of constant filling factor for the LP01 mode.

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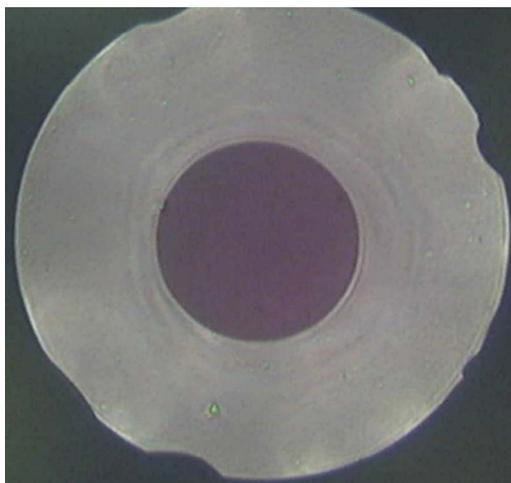


FIG. 2. (Color online) Photograph of the polished output face of an experimental Nd:phosphate fiber with a  $250\ \mu\text{m}$  outer diameter and a  $100\ \mu\text{m}$  diameter 10% Nd-doped core having an  $\approx 0.35\%$  lower index than in the cladding.

in the figure, up to values of  $G$  two to three times larger.

The gain-guiding effect predicted here is quite weak, since a (fairly large) gain coefficient of  $g=1\ \text{cm}^{-1} \approx 4\ \text{dB/cm}$  corresponds to an imaginary index of only  $\sim 10^{-5}$ . Nonetheless, the prediction is that this effect can still provide single transverse mode operation over a wide range of parameters in fiber lasers with very large diameter cores, e.g.,  $2a \geq 100\ \mu\text{m}$ . This behavior moreover only depends weakly on the negative index parameter  $\Delta N$  across the entire region shown, indicating that thermal index changes (a recurring cause of difficulty in conventional fiber lasers) may have little deleterious effect in the IAG region.

We report in this letter recent experimental confirmation of this interesting type of GG+IAG fiber propagation, as demonstrated by the observation of apparently single transverse mode, purely gain-guided laser oscillation in a step-profile optical fiber with a  $100\ \mu\text{m}$  diameter core in which the core index of refraction is  $\approx 0.35\%$  lower than the cladding index. Figure 2 shows the backlit end face of one of these fibers. This fiber was drawn at Clemson University from a “rod and tube” preform prepared by Kigre Incorporated using their Q100 laser glass, and the fiber laser experiments were carried out at CREOL. The index of refraction of the starting material as measured by Kigre at  $590\ \text{nm}$  was  $1.5734$  in the undoped cladding region and was  $1.5689$ , or  $\sim 0.35\%$  lower, for the 10% Nd-doped core. The core-to-cladding index difference at the operating wavelength of  $1.06\ \mu\text{m}$  can be expected to be of comparable magnitude.

Our calculations indicate that sufficient gain should be produced to reach the threshold for gain guiding when a fiber of this type is excited with a few watts of pump power per centimeter or less. Fibers of this type should thus be entirely suitable for diode laser pumping, although the large antiguiding core, the heavy doping, and in general the short length of such lasers may require some changes from conventional diode-pumped fiber laser designs. Suitable pump diodes for this purpose were, however, not immediately available to us. As a temporary substitute we turned therefore to flashlamp pumping (historically the technique used in the first fiber laser devices).<sup>5</sup> A diffuse flashlamp pump cavity originally used to pump solid-state laser rods was modified to hold 12–15 cm lengths of this fiber inside a capillary tube, with a

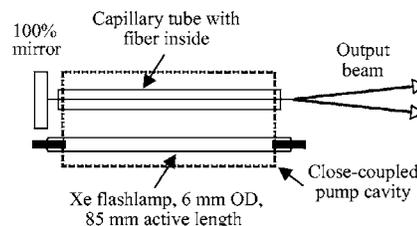


FIG. 3. Flashlamp pump cavity used for experimental tests. The pump cavity and the internal portion of the flashlamp are approximately 10 cm in length; the distance between the tips of the flashlamp electrodes is approximately 85 mm.

contacted 100% mirror at one end of the fiber and a polished but uncoated face at the output end shown in Fig. 3. This arrangement means that a centimeter or two of the fiber was left unpumped or only partially pumped in the end segments where the capillary and fiber extended through the end walls of the pump cavity.

Figure 4 shows the output pulse energy from the output end of one such fiber as a function of flashlamp input energy. This plot demonstrates a clear-cut threshold for laser action at approximately 50 J input and a linear increase in output beyond this point. Later experiments with improved fibers have shown threshold values as low as 33 J. Observations of the output spectrum from the fiber show that above threshold the spectrum is located at the center of the 1052 nm gain line of the Nd ions and is a single peak to within the resolution limit of our spectrometer. Time-resolved measurements of the output signal show clear-cut relaxation oscillations at rates characteristic of Nd lasers. All of these observations are distinctive signatures of laser oscillation and are observed only when the 100% mirror on the back end of the fiber is aligned perpendicular to the fiber axis. Calibrating the optical pumping energy actually delivered to the fiber in this setup is not readily possible, but even a very rough geometrical estimate of the energy transfer from the lamp to the fiber suggests that these fibers may be lasing with quite significant efficiency with respect to the absorbed pump light.

Finally, Fig. 5 shows a typical beam profile of the output beam as observed 15 cm from the output face of the fiber. Beam profiles measured at this and other distances display similarly clean, Gaussian-like, and apparently single-mode profiles in all cases. Of particular importance, we observe with no visible changes in the appearance of these beam profiles from threshold up to as much as 2.5 times threshold.

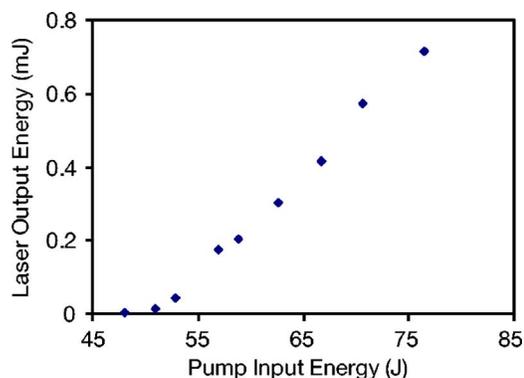


FIG. 4. (Color online) Laser output energy vs flashlamp input energy for one of the fiber samples tested, showing a sharp laser threshold at a flashlamp input energy of  $\approx 50\ \text{J}$ .

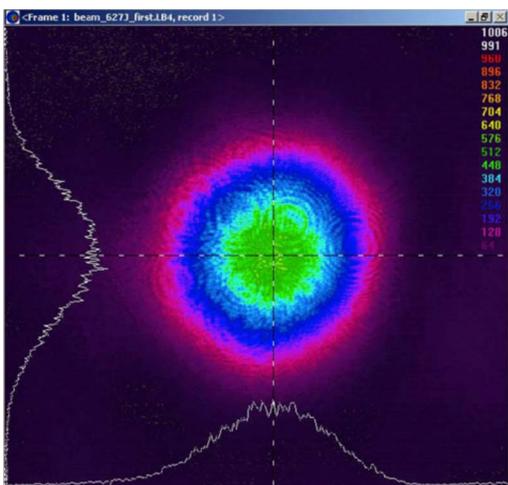


FIG. 5. (Color online) Typical far-field intensity profile for the output beam from the fiber output face.

We interpret this as evidence for unusually good single transverse mode selection in this fiber. From an initial very rough measurement we can only confirm that the output beam has a value of  $M^2 \leq 2$ , but we expect that an improved measurement may yield a value significantly closer to unity.

We believe that this GG+IAG type of fiber operation can very likely be extended to even larger core diameters

with similar performance characteristics. If so, fiber lasers employing this type of propagation, combined with suitably designed diode laser pumping, appear very promising for large mode area diode-pumped fiber lasers having a wide range of stable single transverse mode operation. Fiber lasers of this type, operating either as amplifiers or oscillators, may become useful for generating large single-mode cw powers or for generation or amplification of ultrashort pulses with high peak powers and greatly reduced nonlinear pulse distortion effects.

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<sup>1</sup>W. Streifer, R. D. Burnham, and D. R. Scifres, *IEEE J. Quantum Electron.* **QE-18**, 856 (1982).

<sup>2</sup>L. W. Casperson, *J. Opt. Soc. Am.* **66**, 1373 (1976).

<sup>3</sup>A. E. Siegman, *J. Opt. Soc. Am. A* **20**, 1617 (2003).

<sup>4</sup>B. E. A. Saleh and M. Teich, *Fundamentals of Photonics* (Wiley, New York, 1991), p. 279–280.

<sup>5</sup>E. Snitzer, *Phys. Rev. Lett.* **7**, 444 (1961).