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Yb^{3+}-doped 200 μm diameter core, gain guided index-antiguided fiber

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Abstract The lasing in an end-pumped gain guided index-antiguided (GG-IAG) Yb^{3+}-doped silicate glass fiber with a 200 μm diameter core is demonstrated. Laser beams with similar beam propagation factors M^2 and mode field diameters W_0 (>160 μm) were observed at the output end of the GG-IAG fibers under different pump powers, which indicated that single mode behavior and excellent beam quality were achieved during propagation. Furthermore, the laser amplifier characteristics in the present Yb^{3+}-doped GG-IAG fiber were also evaluated.

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1 Introduction

The laser was one of the greatest inventions in last century. However, applications of lasers were limited due to their complexity and high costs of production. Fortunately, with the advent of fiber lasers [1], many of these limitations have been bypassed; and with the fiber lasers' superior efficiency, robustness, thermal management, integrability, beam quality (single mode), and lower cost of production, a new generation of lasers were introduced. Conventional single mode fibers with smaller core sizes were able to maintain outstanding beam qualities during light propagation over long distances; however, they also suffer large nonlinear effects and optical damage under high pump power conditions. Large mode area fibers [2] and photonic crystal fibers [3] with core sizes up to 100 μm were then designed to solve this problem. However, near diffraction limited beam quality was difficult to maintain when the core size was beyond this core diameter. Therefore, fibers with high power stability and a large core size were desirable.

In 2003, Siegman proposed the concept of gain guided index-antiguided (GG-IAG) [4]. On the basis of the GG-IAG idea, core sizes can be increased over 100 μm while still allowing for single mode laser operation in a GG-IAG fiber. Compared to conventional index guiding fibers, GG-IAG fibers are optical fibers with cores that have a lower refractive index than that of the surrounding claddings and thus do not rely on total internal reflection to confine light to the core. However, light in the core, which can leak out to the cladding, can be compensated by signal amplification due to gain present in the core (i.e. gain guiding). The gain guiding effect in a GG-IAG fiber can be described as reshaping the mode profile and confining the field in the core reign. Recently, Sudesh et al. [5] obtained single mode laser action in an Nd^{3+}-doped phosphate glass GG-IAG fiber with a 200 μm diameter core.

Due to their advantages over conventional fibers, GG-IAG fibers show great potential in laser applications, especially in the fiber-based inertial fusion laser driver [6], which needs an Yb^{3+}-doped glass fiber with a core diameter over 100 μm, while maintaining single mode behavior. However, no detailed studies of lasers with Yb^{3+}-doped GG-IAG fibers were reported so far. In this paper, experimental evidence for the propagation of a single transverse mode in an Yb^{3+}-doped GG-IAG fiber with a 200 μm diameter core whose index of refraction is ≈0.06% lower than that of the

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cladding and the laser amplifying characteristics of Yb^{3+}-doped GG-IAG fiber for the first time are presented.

2 Experiments and discussion

The GG-IAG fiber without coating was drawn from a preform prepared by State Key Laboratory of Transient Optics and Photonics, Xi'an Institute of Optics and Procession Mechanics. The refractive indexes of the core and undoped cladding materials measured at 589.3 nm were 1.57224 and 1.57318, respectively. The core diameter of the fiber was 200 μm, and the diameters of the inner and outer claddings were 400 and 450 μm, respectively. It should be noted that fibers of this type are difficult to cut with fiber cleavers; thus, the end face of the fiber was not well polished, as shown in Fig. 1.

To investigate the laser amplifier characteristics of the present GG-IAG fiber, a diode pumped laser experimental setup (as shown in Fig. 2) was built. A 120 mm long GG-IAG fiber acting as a laser amplifier was end-pumped by a fiber-coupled ~8 W laser diode, which emitted at 976 nm. The delivery fiber core with a diameter of 125 μm has a numerical aperture (NA) of 0.22. The pump light was free-space coupled with the aspheric lenses (Lens 1 and Lens 2) and produced a spot of 280 μm diameter on the end of the fiber. Since the end face of GG-IAG fiber was not well polished, ~70% of the pump light was lost due to scattering. This means that ~30% energy was coupled into the core of the fiber. The signal light at 1040 nm was focused and injected with a spot diameter of 160 μm on the other side of the fiber by two identical microscope objective lenses (Lens 3 and Lens 4), which worked as a coupler. The amplified signal light was collimated by Lens 2 and reflected to the power detector (Spectra-physics model 407 A, Newport) by a dichroic mirror (HR at 1 μm, HT at 980 nm). At the same time, an auxiliary waist, which can be used to evaluate the beam propagation factor M^2 of the beam by substituting a beam propagation analyzer (M2200S-FW, Ophir-spiciron Inc, USA) for the power detector was produced.

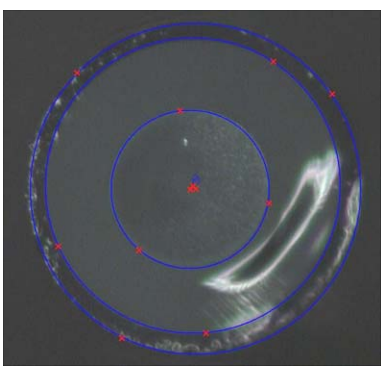

Fig. 1 Photograph of the non-polished output face of an experimental Yb^{3+}-doped fiber. The core, inner and outer claddings were separated by blue rings

According to Siegman [4], the propagating mode in a step-profile fiber can be characterized in terms of two dimensionless indexes and gain parameters ΔN and G: the real and imaginary parts of the V squared parameter. According to reference [5], the value of ΔN for the present GG-IAG fiber was calculated to be -1078, indicating that the anti-index guiding effect in the present fiber is so strong that the propagation of the single mode laser was confined in the core and was not scattered by the gain guiding effect [7]. However, the gain guiding effect also played a very important role in the reshaping and trapping of the mode profile in the core reign. The threshold gain parameters G of the two lowest-order modes, namely LP_{01} and LP_{11}, can be calculated on the basis of reference [5] and the values of G_{01} and G_{11} were estimated to be 0.352 and 0.894, respectively. Since the gain saturation took place when the LP_{01} mode first oscillated, the gain was depleted and only the lowest-order mode was confined in the fiber. In reference [5], it can be seen that the value of the gain coefficient threshold for the LP_{01} mode g_{01} is inversely proportional to the cube of the core radius. This indicates that an increase in core diameter will significantly reduce the threshold for the propagation of the LP_{01} mode.

With the present data, the value of g_{01} was estimated to be 0.0289 cm^{-1}. Since the cross section of Yb^{3+} in the present silicate glass is 4.264×10^{-19} cm^2, the inversion population density at the lasing threshold for the LP_{01} mode

Fig. 2 Experimental setup for laser amplifier and beam quality tests

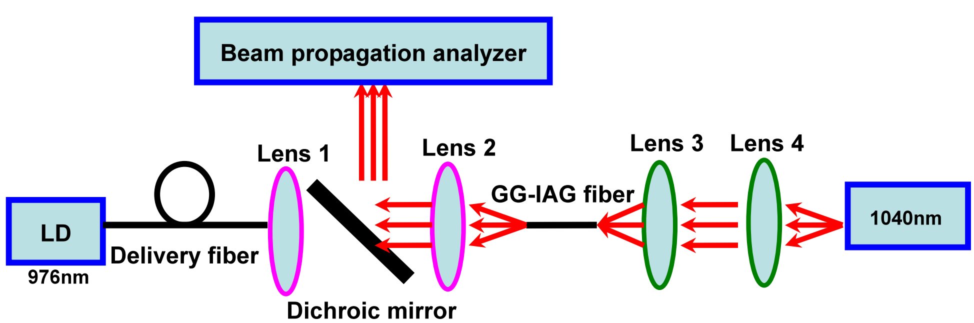

Table 1 Some parameters of beam propagation with different pump energy

Pump power (W)	Output power (mW)	Measurement directs	M^2	Beam waist ω_0 (mm)
3.5	20	Horizontal	2.943	1.776
		Vertical	2.814	1.836
6.5	26	Horizontal	2.951	1.794
		Vertical	2.823	1.819

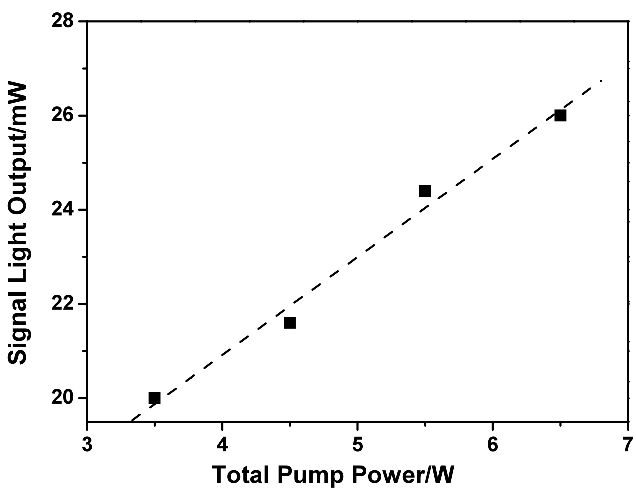

Fig. 3 Signal light output versus total pump power

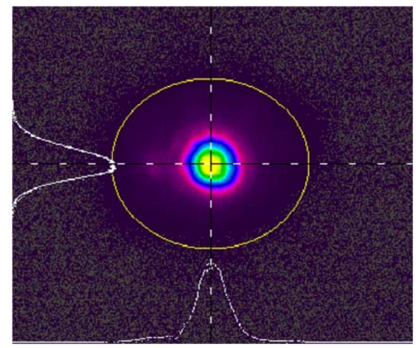

Fig. 4 Mode pattern of signal light

of the GG-IAG fiber is 3.61×10^{17} cm^{-3}. From the dimension of the gain reign of the fiber and the threshold of the inversion population density, the number of excited ions at the threshold was found to be $\sim 1.36 \times 10^{15}$. For an Yb^{3+}-doped fiber, the pump source operates near 980 nm. Thus, we obtained a total absorption of 277×10^{-6} J during one fluorescent lifetime, which is 2.36 ms for the present Yb^{3+}-doped silicate glass. This implies that a pump power of 117 mW is needed to produce such numbers of excited ions at the lasing threshold in the present experimental situation, assuming no other losses in the fiber. However, the experimental pump power is higher than 117 mW, because the end face of the fiber was not well polished.

Measurements of the performances of the GG-IAG fibers on laser amplifier characteristics were carried out at different pump powers, while maintaining a constant signal power (16 mW). The output power as a function of the total pump power is plotted in Fig. 3. Due to the poor end face of the GGIAG Yb fiber, we think that the experimental pump power is greater than 117 mW; thus in this experiment, the pumping threshold is not taken into account and the fiber is end-pumped under higher power. It is seen in Fig. 3 that the signal light at 1040 nm was amplified to 20 mW with 3.5 W pump power in the present Yb^{3+}-doped GG-IAG fiber, and that the output power increased proportionally with increasing pump power. Moreover, no significant variations of the M^2 values (listed in Table 1) in both horizontal and vertical directions were observed, which indicates that the output light is of good beam quality [8].

It is well known that the efficiency of a fiber laser is strongly dependent on the coupling of the pump light from the pump core or the inner cladding to the laser core. In GGIAG Yb fibers with circular pump cores and negative refractive index profiles between cores and claddings, the pump light is only partly absorbed. To improve the pump absorption and subsequently increase the optical efficiency of the GGIAG Yb fibers, fiber designs have to be developed in order to prevent the propagation of helical rays. This can be done by using the asymmetric structure of pump cores to hold back the propagation of helical rays. Rectangular and D-shaped pumping-core cross sections enforce a chaotic spreading of the pump radiation and ensure that the pump light coupled into the pump core crosses the laser core during propagation. In future works, asymmetric structures of pump cores or inner claddings, such as D-shaped and rectangular or eccentricity-based ones, will be developed in GGIAG Yb fibers by our group.

The mode pattern of output light with maximum pump power (6.5 W) is depicted in Fig. 4. It can be seen that the mode profile in the core reign is much better than that of the inner cladding, which demonstrates the single mode behavior of the light. This result is in good agreement with the prediction that oscillations of the lowest-order mode in a GG-IAG fiber deplete the gain, so that higher-order modes cannot oscillate. Therefore, we believe that a much better mode pattern will be obtained when the scattering loss, caused by the poor quality of the end faces of the fibers, is eliminated.

3 Conclusion

We have experimentally demonstrated the laser amplifier characteristics in a Yb^{3+}-doped 200 µm diameter core gain guiding anti-index guiding (GG-IAG) fiber with laser diodes (LDs) pumping at 976 nm. A signal beam at 1040 nm showing single mode behavior and good beam quality at the output end of the fiber was observed. We believe that this GG-IAG fiber is a promising candidate for future laser applications that require high power and quality light from fiber lasers.

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