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Efficient, high-power, and radially polarized fiber laser

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Abstract

We demonstrate an ytterbium-doped fiber laser that emits high-power radially polarized light efficiently. In this study, a photonic crystal grating (PCG) was used as a polarization-selective output coupler, and the power of the radially polarized laser reached 2.42 W with a slope efficiency of 45.9% and a polarization purity of 96%. The results reveal that the inclusion of the PCG mirror into the fiber laser are particularly promising for generating high-power radially polarized light efficiently in view of its many important applications.

Radially polarized vector light exhibits axial symmetry both in field amplitude and polarization with polarization singularity in the beam axis, and it is characterized by a doughnut-shaped intensity pattern. Such light can be tightly focused [1] and has applications that include material processing [2], particle trapping [3,4], and high-resolution microscopy [5].

Usually the radially polarized light is excited in the solid-state and gas-filled laser resonators [6–9]. As is known, the TM_{01} mode in optical fiber intrinsically resembles a radially polarized vector beam. A fiber laser emitting a high-power and radial polarized mode efficiently is, therefore, desirable. We have previously reported the TM_{01} mode lasing in an ytterbium-doped active fiber based on an intracavity Brewster axicon [10–12]. Nevertheless, the silicate-glass-based axicon brings a low transmission discrepancy for the tangential and radial polarization, and the non-radial-polarization modes are also easy to lase, which degrade the radial-polarization purity. Other reported investigations mention the utilization of a birefringent crystal [13] and spatially variable retarder [14] in erbium-doped fiber lasers. All of these schemes experienced either low laser efficiency and power or low polarization purity; therein the highest quoted laser power and efficiency to date are 140 mW [13] and 17% [12], respectively, which are far below those with radially polarized thin-disk and microchip lasers [7,15]. Prior to practical applications of the radially polarized fiber laser, the significant improvements to these laser parameters are expected.

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In the present Letter, we demonstrated an efficient, high-power, and radially polarized ytterbium-doped fiber laser by employing a photonics crystal grating as the polarization-selective output coupler. This grating mirror consists of high- and low-refractive-index layers ($\text{Nb}_2\text{O}_5/\text{SiO}_2$), alternately with the subwavelength layer thickness. In a single layer, it exhibits a subwavelength-pitch triangle concentric pattern. It has polarization-dependent spectra bandpass characteristics of the TE and TM waves, which is based on combining the form-birefringence effect of the subwavelength structure with the resonant interference of a multilayer structure. Such a grating mirror has been utilized in the radially polarized microchip laser [7,15] and proved its merit in providing laser emission with high polarization purity. More details about this grating have been given in [7].

Our experimental setup is illustrated in Fig. 1, where an ytterbium-doped double-cladding fiber is used as the gain medium. The fiber core diameter and NA are $20\text{ }\mu\text{m}$ and 0.07, respectively. The inner clad diameter and NA are $125\text{ }\mu\text{m}$ and 0.4, respectively. The fiber V parameter was calculated to be 4.07, ensuring that only limited modes, including the fiber fundamental mode and its neighbor modes, can be propagated along the fiber. The rear end of the gain fiber was cleaved at an 8° angle to suppress the backreflection. A fiber-coupled 976 nm laser diode with a $125\text{ }\mu\text{m}$ core diameter and $\text{NA} = 0.22$ was used as pumping source, and the emitted light was coupled into the fiber inner clad with about 88% coupling efficiency (measured). The absorption coefficient of the gain fiber inner clad was measured to be 2.71 dB/m at the pump wavelength. An achromatic doublets lens with focal length 20 mm was used to collimate the light beam emerging from the fiber rear end. The plane mirror M1 has >99% transmission at 976 nm and >99.9% reflectivity within the wavelength range of 1.0–1.1 μm . Mirror M2, having a high reflectivity at 976 nm and high transmissivity between 1.0 μm and 1.1 μm , was used to reflect the unabsorbed pump light back to the Yb-doped fiber without disturbing the lasing light. A photonic crystal grating (PCG) was employed as an output coupler with 90% reflectivity around 1064 nm for TM polarization and high transmission for TE polarization. The laser output power and beam profile are monitored by a power meter and CCD camera, respectively.

Above the lasing threshold, the laser beam had a doughnut-shaped intensity distribution, and the beam shape was well maintained with the increased output power. Nevertheless, the beam shape was sensitive and the cylindrical symmetry can be broken by the environmental or artificial disturbance imposed on the gain fiber. Figure 2 plots the laser output power as a function of launched pump power at different lengths of gain fibers. $L = 1.8\text{ m}$ (long fiber) and 0.7 m (short fiber), respectively. When applying the long fiber, the fiber laser started to oscillate at 878 mW pump power; the output power increased linearly with the launched pump power in a slope efficiency of 45.9% and reached 2.42 W at 6.2 W pump power. In the case of the short fiber, the pumping threshold of the laser was 1.32 W; the output power increased linearly with the launched pump power in a slope efficiency of 39.2% and reached 1.93 W at 6.2 W pump power. In both cases, the laser slope efficiencies were elevated significantly, whereas they were still below that of 70% to 80% for standard Yb-doped fiber lasers. This discrepancy could be attributed to the unoptimized transmission of the output coupler as well as the spatial mismatch between the circular gain distribution profile in the fiber core and the doughnut-shaped intensity pattern of the radially polarized lasing mode.

Whatever, the output power of this fiber laser could be scaled up with higher pumping power because no saturation of laser output power occurred at the maximum pumping.

The laser beam showed a doughnut-shaped intensity pattern within the whole range of lasing. Figures 3(a) and 3(b) give, when applying the long fiber, examples of the measured full beam intensity profile at a distance of 1.5 m behind the PCG at two representative output powers, $P_{\text{out}} = 0.2$ W near the lasing threshold and $P_{\text{out}} = 2.14$ W around the maximum output power, respectively. As a comparison, Fig. 3(c) describes the obtained annular beam profile at $P_{\text{out}} = 1.9$ W when applying the short fiber. The polarization state of the laser beam was verified by inserting a linear polarizer perpendicularly into the optical path in front of the CCD camera. The images in Figs. 3(d)–3(g), Figs. 3(h)–3(k), and Figs. 3(l)–3(o) show the intensity distribution of beams in Figs. 3(a)–3(c) passing through a polarizer analyzer, respectively. As seen in each picture, the symmetric two-lobe distribution patterns are always parallel to the respective polarizer axis, manifesting that the output beams were radially polarized.

Figure 4 plots the laser spectrum at $P_{\text{out}} = 2.14$ W when applying the long fiber, where the laser oscillates around 1050 nm with 3.5 nm FWHM. During the experiment, the wavelength peaks were somewhat unstable; however, the full bandwidth was confined between 1047 nm and 1055 nm.

The polarization purity of the obtained laser beam was also measured. At an arbitrary point of the ring profile of an ideal radially polarized vector beam, the light is locally linearly polarized along the radial direction; therefore, the polarization extinction ratio (PER) of this localized point can represent that of the whole vector beam. Based on this principle, a 200 μm diameter aperture was placed into the optical path at a distance of 1.5 m behind the output coupler, where the size of the full beam profile was measured to be about 4 mm in diameter. Adjusting the lateral position of the narrow aperture enabled the transmitted light intensity to be at the maximum. As the aperture is much smaller than the laser beam diameter, the localized light passing through the aperture can be considered to be approximately linearly polarized; thereafter, its PER could be measured by rotating the polarization analyzer. The inset in Fig. 5 depicts the power variation of leaked light through the aperture when rotating the polarizer analyzer at $P_{\text{out}} = 2.14$ W in the case of applying the long fiber, which implies a PER of 43.1. According to the definition in [16], this PER value corresponds to a 95.5% polarization purity (i.e., polarization degree). The polarization purity at different pumping power was also measured in the same way. As illustrated in Fig. 5, the polarization purity was above 95% in the whole lasing range.

In conclusion, we presented a radially polarized ytterbium-doped fiber laser by employing a PCG as the polarization-selective output coupler. The laser power reached 2.42 W with a slope efficiency of 45.9% and a polarization purity of 95.5% at 6.2 W pump power when applying a 1.8 m long gain fiber. To the best of our knowledge, this is the highest laser power and efficiency obtained in a radially polarized fiber laser. Furthermore, both of them can be elevated by optimizing the length of the gain fiber and reflectance of grating mirror. The high-power, efficient, and radially polarized fiber laser employing a PCG has great

potential for use in various applications, including material processing and particle manipulation.

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References

1. Dorn R, Quabis S, Leuchs G. Phys. Rev. Lett. 2003; 91:233901. [PubMed: 14683185]
2. Niziev VG, Nesterov AV. J. Phys. D. 1999; 32:1455.
3. Kavauchi H, Yonezawa K, Kozawa Y, Sato S. Opt. Lett. 2007; 32:1839. [PubMed: 17603587]
4. Zhan Q, Leger JR. Appl. Opt. 2002; 41:4630. [PubMed: 12153096]
5. Zhan Q. Opt. Express. 2004; 12:3377. [PubMed: 19483862]
6. Tidwell SC, Ford DH, Kimura WD. Appl. Opt. 1990; 29:2234. [PubMed: 20563156]
7. Li JL, Ueda KI, Zhong LX, Musha M, Shirakawa A, Sato T. Opt. Express. 2008; 16:10841. [PubMed: 18607500]
8. Pohl D. Appl. Phys. Lett. 1972; 20:266.
9. Mushiaki Y, Matsumura K, Nakajima N. Proc. IEEE. 1972; 60:1107.
10. Li JL, Ueda KI, Musha M, Shirakawa A. Opt. Lett. 2006; 31:2969. [PubMed: 17001369]
11. Li JL, Ueda KI, Musha M, Shirakawa A, Zhang ZM. Opt. Lett. 2007; 32:1360. [PubMed: 17546121]
12. Li JL, Ueda K-I, Shirakawa A, Musha M, Zhong L-X, Zhang Z-M. Laser Phys. Lett. 2007; 4:814.
13. Zhou RJ, Escamilla BI, Haus JW, Powers PE, Zhan Q. Appl. Phys. Lett. 2009; 95:191111.
14. Fridman M, Machavariani G, Davidson N, Friesem AA. Appl. Phys. Lett. 2008; 93:191104.
15. Li JL, Ueda K-I, Musha M, Zhong LX, Shirakawa A. Opt. Lett. 2008; 33:2686. [PubMed: 19015709]
16. Nesterov AV, Niziev VG, Yakunin VP. J. Phys. D. 1999; 32:2871.

Fig. 1.
(Color online) Experimental setup of radially polarized fiber laser.

Fig. 2.

(Color online) Output power of the fiber laser versus the launched pump power at different fiber lengths.

Fig. 3.

Intensity distribution of the full laser beam profile at (a) $P_{\text{out}} = 0.19$ W, (b) $P_{\text{out}} = 2.14$ W when applying the long fiber, and (c) $P_{\text{out}} = 1.9$ W when applying the short fiber. Intensity distribution of the passage beam through a polarizer analyzer at (d)–(g) $P_{\text{out}} = 0.19$ W and (h)–(k) $P_{\text{out}} = 2.14$ W when applying the long fiber and (l)–(o) $P_{\text{out}} = 1.9$ W when applying the short fiber. The white arrows indicate the orientations of the polarizer analyzer, respectively.

Fig. 4.

(Color online) Laser spectrum at 2.14 W output power when applying the long fiber.

Fig. 5.

(Color online) Polarization purity of radially polarized light as a function of output power when applying the long gain fiber. Inset, intensity variation of extracted output beam by a 200 μm diameter aperture in the optical path when the polarizer analyzer was rotated at different orientations.