Published in final edited form as:

Opt Lett. 2010 November 01; 35(21): 3574–3576.

Radially polarized and passively Q-switched fiber laser

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Abstract

We report, for the first time to our knowledge, a radially polarized and passively *Q*-switched Yb-doped fiber laser. By using a Cr⁴⁺:YAG crystal as a saturable absorber and a photonic crystal grating as a polarization mirror, a radially polarized pulse is produced, which has 202 W of peak power, 75 ns duration, and ~92% polarization purity at a 56.6 kHz repetition rate. The *Q*-switched pulse with radial polarization from the fiber laser would facilitate numerous applications.

OCIS codes

060.2320; 140.3540; 230.5440; 260.5430; 140.3300

Radially polarized light is characterized by axial symmetry in both amplitude and polarization with polarization singularity in the beam axis. This vectorial light can be tightly focused and has important applications in optical tweezers [1,2] and material processing [3,4]. These merits have attracted increasing attention to radially polarized laser sources. For specific applications, such as metal cutting, highly intensive laser irradiation is necessary to reach or exceed the ablation threshold. As *Q* switching allows the production of a high-peak-power pulse, the association of the radially polarized excitation with *Q* switching in one laser resonator could become the preferred option for the sake of high-field applications.

Previously, the radially polarized light pulse was achieved mainly from solid-state lasers by utilizing active or passive *Q* switching [4–6] or active mode locking [7]. Nevertheless, the thermal lens effect in bulk gain material restricts the extraction of stored energy. Instead of the solid-state laser, the fiber laser has attracted increasing interest in generating a cylindrical vector mode, owing to the rare-earth fiber affordability in high gain, thermal dissipation, and modal confinement [8–12]. Most recently it has been shown that the performance of the radially polarized fiber laser has become comparable to that of conventional solid-state or

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fiber lasers [13]. However, these reported investigations mentioned only cw lasing of the radially polarized fiber laser; the Q -switched operation remains unexploited.

In this Letter, we report what we believe to be the first passively Q -switched and radially polarized Yb-doped fiber laser, in which a Cr^{4+} :YAG crystal acts as the saturable absorber (SA) and a photonic crystal grating (PCG) acts as the polarization-selective output coupler. Details are presented as follows.

The experimental setup of our fiber laser is illustrated in Fig. 1. The gain fiber used is a 0.7-m-long, double-clad, Yb-doped fiber. Its core and inner clad diameters are 20 μm and 125 μm with NAs of 0.07 and 0.4, respectively. The fiber is well chosen, ensuring that only a few low-order modes could be propagated in the fiber core. Further, the rear end of the gain fiber is cleaved at 8° to suppress backreflection. The pumping light from a fiber-coupled 976 nm laser diode is coupled into the fiber inner cladding with about 88% coupling efficiency (measured). The absorption coefficient of gain fiber's inner cladding was measured to be 2.71 dB/m at 976 nm. The dichroic plane mirror M1 has high transmission at 976 nm and high reflectivity within the wavelength range of 1.0–1.1 μm . A PCG is employed as an output coupler with 90% reflectivity for TM polarization and high transmission for TE polarization around 1064 nm. (This grating mirror is composed of high- and low-refractive-index layers alternately, and each layer is subwavelength in thickness and shaped into triangular concentric corrugations. The combination of the subwavelength structure's form-birefringence effect with the multilayer structure's resonant interference brings polarization-dependent spectra bandpass characteristics to TE and TM waves [14].) Lenses L1 and L2 are used to image the fiber end facet inside the Cr^{4+} :YAG crystal of about 50 μm diameter, and another lens, L3, is used to recollimate the light into the PCG. A dichroic plane mirror (M2) is used to reflect unabsorbed pump light back to the gain fiber without disturbing the lasing light. The laser power and beam profile are monitored by a powermeter and CCD camera, respectively. The temporal behavior of the output is recorded by a digital oscilloscope with a fast InGaAs photodiode.

We use two Cr^{4+} :YAG crystals with different initial transmittances ($T_0 = 95\%$ and 70%) as the SAs. Figure 2 plots the function relations between the laser output powers and incident pump power (P_{in}). As seen, the laser has pumping thresholds of 1.1 W at $T_0 = 95\%$ and 1.5 W at $T_0 = 70\%$, respectively. When the pump power is elevated further, the laser powers increase linearly with slope efficiencies of 22.9% and 18.8% and reach 1.1 W and 0.86 W at $P_{\text{in}} = 6$ cases, W for $T_0 = 95\%$ and 70% , respectively. In both cases, the laser output powers could be scaled up further with higher pump power if available, because no saturation phenomenon occurs.

The laser beam exhibits the doughnut-shaped intensity profiles within the whole lasing range. Figures 3(a) and 3(b) depict the captured far- and near-field intensity distributions of the laser beam at $P_{\text{in}} = 6$ W and $T_0 = 70\%$, where the doughnut shape is clearly discerned. The state of polarization is analyzed by inserting a polarizer perpendicularly into the optical path in front of the CCD camera. The images in Figs. 3(c)–3(f) depict the corresponding far-field intensity pattern of the passage beam through the polarizer when the polarizer was rotated. It is obvious that the symmetric two-lobe intensity patterns in each image are always

identical to the respective axis of the polarizer, and this verifies that the laser beam is radially polarized.

The polarization purity of the obtained laser beam is also measured by using the following method. We place a 200 μm diameter aperture into the optical path at a distance of 1.5 m behind the output coupler, where the size of the full beam profile is about 4 mm in diameter. And then the lateral position of the aperture is adjusted to enable the transmitted light intensity to be maximum. With the small size of the aperture, the localized light passing through it can be considered to be approximately linearly polarized, and its polarization extinction ratio (PER) could represent approximately that of the whole laser beam. (It is worthwhile to point out, along the azimuthal locations on a real laser beam with radial polarization, the polarization purity is somewhat inhomogeneous. Therefore, the measured PER of this randomly selected location is rather a qualitative and rough approximation to that of whole beam.) In the case of $T_0 = 70\%$ and $P_{\text{in}} = 6 \text{ W}$, we measure a PER value of $\sim 24:1$, which corresponds to 92% polarization purity. While we utilize the SA with $T_0 = 95\%$, the measured PER is about 10:1 at $P_{\text{in}} = 6 \text{ W}$ and corresponds to 81.8% polarization purity. It seems that the polarization purity was slightly worsened at higher initial transmittance of the SA. This degradation could be contributed to the high fraction of amplified spontaneous emission of the non-radial-polarization fiber modes embodied in the single-shot laser pulse when exploiting higher initial transmittance (i.e., low modulation depth) of the SA.

The pulse repetition rate and pulse width (FWHM) are shown in Fig. 4 as functions of incident pump power. As seen, the repetition rates of the pulse increase nearly linearly with the increase of pump power and reach respective maximum values, 135 kHz for $T_0 = 95\%$ and 56.6 kHz for $T_0 = 70\%$ at $P_{\text{in}} = 6 \text{ W}$, while the pulse durations decrease with the increase of pump power and shorten to 180 ns for $T_0 = 95\%$ and 75 ns for $T_0 = 70\%$ at $P_{\text{in}} = 6 \text{ W}$. Further, when $T_0 = 95\%$, with the increase of pump power, the peak power gradually increase from 18 W to 45 W, and the pulse energy increases from 6.4 μJ to 8.2 μJ . When $T_0 = 70\%$, with the increase of pump power, the peak power increases from 127 W to 202 W; nevertheless, the pulse energy weakly depends on the pump power and varies from 14.1 μJ to 15.2 μJ .

Figures 5 and 6 depict the captured pulse envelope and train by the oscilloscope at $P_{\text{in}} = 6 \text{ W}$ when applying two absorbers. As seen in Figs. 5(a) and 6(a), both envelopes are slightly modulated by the spikes, with a period of 9.12 ns, which is well identical to the cavity round-trip time. Also, we noticed that the modulation depth increased with pump power. This self-mode-locking phenomenon has been observed in passively and actively Q -switched fiber lasers [15,16] and also the self-pulsed fiber laser [17], and usually it is attributed to the mode beats between axial modes of the cavity and is supported by further mode coupling caused by self-phase modulation [18].

In summary, we demonstrate a passively Q -switched fiber laser that emits a radially polarized pulse. The performances of this vectorial fiber laser, including the pulse parameters, laser efficiency, and power, could be elevated further by optimizing the fiber

length and reflectance of the output coupler. The Q -switched pulse from the radially polarized fiber laser is valuable for many important applications.

Acknowledgments

This research is sponsored by the National Natural Science Foundation of China (NSFC) (60978025), the Hundred Talents Program of the Chinese Academy of Sciences (CAS), and the Shanghai Pujiang Program (09PJ1410500). J. Li acknowledges Takashi Sato from Photonic Lattice, Inc., for support with the grating mirror.

References

1. Zhan Q. Opt Express. 2004; 12:3377. [PubMed: 19483862]
2. Kavauchi H, Yonezawa K, Kozawa Y, Sato S. Opt Lett. 2007; 32:1839. [PubMed: 17603587]
3. Niziev VG, Nesterov AV. J Phys D. 1999; 32:1455.
4. Meier M, Romano V, Feurer T. Appl Phys A. 2007; 86:329.
5. Pohl D. Appl Phys Lett. 1972; 20:266.
6. Li JL, Ueda KI, Musha M, Zhong LX, Shirakawa A. Opt Lett. 2008; 33:2686. [PubMed: 19015709]
7. Enderli F, Feurer T. Opt Lett. 2009; 34:2030. [PubMed: 19571989]
8. Li JL, Ueda KI, Musha M, Shirakawa A. Opt Lett. 2006; 31:2969. [PubMed: 17001369]
9. Li JL, Ueda KI, Musha M, Shirakawa A, Zhang ZM. Opt Lett. 2007; 32:1360. [PubMed: 17546121]
10. Li JL, Ueda KI, Shirakawa A, Musha M, Zhong LX, Zhang ZM. Laser Phys Lett. 2007; 4:814.
11. Zhou RJ, Escamilla BI, Haus JW, Powers PE, Zhan Q. Appl Phys Lett. 2009; 95:191111.
12. Fridman M, Machavariani G, Davidson N, Friesem AA. Appl Phys Lett. 2008; 93:191104.
13. Lin D, Xia KG, Li JL, Li RX, Ueda KI, Li GQ, Li XJ. Opt Lett. 2010; 35:2290. [PubMed: 20596223]
14. Li JL, Ueda KI, Zhong LX, Musha M, Shirakawa A, Sato T. Opt Express. 2008; 16:10841. [PubMed: 18607500]
15. Philippov VN, Kiryanov AV, Unger S. IEEE Photon Technol Lett. 2004; 16:57.
16. Lees GP, Newson TP. Electron Lett. 1996; 32:332.
17. Li JL, Ueda KI, Musha M, Shirakawa A. Opt Lett. 2006; 31:1450. [PubMed: 16642135]
18. Myslinski P, Chrostowski J, Koningstein JA, Simpson JR. Appl Opt. 1993; 32:286. [PubMed: 20802686]

Fig. 1.
(Color online) Schematic diagram of the passively *Q*-switched and radially polarized fiber laser.

Fig. 2.
(Color online) Laser powers versus the incident pump power when applying different absorbers.

Fig. 3.

(a) Far- and (b) near-field intensity distributions of the full beam profile and (c)–(f) far-field intensity distribution when the laser beam passes through a polarizer with different orientations of the polarizer axis.

Fig. 4.
(Color online) Repetition rate and pulse duration as functions of incident pump power when the SA had different initial transmittances.

Fig. 5. Captured oscilloscope traces of (a) pulse envelope and (b) train at 6 W of pumping power and $T_0 = 95\%$.

Fig. 6. Captured oscilloscope traces of (a) pulse envelope and (b) train at 6 W of pumping power and $T_0 = 70\%$.