Passively Q-switched photonic crystal fiber laser and intracavity optical parametric oscillator

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Abstract: We report on a passively Q-switched photonic crystal fiber (PCF) laser with Cr^{4+}:YAG as a saturable absorber. Under a pump power of 14.2 W, the maximum pulse energy is up to 630 μJ with a pulse width of 36 ns at a repetition rate of 5.6 kHz. With an intracavity optical parametric oscillator, the passively Q-switched PCF laser is used to generate the signal wave at 1515 nm. The output pulse energy of the signal wave is found to be 140 μJ with a pulse width as short as 1.0 ns at a repetition rate of 3.3 kHz. The very short pulse width leads to the peak power up to 140 kW.

OCIS codes: (140.3510) Lasers, fiber; (140.3540) Lasers, Q-switched; (190.4970) Parametric oscillators and amplifiers.

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1. Introduction

In recent years, double-cladding rare-earth doped fiber lasers have attracted a lot of attention due to their good beam confinement, excellent heat dissipation, spatial beam quality, and high efficiency [1–7]. Q-switched lasers have many applications on industrial processing, measurements of positions, and medical treatments owing to their high peak power than in CW operation [8–10]. By enlarging the active volume of the gain medium, corresponding to the doped core size of the fiber, one can achieve the merit of the high pulse energy [11,12]. However, the conventional large core fibers suffer from mode-quality degradation and their long lengths usually lead to long pulse widths and low peak powers.

Recently, a novel technology [13] has been developed to provide photonic crystal fibers (PCFs) with large single mode core and high absorption efficiency. The PCF laser was lately employed to perform an actively Q-switched operation in which the pulse energy was up to 2 mJ with a pulse width shorter than 10 ns at a repetition rate of 10 kHz. Compared to the active Q-switching, passive Q-switching lasers are more compact and lower cost because they use saturable absorbers in replace of acoustic-optic or electro-optic modulators as the Q-switch.

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Crystal-based [14–17] saturable absorbers have been well developed to replace the dye-cells used in solid-state lasers. Cr^{4+}:YAG crystals have been exploited as saturable absorbers in large-mode-area Yb-doped fibers [18–21], among which the maximum pulse energy was 350 μJ. Nevertheless, the passive Q-switching in a PCF laser has not been investigated so far.

In this paper, we report, for the first time to our knowledge, on the performance of a single-polarization passively Q-switched Yb-doped PCF laser and its application to intracavity optical parametric oscillator (OPO). With a Cr^{4+}:YAG crystal as a saturable absorber and under a pump power of 14.2 W, the PCF laser generates an average output power of 3.4 W at 1030 nm at the repetition rate of 5.6 kHz, corresponding to the pulse energy up to 630 μJ. The pulse width and the peak power are 36 ns and 17.4 kW, respectively. Experimental results revealed that since the Yb-doped PCF provokes a narrow linewidth and a high polarization extinction ratio, the pulse-to-pulse amplitude fluctuation and the temporal jitter were well below 5% for the pump power greater than 8 W. The overall quality of the output pulses is noticeably superior to that obtained in conventional passively Q-switched fiber lasers. With the passively Q-switched PCF laser to pump an intracavity OPO, the output pulse energy of 140 μJ can be generated for the signal wave at 1515 nm at a repetition rate of 3.3 kHz. Owing to the efficient cavity-dumping effect, the signal pulse width is found to be as short as 1.0 ns; consequently, the peak power can reach 140 kW.

2. Performance of passively Q-switched PCF laser

Figure 1(a) shows the setup for the passively Q-switched PCF laser. The cavity consists of a 55 cm polarization maintaining (PM) Yb-doped PCF and an external feedback cavity with a saturable absorber. The external cavity incorporates with a focusing lens of 50-mm focal length to focus the fiber output into the Cr^{4+}:YAG crystal and a high reflective mirror behind the saturable absorber for feedback. The rod-type PCF has a mode field diameter of 55 μm and a low numerical aperture of 0.02 to sustain the excellent beam quality. The pump cladding of the PCF has a diameter of 200 μm and an air-cladding to maintain a high numerical aperture of 0.6, as depicted in Fig. 1(b) for the image of the cross section of the PCF. The small ratio between the inner pump cladding and core diameters brings about the pump absorption coefficient to be approximately 30dB/m at 976nm. The PCF was surrounded with a 1.7-mm thick outer cladding and was sealed with end-caps for protection. The boron doped stress-applying parts were adopted to induce birefringence that produces diverse spectral losses to form a linearly polarization state for the fundamental mode. The Cr^{4+}:YAG saturable absorber had a thickness of 3 mm and was highly doped with a small signal transmission of 28%. Both sides of the saturable absorber were coated for antireflection at 1030 nm (R<0.2%) and the mode diameter on the saturable absorber was approximately 400 μm. The pump source was an 18-W 976-nm fiber-coupled laser diode with a core diameter of 100 μm and a numerical aperture of 0.2. Focusing lens with 25-mm focal length and 90% coupling efficiency was used to re-image the pump beam into the fiber through the dichroic mirror with high transmission (HT, T>90%) at 976 nm and high reflectivity (HR, R>99.8%) within 1030~1100 nm. The pump spot radius was approximately 50 μm, and the pump coupling efficiency was estimated to be around 80%. The pulse temporal behavior was recorded by Leroy digital oscilloscope (Wavepro 7100; 10G samples/sec; 4 GHz bandwidth) with a fast InGaAs photodiode.

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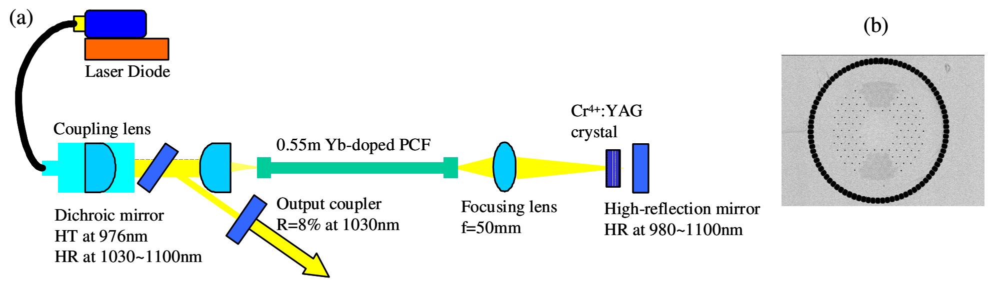

Fig. 1. (a) Setup for the passively Q-switched PCF laser; (b) image of the cross section of PCF.

Figure 2(a) shows the average output power with respect to the launched pump power in the CW and passive Q-switching operations. The external cavity in the CW operation only included a re-imagining lens and a reflective mirror. At a launched pump power of 14.2 W, the average output power in the CW and passive Q-switching operations were 5.4 W and 3.4 W, respectively. The slope efficiency seemed to decrease slightly above 12.5 W of pump power which was due to temperature lifting induced wavelength shift of the pumping laser diode. The lasing spectra for both operations were quite similar with the peaks near 1030 nm and bandwidths to be approximately 0.4 nm, as shown in the inset of Fig. 2(a). The M^2 factor was also measured to be less than 1.3 over the complete output power range, owing to the low-NA feature of the fiber. The laser output was found to be linearly polarized with an extinction ratio of approximately 100:1, evidencing the function of the polarization maintaining in PCF. The pulse repetition rate and the pulse energy versus the launched pump power are shown in Fig. 2(b). The pulse repetition rate increased monotonically with the pump power up to 5.6 kHz at a pump power of 14.2 W. The pulse energy was maintained to be nearly constant at 630 μJ for all the pump power range. Figures 3(a) and 3(b) show typical oscilloscope traces for a single Q-switched pulse and a Q-switched pulse train, respectively. The temporal shape of the single pulse reveals a self-mode-locking (SML) phenomenon that has been observed in conventional fiber lasers and the possible mechanisms for its origin have been discussed in Refs [19,22,23]. During the early research on mode-locking, the SML phenomenon was observed on different types of lasers including He-Ne [24], ruby [25], Nd:glass [26], and argon ion [27] laser systems. Based on the statistical analysis, it has been shown that the mode-locked behavior will always be observed in a multimode laser except when a systematic phase fluctuation over 2π is introduced [28,29]. Although a systematic phase fluctuation is usually caused by dispersion effects, theoretical studies on the SML mechanism have confirmed that the combination tones of the third order nonlinear polarization terms can help in compensating the dispersion-induced phase shift [30–32]. Consequently, the SML typically occurs in a multimode laser without employing an extra nonlinearity except the gain medium. Recently, fairly stable SML pulses have been observed in the experiments of Nd-doped double clad fiber lasers [32] and Nd-doped vanadate crytsal lasers [33]. On the other hand, Laroche et al [19] found that the SML phenomenon can be eliminated by setting the Cr^{4+}:YAG crystal exactly at the focal point of the lens. However, we did not attempt to eliminate the SML phenomenon because this phenomenon did not deteriorate the pulse stability in the present PCF laser. Moreover, putting the Cr^{4+}:YAG crystal at the focal position may cause damage due to the high pulse energy and peak power. Experimental results revealed that both the pulse-to-pulse amplitude fluctuation and the temporal jitter were well below 5% for the pump power greater than 8 W because of the narrow linewidth and the high polarization extinction ratio of the PCF. More importantly, the pulse width of the Q-switched pulse envelope was as short as 36 ns. In short, the overall quality of the output pulses is significantly superior to that obtained in conventional passively Q-switched fiber lasers [34].

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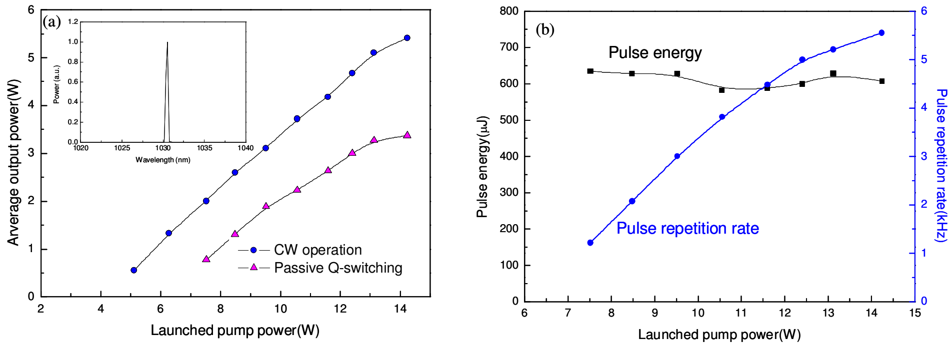

Fig. 2. (a) Average output power with respect to launched pump power in CW and passive Q-switching operations, the inset: typical lasing spectrum. (b) Pulse repetition rate and pulse energy versus launched pump power.

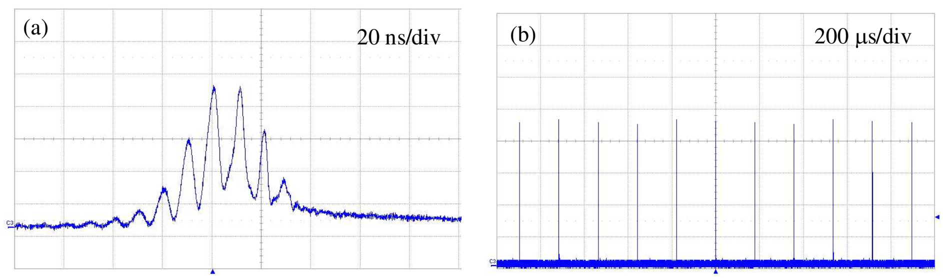

Fig. 3. Typical oscilloscope traces for (a) single Q-switched pulse and (b) Q-switched pulse train.

3. Performance of intracavity OPO

To construct an intracavity OPO, the output coupler in the passively Q-switched PCF laser was replaced with a high-reflection mirror at 1030 nm and inserting a singly resonant OPO cavity behind the Cr^{4+}:YAG crystal. Figure 4 shows the experimental setup for the intracavity OPO pumped by the passively Q-switched PCF laser. The OPO cavity is composed of a dichroic front mirror (HT at 1030 nm and HR at 1515 nm), a KTP nonlinear crystal, and an output coupler with partial transmission (PR) of R = 38% at 1515 nm and high reflectivity at 1030 nm. The nonlinear crystal KTP was *x*-cut with the dimension of $4 \times 4 \times 20$ mm^3 and both sides of the KTP crystal were coated for antireflection at 1030 nm and 1515 nm (R<0.5%). The KTP crystal was mounted on a water-cooled copper heat sink with an indium thermal contact. The length of the OPO cavity was approximately 3 cm. The Cr^{4+}:YAG crystal was placed very close (~1.0 mm) to the front mirror of the OPO cavity to control the mode diameter on the Cr^{4+}:YAG crystal in the range of 400 μm.

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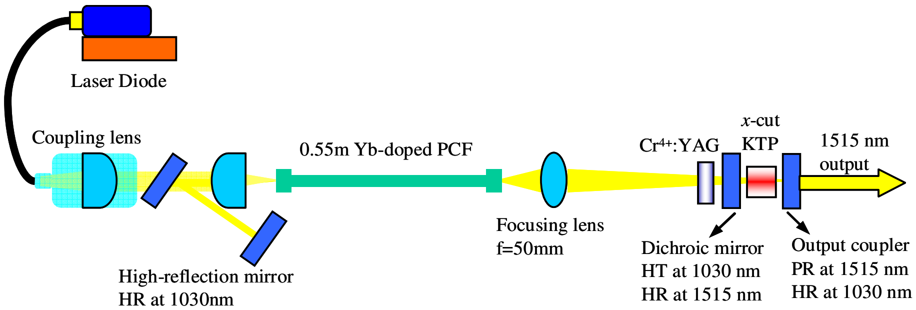

Fig. 4. Setup for the intracavity OPO pumped by the passively Q-switched PCF laser.

The average output power of the signal wave at 1515 nm with respect to the launched pump power is shown in Fig. 5(a). Under a pump power of 14.2 W, the average output power of the signal wave was found to be approximately 470 mW. No idler signal was detected because of the high absorption of the idler radiation in the KTP crystal and the BK7 substrate of the output coupler, so the OPO is resonant on the signal frequency only. Note that no saturation of average output power was seen at the highest pump power, which implied that larger OPO signal output power can be expected with higher pump power. The OPO pulse repetition rate and the pulse energy versus the launched pump power are shown in Fig. 5(b). The pulse repetition rate increased monotonically with the pump power up to 3.3 kHz at a pump power of 14.2 W. The pulse energy was nearly 140 μJ for all the pump power range. The signal output pulse energy obtained with a Q-switched PCF laser was 3-6 times higher than the results obtained with solid-state Nd-doped crystal lasers at the same level of diode-pumped power [35–37]. In other words, the Yb-doped gain medium has a superior energy-storing ability than conventional Nd-doped laser crystals, such as Nd:YAG and Nd:YVO_4.

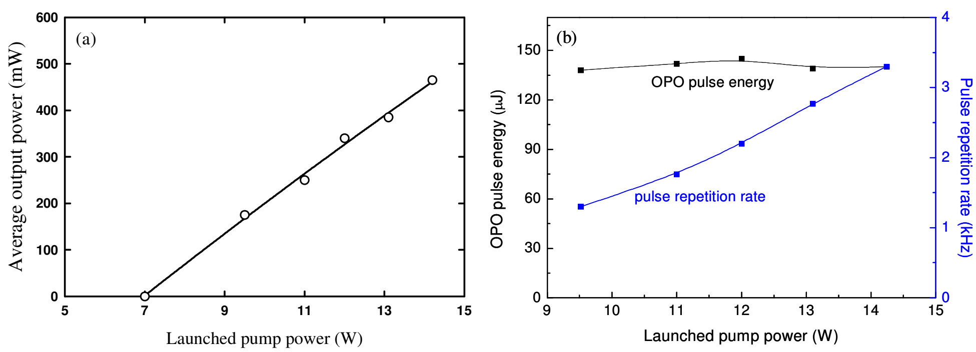

Fig. 5. (a) Average output power of signal wave at 1515 nm with respect to launched pump power. (b) OPO pulse repetition rate and pulse energy versus launched pump power.

Figure 6 shows general oscilloscope traces for the fundamental and OPO signal output pulses. The top half of Fig. 6 depicts the temporal trace of the fundamental wavelength and the bottom half shows the pulse profile of the OPO signal wavelength. The pulse width of the OPO signal can be seen to be as short as 1.0 ns due to the efficient cavity-dumping effect. As a result, the maximum peak power of the signal wave can be up to 140 kW. The optical to optical conversion efficiency of OPO output power to laser diode launched pump power was about 3.3%, and the pulse energy conversion efficiency of OPO wavelength to 1030 nm wavelength was about 22.3%. The large pre- and post- pedestals in Fig. 6 arise from the SML effect. Note that the pulse shapes at 1030 nm were quite different for the cavity with and without the intracavity OPO. The number of the mode-locked pulses at 1030 nm shown in

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Fig. 6 was considerably less than that obtained with pure passive Q-switching shown in Fig. 3(a) because the effective output coupling in the intracavity OPO was a nonlinear cavity-dumping process. Since water absorption in eye tissue and the intraocular fluid prevents light in the spectral range of 1.4-1.8 μm from reaching the retina, there is a considerable interest in laser sources with wavelengths in this eye-safe regime [38–40]. A number of efficient eye-safe intracavity OPOs pumped by passively [35–37] Q-switched Nd-doped crystal lasers have been demonstrated to produce pulse energies of tens of μJ with pulse peak powers of 1-50 kW. Here the PCF laser was recently employed to realize an intracavity OPO with pulse energies greater than 100 μJ with peak powers greater than 100 kW. Although the conversion efficiency for the average power is inferior to that obtained with Nd-doped crystal lasers, this situation might be improved with a shorter cavity to match the OPO cavity. However, the challenge is to manufacture a shorter PCF with sufficient absorption efficiency.

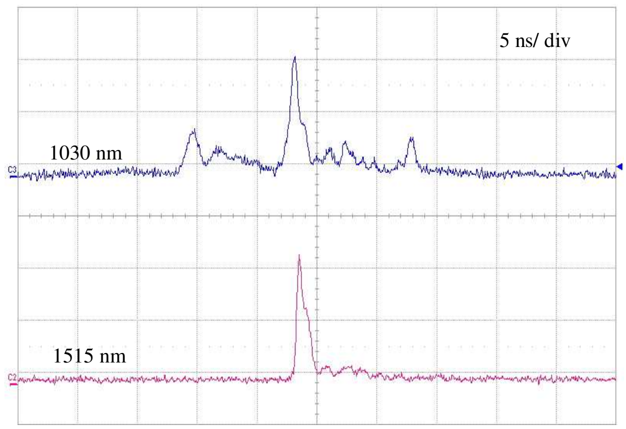

Fig. 6. General oscilloscope traces for the fundamental (top) and OPO signal (bottom) output pulses.

4. Conclusion

In conclusion, we have, for the first time to our knowledge, demonstrated a high-pulse-energy passively Q-switched Yb-doped PCF laser by utilizing Cr^{4+}:YAG crystal as saturable absorber. Stable pulses with an average output power of 3.4 W and a repetition rate of 5.6 kHz were obtained at a launched pump power of 14.2 W. The maximum pulse energy reached 630 μJ which was superior to the results obtained in conventional Yb-doped fiber lasers. Furthermore, the passively Q-switched PCF laser has been employed to pump an intracavity OPO to generate a pulse energy of 140 μJ at a pulse repetition rate of 3.3 kHz with a 14.2 W diode pump power. Owing to the efficient cavity-dumping effect, the pulse duration of the signal wave was approximately 1.0 ns, leading to a peak power up to 140 kW. This high-peak-power intracavity OPO could be a potential light source for many technical applications.

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