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Linearly polarized intracavity passive Q-switched Yb-doped photonic crystal fibre laser

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Abstract. In this paper we report linearly polarized high average power passive Q-switched ytterbium-doped photonic crystal fibre laser with a Cr^{4+}:YAG crystal as a saturable absorber. An average output power of 9.4 W with pulse duration of 64 ns and pulse repetition rate of 57.4 kHz with a slope efficiency of 52% was achieved. Measured polarization extinction ratio (PER) of the Q-switched laser output was 10.5 dB.

Keywords. Fibre lasers; Q-switched fibre lasers; photonic crystal fibre; Cr^{4+}:YAG saturable absorber.

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1. Introduction

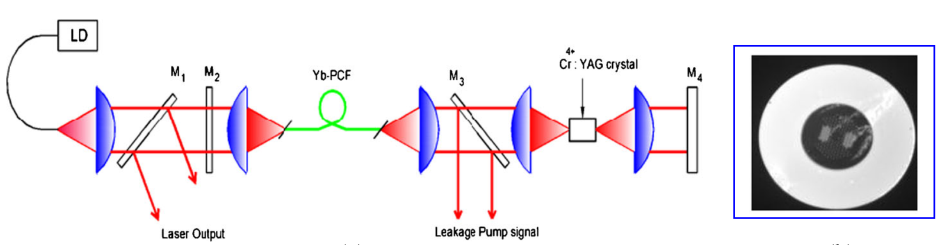
Q-switched fibre lasers with high peak power have attracted a lot of attention due to many applications in the fields of industrial processing and medical treatments. For special applications of nonlinear frequency shifting like frequency doubling and optical parametric oscillation, linearly polarized Q-switched output is essential. High pulse energy and high peak power from the fibre laser can be generated by increasing the active volume of the gain medium. However, the conventional large mode area (LMA) ytterbium (Yb)-doped double-clad fibres suffer from the limitations of nonlinear effects like SRS and SBS due to their long length required for the optimum pump absorption. Further, Q-switching using the long length of conventional Yb-doped fibres produces pulses of large temporal pulse width and low peak powers. Photonic crystal fibres (PCF) are special fibres which consist of a regular microstructured array of holes, where the core is made up of a solid or air-filled defect and the light guidance takes place due to the microstructures present in the fibre [1]. The advantage of such a fibre is that the diameter of the inner cladding can be reduced while retaining numerical aperture of the pump core. Due to the increased ratio of active core area to inner cladding area, the pump light absorption is improved and smaller fibre length becomes possible. There are reports on the passive Q-switching in Yb-doped LMA fibre lasers by using Cr^{4+}:YAG crystal as a saturable absorber. Huang *et al* have reported maximum average power of 6.2 W at 48 kHz repetition rate [2]. The Q-switching efficiency obtained was 61%. Zhuang *et al* have reported linearly polarized passive Q-switched Yb-doped laser by using short length rod type PCF with an average power of 3.2 W and Q-switching efficiency of 62.9% [3].

In this paper, we report the generation of linearly polarized passively Q-switched output from Yb-doped PCF laser using Cr^{4+}:YAG crystal as a saturable absorber. An average power of 9.4 W with a pulse width of 63 ns and a pulse repetition rate of 60 kHz has been achieved. Pulses obtained were polarized with polarization extinction ratio (PER) of 10.5 dB. To the best of our knowledge, this is the maximum average power and Q-switching efficiency reported in Yb-doped Q-switched PCF laser.

2. Experimental set-up

Figure 1a shows the schematic of the experimental set-up for the passively Q-switched Yb-doped PCF laser consisting of a 1.5 m Yb-doped PCF and an intracavity saturable absorber. A Yb-doped double-clad polarizing PCF (YDPCF) having a mode field diameter (MFD) of 29.5 μm at 1060 nm with numerical aperture (NA) of 0.03, and an inner-clad diameter of 200 μm with an NA of 0.55 was used as a gain medium. Large NA of the inner clad relaxes the tolerances on coupling optics for coupling pump light into the inner clad of the PCF. The clad-pump absorption of the fibre is 10 dB/m at 976 nm. Figure 1b shows the transverse cross-section of the PCF, which shows the core, pump clad and the second clad of the fibre. Boron-doped silicate rods in the microstructured inner clad provides a birefringence of about 1×10^{-4}. Both the ends of the fibre are angle polished at 5° to prevent feedback from the end faces. Fibre-coupled laser diode having 30 W CW power at the centre wavelength of 975 nm at 25°C was used as a pump source. Here, the fibre possesses a low NA core to sustain the excellent beam quality. The pump laser output, having a 200 μm core diameter fibre pigtail with 0.22 NA was collimated using a lens of 20 mm focal length and then focussed using another lens of 20 mm focal length to have a focussed spot diameter of about 200 μm on the input end of the doped fibre.

The Cr^{4+}:YAG crystal was used as a saturable absorber for passive Q-switching. Both the sides of the Cr^{4+}:YAG crystal were antireflection coated in a broadband from 1030



(a) (b)

Figure 1. (**a**) Schematic of the passively Q-switched Yb-doped PCF laser, (**b**) cross-section of PCF.

to 1100 nm ($R < 0.2\%$). The saturable absorber was wrapped with indium foil and conductively cooled. The focal lengths of the collimating and focussing lenses were chosen to have a focussed beam diameter inside the saturable absorber corresponding to the fibre core diameter. The saturable absorber was mounted on the translation stage to optimize the focal position depending upon the output performance of the Q-switched laser.

Two dichroic mirrors M_2 and M_4, which form the resonator cavity were used in this configuration; both the mirrors have high transmission at 975 nm whereas M_2 has 4% reflection for the normal incidence and M_4 has high reflection in the broad range of 1035–1120 nm for normal incidence. Mirror M_1 has been used as the output coupler and has similar characteristics as M_4 for 25° angle of incidence. Mirror M_3 has high transmission for laser signal and high reflection for pump signal at 45° and has been used to remove the leakage pump power from the cavity to prevent the bleaching of the saturable absorber by the pump signal. The pulse temporal behaviour was recorded by a LeCroy digital oscilloscope with a 1 GHz InGaAs photoreceiver.

3. Results and analysis

Figure 2a shows the average output power with respect to the incident pump power in CW and passive Q-switched operations. In the cw regime, the PCF laser had a slope efficiency of 73.4% with an output power of 13.4 W at an incident pump power of 22.5 W. In the passively Q-switching regime, an average output power of 9.4 W was obtained at the same value of the incident pump power with a slope efficiency of 52%. Polarization extinction ratio (PER) of the output pulse was recorded to be 10.5 dB.

Figure 2b shows the variation of pulse repetition rate and pulse energy with the launched pump power. Pulse repetition rate increased from 2.2 kHz to 57.4 kHz with increase in the pump power from 5.4 W to 22.5 W, which is the characteristic of the typical passive Q-switched lasers. Pulse energy in the Q-switched laser depends upon the initial population density in the gain medium. For passive Q-switched laser, the initial population density achieved in the gain medium is determined by the initial transmission of the saturable absorber and reflectivity of the output coupler mirror. Hence pulse energy

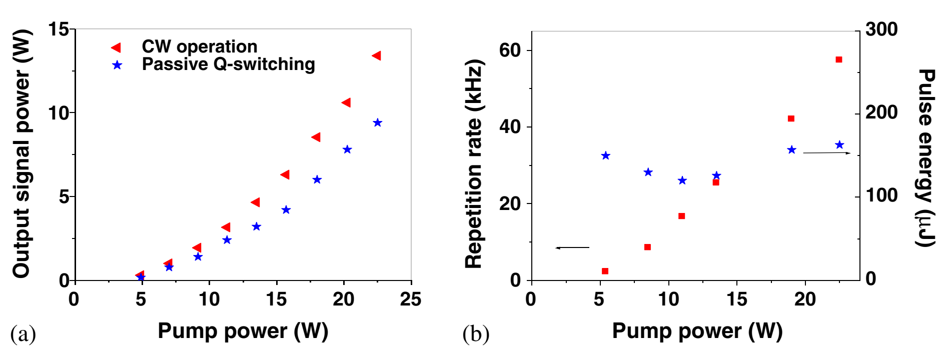


Figure 2. (**a**) Average output power with respect to the launched pump power in CW and passive Q-switching operations. (**b**) Pulse repetition rate and pulse energy vs. launched pump power.

achieved in passive Q-switched laser should remain constant for fixed choice of the saturable absorber and output coupler mirror. However, from figure 2b it can be seen that pulse energy varies from 120 μJ to 160 μJ with increase in pump power. The observed variation in the pulse energy can be attributed to the effect of self-pulsing phenomenon in Yb-doped PCF.

Figure 3a shows oscilloscope trace for single pulse at maximum value of pump power. Figure 3b shows the Q-switched pulse train at the same value of pump power with the repetition rate of 57.4 kHz. Pulse to pulse energy change may be attributed to the self-pulsing phenomena occurring inside the fibre laser which itself generates random pulses due to saturable absorption taking place inside the gain medium. Self-pulsing may also lead to jitter in the repetition rate of the pulses.

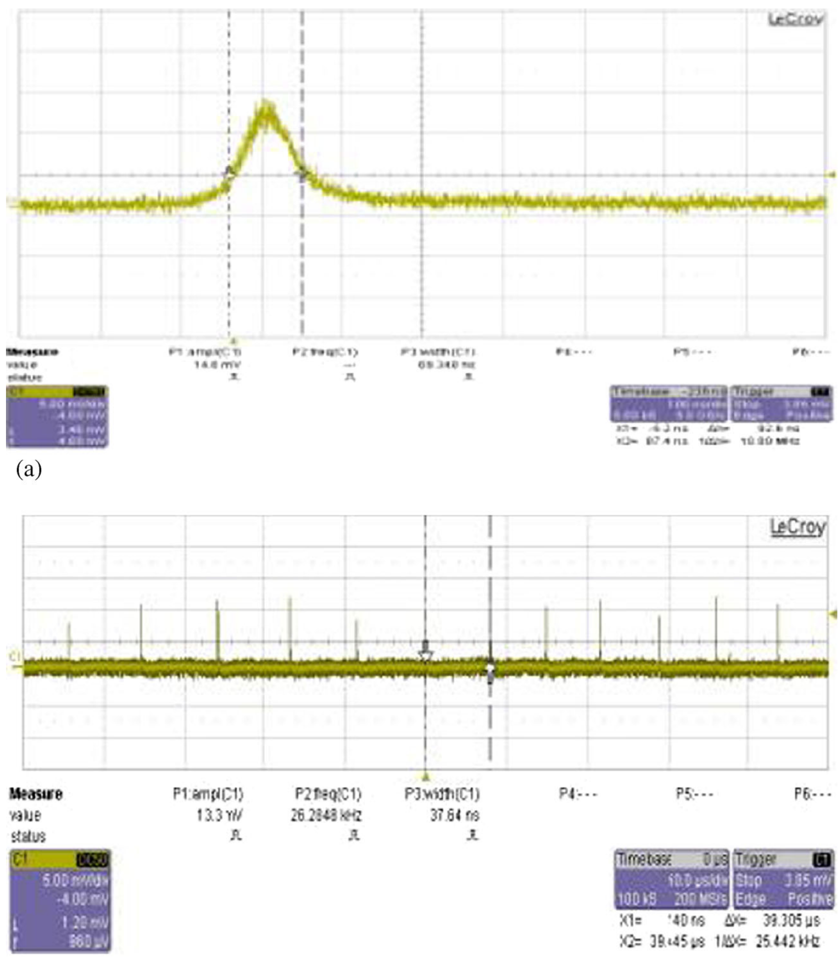


Figure 3. Typical oscilloscope traces for (**a**) single Q-switched pulse, (**b**) train of Q-switched pulses.

These kinds of fluctuations were also reported by various authors in Cr^{4+}:YAG crystal and AlGaInAs QWs structures as passive Q-switches [4]. It is expected that uniform pumping inside the fibre laser will form stable pulses in passive Q-switching.

4. Conclusion

In conclusion, we have demonstrated passive Q-switching in Yb-doped PCF laser with an average power of 9.4 W at 22.5 W pump power. Output power was limited by the available pump power. Further studies will be performed to obtain stable pulses by removing the self-pulsing phenomena in Yb-doped PCF laser.

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