A Q-switched fibre laser operating in the 2 μm region based on nonlinear polarization rotation technique

[1, 2] Azooz S. M., [1, 2] Harun S. W., [2] Ahmad H., [3] Halder A., [3] Paul M. C., [3] Das S. and [3] Bhadra S. K.

[1] Department of Electrical Engineering, Faculty of Engineering, University of Malaya 50603 Kuala Lumpur Malaysia, swharun@um.edu.my
[2] Photonics Research Centre, University of Malaya 50603 Kuala Lumpur, Malaysia
[3] Fiber Optics and Photonics Division, Central Glass & Ceramic Research Institute, CSIR, Kolkata, India, paulmukul@hotmail.com

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Abstract. We demonstrate a Q-switched fibre laser operating at 1949.0 nm, which is based on a nonlinear polarization rotation (NPR) technique. It uses a 2 m long commercial thulium-doped fibre and a 15 m long homemade thulium–ytterbium co-doped fibre as active media. They are pumped respectively by 800 nm single-mode and 905 nm multimode radiations. A stable Q-switched pulse train with the repetition rate 13.49 kHz and the pulse width 3.089 μs is obtained when the 905 nm and 800 nm pump powers are fixed at 2.3 W and 110.4 mW, respectively. The maximum pulse energy, 11 nJ, is obtained at the 800 nm and 905 nm pump powers equal respectively to 110.4 mW and 2.5 W. To the best of our knowledge, this is the first reported Q-switched fibre laser using the NPR technique.

Keywords: 2 μm Q-switched fibre lasers, thulium-ytterbium co-doped fibres, nonlinear polarization rotation

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1. Introduction

Recently there has been growing interests in compact 2 micron Q-switched laser sources. These are mainly driven mainly by applications in spectroscopy, sensing, medicine, and nonlinear optical optics research [1– 4]. Unlike an active Q-switching [5], passive Q-switching is a more convenient and cost-effective way to achieve high-energy pulses, because it does not require additional switching electronics [6, 7]. When compared with lasers based on bulk gain media, a fibre laser format offers distinct advantages, including a small footprint, robust beam confinement and an environmental stability. A thulium-doped silica fibre (TDF) represents a promising two-micron gain material. It exhibits high quantum efficiency and a broad gain spectrum extending from 1.8 to 2.1 μm [3]. Passive Q-switching of Tm fibre lasers has already been implemented, using a number of techniques, including multiple quantum wells [8] and Cr:ZnS or Cr:ZnSe crystals [9, 10]. However, all of these implementations require additional bulk components such as mirrors or lens pairs, thus compromising the key benefits of fibre lasers, their compactness and alignment-free operation.

Nonlinear polarisation rotation (NPR) effect in fibre laser cavities has also been widely used to initiate and shape the pulses, especially in mode-locked fibre lasers. In fact, the NPR technique can produce intensity-dependent optical transmission by a self-phase modulation mechanism, thus providing an artificial saturable absorption effect in fibre ring lasers [11]. The saturable absorption strength can be adjusted by simply rotating a polarization controller. In this article, we report for the first time a passively Q-switched all-fibre ring laser which operates in the near 2 μm region and is based on the NPR technique.

2. Configuration of our Q-switched laser

A scheme of a 2 μm Q-switched fibre laser suggested by us is shown in Fig. 1. It is constructed using a simple ring cavity, in which a 2 m long commercial thulium-doped fibre (TDF) and a 15 m long homemade thulium–ytterbium co-doped fibre (TYDF) serve as active media. The TDF is pumped by a 800 nm laser diode via an 800/2000 nm wavelength division multiplexer, while the TYDF is pumped by a 905 nm multimode laser diode via a multimode combiner (MMC). The MMC functions to send radiation from the multimode laser diode into the inner cladding of a double-clad active fibre. The TDF has the core and cladding diameters respectively 9 and 125 μm, the losses less than 0.2 dB/km at 1900 nm and the Tm-ion absorption equal to 27 dB/m at 793 nm.

The homemade TYDF has an octagonally shaped, double-clad structure. It is drawn from a lithium-alumino-germano-silicate core glass optical preform, which has been fabricated with a modified chemical vapour deposition technique, followed by a solution doping technique. The preform consists of Al_2O_3, Y_2O_3, Tm_2O_3 and Yb_2O_3 dopants with the average weight percentages

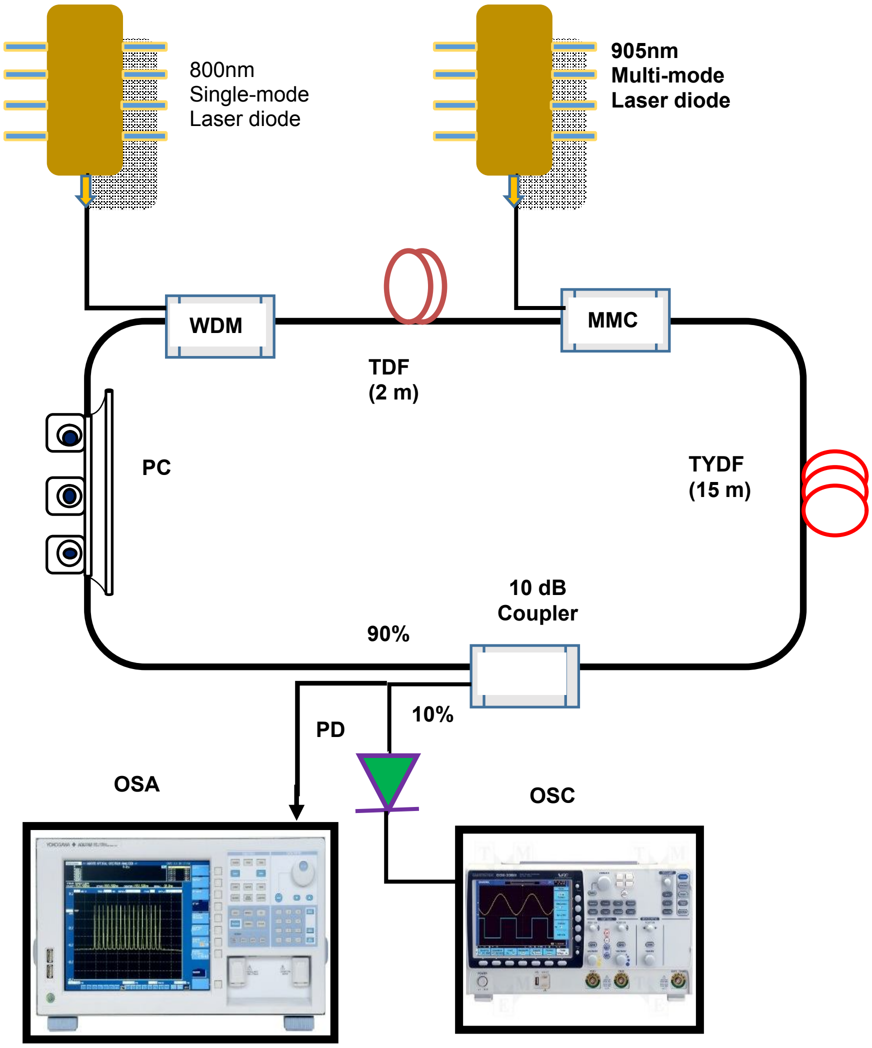

Fig. 1. Schematic configuration of our NPR-based Q-switched fibre laser operating in the 1950 nm region: WDM – wavelength division multiplexer, MMC – multimode combiner, PD – photodetector, OSC – oscilloscope, and OSA – optical spectrum analyser.

5.5, 3.30, 0.70 and 4.0, respectively. The octagonal geometry of the cladding improves the pump absorption efficiency. The doping levels of Tm^{3+} and Yb^{3+} ions for our TYDF have been measured using an electron probe micro-analyser. They are close to 4.85×10^{19} and 27.3×10^{19} ions/cc, respectively. The NA and the core diameter of the TYDF are 0.23 and 5.96 μm, respectively.

The both gain media are cascaded to produce an amplified spontaneous emission near 1950 nm. The pigtails of the optical components have been spliced using a commercially available fusion splicer. A polarisation controller (PC) is employed in the laser cavity to adjust the polarization state of circulating light. This allows for generating a Q-switched pulse in the cavity based on the NPR effect. The basic principle responsible to the Q-switching is associated with the Kerr effect through the NPR. The polarization of light having passed through the PC is rotated inside the first gain medium (i.e., the TDF) due to the Kerr effect. By adjusting the orientation of all three coils inside the PC, one can adjust the cavity such that the maximum optical transmission (and the minimum loss) at the MMC occurs for the highest possible optical intensity. Hence we arrive at an artificial saturable absorber

The laser output is taken by a 10% port of an output coupler. An optical spectrum analyser and an oscilloscope behind the output coupler are used to study the pulse spectrum and the output pulse train, respectively. The output power is measured by an optical power meter. To avoid passive mode-locking in our fibre laser, we intentionally employ a cascaded gain medium while imposing large splicing losses in the laser cavity. It has also been found that the NPR-based Q-switching lasing can be achieved with no polarization-dependent isolator involved in the laser cavity.

3. Results and discussion

As stressed above, we have used the NPR technique for achieving passively Q-switched operation in our fibre laser. After the PC is adjusted, the MMC becomes an artificial saturable absorber, due to the NPR effect, with the intensity-dependent transmission. Then the intense light wave can pass through the MMC and the weak wave becomes reflected. In the experiment, the 800 nm pump power has always been fixed at 110.4 mW. When the 905 nm multimode pump power is increased up to about 2 W, the Q-switched pulses are always observed whenever the polarization plane is properly rotated by the PC. A stable Q-switched operation commences from modulation of the population inversion induced by a phase modulation of the laser cavity, which consists of the PC, the MMC and the gain media revealing high birefringences. The Q-switched pulse is initiated when the PC is regulated so that the cavity loss is high enough. Under this condition, the lasing radiation is weak whereby it encounters a very small polarization rotation. This weak radiation could not pass through the MMC and is blocked from circulating in the cavity. Concurrently, the inversion population would appear as the pumping continues and the gain of the cavity builds up. After some duration, optical amplification due to stimulated emission finally begins. At this time, the radiation becomes strong enough to pass through the polarizer where the loss of the cavity decreases abruptly and the population inversion depletes quickly. So a Q-switched pulse is being formed. The Q-switching operation is maintained when the pump power is further increased (up to 2.5 W). However, the pulse train disappears as the multimode pump power is increased above 2.5 W.

Fig. 2 shows the optical spectrum of our Q-switched laser, as obtained at the 905 nm pump power of 2.3 W. It operates at 1949.0 nm, with the signal-to-noise ratio being more than 36 dB. The corresponding typical Q-switched pulse train is presented in Fig. 3. Here the repetition rate is 13.49 kHz. The pulse duration, which is measured directly from the oscilloscope, is about 3.089 μs. In order to further investigate the characteristics of the output Q-switched pulses, we have fixed the orientation of the PC and changed only the 905 nm pump power (from 2.0 to 2.5 W), while keeping the 800 nm pump power stable at 110.4 mW. Fig. 4 presents the pulse repetition rate under the Q-switched operation and the pulse width as functions of the pump power. Like with any typical Q-switched fibre lasers, the pulse repetition rate increases (from 6.36 to 16.45 kHz) with increasing pump power (from 2.0 to 2.5 W). On the contrary, the pulse width then decreases from 7.82 to 2.93 μs. This effect is due to gain compression in the Q-switched fibre laser [12].

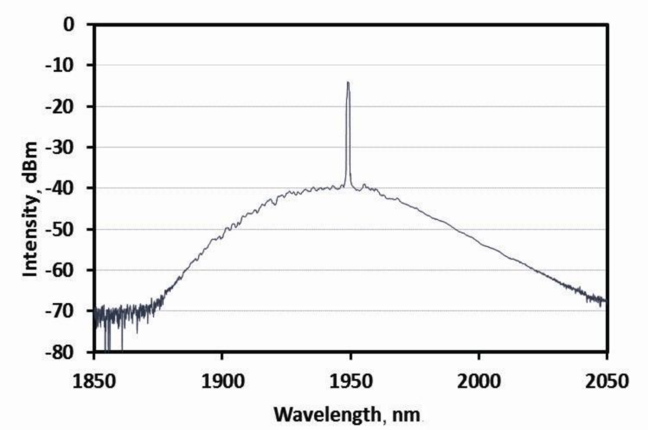

Fig. 2. Output spectrum of our NPR-based Q-switched fibre laser.

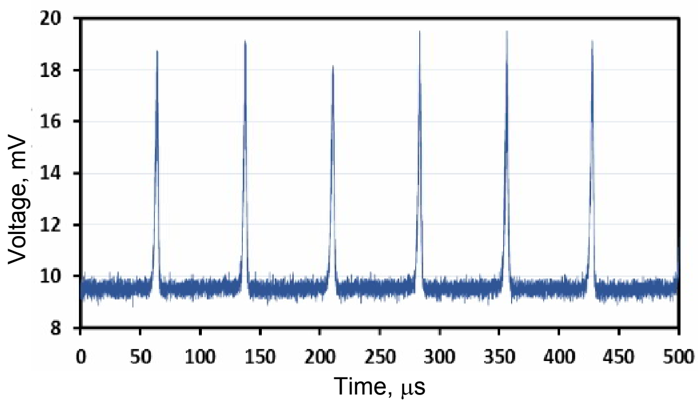

Fig. 3. Typical pulse train of our NPR-based Q-switched fibre laser, as measured with the 800 nm and 905 nm pump powers equal to 110.4 mW and 2.3 W, respectively.

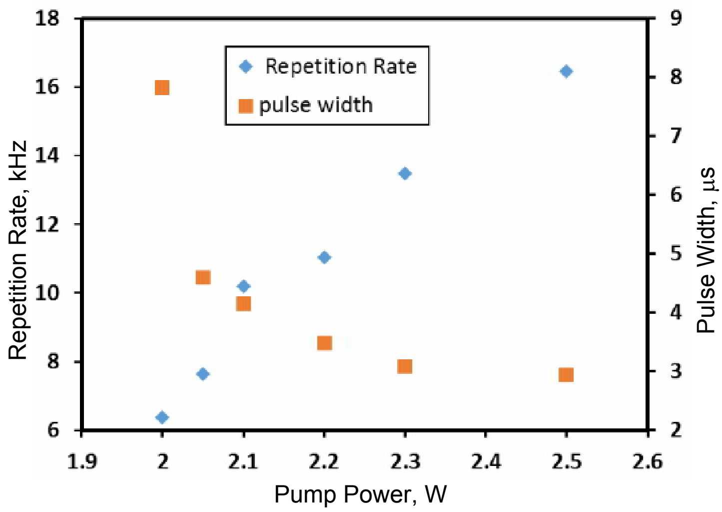

Fig. 4. Dependences of repetition rate and Q-switched pulse width on the pump power.

Fig. 5 shows the dependences of the average output power and the pulse energy of our Q-switched laser upon the 905 nm pump power. In the present experiment, the 800 nm pump power has been fixed at 110.4 mW. Both the output power and the pulse energy increase almost linearly with increasing pump power. The maximum pulse energy, 11 nJ, is obtained at the single-mode and multimode pump powers equal to 110.4 mW and 2.5 W, respectively. We believe that further optimization of the cavity parameters should significantly enhance the Q-switching performance.

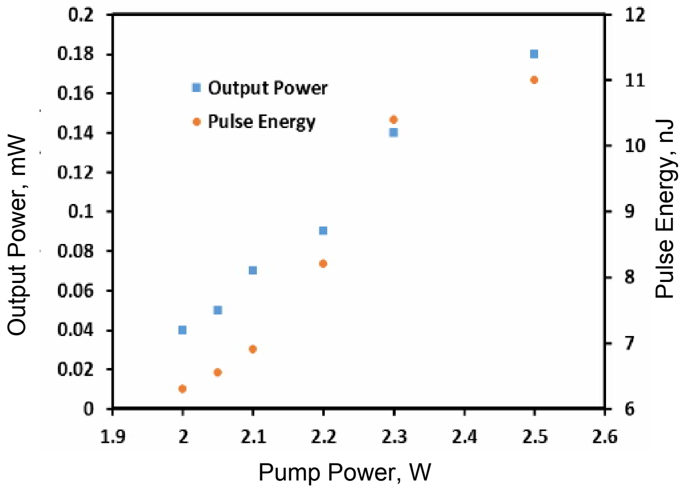

Fig. 5. Average output power and pulse energy as functions of the pump power.

4. Conclusion

We have developed a passively Q-switched fibre laser at 1949.0 nm and demonstrated its successful operation. The laser employs a commercial TDF and a homemade double-clad TYDF as gain media in a ring configuration. Our laser is based on the NPR technique. Its cavity consists of a 2 m long TDF and a 15 m long TYDF which are pumped respectively by single-mode (800 nm) and multimode (905 nm) radiations. The two gain media and a multimode combiner work as an artificial saturable absorber, which enables intensity-dependent optical transmission of the cavity for the Q-switching. The Q-switched laser suggested in this work produces a stable pulse train with the repetition rate 13.49 kHz and the pulse width 3.089 s, when the 905 nm and 800 nm pump powers are fixed at 2.3 W and 110.4 mW, respectively. The maximum pulse energy of the Q-switched laser is obtained at 11 nJ.

Acknowledgements

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Анотація. *Продемонстровано функціонування волоконного лазера з модульованою добротністю на основі нелінійного повертання площини поляризації, який випромінює на довжині хвилі 1949,0 нм. Лазер працює на легованому тулієм волокні завдовжки 2 м і виготовленому в лабораторних умовах волокні, легованому тулієм і ербієм завдовжки 15 м. Волокна нагнітають відповідно одномодовим випромінюванням з довжиною хвилі 800 нм і багатомодовим з довжиною хвилі 905 нм. Отримано стабільний цуґ із модульованою добротністю, з частотою слідування 13,49 кГц і шириною імпульсу 3,089 мкс за умов нагнітання випромінюванням з потужностями 2,3 Вт і 110,4 мВт відповідно на 905 нм і 800 нм. Максимальну енергію імпульсу 11 нДж отримано з нагнітанням 110,4 мВт на 800 нм і 2,5 Вт на 905 нм. Наскільки нам відомо, в цій роботі вперше запропоновано волоконний лазер із модульованою добротністю з використанням нелінійного повертання площини поляризації.*