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# *Q*-switched and mode-locked $Er^{3+}$-doped fibre laser using a single-multi-single fibre filter and piezoelectric

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***Abstract.*** **The active *Q*-switched and passive mode-locked $Er^{3+}$-doped all-fibre laser is presented. The fibre laser centre wavelength is located at 1563 nm and determined by the homemade single-multi-single (SMS) in-line fibre filter. The laser spectrum width is nearly 0.1 nm. The active *Q*-switched mechanism relies on the polarisation state control using a piezoelectric to press a segment of passive fibre on the circular cavity. The nonlinear polarisation rotation technology is used to realise the passive self-started mode-locked operation. In the passive mode-locked regimes, the output average power is 2.1 mW, repetition frequency is 11.96 MHz, and single pulse energy is 0.18 nJ. With the 100-Hz *Q*-switched regimes running, the output average power is 1.5 mW. The total *Q*-switched pulse width is 15 μs, and every *Q*-switched pulse is made up by several tens of mode-locked peak pulses. The calculated output pulse energy of the *Q*-switched fibre laser is about 15 μJ, and the energy of every mode-locked pulse is about 64 – 68 nJ during a *Q*-switched pulse taking into account the power fraction propagating between pulses.**

***Keywords:*** *fibre laser, mode-locking and Q-switching, multi-mode interference filter.*

## 1. Introduction

Interest in self-started fibre lasers with mode locking implemented due to the nonlinear polarisation rotation is explained by the advantages attributed to their in-line all-fibre structure, low repetition rate, ultra-broadband spectrum and high-energy [1 – 3]. The fibre nonlinear Kerr effect and fibre dissipative soliton formation are the intrinsic mechanisms for the self-started nonlinear polarisation rotation mode-locked lasers [4, 5]. As compared to mode-locked fibre lasers, *Q*-switched fibre lasers have higher energy optical pulses and a large pulse width [6 – 8]. Combining the advantages of both *Q*-switched and mode-locked (QML) laser technology, a fibre laser can have a superior performance of a higher pulse energy and narrower pulse width, compared to conventional QML fibre lasers [9, 10]. Based on the multimode interference reimaging phenomenon, a fibre multi-mode interference filter has a simple in-line single-multi-single (SMS) all-fibre structure and is easily fabricated [11, 12]. The SMS filter has been successful used in a fibre laser to acquire a narrow linewidth [13, 14].

We report an active *Q*-switched and passive mode-locked all-fibre $Er^{3+}$-doped fibre laser. The mode-locked pulse energy increases by hundreds of times when *Q*-switched technology is used. The fibre laser has a circular cavity, and the mode-locking is based on the nonlinear polarisation rotation technology. A quick response piezoelectric is used to achieve *Q*-switching by pressing a segment of fibre to change the polarisation state. In the circular cavity, we used a homemade multimode interference filter to determine the centre wavelength of the fibre laser.

## 2. Experimental setup

The setup of the active *Q*-switched and passive mode-locked $Er^{3+}$-doped all-fibre laser is shown in Fig. 1. It is composed of a 6-m-long $Er^{3+}$-doped fibre, two polarisation controllers (PCs), a SMS fibre filter, a polarisation sensitive isolator (PSI), a single-mode 973-nm laser diode (LD) used as a pump source, and a quick response piezoelectric. The SMS fibre filter is homemade using a 12-mm-long 62.5/125-μm multimode fibre and a SMF-28 single-mode fibre. The pump 973-nm single-mode LD has a maximal output power of 150 mW. The single mode $Er^{3+}$-doped fibre has a 5 dB $m^{-1}$ absorption at 973 nm. The piezoelectric driver system has a signal generator and amplifier, which can make the peak voltage reach nearly 200 V, and the piezoelectric itself has the dimension of 3×3×15 mm and produces a maximal 11-μm stretching variable quantity. Except the $Er^{3+}$-doped fibre, all of the left passive fibre is SMF-28 fibre.

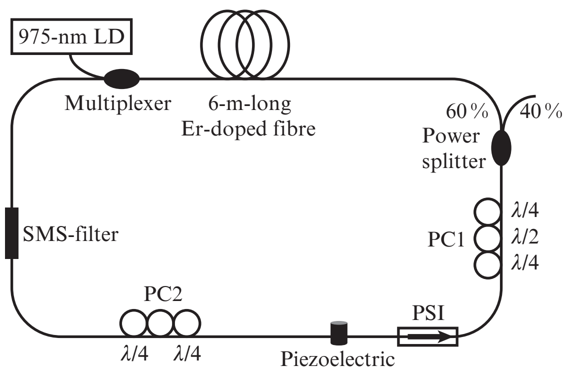


**Figure 1.** Experiment setup of a *Q*-switched and mode-locked narrow linewidth $Er^{3+}$-doped fibre laser.

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The $Q$-switched scheme is shown in Fig. 2. Before the piezoelectric starts operating, the pressed SMF-28 fibre segment is polarised, but the polarised orientation differs from the mode-locked laser's. Thus, the pressed SMF-28 fibre segment has a high polarised loss, and the fibre laser has no output power. When the piezoelectric is rapidly elongated, the pressed SMF-28 fibre segment recovers its original shape, the polarised loss disappears, and the fibre laser generates a $Q$-switched pulse output.

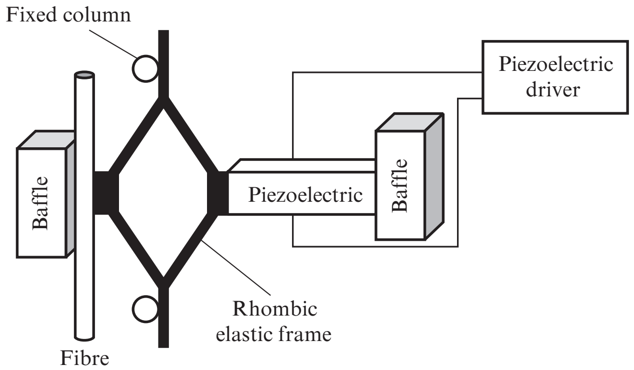


**Figure 2.** Scheme of fibre-laser $Q$-switching using a piezoelectric.

## 3. Experimental results

For the self-started mode-locked operation, precise adjustment of two polarisation controllers is required. The train of self-started mode-locked $Er^{3+}$-doped fibre laser output pulses is shown in Fig. 3. The mode-locked pulse train has a repetition rate of 11.96 MHz and a pulse width of 7.4 ns. The repetition rate is determined by a round trip time of the laser in the circular cavity. The large (7.4 ns) pulse width should be broadened by the relative slow response time of the InGaAs detector, which has a relative slow response speed of only 100 MHz. The output laser spectrum, measured by a Co. EXFO 1500 laser wavemeter, is shown in Fig. 4. The laser spectrum width is nearly 0.1 nm. The SMS filter determines the centre wavelength of the fibre laser. With the 973-nm pump power of 150 mW, the mode-locked fibre laser output average power is nearly 2.1 mW, such that the single pulse

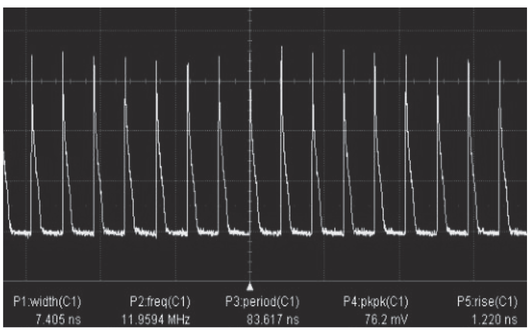


**Figure 3.** Train of output pulses from a mode-locked $Er^{3+}$-doped fibre laser.

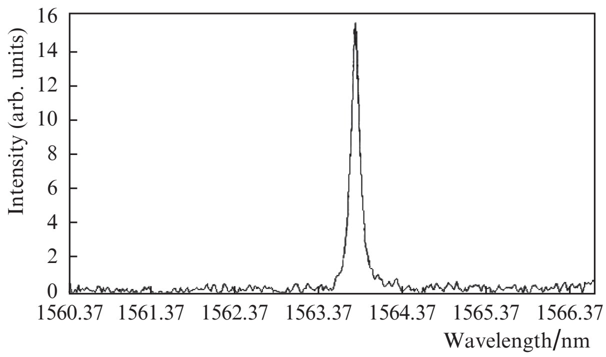


**Figure 4.** Output laser spectrum from the mode-locked $Er^{3+}$-doped fibre laser using an SMS filter.

energy should be 0.18 nJ. This relative low efficiency should be due to the high loss of the SMS filter.

The train of $Q$-switched laser pulses as a result of a quick response of the piezoelectric is shown in Fig. 5a. The total laser pulse width is a little less than 15 μs (Fig. 5b), and every $Q$-switched pulse contains several tens of mode-locked peak pulses. The $Q$-switched pulse repetition rate is only 100 Hz, and at this rate the output pulse train is relative stable. The $Q$-switched output average power is 1.5 mW. Thus, the $Q$-switched pulse energy is 15 mJ. If the mode-locked peak pulses in a $Q$-switched pulse are supposed to be coincident, the estimated QML single peak pulse energy is about 64–68 nJ during a $Q$-switched pulse with the power fraction of 20%–25%. During the QML pulse, the middle mode-locked peak pulse has a much higher energy than the marginal peak pulses.

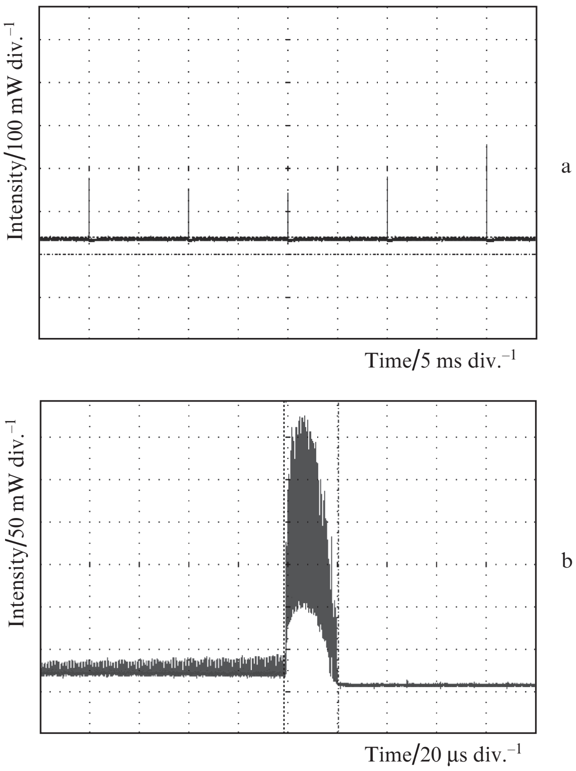


**Figure 5.** (a) Train of QML fibre laser pulses and (b) pulse shape of generated radiation.

## 4. Conclusions

The all-fibre QML $Er^{3+}$-doped fibre laser is demonstrated. The nonlinear polarisation rotation mode-locked technology, piezoelectric pressing *Q*-switched method and SMS filter structure are all realised in in-line all-fibre elements; the scheme makes this fibre laser simple, compact and cheap. The mode-locked pulse energy increases by nearly 350 times using the *Q*-switched technology, and the repetition rate is also reduced. Because our lab has no 1.5-μm autocorrelation function analyser, the pulse duration was measured using a quick response InGaAs detector. As a result, the actual pulse duration should be equal to the measured one or shorter than the measured one. This *Q*-switched and mode-locked pulse wave profile is similar to a train of short pulses. If the mode-locked repetition rate is lowered to 100 kHz by increasing the circular cavity length [3], the single pulse output should be feasible when use id made of this QML fibre laser scheme.

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