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Repetitively pulsed holmium fibre laser with an intracavity Mach–Zehnder modulator

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Abstract. **This paper reports an all-fibre active *Q*-switching scheme for a holmium fibre laser. We have obtained repetitively pulsed lasing at a wavelength of 2098 nm with pulse durations from 0.8 to 1.56 μs, repetition rates of 11.2 and 22.4 kHz, a maximum peak power of 3.9 W and pulse energy of ~3.5 μJ.**

Keywords: *holmium fibre laser, Q-switching, Mach–Zehnder modulator.*

1. Introduction

Q-switched fibre lasers emitting in the 2 μm spectral region are potentially attractive for use in medicine, laser ranging, materials processing, nonlinear optics and other areas [1, 2]. The longest lasing wavelength, 2.2 μm, in silica fibre-based lasers is reached in the case of holmium-doped fibre lasers [3]. One of the most widespread approaches for generating high-energy pulses is laser cavity *Q*-switching, which allows the laser pulse peak power to be raised by approximately a factor of τ_{sp}/τ_c (where τ_{sp} is the upper laser level lifetime and τ_c is the cavity photon lifetime).

To ensure *Q*-switching in holmium fibre lasers, Sholokhov et al. [4] used holmium-doped fibre saturable absorbers with a high active-ion concentration, but the pulse trains obtained were irregular. The use of passive laser switches (PLS's) based on semiconductor saturable absorber mirrors (SESAMs) or single-walled carbon nanotubes (SWCNTs) ensures stable lasing, but in the laser *Q*-switching regime they limit the pulse energy on account of optical damage. Pulsed lasing in holmium fibre lasers was observed as well in the case of self-*Q*-switching [5–7], which was attributed to active-ion clustering in such fibres at high dopant concentrations [8].

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The most convenient approach to fibre laser *Q*-switching is the use of integrated acousto-optic and electro-optic modulators with a fibre input and fibre output [9]. Such devices are hybrid fibre lasers with modulators in which collimators are used for light incoupling and outcoupling [10]. These components are readily available for ytterbium and erbium fibre lasers operating in the 1- and 1.5-μm ranges, respectively. A different situation occurs with components for holmium fibre lasers operating at 2 μm or a longer wavelength, for which modulators are less available.

In this paper, we report a simple, all-fibre *Q*-switched laser design [11] suitable for operation in the wide transmission window of silica fibre: from 1 to 2.2 μm.

2. Experimental setup

Figure 1 shows a schematic of the experimental setup. A 4.5-m length of holmium-doped fibre was used as the gain medium of the laser. The fibre core diameter was 16 μm and the core–cladding refractive index difference was 0.004. Ho^{3+} concentration was 2×10^{19} cm^{-3} and absorption at a wavelength of 1125 nm was 4.7 dB m^{-1}. The gain medium was optically pumped by a cw ytterbium fibre laser emitting at a wavelength of 1125 nm with a peak power of 10 W. The pump light was launched into the fibre through a fibre Bragg grating (FBG) with high reflectivity (99%) at a wavelength of 2098 nm.

As the output coupler of the holmium fibre laser cavity, we used a connector with a perpendicularly cleaved, polished end facet (Fresnel reflection coefficient of 4%). In addition to the active fibre, the laser cavity contained an all-fibre modulator in the Mach–Zehnder interferometer configuration. The modulator consisted of two 50/50 fibre couplers for λ = 2100 nm and two 6-m arms – active and passive. The active arm included a phase modulator formed by fibre wound onto a piezoceramic cylinder. The fibre winding diameter was 8.5 cm in both arms. All the components were made of SMF 28 optical fibre.

A triangular voltage wave from a pulse generator was applied to the phase modulator. The amplitude of the electric control signal was varied from 4 to 10 V. If an ac voltage is applied to a piezoceramic, the geometric dimensions of the cylinder vary periodically due to the inverse piezoelectric effect. This causes a change in the optical path length in the active arm and, accordingly, phase modulation of the light. Phase modulation in one arm of the Mach–Zehnder interferometer leads to amplitude modulation of the light intensity at the interferometer output. Thus, a fibre-optic Mach–Zehnder modulator placed in the cavity of a holmium fibre laser modulates the cavity *Q*.

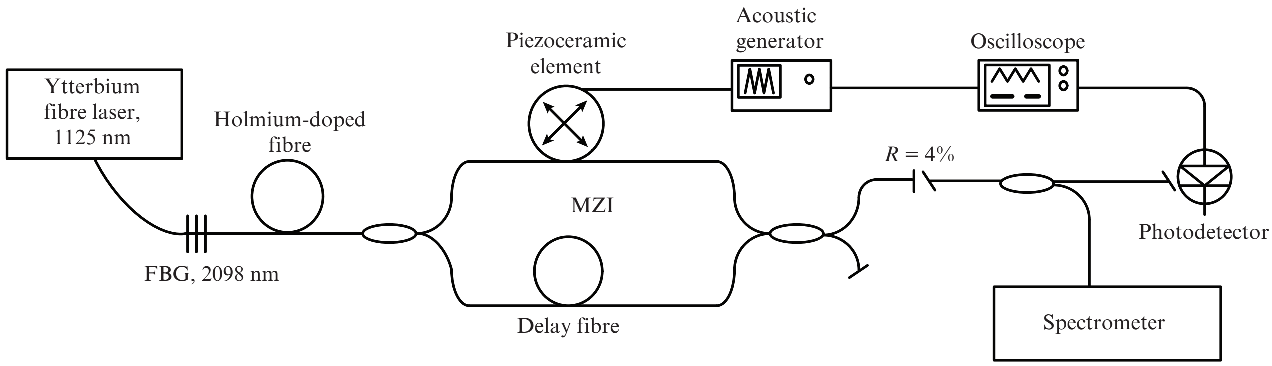

Figure 1. Schematic of the holmium fibre laser with an intracavity Mach–Zehnder modulator (MZI).

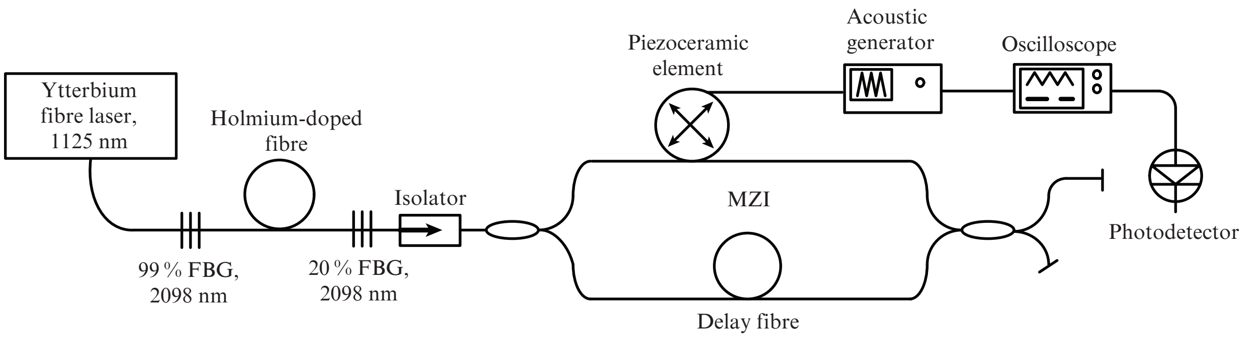

Figure 2. Schematic of the experimental setup used to measure the transfer function of the Mach–Zehnder modulator.

Figure 2 shows a schematic of the setup used to measure the transfer function of the Mach–Zehnder modulator. As a signal source, we used a cw holmium fibre laser with a centre wavelength of 2098 nm. To prevent additional feedback between the laser and modulator, a fibre isolator was placed after the output coupler.

Temporal characteristics of the fibre laser in the active Q-switching regime were studied using a photodetector with a bandwidth of 250 MHz and a matched oscilloscope. The output emission spectrum was analysed by an Avesta ASP-IR-2.6 spectrometer.

3. Experimental results and discussion

The transfer function of the Mach–Zehnder modulator was investigated at voltage amplitudes from 4 to 10 V. Figure 3 shows transfer functions and the corresponding signals applied to the piezoceramic cylinder. It is seen that the transmission of the modulator ranges from 10% to 90%, which may be due to the absence of polarisation controllers. Since the transfer functions have several maxima and minima during the control voltage period, it is reasonable to think that, at the highest voltage, the path difference between the interferometer arms exceeds several wavelengths.

If no control voltage was applied to the phase modulator, the output power was randomly modulated (Fig. 4a) throughout the range of pump powers studied (1–3.5 W). The threshold pump power was 1 W. Stable repetitively pulsed lasing was achieved if a periodic voltage was applied to the phase modulator and the pump power was between 1.8 and 2.9 W.

Figures 4b and 4c (left panels) show oscilloscope traces of signals from the photodetector at the fibre laser output. At a pump power of 1.8 W (Fig. 4b), the pulse repetition frequency coincides with the modulation voltage frequency. The average output power was 30 mW at a pulse duration of 0.8 μs. If a modulation voltage was applied to the phase modulator, the emission spectrum had a complex, jagged shape, with a centre wavelength corresponding to the peak reflectivity of the FBG. Raising the pump power from 1.8 to 2.9 W led to an increase in the peak power of the fibre laser from 2.6 to 3.9 W and a

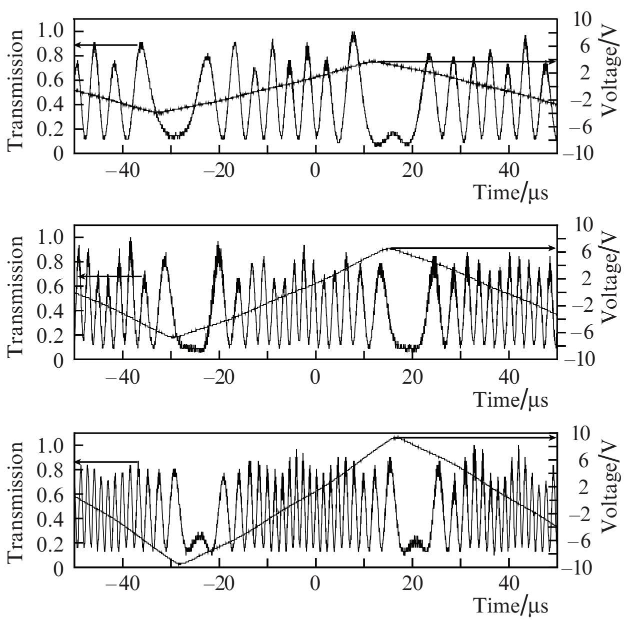

Figure 3. Transfer functions of the Mach–Zehnder modulator and the corresponding voltage signals applied to the piezoceramic cylinder.

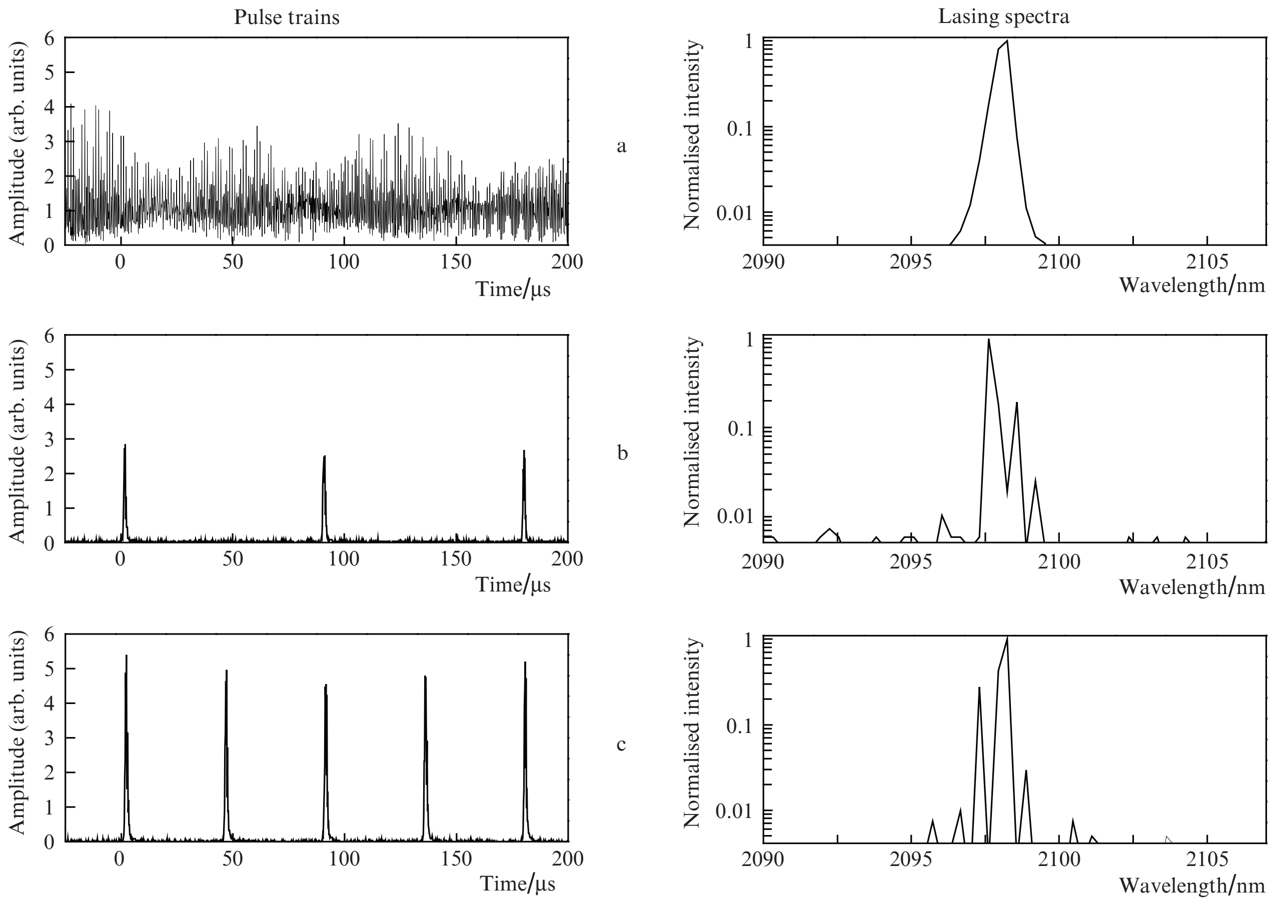

Figure 4. Pulse trains of the repetitively pulsed holmium fibre laser (left panels) and laser emission spectra (right panels) at (a) zero modulation voltage and a pump power of 1.8 W, (b) a 10-V amplitude of the voltage applied to the modulator and a pump power of 1.8 W and (c) a 10-V amplitude of the voltage applied to the modulator and a pump power of 2.9 W.

twofold increase in pulse repetition rate (Fig. 4c). Under these conditions, the average power was 78 mW, the pulse duration was 0.9 μs, and the emission spectrum also had a complex structure. The modulation voltage parameters were not changed: the voltage amplitude was 10 V and the modulation frequency was 11.2 kHz.

We also examined the effect of the modulation voltage amplitude in the range 4–10 V on the pulse shape. The output power of the ytterbium fibre laser used for pumping was constant at 1.8 W, and the modulation frequency was 11.2 kHz. Figure 5 shows pulse shapes at four different voltages applied to the piezoceramic. It is seen that, with increasing control voltage amplitude, the pulse duration decreases from 1.56 to 0.8 μs and the peak power rises from 1.2 to 3.09 W. The above results can be accounted for by the fact that, in our experiments, the *Q*-switching time is of the same order as the pulse duration. As a result, the pulse amplitude and duration depend on the *Q*-switching rate. Increasing the amplitude of the modulation voltage applied to the piezoceramic reduces the *Q*-switching time of the Mach–Zehnder modulator, thereby increasing the amplitude of the laser pulses being generated and reducing their duration.

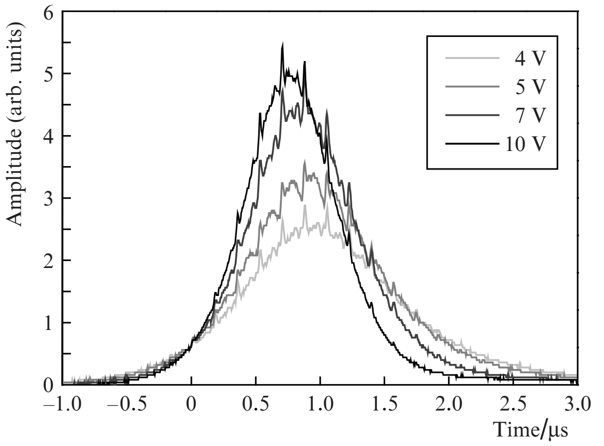

Figure 5. Effect of the modulation voltage amplitude on output pulse parameters.

4. Conclusions

An approach has been proposed for the *Q*-switching of a holmium fibre laser using an intracavity fibre modulator formed by a Mach–Zehnder interferometer in which the optical length of one of its arms is controlled by an ac voltage applied to a piezoceramic element.

We have detected pulses with a duration of 0.9 μs and peak power of 3.9 W. Therefore, at a fibre laser wavelength of 2098 nm, the *Q*-switching pulse energy reaches 3.5 μJ. The shortest pulse duration obtained is 0.8 μs. Thus, we have demonstrated laser parameters comparable to those of lasers *Q*-switched using other, more complex methods. The proposed *Q*-switching method offers greater possibilities for controlling the laser pulse repetition rate (especially at low frequencies) than does self-*Q*-switching, where a laser operates in a relatively narrow frequency range (100–500 kHz). Moreover, the pulse duration can also be controlled. In addition, the proposed configuration is preferable to a scheme with standard electro-optic modulators in terms of availability and ease of control in resolving certain issues, because a simple analog triangular pulse generator is sufficient for controlling the piezoceramic. Nevertheless, this scheme requires optimisation, including the possibility of controlling the polarisation of the modulator arms, which may ensure an increase in the peak power of the laser.

In the future, we will be able to incorporate holmium fibre lasers utilising the proposed *Q*-switching method into laser systems for positioning, surface scanning and range-finding.

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