Birefringent-filter-assisted actively Q-switched tuneable erbium-doped fibre ring laser

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ABSTRACT

We report the performance of a narrow-linewidth, actively Q-switched erbium-doped fibre ring laser emitting at ~1.55 µm. An investigation into the behaviour of a cascaded comb and tuneable filter system was carried out using a length of polarisation-maintaining fibre as a Lyot filter. The resulting comb filter was used to suppress competing modes, and the addition of a tuneable filter allowed wavelength tuning over 33 nm. Proper adjustment of the spectral overlap of the cascaded filters allowed the linewidth to be reduced to 65 pm (8 GHz). Q-switching was achieved using an acousto-optic modulator, providing stable pulses at repetition frequencies between 9 kHz and 166 kHz, with a minimum pulse length of 400 ns. These results demonstrate the feasibility of such a system for use in a narrow-linewidth, tuneable laser.

Keywords: erbium-doped fibre laser, Lyot filter, Q-switching

1. INTRODUCTION

Pulsed narrow-linewidth erbium-doped fibre (EDF) lasers operating between 1.5 and 1.6 µm with good atmospheric transmission are attractive for applications such as remote sensing and optical metrology [1]. The EDF gain medium is spectrally broad, resulting in intrinsically broadline emission. This includes Q-switched lasers for high-energy pulses, in which the laser output including spectrum builds up in a few roundtrips. Several techniques have been adopted to reduce the emission linewidth from EDF lasers, such as the use of Fabry-Perot filters [2], tapered comb filters [3], and Sagnac loop filters [4]. By cascading a comb filter with a tuneable filter in a ring cavity, improvements in stability have been combined with the selection of a range of narrow emission peaks.

This paper presents an erbium-doped fibre ring laser employing a narrow-line all-fibre Lyot filter cascaded with a spectrally-broader tuneable diffraction grating filter to generate narrow-line wavelength-tuneable pulses. The laser was actively Q-switched by an acousto-optic modulator (AOM).

2. ALL-FIBRE NARROW-LINE LYOT FILTER

A Lyot filter exploits the phase delay between light propagating along the fast and slow axes of a birefringent medium to produce a periodically wavelength-dependent state of polarisation and thus transmission through a polariser for light at a wavelength λ. In our case the birefringent medium is a polarisation-maintaining fibre with birefringent coefficient B and length L. Following propagation through the fibre and polariser, the spectral beat period $\Delta\lambda$ of the transmission becomes [5].

$\Delta\lambda = \lambda^2 / (L\,B)$ Eq. (1).

If linearly polarised light launched into the birefringent fibre and the subsequent polariser are both angled at 45° to the fibre's birefringence axes then the transmission varies sinusoidally with wavelength between 0 and 100%, ideally. The transmission T is then defined by Equation 2, where λ_0 is a transmission-peak wavelength.

$T = \cos^2(\pi\,(\lambda - \lambda_0) / \Delta\lambda)$ Eq. (2).

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3. EXPERIMENTAL SETUP

The ring-laser configuration under study is shown in Fig. 1. It includes a 1.48-µm diode laser pump source, capable of up to 120 mW of output power at a current of 650 mA, coupled into the cavity by a wavelength division multiplexer (WDM). A 10-m co-directionally pumped EDF provides the cavity gain. This is followed by a polarisation beam combiner (PBC) used in reverse to linearly polarise the EDF output. The polarised light is passed to a polarisation-maintaining fibre (HB1500, bowtie-type) before the output coupler taps 70% of the cavity light for the laser output, allowing 30% to continue circulating. The 70% output fibre is alternately connected to an optical spectrum analyser (Advantest Q8384), 200-MHz oscilloscope (Unit-T UTD4202C with Thorlabs Det20C/M detector) and power meter (Hewlett Packard 8153A with a Hewlett Packard 81525A Optical Head) to characterise the output spectrum, temporal properties and average output power of the system. An AOM (NEOS 64035-5DS) is used to modulate the cavity loss to produce Q-switched pulses which are then fed into a fibre-coupled diffraction-grating-based TF (JDSU Optical Grating Filter TB9126) with a 3-dB linewidth of 0.55 nm, before being launched into the WDM and closing the ring.

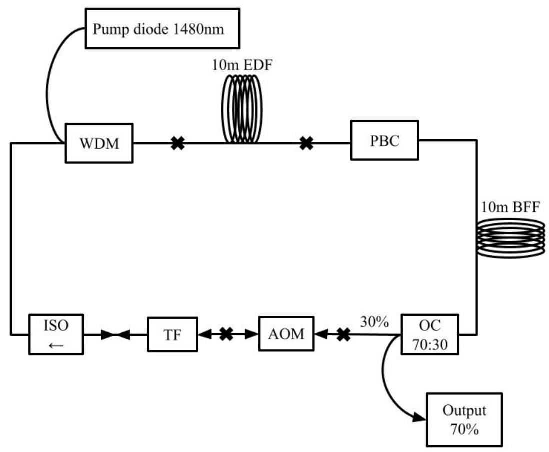


Fig. 1. Schematic of the actively Q-switched, tuneable laser.

The birefringent fibre used in this setup was a 10-m bowtie fibre, spliced to the PBC pigtail with 45° angle between the birefringence axes of the fibres. Prior to the addition of the TF the pulsed lasing spectrum, restricted by the birefringent fibre, was recorded as shown in Fig. 2. The predicted pattern of the birefringent fibre transmission peaks in the range 1550–1560 nm is clearly visible, with a peak spacing of 0.4 nm. The corresponding birefringent coefficient of $3.9 \cdot 10^{-4}$ matches well with the specified minimum birefringence of $3.3 \cdot 10^{-4}$, which also suggests that the cavity birefringence is dominated by that of the polarisation-maintaining fibre.

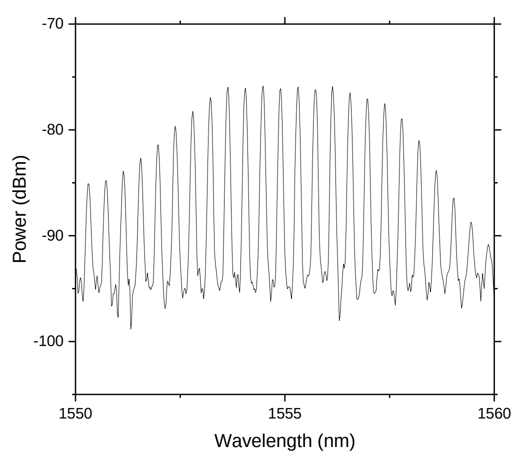
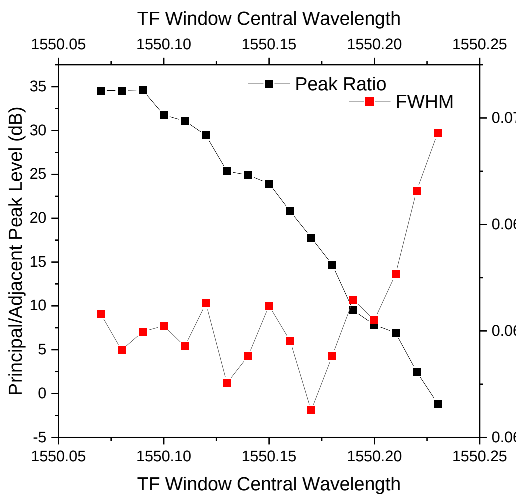


Fig. 2. Output spectrum of tuneable laser following insertion of birefringent fibre. Spectrum taken under AOM gate length and frequency of 2.25 µs and 80 kHz respectively, with a pump power of 54 mW.

4. RESULTS

With the TF in the cavity, its central wavelength was scanned between 1525 and 1565 nm, with lasing peaks observed between 1527 and 1560 nm for a tuneable range of 33 nm. In order to further minimise the spectral linewidth, the central wavelength of the TF transmission window was shifted away from the central peak in 0.01nm intervals. As a result, the window edge cut off one wing of the central peak and transmitted a portion of the adjacent peak, which resulted in a slight decrease in central peak width, but also a slight increase in adjacent peak intensity. This process was hampered by a periodic shift of optical energy between these adjacent peaks - visible in stability measurements later in the paper - but reduction was nonetheless observed. The result, shown in Fig. 3 (a), demonstrated a reduction in 3 dB linewidth to 65 pm, with a consequential increase in intensity of the adjacent peak. The system was found to produce stable pulses at repetition frequencies between 9 kHz and 166 kHz. Beyond these limits, stable Q-switching was no longer possible, with large fluctuations in peak pulse energy being observed as a result.

The effect of altering both pulse repetition frequency (PRF) and pump power on pulse length was also investigated. As the pump power increases beyond threshold, the roundtrip gain increases and the pulse builds up more quickly, resulting in faster depletion of the population inversion and thus a shorter pulse. This can be seen in Fig. 3 (b), where the pulse length falls to 450ns as pump power increases. Notably, the pulse length plateau is not reached, suggesting that a larger pump power could shorten this pulse further for the chosen parameters. A similar investigation was carried out into the effect of PRF, in the assumption that the increased population inversion at lower PRF would likewise increase gain and thus reduce pulse lengths [6]. However, the alteration had little effect, suggesting that under the chosen conditions, the time between pulses was still sufficient for inversion to be replenished.



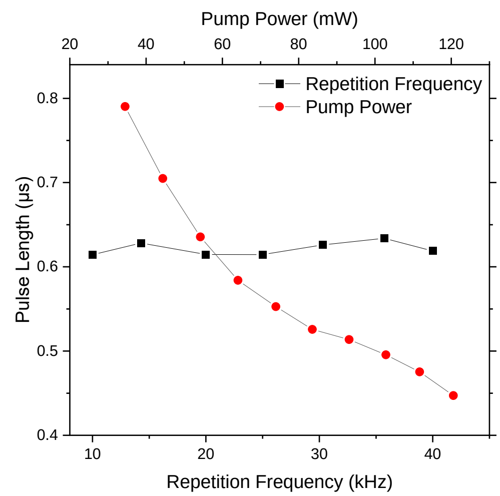


Fig. 3. Study of the effect of TF central wavelength position and pulse repetition frequency on various pulse parameters. Unless specified, pump power was fixed at 54 mW, PRF at 10 kHz, TF window central wavelength at 1550 nm and AOM gate time at 2.25 μs. (a) Plot of 3 dB linewidth and ratio of principal to adjacent peak heights, measured at TF central wavelength positions between 1550.07 and 1550.23 nm. (b) Plot of output pulse length with respect to pump power between 35 and 121 mW, and with respect to PRF from 10 to 40 kHz.

The average output power stability was determined at a chosen typical pump power of 54 mW a PRF of 10 kHz and duration of 2.25 μs by recording the output power at 10-minute intervals over the course of two hours, with the results shown in Fig. 4 (a). An output power fluctuation of 0.9 mW (1.4%) over the course of the two hours was recorded. When the AOM was always-on in order to pause the pulsing, similar-scale variations were also recorded. This instability is therefore unlikely to be induced by Q-switching and may be improved with a more stable environment or different equipment. The output spectrum was also recorded at 5-minute intervals for 70 minutes. The power distribution shift between two adjacent comb filter peaks is shown in Fig. 4 (b).

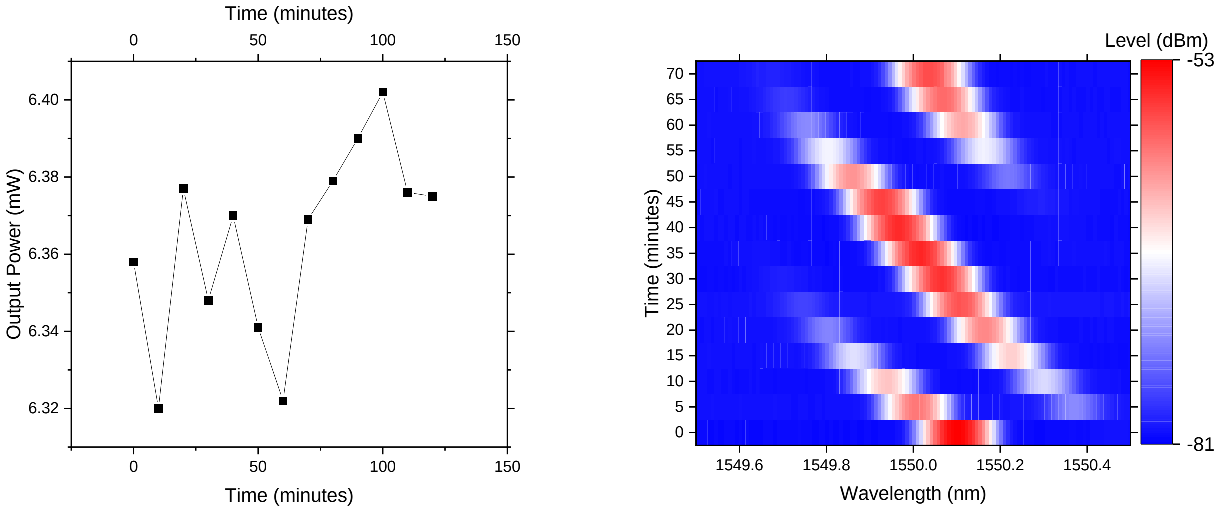


Fig. 4. Spectral and power stability of the system, with 54-mW pump power, 10-kHz PRF, 1550.3-nm TF central wavelength and 2.25-µs AOM gate time. (a) Plot of variation of output power over the course of 120 minutes. Note the fluctuation of 0.9 mW (1.4%). (b) Plot of output spectral stability measurements taken over the course of 70 minutes. A periodic shift in output wavelength can be observed.

5. CONCLUSIONS

In summary, we present an actively Q-switched, narrow linewidth, tuneable fibre laser. An EDF was employed as the gain medium, and stable Q-switching established between 9 kHz and 166 kHz using an acousto-optic modulator. A polarisation-maintaining fibre in Lyot filter configuration was used for narrow-line filtering within a broader, tuneable, diffraction-grating-based filter. This resulted in a spectral width of 65 pm and a tuning range of 33 nm. The spectral stability was restricted by a periodic switching of intensity between adjacent transmission peaks. The report demonstrates the feasibility of a birefringent fibre-TF cascaded system to reduce the spectral linewidth but reveals that further work is required to improve the stability of the system.

ACKNOWLEDGEMENTS

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