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Mode-locked thulium-fluoride fibre laser with an adjustable pulse width using a nonlinear optical loop mirror

H. Ahmad, S.N. Aidit, S.I. Ooi, Z.C. Tiu

Abstract. **A mode-locked thulium-fluoride fibre laser with a tunable pulse width using a nonlinear optical loop mirror (NOLM) for operation in the S-band region is proposed and demonstrated. Stable dissipative soliton resonance (DSR) mode-locked pulses are obtained at a threshold pump power of 186.8 mW and maintain stability until a maximum pump power of 249.7 mW. Pulse width modulation of between 70.8 ns and 120.3 ns is obtained over the operating pump power range, with a fundamental frequency at 97.4 kHz. A maximum output power of 0.99 mW and a pulse energy of 10.21 nJ are obtained. The output pulse has a signal-to-noise ratio of 69 dB at the maximum pump power, indicating a highly stable output. The variable pulse width will find significant applications as modulated light sources for various optical and optoelectronic systems.**

Keywords: *nonlinear optical loop mirror, dissipative soliton resonance, mode-locked fibre laser.*

1. Introduction

Pulse width modulated (PWM) light sources are a crucial technology for a variety of applications, particularly in the area of opto-electronics. These include optical displays, optical storage devices, analogue fibre-optic communication systems and others [1–4]. The PWM technique is used to generate levels of illumination between black (off) and white (on), which is commonly used to improve the display resolution. Additionally, it can also be applied to control the laser beam in write and preheat pulse patterns respectively for optical disks. Similarly, PWM is generated by the natural or uniform sampling of the input analogue signal [4], and is converted to analogue signals for easy passage through digital logic gates [3] as well as has the ability to reduce inter-symbol interference [2] in an optical communication system. However, current advances in PWM techniques still fall short of the needs of most current optical and opto-electronic applications, with various limitations such as the need for additional modulators to achieve the desired pulse-width modulation. This invariably incurs higher costs and makes the system more complex.

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In this regard, significant research efforts have been made to generate an efficient light source capable of PWM outputs over a wide range of operating wavelengths. One of the simpler and more cost-effectives means to overcome these limitations is the use of a nonlinear optical loop mirror (NOLM) in the proposed laser cavity. This approach has been proven, and NOLM-based PWM systems have begun to see wide acceptance of applications in the C-, L-bands for the 1.0 and 2.0 μm regions [5–8]. However, substantial gaps in the emission bandwidth still remain, particularly at the S-band region. In order to generate a NOLM-based PWM laser source in the S-band region, depressed cladding erbium-doped fibres (DC-EDFs) can be used to generate an output at about 1.49 μm to 1.53 μm [9, 10], while other specialty fibres such as bismuth-based erbium-doped fibres (EDFs) can be employed to generate stable mode-locked outputs [11]. However, in both these cases the pulse width cannot be tuned.

In this work, a relatively simple and cost effective PWM laser source in a thulium-fluoride fibre laser (TFFL) is proposed and demonstrated for generating a mode-locked output in the S-band region with a tunable pulse-width. The proposed source is capable of generating outputs with tunable pulse-widths with a relatively constant amplitude in the nanosecond range using an NOLM configuration in the cavity [7, 12, 13]. The use of the TFFL allows for operation in the S-band region, which can cover a very wide bandwidth of approximately 60 nm from 1.45 μm to 1.51 μm [14]. The broad emission range of the TFFL exceeds that of erbium-based gain materials and provides a wider range of optical and opto-electronic applications.

2. Experimental setup

Figure 1 shows the experimental setup of the proposed PWM laser. An 11.6 m long thulium-fluoride fibre (TFF) acts as the linear gain medium for the cavity, with a Tm^{3+} ion concentration of 3200 ppm and numerical aperture of 0.28. The gain medium which is obtained from Fibrelab Inc. in the form of a hermetically sealed module equipped with FC/APC connectors has a mode field diameter of 4.5 μm at 1.5 μm and an absorption rate of ~0.15 dB m^{-1} at 1.40 μm. The TFF is pumped by a 1.40 μm laser diode (LD) with a maximum output power of 250 mW through the 1.40 μm port of a 1.40/1.50 μm wavelength division multiplexer (WDM). One end of the TFF is connected to the common port of the WDM, while the other port is connected through a polarisation independent optical isolator (ISO). The ISO serves to ensure unidirectional signal propagation in the cavity, as well as to prevent possible back-reflections from the NOLM from travelling through the active TFF so as not to damage the LD.

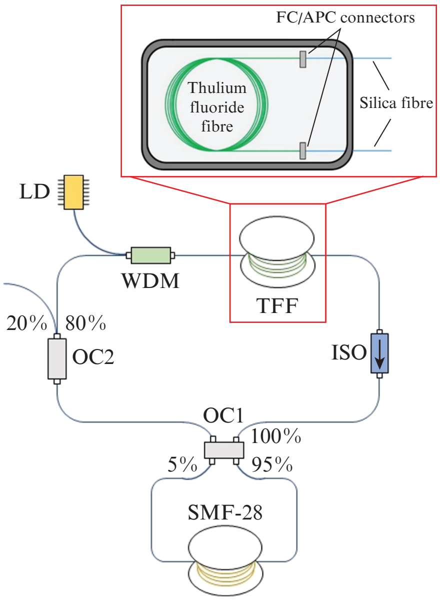

Figure 1. Experimental setup of the TFF laser cavity with a NOLM. The inset shows the TFF module.

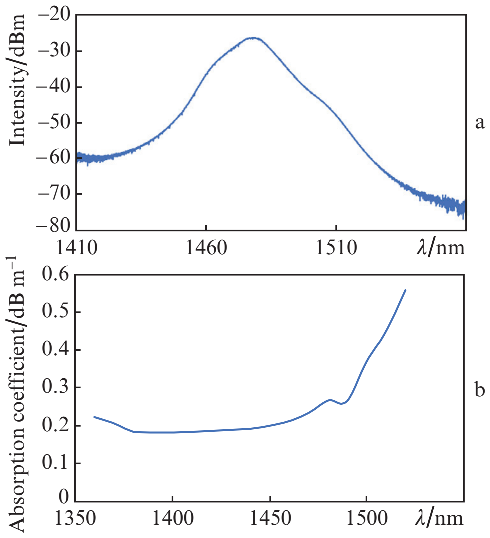

Figure 2. (a) Emission and (b) absorption spectra of the TFF.

The NOLM is constructed by connecting a 2.07 km long single-mode fibre (SMF-28) to the 95% and 5% ports of a 2×2 95:5 optical coupler (OC1). One port of OC1 is then connected to the ISO, while the other port is connected to the input port of an 80:20 optical coupler (OC2). In this configuration, the SMF-28 loop forms the NOLM, which serves as an artificial saturable absorber to induce the ultrafast phenomenon. The second coupler, OC2, is used to extract approximately 20% of the propagating signal for further analysis, while the 80% port is connected to the 1.50 µm port of the WDM, thus completing the laser cavity.

The total length of the proposed cavity is approximately 2.09 km, which corresponds to round trip time of ~10.1 µs, taking into account the refractive index of the SMF-28 of value of 1.45. The overall length of 2.09 km takes into account the length of the 11.6 m long TFF and 2.07 km long SMF-28 in the NOLM loop as well as the length of fibres from the other components such as the WDM, ISO, OC1 and OC2. The TFF has a dispersion coefficient of approximately –20 ps (nm km)$^{-1}$, while the SMF-28 has a dispersion coefficient of 14 ps (nm km)$^{-1}$ at 1500 nm, whereby at 1550 nm the dispersion coefficient is about 17 ps (nm km)$^{-1}$. The total cavity dispersion is about 28.75 ps nm^{-1}. The group velocity dispersion is calculated to be about –34.34 ps^2 which falls in the regime of anomalous dispersion. The extracted signal is analysed using a Yokogawa AQ 6370B optical spectrum analyser (OSA), a 500 MHz Yokogawa DLM2054 oscilloscope (OSC) with a 1.2 GHz photo-detector (PD), and an Anritsu MS2683A radio frequency spectrum analyser (RFSA).

3. Results and discussion

The amplified spontaneous emission (ASE) properties of TFF are given in Fig. 2a. The TFF is pumped with a 1400 nm laser diode at a pump power of 197 mW and has an emission spectrum which corresponds to the $^3H_4-^3F_4$ transition showing a broad spectrum covering a wide wavelength range 1420–1530 nm with maximum peak centred at 1480 nm. The absorption spectrum of the TFF is given in Fig. 2b. As seen from the figure, the absorption of TFF at 1400 nm is around 0.17 dB m^{-1}.

Stable mode-locking is observed to start at a threshold pump power of 186.8 mW and shows stable operation until the maximum pump power of 249.7 mW is reached. Throughout this pump power range, the output from the NOLM laser cavity exhibits characteristics of typical dissipative soliton resonance (DSR) [7, 12, 13]. This is attributed to the balance between cavity dispersion, fibre nonlinear effect, laser gain and losses as well as spectral filtering [5, 7, 15–17]. Through the NOLM effect, a strong peak power clamping effect is induced. Subsequently, the clamping of the peak power results in the lower accumulation of the nonlinear effect in the cavity, confining the operation of the pulse spectrum to within the cavity filter transmission width. Thus, pulse breaking operation is restrained, verifying that the proposed laser is operating in the DSR regime [7].

Figure 3 shows the optical spectrum of the pulses obtained from the TFFL operating in the mode-locking regime. As expected, the spectral width of the output pulses shows substantial broadening, with a 3-dB bandwidth of about 4.9 nm at a centre wavelength of 1504.3 nm. Figure 4 shows the pulse profile of the mode-locked pulses at different pump powers which is taken from the OSC. The inset of the figure shows

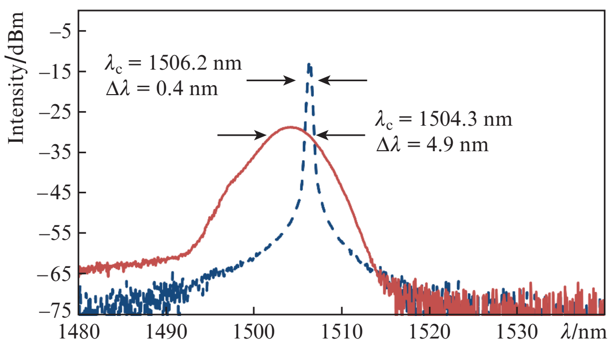

Figure 3. Optical output spectrum of the NOLM laser cavity.

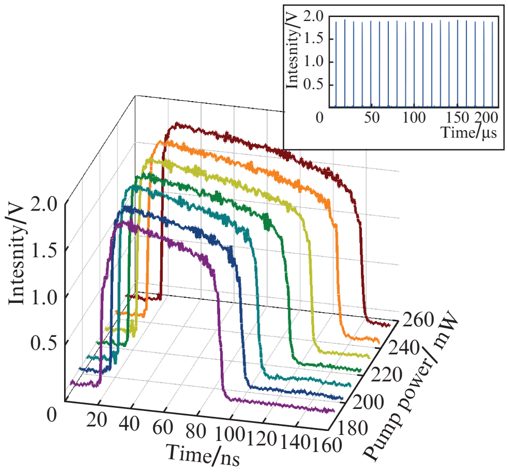

Figure 4. Single mode-locked pulse profile at different pump powers. Inset show a mode-locked pulse train at a maximum pump power of 249.7 mW.

the mode-locked pulse train at a pump power of 249.7 mW. One can see that the width of the generated pulse increases significantly from its narrowest at a pump power of 186.8 mW to its broadest at 249.7 mW. It can also be observed that the amplitude of the generated pulses remains almost constant at 1900 mV, with only slight fluctuations of about 2.1 % throughout the pump power tuning range. The variation of the pulse width and peak power against the different pump power augurs well with the DSR theory, in which the duration of the generated pulse increases as the pump power rises while the amplitude of the pulse remain unchanged [7, 12, 13]. It is this property of the generated pulses that makes the proposed PWM laser highly suited towards the requirements of the afore-mentioned applications. The changing pulse width enables the utilisation of the duty cycle variations to induce several effects in applications such as display, printing, optical disk drive as well as in telecommunication systems.

Figure 5 shows the detailed variation of pulse width and pulse repetition rate of the proposed NOLM mode-locked laser cavity against pump power from 186.8 mW to 249.7 mW. From the DSR threshold of 186.8 mW, the pulse width of the mode-locked laser increases linearly from 70.8 ns to 120.3 ns at the maximum pump power of 249.7 mW. Throughout the DSR operating range, no significant changes in the pulse repetition rate are observed. The consistency of the pulse repetition rate reflects the stability of the proposed NOLM mode-locked laser cavity.

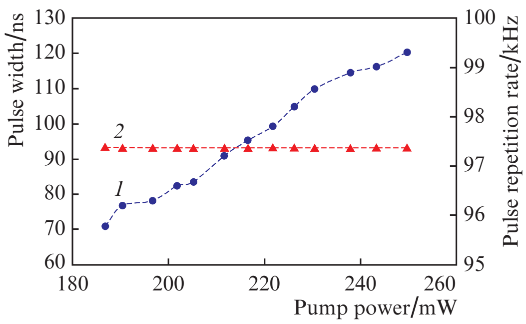

Figure 5. (*1*) Pulse width and (*2*) pulse repetition rate of the proposed NOLM mode-locked laser cavity as functions of pump power.

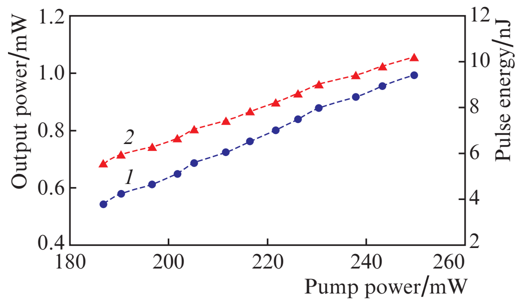

Figure 6. (*1*) Output power and (*2*) pulse energy of the proposed NOLM mode-locked laser cavity as functions of pump power.

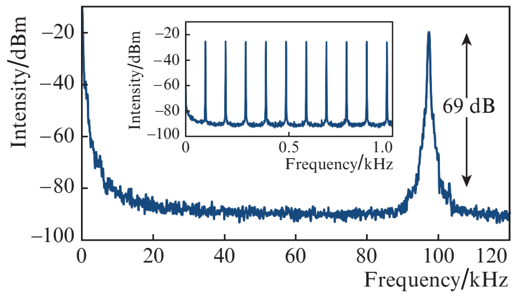

Figure 7. Radio frequency spectrum of the output generated from the proposed laser.

The output power and pulse energy of the proposed cavity is also measured as shown in Fig. 6. It can be seen that throughout the entire pump power range, the output power of the laser cavity increases linearly against the pump power, from 0.54 mW to 0.99 mW as the pump power rises from 186.8 mW to 249.7 mW. In addition, the increasing average pulse energy shows a linear trend, rising from 5.59 nJ to 10.21 nJ along the same pump power range. In the case of the output power and pulse width, the observed increase is consistently linear and shows no sign of saturation, thus indicating that higher output powers and wider pulses can be obtained should higher pump powers be made available.

The RF component of the generated output is measured at the maximum pump power of 249.7 mW using the Anritsu MS2683A RFSA, and shows a fundamental frequency at ~97.40 kHz. As expected, the fundamental frequency corre-

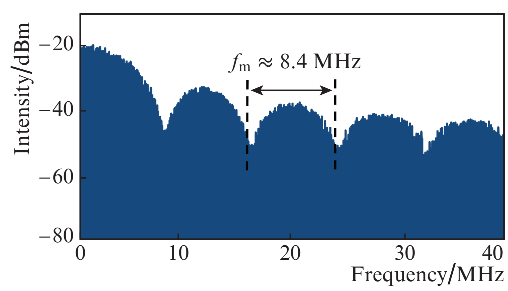

Figure 8. Wideband radio frequency spectrum of the output generated from the proposed laser.

Table 1. Results obtained for various NOLM-based PWM systems operating at different wavelengths.

Operating wavelength/nm	Pulse repetition rate/kHz	Maximum pulse energy/nJ	SNR/dB	Pulse range/ns	Reference
1565 (C-band)	100	33.34	45	25.1 – 81.5	[6]
1567 (L-band)	31.25	236.80	31.25	135 – 2272	[5]
1068 (1 μm)	13.40	2.96	70	0.063 – 0.147	[7]
1975 (2 μm)	1065	~ 85.47	55	3.74 – 72.19	[8]
1505 (S-band)	97.40	10.21	69	70.8 – 120.3	this work

sponds to the total length of the laser cavity. Furthermore, no other frequency components are observed in the RF spectrum of the laser cavity, even at a larger frequency span of 1.0 MHz as shown in the inset of Fig. 7. This complies with the pulse-breaking free theory of the DSR. Moreover, a signal-to-noise ratio (SNR) of ~ 69 dB indicates the very high stability of the oscillating mode-locked pulse in the laser cavity. In addition to the RF spectra at frequency range of 120 kHz and 1.0 MHz, the mode-locked output is also investigated at higher frequency range of 40 MHz, as depicted in Fig. 8. From the measurement, a modulated RF spectrum at 8.4 MHz is observed, corresponding to ~ 120 ns in the time domain. This reflects the pulse width of the mode-locked laser at the maximum pump power of 249.7 mW. From the measurement of the sinc modulated RF spectrum, the generation of a square pulse from the proposed NOLM laser cavity is confirmed.

Table 1 provides the results obtained from previous works in generating PWM light using the NOLM technique. As can be seen from the table, each system that operates at particular wavelength exhibits a different output in the same parameter. This attributes to the fact that each system utilises different gain medium and pump power which might cause a variation in the results. Some of the results obtained in this work are comparable to previous works in certain parameter but some are not. Nevertheless, this work is worthy of attention because the proposed laser is a PWM light source for the undeveloped spectral region between C- and L-bands and between the wavelengths of 1 and 2 μm.

4. Conclusions

The utilisation of a nonlinear optical loop mirror in a TFFL cavity results in the generation of stable dissipative soliton resonance mode-locked laser pulses with a pulse width modulation ability. The generated mode-locked laser operates at the fundamental frequency of 97.40 kHz, which corresponds to the cavity length of 2.09 km. The evolution of the pulse profile with increasing pump power complies with the theory of dissipative soliton resonance. Throughout the pump power range from 186.8 mW to 249.7 mW, mode-locked lasing with increasing pulse width but relatively constant amplitude is achieved. The mode-locked laser output with a pulse profile of 70.8 ns is achieved at the lowest pump power. Moreover, the highest output power of ~ 0.99 mW and highest pulse energy of ~ 10.21 nJ is achieved at the maximum pump power of the laser cavity. The measured sinc modulated RF spectrum at wide RF range validates the generation of a square pulse from the propose NOLM laser cavity. Moreover, the oscillation of generated mode-locked laser at fundamental frequency of 97.40 kHz with a SNR of ~ 69 dB indicates the stability of the mode-locked operation.

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