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# Tunable passively Q-switched thulium-doped fiber laser operating at 1.9 μm using arrayed waveguide grating (AWG)

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## ABSTRACT

Thulium-doped fiber lasers (TDFLs), operating in the 1.8–2.0 μm wavelength region, have been viewed as an important research topic, due to their potential in various fields of applications. However, the growing need to advance the development of applications in various fields for instance medicine and environment sensor, has led to a deeper and specific study of Q-switched TDFLs with wavelength tunability. In this paper, a stable, tunable Q-switched TDFL operating in a wavelength range near to 1.9 μm by exploiting the use of a multiwall carbon nanotube (MWCNT)-based thin film as a saturable absorber (SA), and the use of an arrayed waveguide grating (AWG) for wavelength tunability, is presented. The tuning range of the Q-switched pulses generated covered a wavelength range that spanned from 1871.6 nm to 1888.8 nm. The repetition rate of the generated Q-switched pulses covers a range of frequency starting from 41.19 kHz to 68.3 kHz with a change in pump power from 242.2 mW until 360.9 mW.

## 1. Introduction

There have been great interests in fiber lasers as compared to bulk optics systems due to their compactness and also ease of alignment. Generally, fiber lasers are being constructed from a gain medium, which provides the required amplification, together with a pump laser diode connected through a wavelength division multiplexer (WDM). An optical isolator is also used to force the unidirectional propagation in a ring configuration. There have been numerous reports of amplification in the S- (1480–1520 nm) [1–4], C- (1540–1560 nm) [5–7] and L- (1560–1600 nm) [8–10] bands which can be configured easily into a fiber laser. Due to the rapid increase of the demand of data traffic, there has been interest in the 2 μm band region as to complement the existing bands, whereby thulium is the active medium. Besides continuous wave (CW) operation, there are interests to pursue the development in pulsed fiber laser system based on Q-switching techniques that have wide application in sensing and medical sectors.

Q-switched fiber lasers, which are lasers that emit energetic pulses that can be obtained through active [11] or passive [12] Q-switching techniques, have gained a lot of attention due to their capacity to produce pulses of light with high energy at relatively low repetition rates [13]. Such laser pulses can subsequently be used in many advanced applications – e.g. in range-finding, remote-sensing and in the field of medicine [14]. Though Q-switching can be produced through active systems, the technique usually requires the application of an electric signal, applied to an acousto-optic or electro-optic modulator [15–18] - and can be rather complicated and costly as compared with passive Q-switching systems. Passively Q-switched fiber lasers offer the appealing advantages of compactness, simplicity, and flexibility in design. The technique can be implemented by using a more direct approach, which is the incorporation of an SA in the laser cavity. Numerous different types of SA have been demonstrated to achieve Q-switched operation, of which one example is the semiconductor saturable-absorber mirror (SESAM) [19,20]. Although this method works well in both bulk-laser and fiber-laser systems, SESAMs have several drawbacks that include high cost of fabrication, fragility, and a narrow tuning range that is in the region of only a few tens of nanometers [21].

Many saturable absorbers have been introduced as an alternative to overcome the limitation of SESAMs. Most recently, graphene and CNT-based SAs have been introduced because they could offer simplicity and compatibility in terms of system designs. In addition, they also have low saturation intensities and ultrafast recovery times [22–24], making them a more attractive alternative as compared with other SAs. The reason why graphene is less preferable than CNT-based SAs is that the saturation intensity of graphene depends greatly on the wavelength. At near-infrared wavelengths, graphene exhibits large saturation intensities – while, in the mid-infrared region, its saturation intensity becomes equal to or even less than that of CNT-based SAs [25], making it less appealing for some applications.

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Recently, passively Q-switched thulium-doped fiber lasers (TDFLs) operating in the 1.9 μm region have gained much interest because they could be utilized in various 'eye-safe' applications, especially in the medical field. This is due to their emission being strongly absorbed by water [26], making them suitable to be applied in ophthalmic surgery. Q-switched TDFLs are also able to generate higher pulse energies at their output [27], making them important in the field of material processing and they are more efficient and are more simple as they do not require the subtle balancing of losses associated with mode-locking.

Although Q-switched TDF lasers operating at a single wavelength have many applications, extensive interest in generating Q-switched TDF lasers with wavelength tunability exists for areas such as spectroscopy, material processing, and sensing [28]. In addition, tunability of basic TDF lasers in the 2.0 μm wavelength region has already been widely demonstrated by using volume Bragg gratings (VBGs) [29–31], and also by the use of diffraction gratings [18,32]. However, these methods are quite complex due to the use of bulky optic components in the laser cavity.

This paper presents a method for producing a passively Q-switched output pulses that provide wavelength tunability for a thulium-doped fiber by incorporating a MWCNT-based SA and by utilizing the use of a silica-based arrayed waveguide grating (AWG). The use of the AWG has been previously demonstrated in achieving switchable-wavelength fiber lasers operating in the C-band up until the L-band wavelength region [33–35]. The low propagation loss of the AWG, combined with its high fiber-coupling efficiency [36], has made it quite popular to be used to precisely de-multiplexing a high number of optical signals. Hence, AWG was chosen in this demonstration due to its low insertion loss, low power consumption and more importantly, it could provide a simple, yet effective way to obtain wavelength tunability. By interchanging the channels of the AWG, discrete wavelength tuning of the Q-switching operation can be realized over a span, ranging from 1871.6 nm to 1888.8 nm without using any complex modulation techniques or special filters. The experimental results show that the generated Q-switched microsecond pulses have a wide repetition rate range, commencing from 41.19 kHz up to a maximum value of 68.3 kHz. Fig. 1.

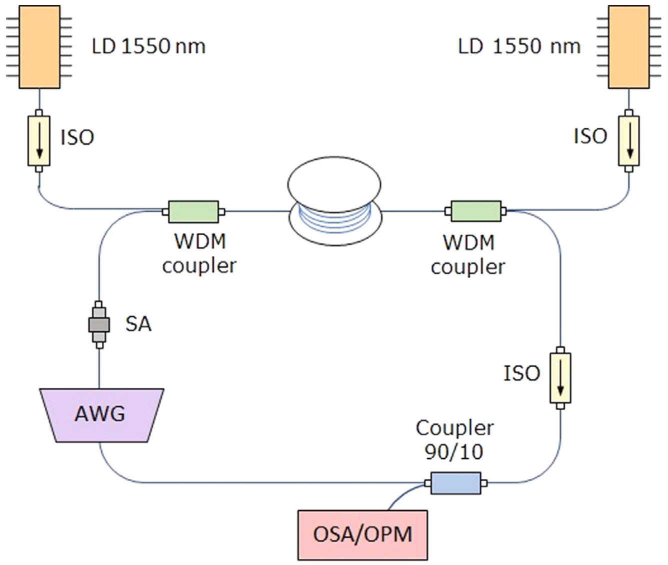

**Fig. 1.** Schematic diagram for wavelength tuning in passively Q-switched fiber laser using an MWCNT/PVA SA.

## 2. Experimental setup

The experimental setup of the proposed tunable passively Q-switched TDFL using AWG is shown in Fig. 1. The fiber ring consisted of two 1562.4 nm central wavelength pump laser diodes (Princeton Lightwave) with 350 mW output powers at 2.6 A of drive current in pulsed mode and 300 mW at 1.75 mW in CW mode. In our experiment, one acted as a forward-pump source and the other as a backward-pump source. However, the output power of each laser diode is limited to 240 mW in CW mode due to the limitation in the laser diode driver that could only deliver up to 1.5 A of current. Each of the laser diodes was then connected to a 1550 nm wavelength isolator, which was then connected to a 1550/2000 nm wavelength division multiplexing (WDM) coupler. One port of each of the two WDMs was fusion spliced to a gain medium comprising of a 4 m long thulium-doped fiber (TDF, OFS), which has a peak absorption of 200 dB/m at 790 nm with a cutoff wavelength at 1350 nm and core and cladding diameters of 5 μm and 125 μm respectively.

The other port of the backward-pump-connected WDM was connected to a polarization insensitive isolator, operating at 2.0 μm to enforce unidirectional propagation of light within the ring cavity. The isolator was then linked to a 90:10 optical coupler where the 10% port of the coupler was used to extract a portion of the signal oscillating in the cavity for further analysis. Meanwhile, the 90% port was connected to an AWG, a silica-based waveguide that acts as a wavelength selective element. The mentioned AWG was used as a splitter to diffract the incident beam into different wavelengths. In principle, an AWG consists of an array of waveguides and two couplers. When an incident beam consisting of multiple wavelengths enters the input coupler, the beam is coupled into an array of waveguides. The beam subsequently propagates through the individual waveguides with different path lengths, towards the second coupler, which is the output. The beam travelling at different path lengths along different array waveguides will arrive at the output coupler with equal phase, resulting in the diffraction and interference at the output coupler. As a result, each wavelength is only focused into only one of the output channels. To obtain fiber lasers at several different wavelengths, 10 input channels of the AWG were used to provide wavelength selectivity inside the cavity.

The output of the AWG was connected to an SA device where the device consisted of a FC/PC adapter containing two FC/PC connector ends that were separated by an MWCNT-PVA composite that acted as the host material. Physical characteristics of the MWCNT/PVA-based SA included a distributed diameter range of 10–20 μm, length of 1–3 μm, and thickness of about 50 μm.

The other end of the SA device was connected to the 2000 nm port of the forward-pump-connected WDM, thus forming and completing the ring laser cavity. The portion of the signal extracted by the 10% port of the 90:10 coupler was connected to an optical spectrum analyzer (OSA Yokogawa AQ6375) with a resolution of 0.05 nm for spectral analysis or to an oscilloscope (Yokogawa DLM2054) through a 12.5 GHz InGaAs photodetector (Newport).

## 3. Results and discussions

A Q-switched pulsed laser with variable wavelengths was obtained from this proposed system. The output spectra of the tunable Q-switched fiber laser taken at pump power of 312.4 mW are shown in Fig. 2. Ten channels from the AWG were used to tune the fiber laser to several distinct and sharp laser lines, ranging from 1871.6 nm to 1888.8 nm, with an approximately 2.0 nm inter-channel wavelength spacing. By just switching the channels of the