Dual-wavelength Q-switched erbium-doped fiber laser using an SMF-MMF-SMF structure and graphene oxide*

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(Received 8 June 2022; Revised 22 July 2022)

We have successfully demonstrated a stable dual-wavelength Q-switched erbium-doped fiber laser (EDFL) using a single mode fiber-multimode fiber-single mode fiber (SMF-MMF-SMF) structure-based filter. Using a graphene oxide (GO) saturable absorber (SA) to modulate the cavity loss, passive Q-switching of the dual-wavelength laser is achieved at 1 549.6 nm and 1 558.6 nm. The laser recorded the shortest pulse width of about 2.9 μs, the maximum pulse repetition rate of 65.27 kHz and the maximum average output power of 0.99 mW at pump power of 225.1 mW. The present laser has the maximum pulse energy of 15.17 nJ. A 2 SMF-MMF-SMF structure has been experimentally confirmed to be very promising as a wavelength filter.

Document code: A **Article ID:** 1673-1905(2022)11-0668-5

DOI https://doi.org/10.1007/s11801-022-2097-3

Dual-wavelength fiber lasers have gained tremendous attentions in recent years for their applications in various areas including the generation of terahertz (THz) signal[1,2]. The THz radiations bring significant value in various applications such as imaging, sensing, manufacturing, military, spectroscopy, and communication[3,4]. On the other hand, erbium-doped fiber (EDF) has been proven to be an outstanding candidate as gain medium for low absorption loss and highly efficient lasing in the near-infrared spectral range. This is attributed to erbium ions, which has ultra-low quantum defect and high quantum efficiency as it is pumped at 980 nm[5]. In addition, EDF possesses broad emission spectrum with high excitation from 1.5 μm to 1.6 μm, in which the wavelength regions around 1.53 μm and 1.56 μm are the two humps of the emission spectrum[6]. The gain peak typically occurs at the wavelength region around 1.53 μm, being most pronounced for high excitation levels. Thus, EDF is particularly suitable for generation of dual-wavelength pulses through spectrum filtering.

However, the wide wavelength spacing enlarged by the homogeneous gain broadening can lead to inherent instability of the emitting pulses, which brings trouble to obtain stable multi-wavelength pulse operation due to the mode competition. Many methods have been investigated to stabilize the multi-wavelength fiber lasers, such as via cooling EDF in liquid nitrogen[7], inhomogeneous loss mechanisms[8], and the four-wave mixing effect[9], and the polarization hole burning effect[10]. Furthermore, a nonlinear saturable absorber (SA) device combined with wavelength selectors including fiber Bragg grating[6] and fiber taper[11] is an alternative method to realize multi-wavelength operation of pulsed fiber laser. Compared with the wavelength selectors, the fiber-based nonlinear polarization rotating (NPR) technique provides a better way to realize multi-wavelength generation with flexibly controlled birefringence[12]. Compared to the previous techniques, the single mode fiber-multimode fiber-single mode fiber (SMF-MMF-SMF) structure-based filter is simpler[13]. It can provide a higher thermal damage threshold while allowing the pulse generation with higher energy.

Q-switched fiber laser with passive SA has been widely studied to generate short laser pulses for various applications range finding, remote sensing, and medical treatment[14,15]. Low-dimensional materials have been widely used to modulate the circulating lases recurringly in the laser cavity and generate pulse train in temporal

* This work has been supported by the Airlangga University Grant Scheme (2022).

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domain[16-18]. For instance, tunable Q-switched erbium-doped fiber laser (EDFL) was demonstrated using an SMF-MMF-SMF structure with graphene oxide (GO) SA[19].

In this paper, we demonstrate a dual-wavelength Q-switched fiber laser operation using an SMF-MMF-SMF structure and GO as filter and SA, respectively. The dual-wavelength operation at 1 549.6 nm and 1 558.6 nm was achieved based on multimode interference (MMI) effect while the Q-switching operation was achieved due to the saturable absorption effect of GO. When the pump power is fixed at the maximum power of 225.1 mW, the Q-switched pulse had a repetition rate of 65.3 kHz, together with pulse duration and pulse energy of 2.9 μs and 15.2 nJ, respectively. Compared to the previous work[20], the proposed laser provides a higher repetition rate and smaller pulse duration.

In the experiment, the MMI filter was fabricated by sequentially fusion splicing of the SMF, a section of 5.1 cm step index MMF, and the SMF, as shown in Fig.1(a). The SMF has a core/cladding diameter of 9/125 μm while the MMF has a core/cladding diameter of 50/125 μm. The transmission spectrum of the SMF-MMF-SMF structure was measured to verify this proposed MMI device is suitable as the filter as shown in Fig.1(b). The MMI device has a wide transmission spectrum from 1 520 nm to 1 570 nm. It has several transmission peaks, which are located at 1 521 nm, 1 531 nm, 1 549 nm, 1 561 nm, and 1 569 nm which are beneficial to filter wavelength of light transmission.

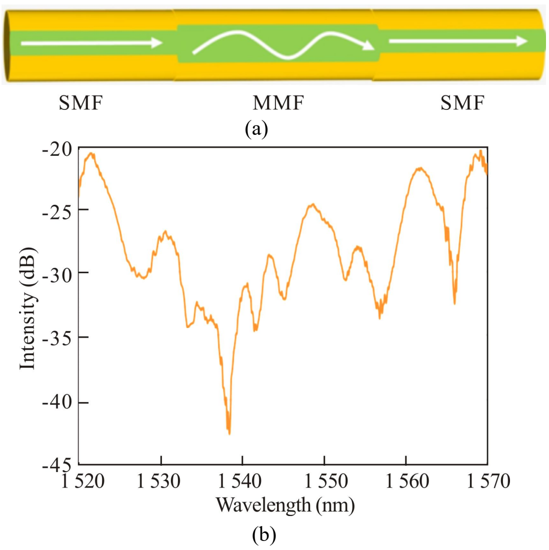

Fig.1 (a) SMF-MMF-SMF structure and (b) its transmission spectrum

The working principle of SMF-MMF-SMF structure could be explained as follows. When light wave from the first SMF enters step index MMF, it excites transverse modes. Whenever these modes have developed a phase shift that is a multiple of π, it causes interference, and the light wave field is allowed to be coupled into the second SMF. Since the interference depends on the wavelength and the inverse propagation constants of the transverse modes, such SMF-MMF-SMF structure can be employed as a filter.

The SA used in this work is based on GO material, which was produced from graphene flakes obtained through an electrochemical exfoliation. During the exfoliation process, a pair of graphite rods was placed inside electrolyte liquid, which was obtained by mixing 1% sodium dedocyl sulphate (SDS) in deionized water. The graphite rod functions as an electrode. An electrical potential was applied between the electrodes, it forces the positive and negative ions to move toward the cathode and anode, respectively. This process removed the graphene layers form the graphite rod and after two hours, a stable graphene suspension can be produced. The graphene suspension was then centrifuged at 3 000 rpm for about 30 min to split large agglomerates. The supernatant portion of the graphene suspension was then decanted to get a homogeneous GO solution. The GO solution obtained was then mixed with polyvinylalcohol (PVA) solution to fabricate a SA film via drop casting technique. The mixed solution was poured into a petri dish and dried at room temperature to produce 50 μm thin film. The GO PVA film was then cut into a small piece so that it can be attached onto a fiber ferrule with the assistance of index matching gel. The ferrule is connected and locked to another fresh ferrule via physical contact adapter to form all-fiber SA device. The index matching gel functions to reduce a spurious reflection at the connection. The nonlinear transmission of the SA film was also measured by using a balanced twin-detector technique as shown in Fig.2. It indicates that the film has non-saturable absorption of 35.1%, nonlinear saturable absorption of 24.1% and saturable intensity of 72 MW/cm^2. It is worth noting that we have not observed any nonlinear response from pure PVA film, confirming that the saturable absorption property solely originates from GO material.

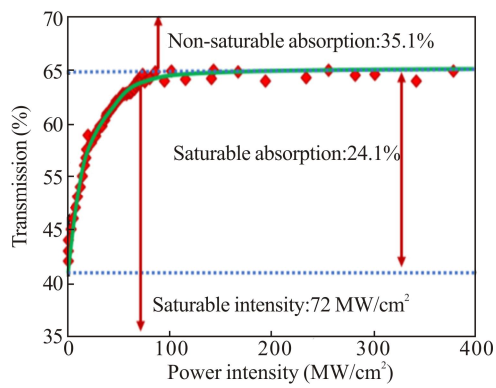

Fig.2 Nonlinear curve of GO PVA film

Fig.3 depicts the experimental setup of the proposed dual-wavelength Q-switched EDFL based on ring cavity using an SMF-MMF-SMF structure and GO SA as a filter and Q-switcher, respectively. A 2.4-m-long EDF is used as gain medium. It is pumped by a 980 nm laser diode via a wavelength division multiplexer (WDM) to generate an amplified spontaneous emission (ASE) operating at 1 550 nm region. A GO SA assembly and MMI filter are integrated inside the ring cavity as a component to generate the Q-switched dual-wavelength laser. An isolator is used to force a unidirectional light propagation inside the ring cavity and ensure the stability of the Q-switched operation. The optical spectrum, pulse train and electrical spectrum of the output laser from 10% port of output coupler was monitored by an optical spectrum analyzer, oscilloscope, and radio frequency spectrum analyzer (RFSA), respectively. High speed photodetector is used to convert the optical signal to electrical signal for use in oscilloscope and RFSA. The total cavity length was measured to be around 14 m. Since the SMF and EDF have group velocity dispersion (GVD) of $-21.7\ \mathrm{ps^2/km}$ and $27.6\ \mathrm{ps^2/km}$ respectively, the net cavity dispersion is estimated to be around $-0.23\ \mathrm{ps^2}$.

Once the pump power is increased to 200.6 mW, the dual-wavelength Q-switched laser was self-started. The Q-switching operation is maintained up to the maximum pump power of 225.1 mW. The output spectrum of the dual-wavelength Q-switched fiber laser at pump power of 225.1 mW is shown in Fig.4. It is observed that the dual wavelengths of outputs are located at 1 549.6 nm and 1 558.6 nm with a spacing of 9.0 nm. The dual-wavelength operation was obtained due to the SMF-MMF-SMF structure, which provides spectral filtering effect in the laser cavity. Only two wavelengths are allowed to oscillate due to the gain spectrum of the EDF, which prominent at 1 550—1 560 nm region due to the high erbium concentration and pumping power in the laser cavity. Without the SA, the laser operates in continuous wave mode. Fig.5 shows the typical pulse train for the dual-wavelength Q-switched EDFL at 225.1 mW pump power. It was recorded for 1 000 μs time span and no significant distortion or fluctuation was observed. The pulse train has repetition rate of 65.27 kHz, corresponding to the time interval of 15.3 μs. The inset of Fig.5 shows the profile of the dual pulse envelop, which indicates the full width at half-maximum (*FWHM*) of 2.9 μs for the output pulses. It has a symmetric temporal profile. The corresponding RF spectrum is also measured as shown in Fig.6 at 225.1 mW pump power. The fundamental frequency is obtained at 65.27 kHz, which is consistent with the oscilloscope data of Fig.5. The signal-to-noise ratio (*SNR*) is about 45.1 dB, which indicates the high stability of the dual-wavelength operation.

Fig.7 displays the evolution of the repetition rate and pulse width as the pump power is increased from 200.5 mW to 225.1 mW. When the repetition rate of the Q-switched pulses rises from 59.21 kHz to 65.27 kHz, the pulse duration reduces from 3.3 μs to 2.9 μs continuously. As the pump power increased, the GO SA is saturated at a higher speed. This is due to the population inversion, which depletes rapidly due to the bleached GO at higher pump power. Therefore, rising and falling times of the pulses would be reduced, which in turn increases the repetition rate and reduces the pulse width.

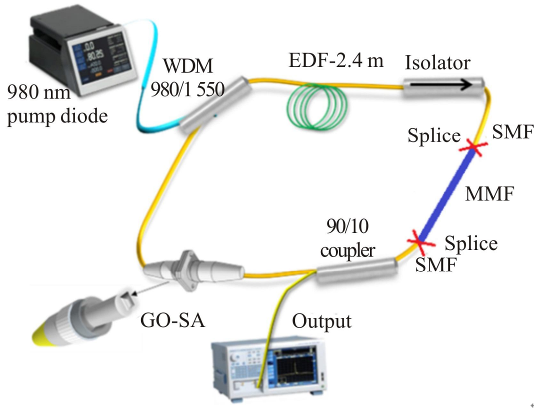

Fig.3 Configuration of the dual-wavelength Q-switched laser with GO SA and SMF-MMF-SMF structure

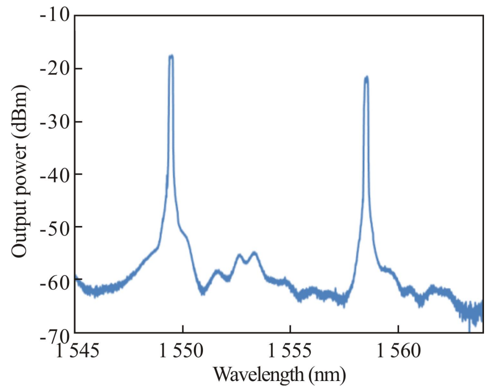

Fig.4 Output spectrum of the dual-wavelength Q-switched laser at 225.1 mW pump power

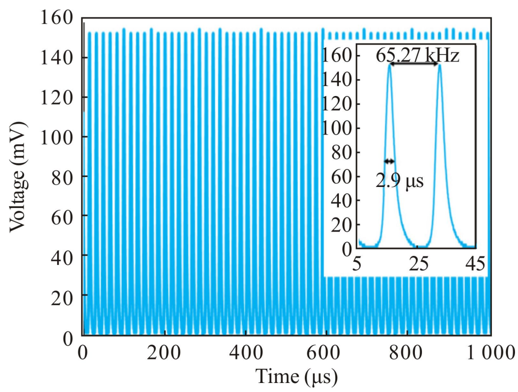

Fig.5 Typical pulse train at 225.1 mW pump power (The inset shows the enlarged dual-pulse envelop)

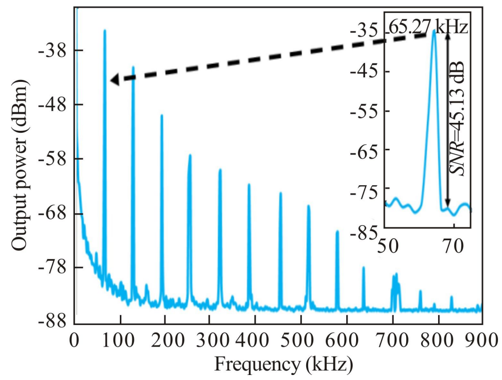

Fig.6 RF spectrum at 225.1 mW pump power (The inset shows the fundamental frequency)

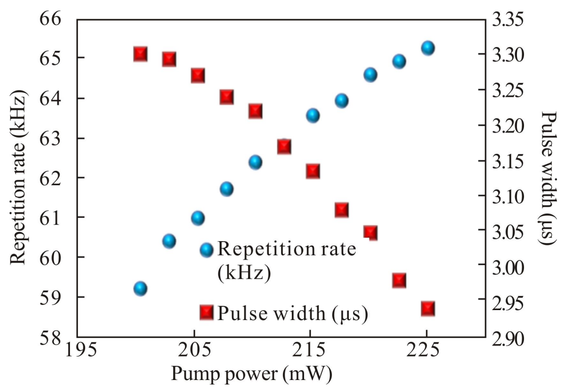

Fig.7 Pulse rate and pulse width obtained at different pumping powers

Fig.8 illustrates the evolution of the average output power and pulse energy with the increase of pump power. The average output power and pulse energy increases from 0.48 mW to 0.99 mW and from 8.0 nJ to 15.2 nJ, respectively. The slope efficiency of the laser was achieved at 2.06 %, which is relatively low due to the high propagation loss at the SMF-MMF-SMF structure. The population inversion depletes faster due to the bleached GO at the higher pump power. This process reduces the pulse duration, which in turn increases the pulse energy from the Q-switching mechanism. The almost linear output power and pulse energy relations with the pump power prove a stable performance of the fiber laser.

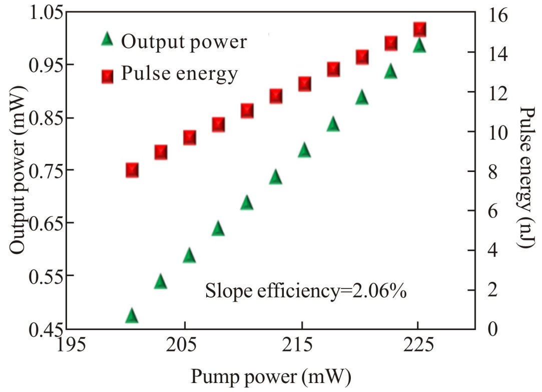

Fig.8 Output power and pulse energy obtained at different pumping powers

Tab.1 compares the performance of the proposed Q-switched EDFL with other lasers which were operated by using other SA materials and filters. The proposed Q-switched EDFL operates at smaller pulse duration compared to other filters such as microsphere resonator, fiber Bragg grating, Sagnac loop mirror (SLM). In future work, GO based SA in conjunction with SMS filter is highly recommended for the formation of dual-wavelength mode-locked EDFL, which required further SA and laser cavity optimization. It is worthy to note that the use of graded index multimode fiber with an inner micro-cavity could be used to generate pulse based on nonlinear polarization rotation effect[21]. The nonlinear multimodal interference in the graded-index MMF could be used to overcome the pulse instability issue.

Tab.1 Performance comparison of the proposed dual-wavelength Q-switched EDFL with other reported works

Filter	Q-switcher material	Wavelength (nm)	Maximum repetition rate (kHz)	Minimum pulse duration (μs)	Maximum pulse energy (nJ)	Ref.
Microsphere resonator	WS_2	1 554.0/1 560.7	85.1	3.47	131.4	[22]
FBG	ITO	1 532/1 533	48.3	5.22	1.93	[23]
SLM	SESAM	1 556.8/1 562.1	58.57	17.07	-	[24]
SMS	GO	1 549.6/1 558.6	65.3	2.9	15.2	This work

In conclusion, a dual-wavelength Q-switched pulse generation was successfully demonstrated in an EDFL cavity using an SMF-MMF-SMF structure based filter and GO SA. The SA was prepared by embedding the GO nanoparticles into PVA. The SA functions to modulate the cavity loss for Q-switching while the MMI filter responsible for dual-wavelength operation. The laser operates at wavelengths of 1 549.6 nm and 1 558.6 nm. The maximum pulse repetition rate and the shortest pulse width are obtained at 65.27 kHz and 2.9 μs, respectively.

At 225.1 mW pump power, the maximum output power and pulse energy were obtained at 0.99 mW and 15.17 nJ, respectively. These results demonstrated that the proposed SMF-MMF-SMF structure has a promising potential to be used as a kind of filter for multi-wavelength laser generation.

Statements and Declarations

The authors declare that there are no conflicts of interest related to this article.

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