Q-switched pulse generation with lutetium oxide absorber*

Nurul Athirah Mohamad Abdul Ghafar[1], Nur Farhanah Zulkipli[2], Rabi'Atul A. Mat Yusoff[3], Arni Munirah Markom[1], Moh Yasin[4], and Sulaiman Wadi Harun[1,4]****

1. School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA, Shah Alam 40450, Malaysia

2. Department of Physics, Faculty of Science and Technology, Airlangga University, Surabaya, Indonesia

3. Department of Physics, Faculty of Science, Universiti Teknologi Malaysia, Skudai, Malaysia

4. Photonics Engineering Laboratory, Department of Electrical Engineering, Faculty of Engineering, University of Malaya, Kuala Lumpur, Malaysia

(Received 17 September 2022)

A lutetium oxide (Lu_2O_3) film was proposed and demonstrated for Q-switching operation at 1.55 μm region. It was obtained by solving Lu_2O_3 powder into isopropyl alcohol and mixing the solution into polyvinyl alcohol (PVA) solution to form a composite precursor solution via stirring, sonicating, and centrifuging processes. The thin film was formed through a drop and dry process and a small piece of this film was integrated into erbium-doped fiber laser (EDFL) cavity to modulate the cavity loss via Q-switching mechanism for pulse generation. The Q-switched laser operated at 1 565 nm with the repetition rate of 75.26 kHz as the pump power was raised to the maximum value of 145.83 mW. The maximum pulse energy of 41.85 nJ was recorded at 145.83 mW pump power. The mode-locked pulse operated at 968.5 kHz with a pulse width of 510 ns was also realized in an extended EDFL cavity. The simple and cost-effective laser should have various applications including material processing, sensing and biomedical areas.

Document code: A **Article ID:** 1673-1905(2023)03-0129-5

DOI https://doi.org/10.1007/s11801-023-2154-6

Q-switched fiber lasers have been proven indispensable in many applications, including communication, material processing, medical devices, sensing, and other fields[1-3]. This is attributed mainly to their simplicity, compactness, flexibility, and low manufacturing cost. The Q-switching can be implemented actively or passively. The active technique requires external modulator based on electro-optic or acousto-optic effect to modulate the intracavity losses[4]. However, the external modulation tends to produce smaller pulse energy compared to pulse energy generated by passive technique. This drawback can be overcome by utilizing the passive saturable absorber (SA) to replace the external modulator. In addition, the SA is simpler, more compact, and far less expensive compared to the external modulator[5].

The ideal SA should exhibit wide bandwidth tunability, high optical damage threshold, excellent long-term stability, and good optical properties. Most of the previous materials utilized as SA were meet those criteria. However, they may require a tedious sample preparation to fabricate a functional SA device. Semiconductor saturable absorber mirrors (SESAMs) were first demonstrated in 1992, and since then, they have been widely explored, but they have suffered from low operational bandwidth, bulky and high cost[6]. In 2004, YAMASHITA et al[7] reported the use of carbon nanotubes (CNTs) based SA for pulse generation in erbium doped fiber laser (EDFL). The use of CNTs as passive SA has a few advantages including ultrafast time relaxation, excellent operational mode including transmission, reflection, and bidirectional and robust device. The main drawback of CNTs was geometry-dependent wavelength operation contributed to complicated sample fabrication procedure, which advances to the development of other carbon materials as SA devices. Besides CNTs, graphene possessed faster relation time (~100 fs), which was attributed to zero bandgap nature of semi-metal. The graphene has limitation due to its small modulation depth[8].

Another two-dimensional (2D) material such as black phosphorus (BP) was also used as SA. For instance, in 2016, ISMAIL et al[9] demonstrated the use of mechanically exfoliated BP as an SA to generate a short pulse in EDFL cavity. However, BP was very sensitive to the ambient environment causing the property of saturable absorption to deteriorate after long exposure to air. Thus, synthesizing a BP based SA requires careful handling

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

** E-mails: yasin@fst.unair.ac.id; swharun@um.edu.my

and tedious sample preparation. Recently, several other types of nanomaterials were used as SA for short pulse generation operating in the 1.55 μm region[10-14]. These materials were chosen due to their easy and simple fabrication process while capable in producing stable pulsed fiber lasers.

Lanthanide oxide elements are one of the preferred groups for SAs especially for operation in 1.55 μm regime. They have also been used in many other applications including lasing, optical glass electrical and thermoelectric materials. Lutetium oxide (Lu_2O_3) is one of its elements in the form of a white compound that is normally used for optical and new glass applications such as initiating elements or material in the production procedure of laser crystals. The Lu_2O_3 has been verified to have enough optical absorption in the 1.55 μm locality by experiment, thus a suitable candidate for potential SA application for Q-switching in EDFL cavity[15].

In this letter, Lu_2O_3 was embedded into the polyvinyl alcohol (PVA) to form a composite film as thin as 40 μm roughly. A tiny piece of the Lu_2O_3 thin film was integrated into the EDFL cavity by inserting it in between two fiber ferrules. In regards, a stable Q-switched laser running at 1 565 nm with a maximum repetition rate of 75.26 kHz and narrowest pulse width of 4.91 μs was demonstrated.

The Lu_2O_3 SA film is prepared by mixing Lu_2O_3 solution and PVA solution together. To make Lu_2O_3 solution, 5 mg of Lu_2O_3 powder is dissolved in 50 mL isopropyl alcohol (IPA) through a stirring and centrifuging process. The stirring was carried out using a magnetic hot plate stirrer for approximately 24 h. The Lu_2O_3 solution was then centrifuged for about 6 h. These processes were enough to break the van der Waals forces and thoroughly distribute the powder. On the other hand, the PVA solution was made by mixing a tiny amount of PVA powder (1 g) with deionized water (120 mL) as its solvent. This Lu_2O_3 and PVA mixture was also stirred but at a high temperature (90 °C) and was cooled down to room temperature when the stirring was completed. The Lu_2O_3 and PVA mixture was then thoroughly sonicated in an ultrasonic bath for about 2 h to produce a composite precursor solution. After pouring the precursor solution into a Petri dish, it was then dried in a vacuum oven for about 48 h to make a 30-μm-thick film. Fig.1 depicts the preparation of the Lu_2O_3 SA film.

The linear optical absorbance spectrum of the prepared Lu_2O_3 SA film is illustrated in Fig.2(a). It shows an absorption of about 3 dB at 1.55 μm region. The nonlinear absorption spectrum, which was obtained based on the commonly utilized balanced twin detector approach, is shown in Fig.2(b). In the measurement, we employed a stable mode-locked pulse as a pump source. It operated at 1 557.7 nm with a repetition rate of 1.89 MHz and pulse width of 3.6 ps. As shown in Fig.2(b), the saturable absorption was about 10% while the saturable intensity, and non-saturable absorption of the film were 90 MW/cm^2 and 58%, respectively.

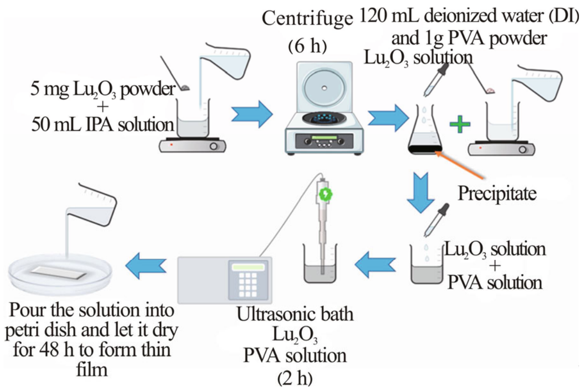

Fig.1 Preparation of the Lu_2O_3 SA

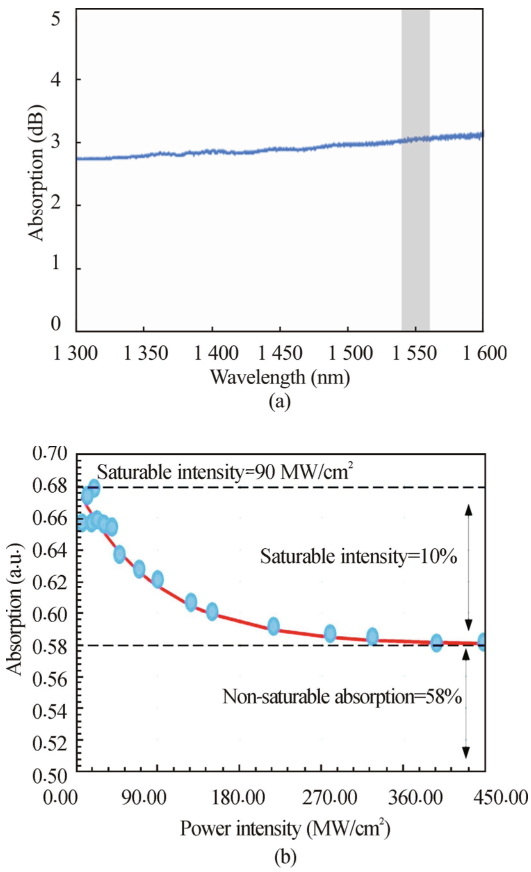

Fig.2 The measured (a) linear absorption and (b) non-linear absorption curves for the Lu_2O_3 SA

The EDFL setup used in this work is based on ring configuration. This setup is simple and easy to build, whereby the output light from the erbium-doped fiber (EDF) is fed back to its input using a coupler to complete its cycle. Fig.3 displays the experimental setup for Q-switching operation by fitting in the fabricated Lu_2O_3 SA film into the EDFL cavity. To integrate the SA into the cavity, a piece of 1 mm×1 mm SA film was squeezed between two clean FC/PC fiber ferrules. The sandwiched components were then carefully fixed by using a clean fiber adapter. An adequate amount of index matching gel was applied on the surface of fiber ferrule before putting the SA film onto the tip to make it easier to stick and lessen undesired reflections between the connecting parts.

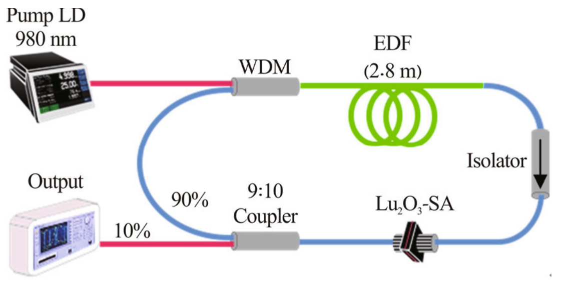

Fig.3 EDFL setup to obtain a Q-switched pulse with Lu_2O_3 SA film

The cavity of the proposed configuration consists of 2.8-m-long EDF as an active material. The EDF used has a numerical aperture of 0.23 at the pumping wavelength of 980 nm with a core/cladding diameter of 4 µm/125 µm. The EDF was pumped through the 980 nm port of the 980/1 550 nm wavelength-division multiplexer (WDM) using a 980 nm wavelength laser diode (LD). An optical isolator is connected at another end of the EDF to maintain unidirectional propagation of the oscillating laser in the ring laser cavity. The SA film functioned to automatically modulate the intra-cavity loss and thus changing the Q-factor in the cavity. After that, the light travelled into a 90: 10 optical coupler which divided the laser into 10% of the total output for optical measurements. The rest of the laser which was 90% of the laser output remained inside the cavity and completed the loop via the 1 550 nm port of the WDM.

To measure the optical parameters desired, a radio frequency spectrum analyzer (RFSA) and a digital oscilloscope (OSC) were used to observe the shape and quality of the pulsed signal in the frequency domain and time domain respectively with help of a fast photodetector (PD). The proposed laser's optical spectrum was examined using an optical spectrum analyzer (OSA) with 0.02 nm resolution. The optical power meter coupled with the power head was utilized to determine the output power of the Q-switched laser.

The stable Q-switched laser started to take form at threshold pump power of 18.1 mW with initial frequency of 21.95 kHz. The stability of this proposed fiber laser remained unchanged until the power was increased to a maximum point at 145.8 mW with a frequency of 75.26 kHz. Exceeding this limit, the pulsed laser began to destabilize and devolved into a continuous wave (CW) operation. Fig.4 shows the optical spectrum of the proposed laser, which describes a single wavelength laser centered at 1 565 nm with a peak power intensity of −38.23 dBm.

The oscilloscope trace of the pulsed laser at 145.83 mW pump power is shown in Fig.5. It indicates a uniform pulse train with peak-to-peak time interval or pulse period of 13.20 µs that correlates to repetition rate of around 75 kHz. By enlarging the pulse trace, as shown in the inset, the pulse width was measured to be around 4.91 µs. Meanwhile, the frequency domain of the Q-switched EDFL observed via the RFSA is portrayed in Fig.6. It shows that about ten frequency harmonics were generated within span of 800 kHz. The fundamental frequency was obtained at around 75 kHz, which is correlated very well to the time domain, hence confirming both optical measurements. The signal-to-noise ratio (*SNR*) of the fundamental frequency stated earlier was around 53.11 dB, implying a stable Q-switching operation.

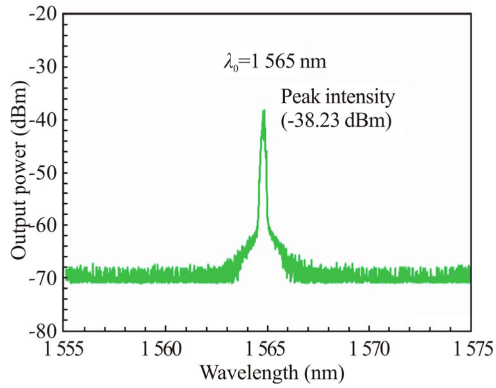

Fig.4 Optical output spectrum at 18.1 mW pumping

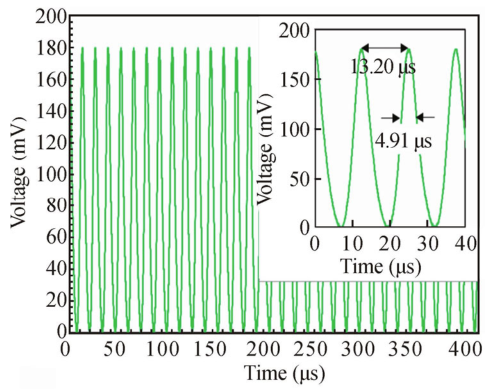

Fig.5 Oscilloscope trace at 145.83 mW pumping (Inset shows the enlarged pulses)

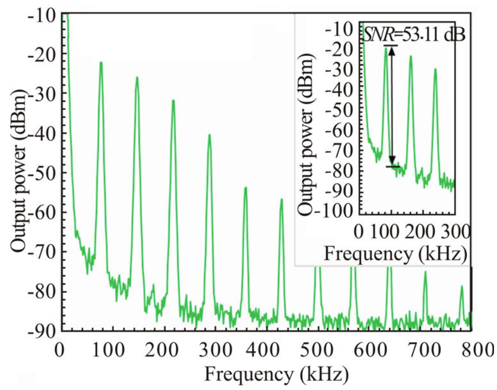

Fig.6 RF spectrum within 800 kHz span (Inset illustrates the enlarged view of the spectrum)

With the rise of pump power from 18.08 mW to 145.83 mW, the output power of the Q-switched EDFL increases from 0.06 mW to 3.15 mW as depicted in Fig.7(a). The slope efficiency in relation to output power response is obtained as 2.54%, which indicates an acceptable amount of intra-cavity losses. Moreover, the pulse energy rises from 2.64 nJ at threshold pump power to 41.85 nJ at the maximum pump power. Fig.7(b) illustrates the expected increase of repetition rate from 21.95 kHz to 75.26 kHz as the pump power was increased from the threshold to the maximum power of 145.8 mW. As the repetition rate increases, the pulse width decreases accordingly from 19.76 μs to 4.91 μs as shown in the same figure. Different from the mode-locking technique, where the repetition rate maintains at a constant frequency that corresponds to the total cavity length, the repetition rate of Q-switched laser pulses generally ascends alongside the increase of pump power within the acceptable range. The threshold energy needed to saturate the SA can be achieved earlier by inputting more pump power, which increases the amount of gain available. Hence, a higher repetition rate of the pulse and narrower pulse width will be obtained. The peak power rose from 0.06 mW to the maximum of 3.15 mW and to confirm that the Q-switch laser was the result of integrating SA film, and the experiment was repeated under the same environmental conditions and procedures. As expected, no generation pulsed laser could be observed because of the absence of the SA element.

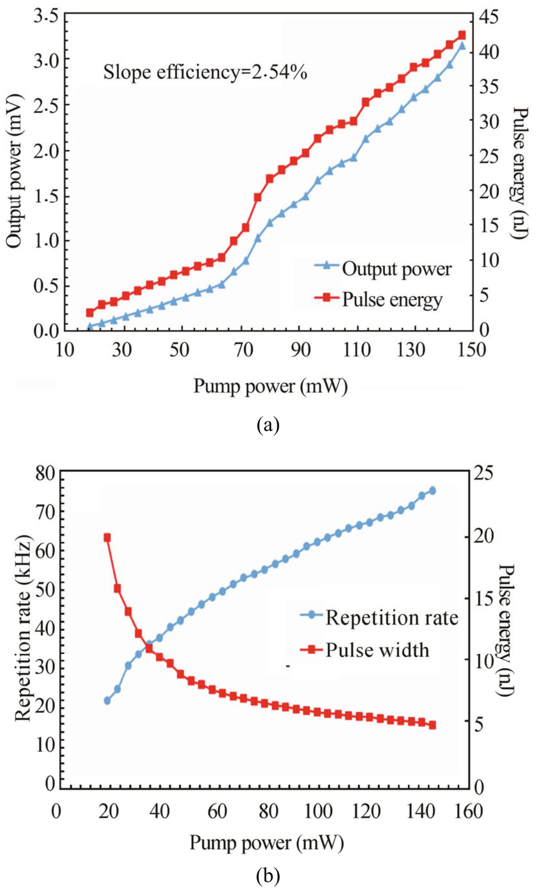

Fig.7 (a) Output power and pulse energy vs. pump power; (b) Repetition rate and pulse width vs. pump power

It is also worthy to note that the mode-locking pulse cannot be realized by using the current cavity. However, as a 200-m-long SMF was added in the EDFL cavity of Fig.3, the mode-locked pulse train was successfully realized. The typical oscilloscope trace of the mode-locked pulse at pump power of 212.39 mW is illustrated in Fig.8. It operated at 968.5 kHz with a pulse duration of 510 ns. Tab.1 shows the comparison of the proposed Q-switched EDFL and the previous works using other materials. Our Q-switched laser has demonstrated a comparable performance compared to other SAs. Also, the proposed laser obtained the highest repetition rate.

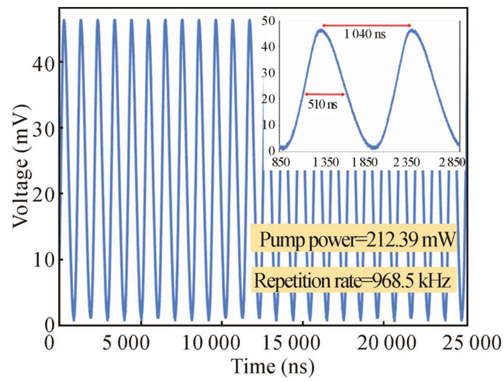

Fig.8 Oscilloscope trace for mode-locking operation (Inset shows the enlarged pulses)

Tab.1 Q-switched fiber lasers with various SAs

Material	λ (nm)	Minimum pulse width (μs)	Maximum repetition rate (kHz)	Pulse energy (nJ)	Modulation depth (%)	Ref.
FIrpic	1 560.4	3.40	87.40	122.60	12.8	[16]
Ti_2AlC	1 560.4	4.88	27.45	22.58	6.3	[17]
WTe_2	1 560.5	1.77	55.56	18.90	21.4	[18]
NiO	1 561.2	5.20	52.18	31.50	39.0	[19]
Ho_2O_3	1 563.0	0.64	115.80	129.36	45.0	[20]
WSe_2	1 560.0	3.10	49.60	33.20	3.5	[21]
P_3HT	1 562.0	3.79	78.63	15.00	11.0	[22]
Eu_2O_3	1 568.0	3.60	68.60	162.00	20.0	[23]
WO_3	1 562.8	1.85	56.70	142.85	20.0	[24]
Lu_2O_3	1 565.0	4.91	145.83	41.85	10.0	This work

In conclusion, a stable, robust, and reliable Q-switched laser was successfully produced by integrating Lu_2O_3 thin film SA into EDFL cavity. When the cavity was pumped in a range from 18.08 mW to 145.83 mW, the pulsed laser was stably operated at 1 565 nm within a frequency range from 21.95 kHz to 75.26 kHz. The maximum output power of 3.15 mW and the maximum pulse energy of 41.85 nJ were recorded at the maximum pump power. Moreover, the shortest pulse width of 4.91 μs was obtained at the maximum repetition rate of 75.26 kHz and at the maximum pump power. By adding 200-m-long SMF in the EDFL cavity, the mode-locked pulse operating at 968.5 kHz with a pulse width of 510 ns was also obtained. The pulse laser emitted through assimilation of the thin film SA offers great flexibility and simplicity that may suit industrial applications like material processing and the biomedical sector.

Statements and Declarations

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

References

[1] SCHIMMEL G, PRODUIT T, MONGIN D, et al. Free space laser telecommunication through fog[J]. Optica, 2018, 5(10)：1338-1341.

[2] ADACHI S, KOYAMADA Y. Analysis and design of Q-switched erbium-doped fiber lasers and their application to OTDR[J]. Journal of lightwave technology, 2002, 20(8)：1506.

[3] SKORCZAKOWSKI M, SWIDERSKI J, PICHOLA W, et al. Mid-infrared Q-switched Er：YAG laser for medical applications[J]. Laser physics letters, 2010, 7(7)：498.

[4] WANG Y, HUANG W, WANG C, et al. An all-optical, actively Q-switched fiber laser by an antimonene-based optical modulator[J]. Laser & photonics reviews, 2019, 13(4)：1800313.

[5] MUHAMMAD A R, AHMAD M T, ZAKARIA R, et al. Q-switching pulse operation in 1.5-μm region using copper nanoparticles as saturable absorber[J]. Chinese physics letters, 2017, 34(3)：034205.

[6] WANG M, CHEN C, HUANG C, et al. Passively Q-switched Er-doped fiber laser using a semiconductor saturable absorber mirror[J]. Optik, 2014, 125(9)：2154-2156.

[7] YAMASHITA S, INOUE Y, MARUYAMA S, et al. Saturable absorbers incorporating carbon nanotubes directly synthesized onto substrates and fibers and their application to mode-locked fiber lasers[J]. Optics letters, 2004, 29(14)：1581-1583.

[8] ISMAIL M A, AHMAD F, HARUN S W, et al. A Q-switched erbium-doped fiber laser with a graphene saturable absorber[J]. Laser physics letters, 2013, 10(2)：025102.

[9] ISMAIL E I, KADIR N A, LATIFF A A, et al. Black phosphorus crystal as a saturable absorber for both a Q-switched and mode-locked erbium-doped fiber laser[J]. RSC advances, 2016, 6(76)：72692-72697.

[10] LI L, PANG L, ZHAO Q, et al. VS_2 as saturable absorber for Q-switched pulse generation[J]. Nanophotonics, 2020, 9(8)：2569-2576.

[11] ZHENG Y, TANG X, WANG W, et al. Large-size ultrathin α-Ga_2S_3 nanosheets toward high-performance photodetection[J]. Advanced functional materials, 2021, 31(6)：2008307.

[12] NIZAMANI B, JAFRY A A A, ABDUL KHUDUS M I M, et al. Indium tin oxide coated D-shape fiber as saturable absorber for passively Q-switched erbium-doped fiber laser[J]. Optics and laser technology, 2020, 124：105998.

[13] AL-HITI A S, YASIN M, HARUN S W. Poly (3, 4-ethylenedioxythiophene)：Poly (styrenesulfonate) spin-coated onto polyvinyl alcohol film as saturable absorber for generating Q-switched laser at 1.5 μm region[J]. Optical fiber technology, 2022, 68：102763.

[14] NAJM M M, AL-HITI A S, NIZAMANI B, et al. Effect of MAX phase chromium aluminum carbide thin film thickness on Q-switched erbium-doped fiber lasers[J]. Optical fiber technology, 2022, 70：102853.

[15] GUZIK M, LEGENDZIEWICZ J, SZUSZKIEWICZ W, et al. Synthesis and optical properties of powders of lutetium and yttrium double phosphates-doped by ytterbium[J]. Optical materials, 2007, 29(10)：1225-1230.

[16] SALAM S, AL-MASOODI A H H, AL-HITI A S, et al. FIrpic thin film as saturable absorber for passively Q-switched and mode-locked erbium-doped fiber laser[J]. Optical fiber technology, 2019, 50：256-262.

[17] LEE J, KWON S, LEE J H. Ti_2AlC-based saturable absorber for passive Q-switching of a fiber laser[J]. Optical materials express, 2019, 9(5)：2057-2066.

[18] AHMAD H, ALBAQAWI H S, YUSOFF N, et al. 56 nm wide-band tunable Q-switched erbium doped fiber laser with tungsten ditelluride (WTe_2) saturable absorber[J]. Scientific reports, 2020, 10(1)：1-10.

[19] NADY A, AHMED M H M, LATIFF A A, et al. Nickel oxide nanoparticles as a saturable absorber for an all-fiber passively Q-switched erbium-doped fiber laser[J]. Laser physics, 2017, 27(6)：065105.

[20] AL-HITI A S, RAHMAN M F A, HARUN S W, et al. Holmium oxide thin film as a saturable absorber for generating Q-switched and mode-locked erbium-doped fiber lasers[J]. Optical fiber technology, 2019, 52：101996.

[21] CHEN B, ZHANG X, GUO C, et al. Tungsten diselenide Q-switched erbium-doped fiber laser[J]. Optical engineering, 2016, 55(8)：081306.

[22] SAMSAMNUN F S M, ZULKIPLI N F, SARJIDAN M A M, et al. Poly (3-hexylthiophene-2, 5-diyl) regioregular (P3HT) thin film as saturable absorber for passively Q-switched and mode-locked erbium-doped fiber laser[J]. Optical fiber technology, 2020, 54：102073.

[23] ZULKIPLI N F, JAFRY A A A, APSARI R, et al. Generation of Q-switched and mode-locked pulses with Eu_2O_3 saturable absorber[J]. Optics & laser technology, 2020, 127：106163.

[24] AL-HITI A S, AL-MASOODI A H H, AROF H, et al. Tungsten tri-oxide (WO_3) film absorber for generating Q-switched pulses in erbium laser[J]. Journal of modern optics, 2020, 67(4)：374-382.