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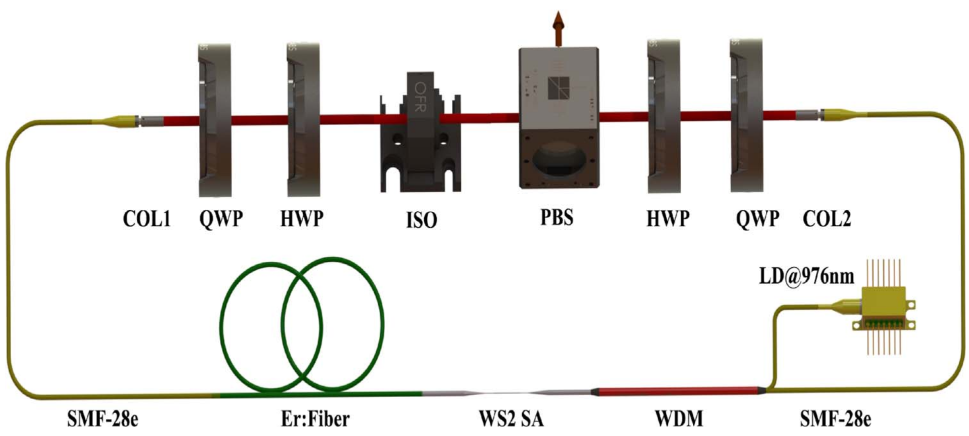

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Nanosecond Hybrid Q-Switched Er-Doped Fiber Laser With WS_2 Saturable Absorber

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Abstract: We demonstrate a stable hybrid Q-switched Er-doped fiber (EDF) laser with WS_2 as the saturable absorber (SA). The SA device is obtained by depositing WS_2 on a tapered fiber using the pulsed laser deposition method. The modulation depth of the SA is 8.0%, the nonsaturable loss is 30%, and the saturation intensity is 200 MW/cm^2. By combining the saturable absorption of fiber-taper WS_2 and the effect of nonlinear polarization rotation, the Q-switched EDF laser is achieved with a pulse duration of 443 ns and average power of 43 mW. The repetition rate can be adjustable among 235–365 KHz. To our best knowledge, both pulse duration and output power are the best results among Q-switched EDF lasers with transition mental dichalcogenide materials like SAs. These results indicate that the proposed hybrid Q-switched EDF laser performs better to achieve shorter pulses with higher power in the future.

Index Terms: Q-switched, fiber lasers, nonlinear optical materials.

1. Introduction

High power Q-switched fiber lasers, for the obvious superiority of compactness and robustness, are widely applied in material processing, remote sensing, medicine, and nonlinear frequency conversion [1]–[3]. In general, nonlinear polarization rotation (NPR) [4] and saturable absorbers (SAs) are two main powerful techniques for Q-switching. The NPR method has been used to generate Q-switched pulses due to such advantages of simple structure, flexibility, long term stability [5]. By applying the effect of NPR, researchers have led to a significant spread of pulse parameters obtained at different polarization settings of the intra-cavity laser radiation [6] and discovered non-trivial long-scale internal periodicity in stochastic generation of partially mode-locked fiber lasers operating in dynamic spatiotemporal regimes [7]. In 2008, the simple and all-fiber passively Q-switched EDF ring laser based on NPR has been experimentally demonstrated. The intensity-dependent transmission due to the effect of the NPR acts as an artificial Q-switcher [8]. In 2012, an all-fiber wide-band tunable passively Q-switched laser based on the NPR technique also has been reported [9].

At the same time, SAs, such as semiconductor saturable absorber mirrors (SESAMs) [10]; carbon nanotubes (CNTs) [3], [11]; graphene [12], [13]; topological insulators (TIs) [14], [15];

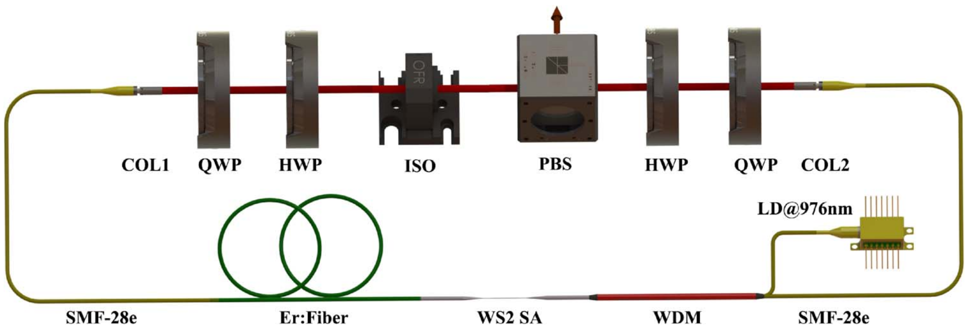

Fig. 1. Schematic of passively Q-switched EDF laser. COL: collimator. PBS: polarization. WDM: wavelength-division multiplexer.

TMDs [16], [17]; and black phosphorus (BPs) [18], [19] are also the excellent passively Q-switchers. In order to enhance the performance of these SAs, evanescent field interaction has been employed. Tapered fiber with SAs method is the most common used technology [20]–[22]. For carbon nanotubes (CNT), the easy fabrication and cheap cost make it very popular, but CNT is an intrinsically selective-broadband SA depending on tube diameter, which usually leads to a larger non-saturable loss for obtaining a broadband operation. Although graphene possesses the property of wavelength-independent saturable absorption, it has a small absorption of only 2.3% at 1550 nm and a relatively low MD. As the analogs of graphene, TMDs, such as MoS_2 and WS_2, consist of alternating hexagonal planes of Mo (W) and S atoms bound by van der Waals interaction [23], which allows formation of nanosheet structures and are considered to be a promising SAs [24]. In addition, these TMD materials can be fabricated easier with more methods and the character of optical saturable absorption has been confirmed. The first demonstration of MoS_2 based Q-switched EDF lasers in 1, 1.5, and 2 μm has been reported in 2014, which reveals that the performance of MoS_2 Q-switching can be superior of at least comparable to graphene, CNT, and TIs [25]. In 2015, Q-switched EDF laser by WS_2 with 710 ns pulse duration has also been obtained, but the maximum average output power has just been 2.5 mW [26]. For those compact all-fiber Q-switched lasers with TMDs as SAs, the disadvantage of them is the low average output power and μs-level pulse duration. The high average output power with nanosecond pulse is rarely reported.

In this paper, we propose a novel design of Q-switched EDF laser, which operates on a hybrid scheme devised by incorporating NPR and fiber-taper WS_2SA. The NPR technique adopted here is intended to shape Q-switched pulses and enhance the stability. The fiber-taper WS_2 SA is added to perform nonlinear filtering of the pulse amplitude to avoid excessive intra-cavity nonlinear side effects and help improve the output power. Without excessive nonlinear side effects, the pulse can obtain more energy accumulation through the Er-doped gain fiber [27], [28]. The fiber-taper WS_2 SA is obtained by preparing bulk WS_2 into thin film deposited onto the tapered fiber through PLD method, which has a MD of 8.0%, non-saturable loss of 30% and saturation intensity of 200 MW/cm^2. Incorporating such SA into the NPR laser cavity, Q-switching operation near 1530 nm is realized with tunable repetition rate range from 235 KHz to 362 KHz. The maximum output power is measured to be 43 mW, corresponding single pulse energy of 116 nJ. The shortest pulse duration of 443 ns is near to the limit of theoretical. To our best knowledge, this is the shortest pulses ever produced by any Q-switched fiber lasers with TMDs as SAs. High signal-to-noise ratio (SNR) of 80 dB further confirms the excellent performance of the hybrid Q-switched laser.

2. Experimental Setup

The schematic diagram of hybrid Q-switched EDF laser is presented in Fig. 1. The ring cavity consists of a gain fiber, a fiber-taper WS_2 SA, a wavelength division multiplexer (WDM), a

TABLE 1

Nonlinear parameters of different SAs

SA type	MD	saturation intensity	non-saturable loss	Ref
SWNTs	0.94%	--	--	[31]
Graphene	1.3%	--	--	[32]
WS_2-PVA	2.53%	148.2 MW/cm^2	58.3%	[33]
Bi_2Se_3	4.3%	11 MW/cm^2	--	[34]
Bi_2Te_3	22%	57 MW/cm^2	21%	[35]
WS_2	4.9%	3.83 MW/cm^2	6.9%	[36]
MoS_2	2%	10 MW/cm^2	--	[37]
MoS_2	1.6%	13 MW/cm^2	54.8%	[25]
$MoSe_2$	4.7%	3.4 MW/cm^2	6.6%	[38]
BP	18.55%	10.74 MW/cm^2	8.1%	[39]
WS_2-taper	8.0%	200 MW/cm^2	30%	Our work

polarization-dependent isolator (ISO), two SMF-28 leading fiber collimators, a polarization beam splitting (PBS), two half wave plates (HWPs), and the quarter wave plates (QWPs). A 30 cm long EDF with absorption coefficient of 250 dB/m at 976 nm is employed as the gain medium. Two HWPs and QWPs are used to finely adjust the polarization state. The polarization-dependent isolator (ISO) not only is used to get the unidirectional operation in the fiber laser, but also plays the role of a polarizer so that light leaving the isolator is linearly polarized. The fiber-taper WS_2 SA is prepared by PLD method as [29]. The waist diameter of tapered fiber is 18 μm and the length is 1 mm. The entire waist region is coated with WS_2 film. When the WS_2 is split into monolayer or few layers, the property of semiconductors with indirect bandwidth in bulk states can turn into direct band gap in thin film, which is good for the saturable absorption property [30]. Fiber-taper WS_2 SA prepared by PLD method, which has the advantages of the strong nonlinear optical response in material together with the sufficiently long range interaction length. Table 1 lists the nonlinear parameters of different SAs. The MD, non-saturable loss and saturation intensity of our SA are measured to be 8.0%, 30% and 200 MW/cm^2, which are in excellent level. The EDF is pumped by a 976 nm laser diode (LD) with maximum output power of 500 mW. The output pulses from the PBS are measured by a 1-GHz photo-detector and a 250 MHz oscilloscope (Tektronix TDS 714 L), radio frequency (RF) spectrum analyzer (Agilent E4407B), an optical intensity autocorrelator (Femtochrome, FR-103XL), and an optical spectrum analyzer (Yokogawa AQ6315A).

3. Experimental Results and Discussions

In the experiments, the EDF laser starts to operate in Q-switched regime by gradually increasing the pump power to 285 mW and optimizing the polarization sates. Actually, the nonlinear effect plays a significant role in pulse stabilization and helps achieve shorter pulse. When the polarization sates are changed, the nonlinearity would be changed. Therefore, the wave plates states effect the Q-switched operation. The duration and the energy of the pulses would be changed under different polarization states, which is a result of the mutual interaction among the laser gain and losses. The Q-switched threshold is relatively high, which can be attributed to the high saturation intensity of fiber-taper WS_2. Through continuously increasing the pump power to 356 mW, 416 mW and 486 mW, the repetition rate varies from 235 KHz to 285 KHz, 315 KHz and 327 KHz, respectively. As clearly shown in Fig. 2, the pulse train remains as a uniform intensity distribution without obvious amplitude fluctuation. This suggests that our EDF laser operates in stable Q-switching regime with variable repetition rates. The output performance of the stable Q-switched laser is presented in Fig. 3. The pulse train under pump power of 300 mW is shown in Fig. 3(a). The repetition rate is 240 KHz, corresponding to a time interval

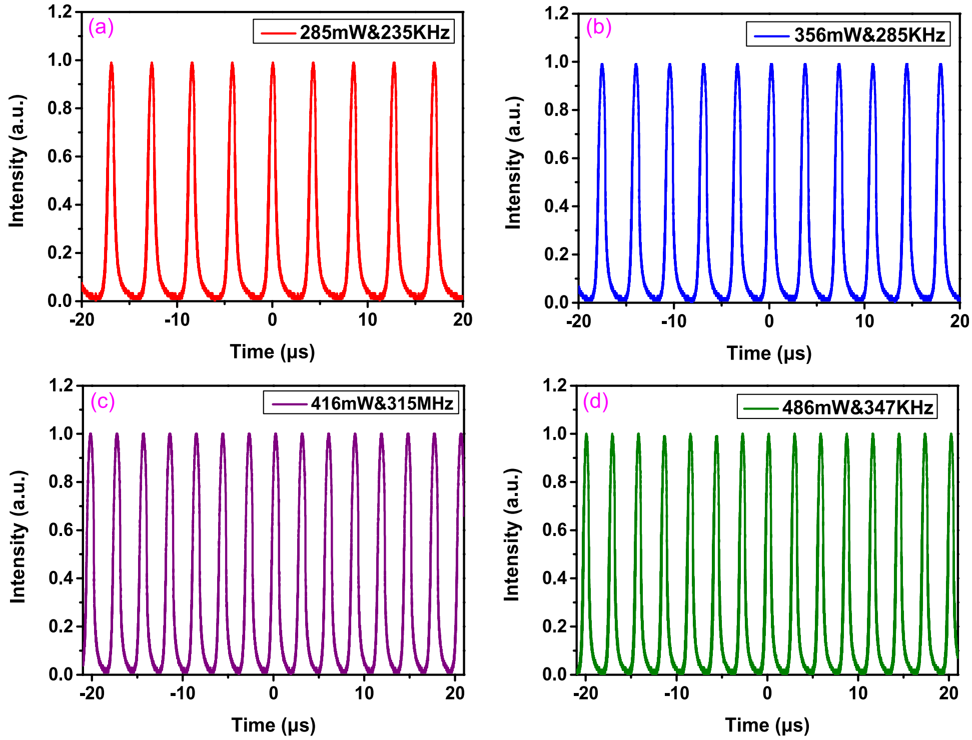

Fig. 2. Q-switched pulse trains with different pump power values.

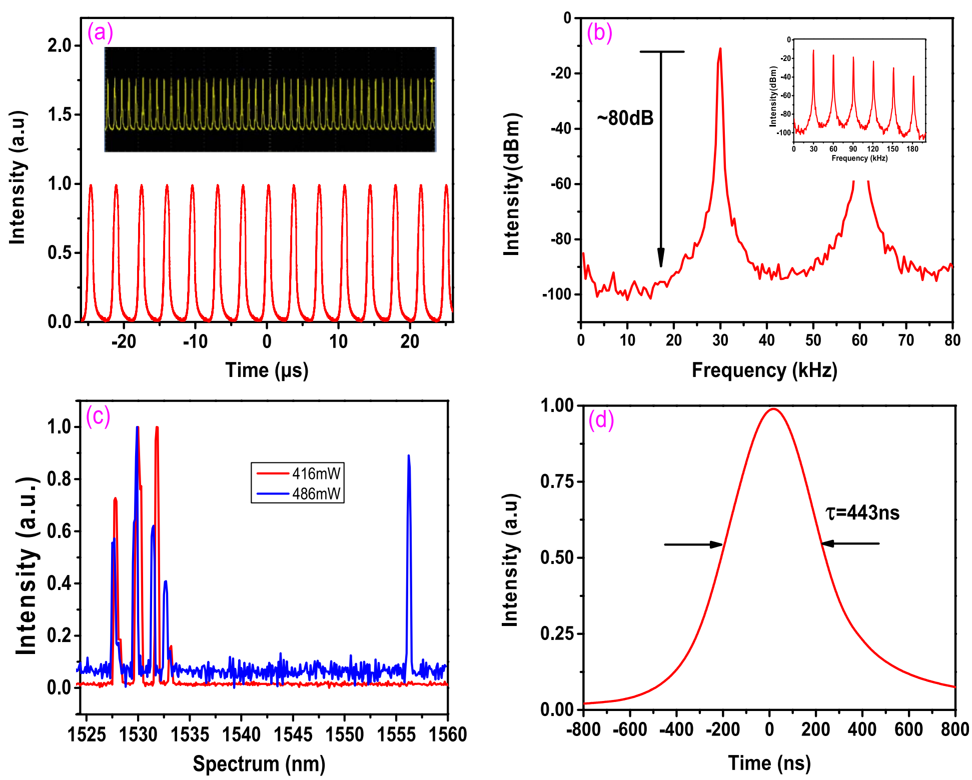

Fig. 3. (a) Oscilloscope trace of the Q-switched pulse train with the pump power of 300 mW. (b) RF optical spectrum and wideband RF spectrum. (c) Optical spectra with the pump power values of 416 and 486 mW. (d) Pulse duration with the pump power of 510 mW.

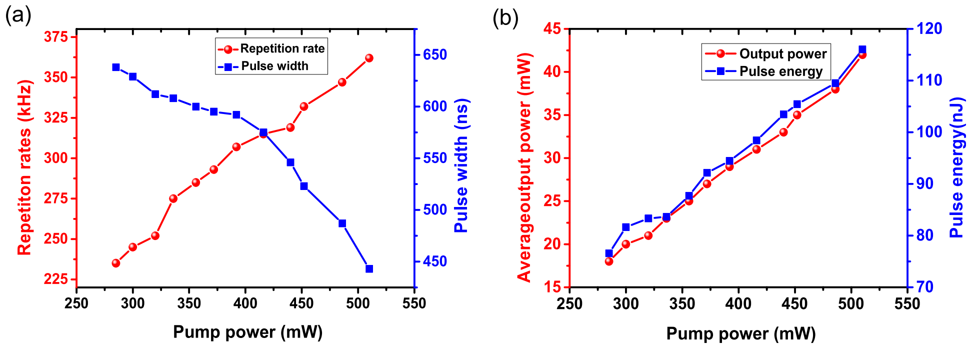

Fig. 4. (a) Repetition rates and pulsewidth versus pump power values. (b) Average output power and single pulse energy versus pump power.

of 4.25 μs. The insert shows the pulse train in a long time scale, which demonstrates a nearly uniform intensity distribution without peak intensity modulation. The corresponding RF spectrum with resolution bandwidth (RBW) of 100 KHz is illustrated in Fig. 3(b). The SNR of our fiber laser is over 80 dB, which is the highest value among the passively Q-switched lasers, clearly indicating that this Q-switching operates in a stable regime all the time. Fig. 3(c) shows the optical spectrum of the Q-switched pulses, which is multi-peak structure almost strictly 2 nm interval distribution at the center of 1530 nm. Determined by the EDF length of 30 cm, the central wavelength locates in 1530 nm. The shorter length of the gain fiber, the more number of inversion particles, leading to the gain spectrum move to shorter wavelength. With increasing the pump power, the multi-peak optical spectrum is slightly blue shift. As pump power goes up to 486 mW, another peak appears at the center of 1556 nm. As shown in Fig. 3(d), the shortest pulse duration is 443 ns with the pump power of 500 mW, which is near the limited pulse duration. According to the theoretical pulse width of passively Q-switched lasers by the following equation [40]:

$$\tau = \frac{3.52\ T_R}{\Delta T}$$

T_R is the cavity-round trip time, and ΔT is the MD of SA. The limited pulse width is calculated to be 419 ns. So it can be concluded that both the quality of fiber-taper WS_2 SA and the design of cavity length are suitable for the Q-switched laser. In further work, we would investigate the mode-locking state, multiple pulse state, and soliton rains.

The repetition rate and pulse duration versus pump power are shown in Fig. 4(a). The repetition rate increases from 235 KHz to 365 KHz with the pump power increasing from 285 mW to 510 mW, and the pulse width decreases non-linearly from 638 ns to 443 ns, which is in agreement with the typical feature of passively Q-switched lasers [41]. The Q-switched operation is determined by the cavity gain, cavity loss and so on. With increasing the pump power, more and more electrons are excited and accumulated in the upper energy level. The increase of the number of photons and the decay of the number of inversion photons are more rapid, therefore, the pulse width is shorter and the repetition rate is larger. The average output power and single pulse energy versus incident pump power are shown in Fig. 4(b). Limited by the available pump power, the maximum average output power is 42 mW, corresponding to the single pulse energy of 116 nJ. As shown in Table 2, the Q-switched results of EDF with TIs, TMDs, and BPs are compared. It can be seen that the pulse duration reported in Q-switched EDF lasers are mostly in a range of μs-level. In our experiment, this value is significantly advanced and the shortest pulse width of 443 ns is obtained, which are due to the mutual effect of saturable absorption of WS_2 and NPR. It is also noted that the average output power of 43 mW is the highest output power among the Q-switched EDF lasers. Compared the SNR value in Table 2, the SNR obtained by Q-switched fiber lasers only with TMD SAs is no more than 50 dB. This value of our fiber laser is over 80 dB, which is contributed by the effect of NPR to a large extent. These

TABLE 2

Q-switched EDF lasers by different SAs

Q-switcher type	Pulse width	Output power	Repetition rate	SNR	Ref
Bi_2Se_3	1.9 μs	22.35 mW	459-940 KHz	50 dB	[34]
Bi_2Te_3	13 μs	19.56 mW	2.15-12.8 KHz	36.4 dB	[35]
WS_2	1.1 μs	16.4 mW	79-97 KHz	44 dB	[36]
WS_2	710 ns	2.5 mW	82-134 KHz	--	[26]
MoS_2	3.3 μs	5.9 mW	8.77-43.47 KHz	50 dB	[37]
MoS_2	5.4 μs	1.7 mW	6.5-27 KHz	54.5 dB	[25]
$MoSe_2$	4.8 μs	29.2 mW	26.5-35.4 KHz	--	[38]
BP	9.35 μs	0.6 mW	4.43-18 KHz	--	[42]
BP	10.32 μs	1.5 mW	6.983-15.78 KHz	45 dB	[39]
NPR+WS_2	433 ns	43 mW	235-365 KHz	80 dB	Our work

results clearly indicate that the stable Q-switched operation of the laser is indeed contributed by the effect of NPR and saturable absorption of WS_2. To investigate the long-term stability of the Q-switched laser, we also note the pulse trains over 24 h at a fixed pump power of 486 mW. There is no obvious amplitude fluctuation occurs, showing that the Q-switched laser provided with excellent stability.

4. Conclusion

In summary, we present a hybrid Q-switched EDF laser with the nanosecond level pulse duration and high average output power, which is based on the NPR and fiber-taper WS_2 SA devices jointly act as a passive optical Q-switcher. The electrical SNR has been better than 80 dB, suggesting Q-switching operating in a stable regime. With increasing the pump power, the repetition rate is tuned within 235–365 KHz range. The shortest pulse width of 443 ns and the maximum average output power of 43 mW have been the best results from any Q-switched EDF lasers with TMDs SAs.

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