Black phosphorus (BP), a new two-dimensional (2D) material, has been deeply developed for extensive applications in electronics and optoelectronics due to its similar physical structure to graphene and thickness dependent direct band gap. Here, we demonstrated a submicrosecond passive Q-switching Er-doped fiber laser with BP as saturable absorber (SA). The BP saturable absorber was fabricated by mechanical exfoliation method. By taking full advantage of the ultrafast relaxation time of BP-SA and careful design of compact ring cavity, we obtained stable Q-switching pulses output with a shortest duration as narrow as 742 ns. With increasing the pump power, the pulse repetition rate accreted gradually almost linearly from 9.78 to 61.25 kHz, and the pulse duration declined rapidly at lower pump power regime and retained approximate stationary at higher pump power regime from 3.05 to 0.742 \( \mu \)s. The experimental results indicate that BP-SA can be an effective SA for nanosecond Q-switching pulse generation.

1. Introduction

Pulsed fiber lasers have been widely applied in various applications ranging within machining, material processing, environmental sensing, medicine, laser processing, fiber sensor, and long-range optical communication. The most common pulse generation methods used in fiber laser include Q-switching and mode-locking techniques [1–6]. There are two types of Q-switching approaches: active and passive one. Among them, passive Q-switching technology based on saturable absorber (SA) has made remarkable progress in view of compact, low cost, flexible, and so on. Since the Nd:glass (the first generation of SA) was successfully used for pulse generation in 1966 [7], a wide variety of SAs have been intensively developed, such as Semiconductor Saturable Absorption Mirrors (SESAMs) [8, 9], Carbon Nanotubes (CNTs) [10–13], graphene [14–18], Topological Insulator (TI) [19, 20], and Transition Metal Dichalcogenides (TMDs) [21–24]. The SESAMs are utilized in most of commercially available laser systems for high flexibility and stability. However, SESAMs have relatively narrow operation bandwidth and require complex fabrication and packaging [1]. Recently, the research on broadband SAs based on CNT or graphene has presented explosive development for broad operation bandwidth, ultra-fast recovery times, low saturation intensity, low cost, and easy fabrication [10–18]. Nevertheless, they still have some drawbacks. The spectral response range of CNTs sensitively depends on their diameter and chirality, restricting their practical applications in specific wavelength or broadband tenability [13]. And, graphene has relatively weak optical absorption (\( \sim 2.3% \)/layer [20]) due to its gapless band structure, which limits its application in fiber laser. Another 2D material, transition metal dichalcogenides (TMDs) (MoS\(_2\) [21], WS\(_2\) [22], MoSe\(_2\) [23, 24], etc.) has been developed as saturable absorber with high performances [21]. Although they have higher optical absorption at specific wavelength, the optical response mainly locates at visible region due to their comparatively large band gap (\( \sim 1.8 \) eV for MoS\(_2\), \( \sim 2.1 \) eV for WS\(_2\), and \( \sim 1.7 \) eV for MoSe\(_2\)) [25, 26].

Very recently, another 2D material, black phosphorus (BP), has been rediscovered for various applications in electronics and optoelectronics [27]. Its structure is similar to graphene, in which individual atomic layers stacked together by van der Waals interaction. BP has layer-dependent direct
electronic band gap, which can be tuned from ~0.3 (bulk) to ~2 eV (monolayer) [28], covering nearly whole near and mid-infrared wavelength. Therefore BP can be regarded as a significant benefit material for ultrafast photonics and high frequency optoelectronics in infrared wavelength. Lately, researches have paid close attention to its nonlinear optical response and used it as SA in lasers [29–31]. Even [32] shows the recovery time of BP is as short as 26 fs (much shorter than other SAs mentioned above), revealing its tremendous potential in ultrafast pulse generation.

In this paper, we also focus on the capacity of BP in ultra-short pulse generation and demonstrate a submicrosecond Q-switching pulse with a compact Er-doped all-fiber ring laser. The BP material was prepared by mechanical exfoliation method and as an effective SA for short Q-switching pulse generation. After inserting this BP-SA into a well design compact Er-doped fiber laser, we achieved stable Q-switching pulse output. The narrowest Q-switching pulse we obtained is as short as 742 ns. The experimental results show the BP's potential for narrow Q-switching pulse generation.

2. Experimental Setup and Results

The black phosphorus-based SA was prepared by mechanical exfoliation method, whose details have been shown in [30]. To achieve a submicrosecond Q-switched pulse, ultrashort laser cavity should be employed. We designed a special compact all-fiber ring cavity shown in Figure 1(a) with an optical integrated device for the joint function of wavelength-division multiplexer (WDM), polarization-insensitive isolator (PI-ISO), and 10% output coupler (OC). The total cavity length is 4.7 m with 0.95 m highly doped erbium-doped fiber (EDF, LIEKKI Er 80-8/125) as gain medium. Others are standard single-mode fiber (SMF-28). The laser is pumped by a 975 nm laser diode (LD) with maximum power of 500 mW. The BP-SA is incorporated into the cavity between the EDF and integrated device. There is not any extra component in this fiber laser. The output is characterized by an optical spectrum analyzer (Ando AQ-6317B) and a real-time oscilloscope with bandwidth of 4 GHz (Agilent Technol., DSO9404A) combined with a 5 GHz photodetector (Thorlabs SIR5).
Without the BP-SA device, the central wavelength is located at 1600 nm, suggesting that the optical integrated device possesses low insertion loss. In this condition, we cannot obtain Q-switching operation state no matter how we adjust pump power and apply stress on fiber (correspondingly changing fiber birefringence to control the polarization rate of light in cavity). After the BP-SA device is introduced into the cavity, stable Q-switching output can be obtained once the pump power exceeds 40 mW. Figure 1(b) shows typical Q-switching spectrum with slight modulation. The central wavelength is 1557.9 nm. With increasing pump power, the durations of Q-switching pulse decrease gradually. At max revealable pump power of 160 mW, we obtained minimum pulse width as narrow as 742 ns as shown in Figure 1(c). It is worth noting that, keeping increasing pump power above 160 mW, the Q-switching state becomes unstable and disappears ultimately.

In addition, we also measured the evolution process of pulses with the pump power increasing to confirm the Q-switching operating state, shown in Figure 2. As it can be seen, with pump power increasing from 40 to 160 mW, the average output power increases almost linearly from 198 µW to 2.43 mW, but the pulse energy fluctuates between 20.2 and 40.8 nJ. Simultaneously, the pulse repetition rate accretes gradually also almost linearly from 9.78 to 61.25 kHz, and the pulse duration declines rapidly at lower pump power regime and keeps approximately unchanged at higher power regime from 3.05 to 0.742 µs. These entire matches with typical Q-switching state confirm its operating state.

3. Conclusions

In conclusion, we focus on the capacity of BP in ultra-short pulse generation and demonstrate a submicrosecond Q-switching pulse with a compact Er-doped all-fiber ring laser. The BP material was prepared by mechanical exfoliation method and as an effective SA for short Q-switching pulse generation. It has narrow Q-switching pulse as short as 742 ns. With increasing the pump power, the pulse repetition rate accreted gradually almost linearly from 9.78 to 61.25 kHz, and the pulse duration declined rapidly at lower pump power regime and retained approximate stationary at higher pump power regime from 3.05 to 0.742 µs. The experimental results indicate that BP-SA can be an effective SA for nanosecond Q-switching pulse generation.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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