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Q-switched thulium/holmium fiber laser with gallium selenide

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ABSTRACT

A passively Q-switched thulium/holmium fiber laser with a gallium selenide (GaSe) saturable absorber (SA) is proposed and demonstrated for the first time. The GaSe based SA is prepared by mechanical exfoliation and inserted into the proposed laser cavity to generate Q-switched pulses. Stable Q-switching operation is achieved at 1986.0 nm, with output pulse repetition rates ranging from 22.9 kHz to 32.3 kHz over a pump power range of 112.0 mW to 235.0 mW. The generated Q-switched pulses have a maximum pulse energy of 120.3 nJ and minimum pulse width of 6.9 μs. The proposed thulium/holmium fiber laser with GaSe SA will be able to cater to multiple applications requiring pulsed laser outputs in the 2.0 μm region.

1. Introduction

Q-switched fiber laser have attracted significant attention for use in various applications such as laser material processing, environmental sensing, medicine and optical imaging [1–5] due to their numerous advantages such as compactness, high flexibility and low operating cost [6–8]. In general, Q-switching operation can be obtained by either active or passive techniques [9]. Active techniques involve either an electro-optic or acoustic-optic modulator in the laser system [10–12], thus increasing the complexity of the laser system as well as the total cost of the system [12]. As a result of this, passive Q-switching is preferable due to its ease of operation as compared to active Q-switched systems.

Normally, in a passive system, a saturable absorber (SA) is used in the laser cavity to generate a Q-switched output. The current common approach is the use of semiconductor saturable absorber mirrors (SESAMs) to achieve passive Q-switching operation in fiber laser systems [13]. Despite this, SESAMs still exhibit numerous drawbacks such as complex implementation into a fiber laser system, larger insertion loss and high fabrication cost [12,14]. This has thus motivated researchers to investigate other potential materials to serve as inexpensive and simple alternatives for new high performance SAs. The significant breakthrough of 2-Dimensional (2D) nanomaterials such as carbon nanotubes (CNTs) and graphene [15–19], have shown significant promise as SAs in generating passive Q-switched pulses. This has in turn encouraged researchers to pursue for new materials which are capable of acting as SAs. Some of the new SAs that have successfully generate passively Q-switched pulses are topological insulators [20–22], transition metal dichalcogenides [9,23,24], silver nanoparticles [25], black phosphorus [26,27] and MXenes [28].

In this work, gallium selenide (GaSe), a material classified as a 2D layered metal monochalcogenide is used to achieve Q-switched pulses in a fiber laser system. GaSe has the advantages of having broadband transparency and low optical transmission losses, in addition to having a large surface damage threshold and a large nonlinear optical coefficient [29]. Currently, GaSe has seen significant applications in the areas of nonlinear optics and terahertz system [30,31] and opto-electronics [32]. Additionally, GaSe based SAs have also been demonstrated to be able to generate Q-switched pulses in the 1.0 μm [33], S+/S band [34] and also 2.0 μm [35]

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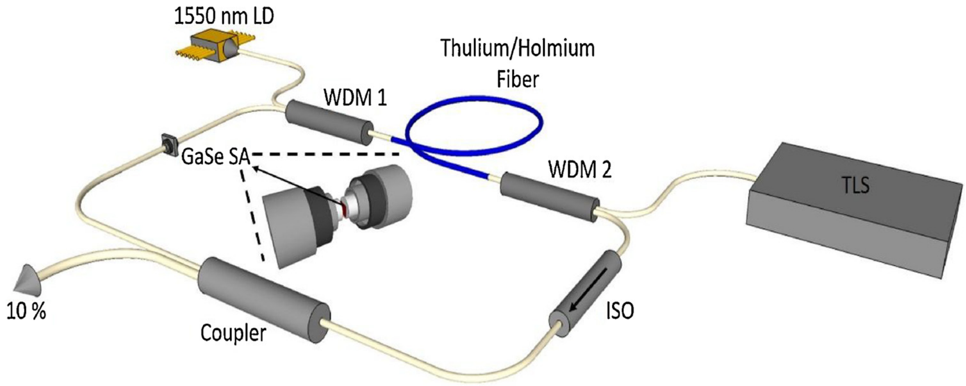

Fig. 1. Schematic of passively Q-switched thulium/holmium doped fiber with GaSe SA.

regions, indicating their capability as a broadband SA. As such, its use as an SA is highly potential. Furthermore, GaSe shows unique optical properties such as upconversion luminescence [36], that is seen to be an advantage of GaSe to generate a Q-switched pulses.

In this demonstration, a thulium/holmium fiber is used as the gain medium for the proposed laser. Thulium/holmium fibers are capable of producing a laser output at the 2.0 μm region and beyond as reported by Marc Eichhron et. al. [37]. Previous works on the development of 2.0 μm region laser using thulium-doped fiber laser system have also been reported, although these are limited to operational wavelengths in the range of 1.8 μm–2.05 μm [38–40]. Thus, the combination of thulium/holmium fiber laser system and GaSe as SA would be able to generate passive Q-switched pulses in 2.0 μm region, as well as the opportunity to go beyond this region. This proposed laser would have a wide range of applications such as medicine, remote sensing and mid-IR spectroscopy [41–43]. Furthermore, the 2.0 μm region is also an 'eye-safe' region, giving the proposed laser significant potential for real-world applications [44]. This is the first demonstration, to the best of author's knowledge, of passively Q-switched thulium/holmium fiber laser using a GaSe based SA.

2. Experimental setup

The setup of the proposed thulium/holmium fiber laser is given in Fig. 1. The fiber laser is configured in a ring cavity and consists of a 4-m long TH512 thulium/holmium fiber with an absorption rate of ~21.0 dB/m at 1550.0 nm and core diameter of 9.0 μm as the gain medium. The thulium/holmium fiber is bidirectionally pumped using a Princeton Lightwave 1550 nm laser diode (LD) and a Santec WLS100 tunable laser source (TLS). Both the LD and TLS are connected to the 1550 nm ports of 1550/2000 nm wavelength division multiplexers (WDMs), designated as WDM 1 and WDM 2 for the forward and backward pumping sources respectively. The common port of both WDMs is connected to the gain medium, and an isolator is linked to the 2000 nm port of WDM 2 to ensure the unidirectional propagation of the signal within the laser cavity. The output from the isolator is then connected to a 90:10 optical tap coupler, which is used to extract approximately 10% of the signal from the cavity for further analysis. The 90% port of the tap coupler is connected to the GaSe SA assembly, which induces the passive Q-switching effect in the cavity. The pulsed output from the SA is then connected to the 2000 nm port of WDM 1, thus completing the laser cavity. The cavity has a total measured length of approximately 14.0 m, which includes the thulium/holmium fiber, all other fiber devices and connecting fibers.

The GaSe based SA used in this work is prepared using the mechanical exfoliation. This technique is widely used by various researchers in this field due to its reliability and simplicity [24,26]. A monochalcogenide (MX) GaSe crystal flake is obtained from 2D Semiconductors in bulk form, and slowly exfoliated by using the scotch tape technique [45]. The fabrication and characterization of the SA have been detailed by Ahmad et al. [35].

The output pulse signal is investigated using a Yokogawa AQ6375 Optical Spectrum Analyzer (OSA) for its optical spectral characteristics, while its pulse characteristics are studied using a Yokogawa DLM2054 Oscilloscope (OSC) with a Newport 818-BB-51 F InGaAs 12.5 GHz photodetector. An Anritsu MS2683 A Radio-Frequency Spectrum Analyzer (RFSA) is used to examine the signal-to-noise ratio (SNR) of the generated pulsed laser while a Thorlabs optical power meter is used to monitor the output power.

3. Results and discussions

In the proposed experiment, the continuous-wave starts to lase at a pump power of 100.0 mW, with Q-switching operation beginning at 112.0 mW. Fig. 2 summarizes the Q-switching characteristics of the proposed laser at a pump power of 112.0 mW. From the optical spectrum in Fig. 2(a), it can be seen that the laser has a central wavelength of 1986.0 nm with a 3-dB bandwidth of ~10.0 nm. Fig. 2(b) illustrates the corresponding pulse train, which has a fundamental frequency of 27.8 kHz and time interval between pulses of around 36.0 μs. The intensity distribution of the pulses nearly uniform without any observable modulation as illustrated in Fig. 2 (b), indicating no self-mode locking in the laser system [44].

The corresponding radio frequency (RF) spectrum has a SNR of around 41.6 dB, with a fundamental frequency and resolution bandwidth of 27.8 kHz and 300 Hz respectively. This is given in Fig. 3(a). The measured SNR value indicates highly stable Q-