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Tunable Q-switched thulium-doped fiber laser (TDFL) in 2.0 μm region based on gallium selenide saturable absorber

H. Ahmad [a,b,*], S.A. Reduan [a]

[a] Photonics Research Centre, University of Malaya, 50603 Kuala Lumpur, Malaysia
[b] Department of Physics, Faculty of Science and Technology, Airlangga University, Surabaya 60115, Indonesia

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ABSTRACT

A tunable Q-switched thulium-doped fiber laser (TDFL) using a Gallium Selenide (GaSe) based saturable absorber (SA) is proposed and demonstrated for operation in the 2.0 μm region. The Q-switched TDFL operates from 1960.0 nm to 1998.0 nm, covering a wavelength range of 38.0 nm. The generated output pulses have a repetition rate from 14.9 kHz to 40.9 kHz and minimum pulse width of 4.9 μs at the maximum pump power of 126.6 mW, as well as a maximum pulse energy of 92.8 nJ. This is, to the author's knowledge, the first successful combination of a TDF and a GaSe based SA to generate tunable Q-switched pulses in 2.0 μm region.

1. Introduction

In recent years, there has been a significant increase of interest in the development of passively Q-switched fiber lasers for use in a wide variety of application ranging from material processing, environmental sensing to optical imaging and medicine [1–5]. The increased interest arises due to the numerous advantages offered by passively Q-switched fiber lasers, most notably their compact form factor, flexible application and low fabrication and operating cost, while still being able to provide an output that is capable of meeting the needs of most real-world applications [6]. Of particular interest would be passively Q-switched fiber lasers capable of operating in the 2.0 μm region of the wavelength spectrum. This region, well known as an 'eye-safe' region [7] has seen many applications in medicine [8], spectroscopy [9,10] and sensing [11,12]. Additionally, 2.0 μm lasers have also seen substantial use in various nonlinear optical phenomena such as supercontinuum spectrum generation in the near to mid-infrared regions [13].

TDFs can operate as either continuous or pulsed lasers. For pulse lasers, Q-switching can be realized through either active or passive means. Both approaches have their advantages and disadvantages; active Q-switching gives a high degree of control over output pulses parameters, such as repetition rate and pulse width [14] but at the cost of complex electronics, making the system difficult to operate and very costly. Passive Q-switching provides less control over these output parameters, but in return provides compactness, simplicity and flexibility in laser design, giving them numerous real-world uses. Passive Q-switching was typically realized in the early days using semiconductor saturable absorber mirrors (SESAMs) though their complex fabrication process encouraged researchers to seek simpler alternatives. In this regard, there has been increasing interest in the potential of saturable absorbers (SAs) that can complement and replace SESAMs for passively Q-switched fiber lasers [15,16]. Researchers have made significant breakthroughs with carbon nanotubes (CNTs) and graphene [17,18] early on, and subsequently focused on topological insulators [19,20] and transition metal dichalcogenides (TMDs) [21] in the development of next generation SAs. Research efforts were also made into new and exotic materials such as black phosphorus [22], silver nanoparticles [23] and titanium dioxide [24], all of which successfully showing high performance Q-switching generation.

In this work, gallium selenide (GaSe) is proposed and demonstrated as a viable SA material for use in a Q-switched thulium doped fiber laser (TDFL) for operation in the 2.0 μm region. GaSe has a broad transparency and low optical losses, as well as large nonlinear optical coefficient with a high surface damage threshold [25], making it highly suitable for use in photonics applications including in the areas of opto-electronics [26], nonlinear optics [27] and terahertz systems [28]. Furthermore, GaSe has also been

* Corresponding author at: Photonics Research Centre, University of Malaya, 50603 Kuala Lumpur, Malaysia.
E-mail address: harith@um.edu.my (H. Ahmad).

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seen to demonstrate up-conversion luminescence, a unique optical property that makes it highly suited as an SA material [29]. The incorporation of a GaSe based SA into a TDFL cavity as proposed and demonstrated in this work would see the development of a high performance Q-switched fiber laser at the 2.0 μm region. The ability to tune the output wavelength further enhances the capabilities of the proposed TDFL, and to the best of author's knowledge, this would be the first demonstration of using GaSe in TDF laser cavity.

2. GaSe characterization

The GaSe based SA used in this work is prepared using the simple mechanical exfoliation technique [22,30]. In fabricating the SA, a monochalcogenide (MX) GaSe crystal flake obtained from 2D SEMICONDUCTORS is used in its bulk form. The crystal flake is slowly exfoliated using scotch tape, and the resulting GaSe layers are carefully removed from the scotch-tape before being transferred onto fiber ferrules using index matching gel. Finally the fiber ferrule with the GaSe layers is connected to another 'clean' fiber ferrule using an FC/PC adaptor, thus forming the SA assembly. This technique has been successfully demonstrated by Ahmad et al. [30] and is well described in that work.

The nonlinear absorption profile of GaSe based SA is shown in Fig. 1, with the Raman spectrum and the linear optical absorption of SA also illustrated as insets (a) and (b) respectively. The nonlinearity absorption of GaSe based SA is determined by the twin-detector method, using a passively mode-locked erbium-doped fiber laser (EDFL) as the pulse seed. The EDFL is capable of generating pulses with a pulse width and repetition rate of 0.70 μs and 28.0 MHz respectively. The data obtained from the twin-detector measurement is then fitted into the saturation model equation [31], which gives a modulation depth and saturation intensity of 7.0% and ~0.01 MW/cm^2, respectively. It is noted that the modulation depth of the SA in this work is comparable to those of other reported SA materials such as MoS_2 at 6.3% [31], $MoSe_2$ at 6.72% [21] and Bi_2Se_3 at 4.0% [32].

The Raman spectrum of the GaSe sample is obtained using a Renishaw Raman Spectroscope at an excitation wavelength of 532 nm with a 1800 l/mm grating. Analysis of the bulk GaSe sample reveals three distinct peaks at 148.6 cm^{-1}, 215.7 cm^{-1} and 324.2 cm^{-1}, auguring well with previous reports [27,33]. On the other hand, analysis of the few-layer GaSe sample reveals a single peak at 321.0 cm^{-1}, corresponding well to the observations made by Yuan et al. [34] and Sidong et al. [27]. It was also observed that the Raman spectrum intensity of the few-layer GaSe sample is higher than that of the bulk GaSe sample, which is attributed to the reduction of GaSe scattering mode that in turn results in less effective Raman scattering [26].

The linear optical absorption of the few-layer GaSe sample is measured by a broadband source from 1900 nm to 2000 nm. Measurement of the absorption characteristics shows a rising absorbance trend from 1900 nm to 1920 nm, reaching a maximum absorbance of around 4.9 a.u. Subsequently, a decreasing trend is then observed, with the absorbance dropping to 4.7 a.u. from 1920 nm to 1940 nm, before plateauing out at the same absorbance value until a wavelength of 2000 nm. The region of inset (b) highlighted in blue indicates the region of interest in this work for tunable Q-switched operation, and is seen to be within the stable absorbance region. As such, the GaSe based SA can be assumed to be able to operate well in the 2.0 μm region.

3. Experimental setup

The setup of the proposed passively Q-switched tunable TDFL is shown in Fig. 2. The laser cavity is configured as a ring, and uses a 4-m long TMDF200 OFS thulium-doped fiber (TDF) as the linear gain medium. The gain medium length was determined to be optimal for the generation of a 2.0 μm laser output, as reported previously by Li et al. [35]. The TDF has an absorption rate of ~20 dB/m at 1550 nm, as well as a core diameter of 5 μm. The TDF is bi-directionally pumped using Princeton Lightwave 1550 nm laser diodes (LDs), which are connected to isolators as to protect the LDs from possible back reflections. Each LD is connected to the 1550 nm ports of 1550/2000 wavelength division multiplexers (WDMs), designated as WDM 1 and WDM 2 for the backward and forward pumping LDs respectively. The TDF is connected to the common port of both WDMs, and the 2000 nm port of WDM1 is connected to an isolator. The isolator is used to ensure the unidirectional propagation of signals within the ring cavity, and is in turn connected to the input of a 90/10 coupler. The 90:10 coupler which is used to extract a portion of the propagating signal for further analysis, while the remainder of the signal is emitted back into the cavity by the 90% port. From here, the signal within the cavity now encounters the GaSe based SA assembly, which induces the passive Q-switching effect. The signal, which is now travelling as a pulse, is directed to a tunable bandpass filter (TBPF) to tune the lasing wavelength, and is finally connected to the 2000 nm port of WDM2, thus completing the cavity. The laser cavity has a total cavity length of approximately 23.0 m, which comprises of all the optical fibers of various components in the cavity.

The output signal, obtained by the 10% port of the 90:10 coupler, is analyzed using a Yokogawa AQ6375 Optical Spectrum Analyzer (OSA) for its spectral characteristics. The signal is also

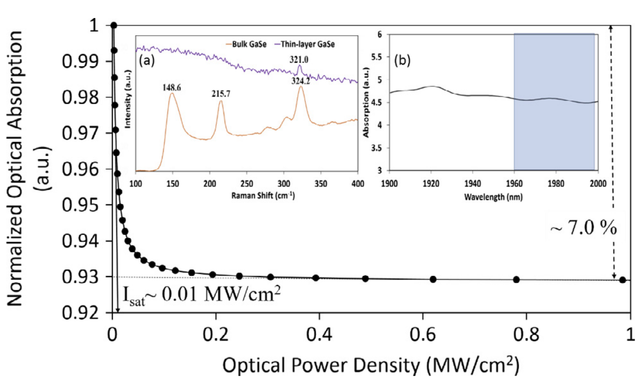

Fig. 1. Nonlinear absorption profile of GaSe SA. Inset of Fig. 1. (a) Raman spectrum and (b) linear optical absorption of GaSe SA.

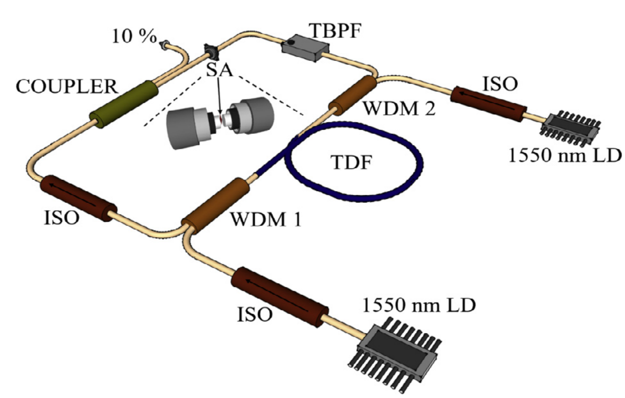

Fig. 2. Experimental setup of tunable passive Q-switched thulium-doped fiber laser (TDFL).