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Dual-tapered Mach Zehnder Interferometer for Dual-wavelength Q-Switched YDFL using Molybdenum Diselenide

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Abstract. A dual-wavelength Q-switched YDFL by utilizing $MoSe_2$ thin film was successfully achieved in cavity ring. The dual synchronous wavelength output spectrum centered at 1035.8nm to 1040.2nm was achieved with repetition rate of 15.3 kHz to 35.2 kHz. Moreover, the maximum pulse energy was 2.8nJ and minimum pulse width was 1.8µs. In this paper, $MoSe_2$ thin film capabilities as saturable absorber in 1-micron region was successfully achieved. Thus pave a new insight of transition metal chalcogenides (TMD) based photonics device.

1. Introduction

Q-switching ytterbium-doped fiber laser (YDFL) has earned great attention in pulse laser operations with its compactness and uniqueness configurations. Q-switching in YDFL has been widely reported in developing various techniques of pulse laser applications. Saturable absorber (SAs) is one of the efficient methods as an optical material in order to generate passive pulse laser. Previously, semiconductor saturable absorbers mirrors (SESAMs) have been a leading technique to generate pulse laser including at 1-micron region [1, 2]. Nevertheless, SESAMs require costly cleanroom equipment's and complicated fabrication and packaging system [3, 4] which indicate their disadvantages. Besides, its experience narrowband wavelength range too [5]. Carbon nanotubes (CNTs) [5-7] and graphene [8, 9] as a carbon-based nanomaterials have been developed to address disadvantageous of SESAMs. Their advantageous properties for instance straightforward fabrication procedure and ultra-fast recovery period make its practical saturable absorber for pulse mode generation. Nevertheless, CNTs have complicated bandwidth control [10], that preventing saturable absorption at certain wavelength whereas graphene has a limited modulation depth and optical absorption [10]. Thus, many studies have been conducted to search for a novel SA, that have ideal

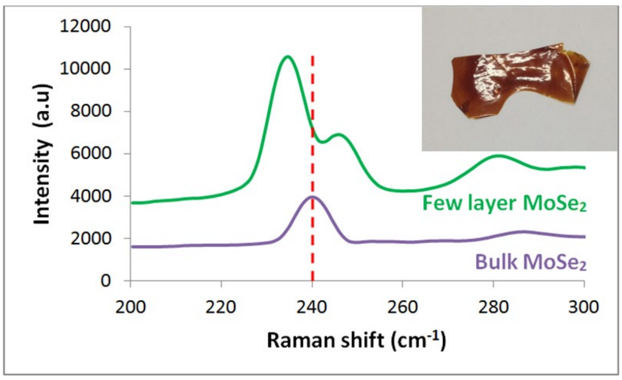
characteristics such as high threshold damage, wavelength-independent, economical fabrication process, and high modulation depth.
In recent progress, there has been an interest in molybdenum diselenide ($MoSe_2$) which is a group member of transition metal chalcogenides (TMD). A mixture of electropositive element and chalcogen ion is called chalcogenide. A number of studies [11-13] show $MoSe_2$, a suitable material as photodetector, pulse-laser operations and thermoelectric as a result of its incredible optoelectronic properties such as ultra-fast dynamic carriers for few-layers and mono form, large optical nonlinearity and high photoluminescence [14]. In this paper, we have achieved Q-switched dual-wavelength by employing $MoSe_2$ SA in YDFL. Dual-tapered microfiber [15] was used as an optical filter to generate dual-wavelengths laser [16, 17] centered at 1035.8 and 1040.2nm with wavelength interval and repetition rates of 4.4 nm and 13.5 to 54.3 kHz respectively.

2. $MoSe_2$ Fabrications and Characterization

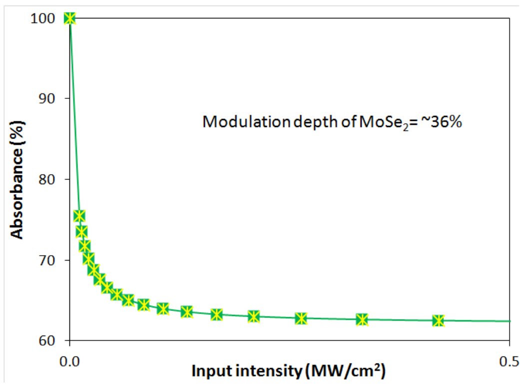
In our previous work, we have explained the synthesis and preparation of the purchased bulk $MoSe_2$ and exfoliated $MoSe_2$ [18, 19]. In the beginning, Renishaw inVia confocal Raman Microscope was used to characterize Raman shift analysis as shown in Figure 1(a). For bulk $MoSe_2$, the (A_g^1) peak is focused at 240 cm^{-1}, whereas for few layers of $MoSe_2$ is focused at 235 cm^{-1}. The shifting confirms the exfoliation of $MoSe_2$ few layers. Later, the $MoSe_2$ solution was prepared to create a few layers as shown in inset of Figure 1(a).
The few layer of $MoSe_2$ saturable absorption was characterized using a dual-detector measurement setup [20]. The mode-locked based CNT was used to produce femtosecond laser at 27.6 MHz repetition rate and 0.51 ps pulse duration. An erbium amplifier was used to amplify generated pulse signal and produced a high peak power for efficiently saturating the $MoSe_2$ up to ~20mW by employing a variable optical attenuator (VOA). The saturable absorption behavior is shown in Figure 2 by using the formula given [21]:

$$\alpha = \frac{\Delta\alpha}{(1+\frac{I}{I_{sat}})} + \alpha_{linear} \quad (1)$$

where $\Delta\alpha$, α_{linear}, and I_{sat}, represent the modulation depth, non-saturation loss and saturable optical intensity respectively. Thus, the measured saturable intensity and modulation depth of $MoSe_2$ are ~0.01MW/cm^2 and 36% respectively as given in Figure 1(b).



(a)



(b)

Figure 1. The characterization of bulk and few layer $MoSe_2$ for (a) trace by Raman spectroscope and a photo of fabricated $MoSe_2$ thin film (*inset*). (b) The characteristic of $MoSe_2$ saturable absorption.

3. Laser Setup

The ytterbium fiber laser configuration of dual wavelength embedded dual-tapered microfiber and Q-switching embedded $MoSe_2$ is given in Figure 2. The YDFL comprises of 70 cm length of gain medium and a pumping source for YDF with centered wavelength of 974 nm laser diode (LD) was linked to pumping port of wavelength division multiplexing (WDM) and the common port of WDM was linked to YDF, and then connected to an isolator. The output port of isolator was attached to the dual-taped Mach-Zehnder Interferometer [22], that work to induce dual wavelength laser [23]. Another port of microfiber was attached to $MoSe_2$ SA that was placed in the middle of the fiber ferrules, then linked to 90:10 input port of optical coupler 1, (OC1). In order to complete the ring cavity setup, 90% output port of optical coupler was attached to reflection port of WDM. Another 10% output port was analyzed by connecting to 50:50 optical coupler 2, (OC2) that separates the light. Hence, the Q-switched laser was characterized instantaneously with one channel via an optical spectrum analyzer (OSA) and another channel by oscilloscope.

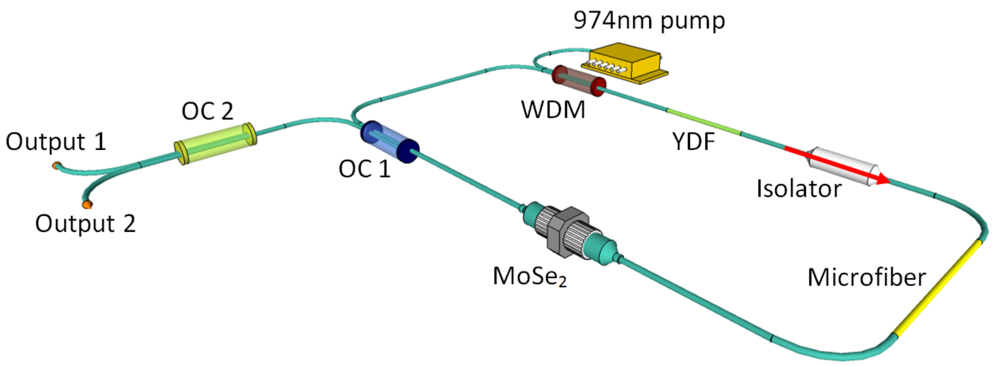
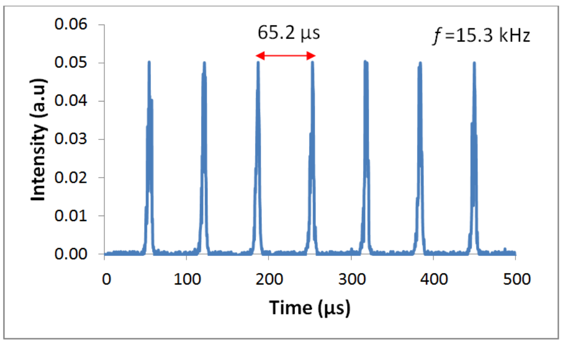


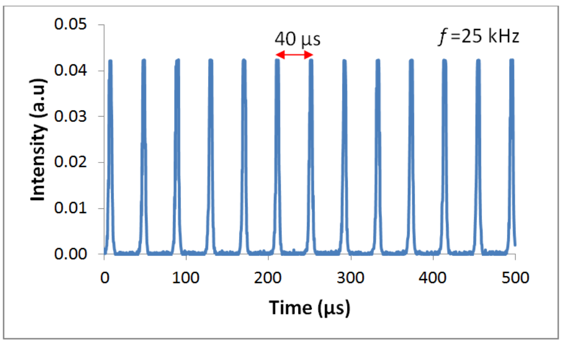
Figure 2. Cavity ring of dual wavelength Q-switched based $MoSe_2$ SA

4. Results and Discussion

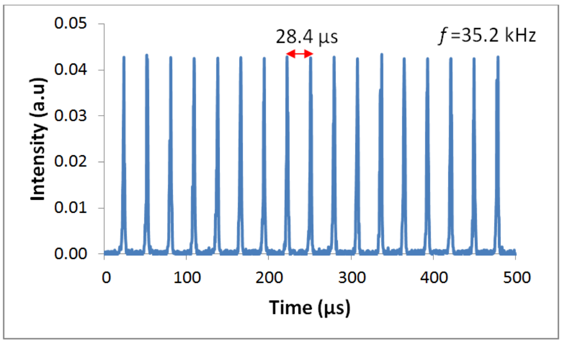
Q-switching mode was detected as early at 166.6 mW pump power next increased up to 180.9 mW at 15.3 kHz repetition rate as given in Figure 3(a). Later the pump power was raised to 209.7 mW and 261.2 mW, as portrayed in Figure 3(b) and Figure 3(c) respectively. Once the pump power was increased, the greater repetition rate was detected indicating a typical behavior during Q-switching. Besides, the pulse duration was decreasing once the pump power was increased, from 65.2 μs of pulse duration at 166.6 mW, to 28.4 μs of pulse duration at 261.2 mW pump power, as a result of the gain compression [24].



(a)



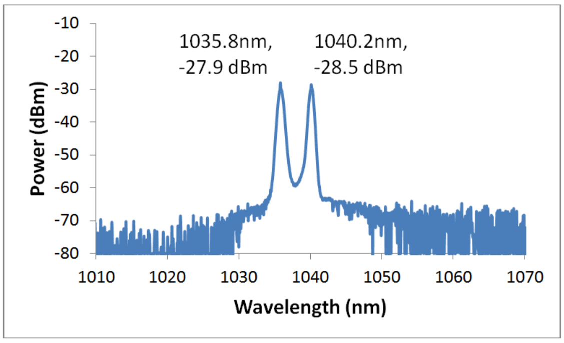
(b)



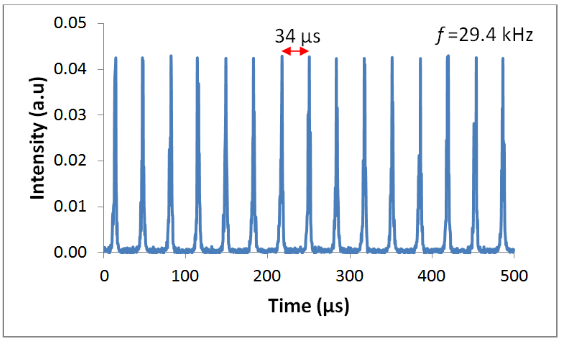
(c)

Figure 3. Raising pump power of (a) 180.9 mW, (b) 217.8 mW and (c) 290.4 mW resulting changes in pulse trains spectrum

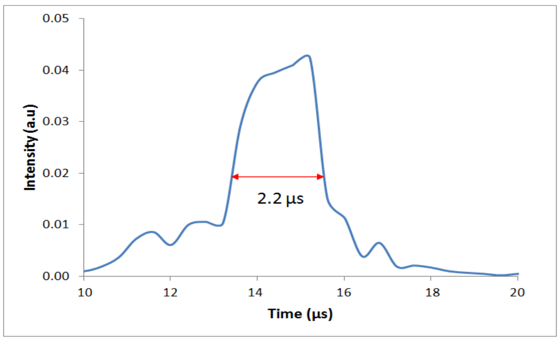
Figure 4(a) shows a stable optical spectrum at 231.6mW, with dual-wavelength lasing center on 1035.8 nm and 1040.2 nm. Figure 4(b) shows the characterization of pulse train spectrum with 29.4 kHz repetition rate at 231.6 mW pump power. The calculated pulse width of 2.2 μs, is depicted in Figure 4(c) whereas Figure 4(d) illustrated the stable traces indicated by its 48 dB peak-to-pedestal ratio with 29.4 kHz harmonic frequency (inset). Additionally, no spectral modulation traced, indicating stable pulse in ring cavity configuration as depicted in Figure 4(d).



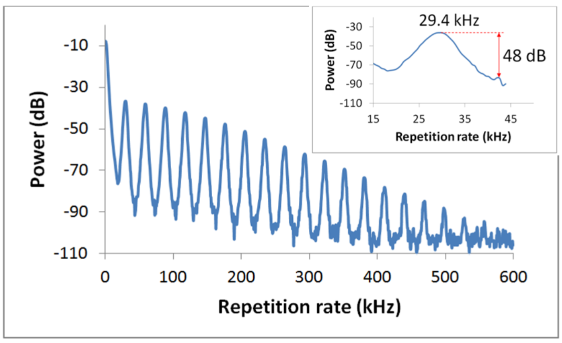
(a)



(b)



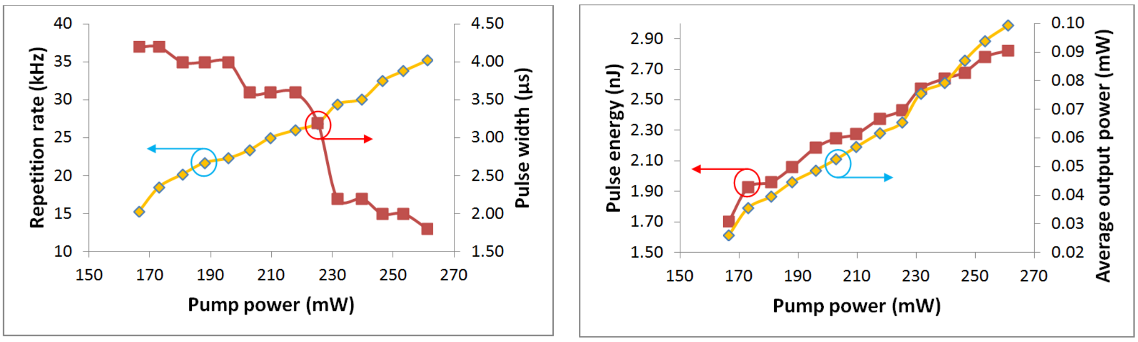
(c)



(d)

Figure 4. Q-switched (a) optical spectrum, b) with pulse duration of 34 μs, c) pulse width of 2.2 μs and (d) fundamental frequency of 29.4 kHz at 231.6 mW pump power.

Figure 5(a) illustrates the pulse duration and pulse repetition rate corresponding to pump power from 166.6 to 261.2 mW. The repetition rate raised from 15.3 to 35.2 kHz whereas pulse width reduced from 4.2 to 1.8 µs. However, Figure 5(b) shows pulse energy and average output power were evaluated and linearly enhanced as we increased pump power. Furthermore, the maximum average output power was presented at 0.1 mW, while the maximum pulse energy gained was 2.8 nJ at 261.2 mW highest pump power. The generated pulse might be enhanced via employing a double-clad gain fiber in the cavity [25].



(a) (b)

Figure 5. Results of (a) repetition rate and pulse width and (b) average output power and pulse energy changes corresponding to pump power.

5. Conclusion

In conclusion, Q-switched dual-wavelength YDFL employing $MoSe_2$ thin film as saturable absorber has been successfully demonstrated in cavity ring. A consistent Q-switched dual wavelength centered at 1035.8 nm and 1040.2 nm. The repetition rate span at 15.3 kHz to 35.2 kHz with maximum pulse energy of 2.8 nJ and minimum pulse width of 1.8 µs. Therefore, foresee such results demonstrated in this work will expand the developments of passive pulse laser by using TMD materials.

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