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Pulse Laser Generation at 2.0 μm Region based on Polyvinyl Alcohol Doped Graphene Nanoplatelets Saturable Absorber

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***Abstract*—** A passive Q-switcher based on graphene nanoplatelets (GnP) doped with polyvinyl alcohol (PVA) is proposed for pulse laser generation at 2.0 μm region. An optimized solution casting approach is adopted in the customized preparation of a 12.04 wt.% weight ratio of GnP to PVA. The fabricated saturable absorber (SA) is characterized using field emission scanning electron microscope (FESEM), which confirmed the embedment of GnP in PVA composite. A 5 m long thulium doped fiber (TDF) is used as a gain medium in the laser cavity measurement. Our characterization demonstrates dual-wavelength Q-switched pulse generation at 1904.0 nm and 1904.9 nm for input power ranging from 644 mW to 698 mW, respectively. The repetition rate is tunable from 69 kHz to 98 kHz with the shortest pulse width of 1.4 μs. The calculated output peak power, pulse energy and signal-to-noise ratio are recorded at 143 mW, 0.21 μJ and 35 dB, respectively. Notably, the present work is the first-ever work of a Q-switcher based on GnP doped with PVA host at 2.0 μm region.

***Keywords*—** Saturable absorber; Pulse laser; Q-switch; Graphene nanoplatelets; Polyvinyl alcohol.

1. INTRODUCTION

Saturable absorber (SA) is a small component used in pulse laser generation with reduced absorption loss at high optical intensities. Pulsed lasers are widely used in medical surgery [1], range finder [2], and spectroscopy application [3]. According to Bonaccorso et al. [4], different materials have been applied as passive saturable absorbers (SA), and this is hugely dependent on their intrinsic properties, which include high nonlinearities, ultrafast carrier relaxation, and broadband operating wavelength. From this huge selection of applied materials, our main interest focuses on the graphene class of material. Graphene has attracted great interest from the research community due to its richness in optical and electronic properties. This has led to the creation of numerous applications in medical [5], electronics and photonics [6], energy storage [7], and biosensors [8]. The extensive application of graphene as SA in pulse fiber laser generation is mainly due to its rapid recovery time and zero band gap energy properties that produce ultra-wideband absorption. Undoubtedly, the works related to graphene and its derivatives as SA have been well established and significantly demonstrated by many researchers, as reviewed by Peng and Yan [9]. However, from our perspective, there is limited literature on graphene nanoplatelets (GnP) application as the SA,

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especially at wavelength regions higher than 1.5 μm, particularly at 2.0 μm, which is the main motivation of this work. At 2.0 μm region, the laser source has been very attractive owing to its eye-safe spectral range and strong water absorption peak [10]. As such, it has gained wide attention in the fields of medical surgery, environmental monitoring, micromachining, and laser radar [11]. GnP is another derivative of graphene, which has a multi-layered structure in the form of flakes with a thickness of 1-20 nm [12]. Due to its broad application in the nano-composite field of research [12,13], we have put in an initial effort to investigate the possible application of GnP as SA. As a result, a Q-switcher has been successfully demonstrated in pulse laser generation at 1.5 μm region by using polyvinyl alcohol (PVA) as the host material [14]. Meanwhile, other researchers' work on GnP, particularly on pulse laser generation at 1.5 μm, has been published in recent years [15–17]. Additionally, we have also investigated the impact of GnP flakes thickness and weight ratio of GnP to PVA for SA at 1.5 μm region in our recent publication [18].

For Q-switched pulse generation at 2.0 μm region, works on graphene-based SA have been reported by Ahmad, et al. [19–21] and Jinho and Ju Han [22]. In these publications, a Q-switcher has been demonstrated by using graphene oxide (GO) [19,22], graphene-PVA [20], and N-doped graphene [21]. Note that the graphene-PVA fabrication technique in [20] is different as compared to our previous works [14,18], which are mainly due to the nature of GnP. Their technique of graphene-based SA fabrication is akin to the work of Sulaiman et al. [23], which is based on polyethylene oxide (PEO) as the host polymer. Meanwhile, in [22], the fabricated all-fiber SA is based on the deposition of GO particles on a fiber polished surface. Based on our thorough review, we believe that our present work is the first ever effort of pulse laser generation at 2.0 μm region using GnP flakes doped with PVA as the host material.

2. METHODS

In this work, we report on the solution casting approach in thin film GnP fabrication and the characterization of fabricated SA. The dispersed GnP suspension was mixed with polyvinyl alcohol (PVA), which acted as a host. The solution casting approach is relatively simple and low-cost as compared to the widely used chemical vapor deposition (CVD) technique [24]. Motivated by our reported work in [18], an optimized 12.04 wt.% weight ratio of GnP to PVA was prepared and tested in the present work. For cavity ring measurement, 5 meters of thulium-doped fiber (TDF) were used as a gain medium. From the characterization results obtained, we can prove that the proposed GnP-PVA SA, which is based on the economic solution casting approach can still produce competitive performance and is comparable with previously reported work on graphene-based SA at 2.0 μm region [19–21].

In the first step of GnP preparation, 40 mg of GnP nano powder was added to 40 ml of 1% sodium dodecyl sulphate (SDS). The mixture was sonicated for 1 hour at 50 watts (W). The centrifugation process at 1000 rpm produced stable GnP suspensions through undispersed particle removal. A stable GnP suspension was mixed with the PVA solution prepared earlier in a 1:1 mixture ratio, which was formulated as a 12.04 wt.% weight ratio of GnP to PVA. To produce a homogeneous GnP-PVA composite, an ultrasonication process was applied for one hour. Finally, the homogeneous suspension was dried at room temperature for 48 hours to produce GnP-PVA film.

Field Emission Spectroscopy (FESEM) Zeiss Crossbeam 340 was used to analyze the morphology of the fabricated film. Fig. 1 displays the 3000x magnification of the FESEM image, which shows that GnP was thoroughly mixed in the PVA polymer with a smooth surface and low aggregation.

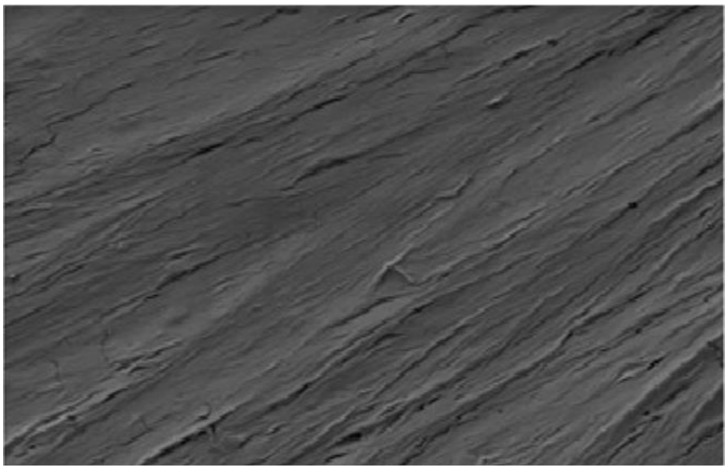

Fig. 1. FESEM image of the fabricated GnP-PVA flakes.

To characterize pulse laser generation, a 14-meter-long cavity ring with TDF gain medium had been setup, as shown in Fig. 2. The gain medium was a 5-meter-long TDF and pumped with a 1552 nm laser diode through 1550/2000 Wavelength Division Multiplexing (WDM). A small part (2mm × 2mm) of the fabricated GnP-PVA film was prepared and sandwiched in between two ferrule connector/physical contact (FC/PC) fiber connectors with the aid of index-matching gel. 10% of the output light was tapped out for optical spectrum and oscilloscope monitoring. A few parameters, which include repetition rate, pulse width, output power, and pulse energy, were measured and calculated from this signal.

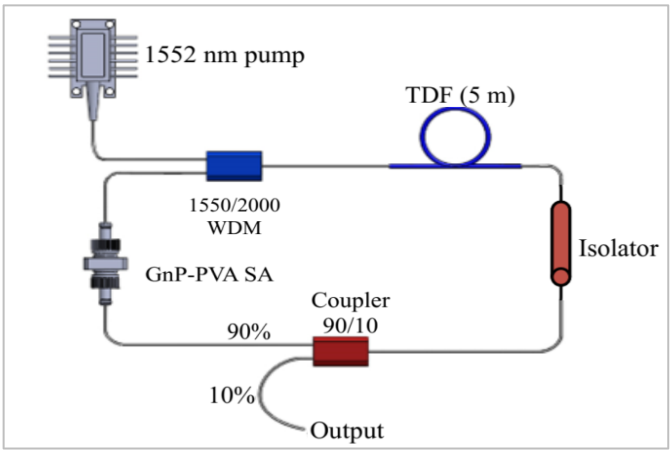

Fig. 2. Cavity ring measurement setup.

3. RESULTS AND DISCUSSION

This section illustrates and explains measurement results based on the experimental setup of Fig. 2. Based on our observation, a threshold pump power of 644 mW generated

Q-switch pulses. The pulses were continuously generated up to the maximum pump power of 698 mW. Above this value, pulse lasers were not observed, which may be due to film damage because of high pump power. The optical spectrum shown in Fig. 3 indicates dual-wavelength Q-switch pulses at 1904.0 nm and 1904.9 nm with a wavelength separation of 0.9 nm.

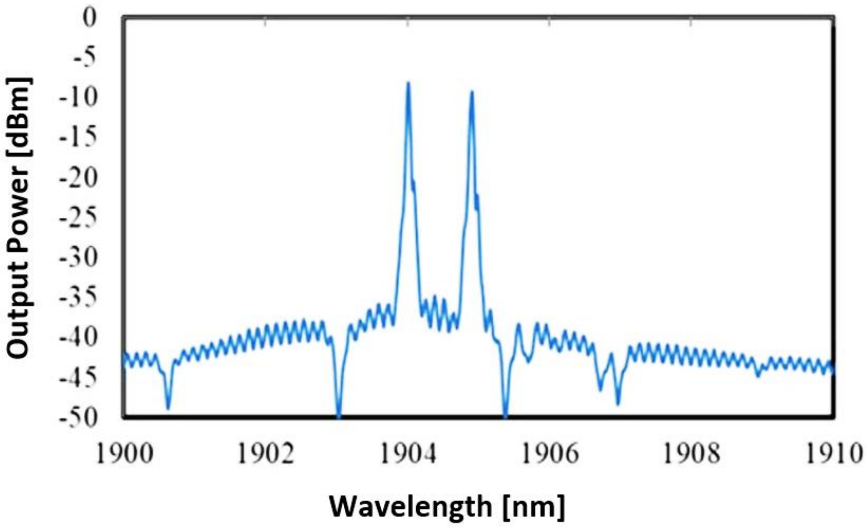

Fig. 3. Optical spectrum analyzer trace of a dual-wavelength pulse fiber laser.

Fig. 4(a-b) shows the measured oscilloscope trace for pump powers of 644 mW and 698 mW with their respective pulse widths. From the recorded pulse train, it was observed as a small fluctuation between peaks. The pulse widths were inversely proportional with respect to the increment of pump power, which is consistent with the previous findings [14-21].

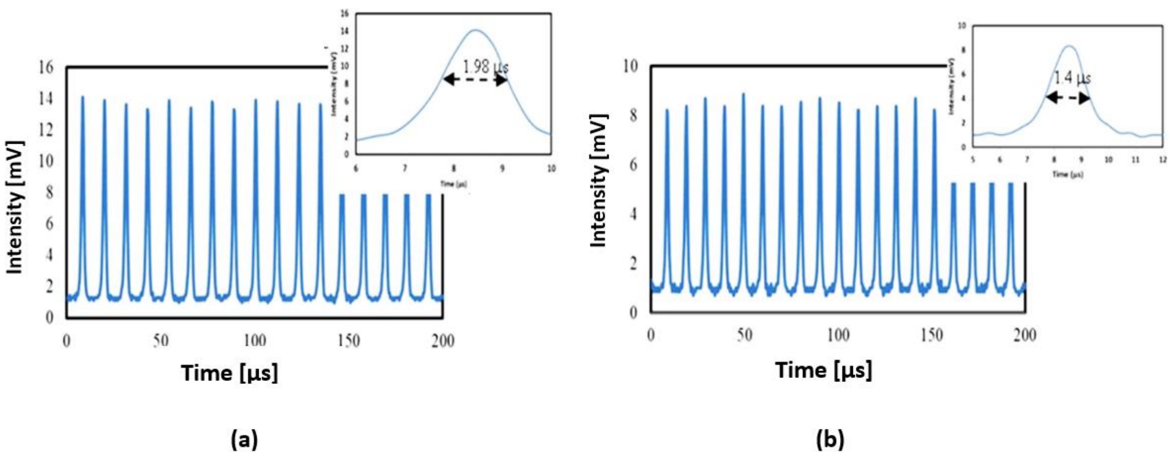

Fig. 4. Pulse train and single pulse envelope at input pump powers of: a) 644 mW; b) 698 mW.

Fig. 5 illustrates the variation of generated pulse width and repetition rate with respect to pump power value. The repetition rate was recorded to vary from 69 kHz to 98 kHz due to the pump power increment from the 644 mW threshold to the maximum allowable of 698 mW. Thus, it can be observed that the generated pulse width decreased from 1.98 µs to 1.4 µs. These measured parameters were used in pulse energy and peak power calculations. Based on our calculation, pulse energy varied from 0.18 µJ to 0.21 µJ with respect to the pump power increment from 644 mW to 698 mW. Notably, the peak power increased from 88 mW to 143 mW for the same pump power range.

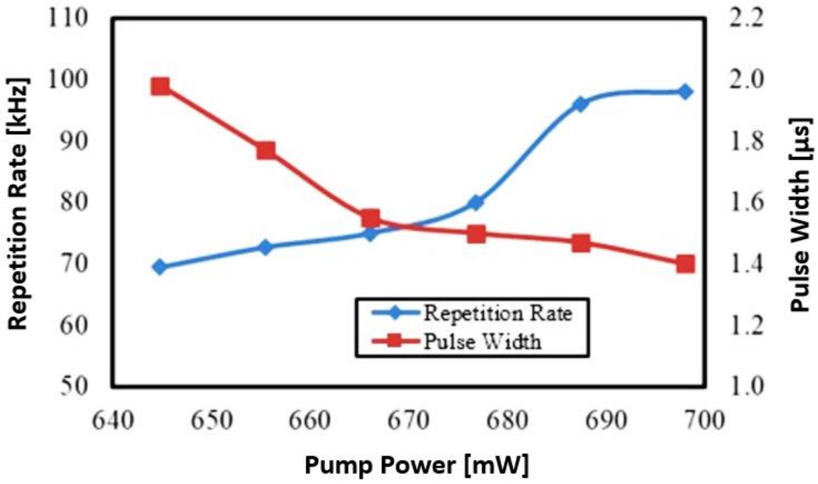

Fig. 5. Pulse width and repetition rate variation with pump power.

Radiofrequency spectra for this SA was measured to verify the stability of the generated laser. The measurement plot is shown in Fig. 6, with a measured signal-to-noise ratio (SNR) of 35 dB. This is a plot at a fundamental repetition rate of 98 kHz (698 mW pump power), and it vindicates the stability of the generated Q-switch pulse (more than 30dB).

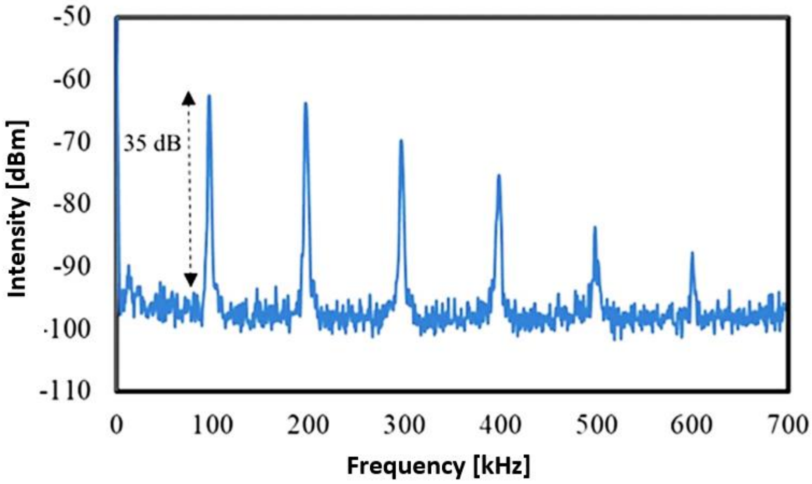

Fig. 6. Radio frequency spectrum analyzer measurement of SNR at 698 mW pump power.

The obtained results were compared with previous related literature, which shows the competitiveness of our proposed work. Technically, our value of repetition rate is superior as compared to the highest recorded work by Jinho and Ji Han [22], which produced 56.12 kHz. We have also recorded the shortest pulse width as compared to 9.8 µs [19], 6.8 µs [20], 4.4 µs [21], and 1.56 µs [22]. Importantly, with our proposed GnP-PVA SA at 2.0 µm, the most stable generated Q-switch pulse has been generated thus far, as compared to GO at 28 dB [19], graphene-PVA at 31.75 dB [20], and N-doped graphene at 32.25 dB [21]. However, no stability data could be observed from [22]. Note that this work has only been based on a 12.04 wt. concentration of GnP to PVA. We strongly believe that future in-depth investigations of the GnP to PVA weight ratio will feasibly improve the SA performance at 2.0 µm region.

4. CONCLUSIONS

A passive saturable absorber utilizing GnP with PVA as a doped polymer was proposed for pulse laser generation at 2.0 µm. At 12.04 wt.% concentration of GnP to PVA, we successfully generated the Q-switch pulses at pump power ranging between 644 mW and 698 mW. For this pump power range, the repetition rate was varied from 69 kHz to 98 kHz. Accordingly, the generated pulse width decreased from 1.98 µs to 1.4 µs. With a measured SNR of 35 dB, the stability of our generated Q-switch pulses was confirmed. Comparison with reported in literature works exhibited the competitiveness of the proposed work in terms of repetition rate, pulse width and stability. Indeed, future investigations of the GnP-to-PVA weight ratio are expected to improve the SA's performance.

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