

# Mode-locked Thulium Ytterbium co-Doped Fiber Laser with a Graphene Saturable Absorber

Ibrahim M. Babar,<sup>1</sup> Mukul C. Paul<sup>\*2</sup>, Shyamal Das,<sup>2</sup> Anirban Dhar,<sup>2</sup> Harith Ahmad<sup>1</sup> and Sulaiman W. Harun<sup>\*1,3</sup>

<sup>1</sup>Photronics Research Centre, University of Malaya, 50603 Kuala Lumpur, Malaysia,

<sup>2</sup>Fiber Optics and Photonics Division, CSIR-Central Glass & Ceramic Research Institute, Kolkata, India,

<sup>3</sup>Department of Electrical Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia

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**Abstract**—A passively mode-locked Thulium Ytterbium co-doped fiber laser (TYDFL) is demonstrated using a graphene polyvinyl alcohol saturable absorber as the mode-locker. With 980nm multimode pumping, the laser operates at 1942.95nm with repetition rate of 11.76MHz. The pulse width is calculated to be around 52.85ps. The maximum pulse energy of 1190.5pJ is achieved at pump power of 1750mW.

Mode-locked fiber lasers operating at 2 $\mu$ m region have attracted intense interest in recent years for a number of potential applications, including atmospheric measurements, laser radar, longer-wavelength laser pumping, laser plastics, material processing, biomedical and medical applications [1-2]. Previously, a new approach was proposed to enhance Thulium-doped fiber emission at 2  $\mu$ m wavelength by co-doping the fiber with Yb<sup>3+</sup> ions as a sensitizer to the Tm<sup>3+</sup> ions [3]. This approach is feasible due to the fact that the Yb<sup>3+</sup> emission at 1200nm wavelength is one of the absorption bands of Tm<sup>3+</sup>. The excited Yb<sup>3+</sup> ions at <sup>2</sup>F<sub>5/2</sub> release their energy, which is (quasi-) resonant to the Tm<sup>3+</sup> energy level of <sup>3</sup>H<sub>5</sub>. In addition, the high absorption of Yb<sup>3+</sup> ions and the uniqueness of the energy level of Yb provide a sufficient contribution to the high power laser application. The low quantum defect of the Yb enables pumping at high power.

Up to now, most ultra-short pulse fiber lasers have adopted passive mode-locking technology, in which saturable absorbers (SAs) act as a key part [4-6]. Various types of SAs have been attempted such as a semiconductor saturable absorption mirror (SESAM) [4], carbon nanotubes (CNTs) [5] and graphene [6]. Among them, SESAMs are the most widely used SA owing to their high flexibility and stability. However, SESAMs are expensive, complicated in the fabrication process and have a limited range of optical response, which limits their applications to a great extent. Developing low cost SAs for a broadband operation has always been an objective for laser experts. Recently, both single-walled carbon nanotubes (SWCNTs) and graphene have been extensively investigated for mode-locking applications

due to their various advantages, such as fast recovery time, large saturable absorption, and ease of fabrication [5-6]. Graphene is superior to CNTs in broadband saturable absorption due to its gapless linear dispersion of Dirac electrons [6]. To date, many works have been reported on the integration of a graphene polyvinyl alcohol (PVA) SA into a fiber laser system for ultra-short pulse generation. For instance, a mode-locked Erbium-doped fiber laser with a stable soliton-like pulse was achieved using a graphene from the CVD process [7]. In this letter, a mode-locked thulium ytterbium co-doped fiber laser (TYDFL) is demonstrated by using the graphene PVA film as an SA.

The graphene is synthesized by electrochemical exfoliation of graphite at room temperature in a 1% sodium dodecyl sulfate (SDS) aqueous solution. Graphene flakes obtained from the process are mixed with PVA as the host polymer to produce free standing composite thin film which acts as a passive mode-locker in the ring laser cavity. The saturation intensity, non saturable absorption and modulation depth of the film are 971 MW/cm<sup>2</sup>, 10% and 14%, respectively. The SA is integrated in the fiber laser by sandwiching the graphene film between two fiber connectors, resulting in a stable mode-locking pulse train with a fixed repetition rate.

Figure 1 shows the experimental setup for the proposed graphene based mode-locked TYDFL. It uses a homemade double-clad thulium ytterbium co-doped fiber (TYDF) as gain medium in the ring oscillator. The fiber has an octagonal shaped pump inner cladding with a core diameter of 5.96 $\mu$ m and NA of 0.23. The doping host is based on nano-engineered yttria stabilized zirconia-alumina silica glass having phase-separated nano-particles containing Y, Al, Tm and Yb ions rich. The selected fiber length of 10m provides more than 90% pump absorption. The TYDF was pumped by a 980nm multimode laser diode through a multimode combiner (MMC). The output pulses are coupled out of the oscillator from a 20% port of the 80/20 dB output coupler while allowing 80% of the light to oscillate in the ring cavity. The length of the total cavity is set at around 17m so that the net cavity dispersion is anomalous for facilitating a self-starting

\* E-mail: swharun@um.edu.my, paulmukul@hotmail.com

mode locked laser. For the measurements of the laser output, a fast photodetector connected to a digital oscilloscope was used to measure the pulse train and pulse waveforms. The spectrum of the output pulse was measured by an optical spectrum analyzer (OSA).

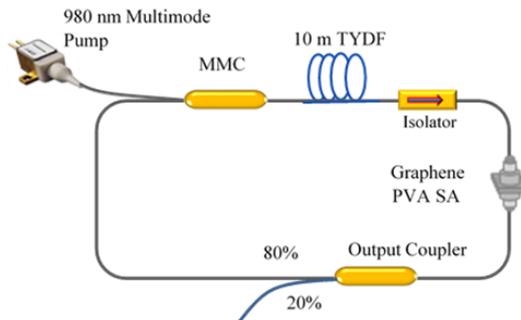


Fig. 1. The schematic setup of the mode locked TYDFL employing the fabricated graphene PVA film based SA.

Mode-locking was self-started by increasing the pump power above a threshold of 1487mW. The mode-locked operation was maintained as the pump power was increased up to the maximum power of 1964mW. Figure 2 shows the output spectrum of the mode-locked pulse train when the pump power is fixed at 1610mW. As shown in the figure, the spectrum was centered at 1942.95nm with 3dB bandwidth of 0.08nm. Without the SA, the CW TYDFL was observed to operate at 1943.50nm. It is found that the operating wavelength shifts to a shorter wavelength with the insertion of the SA into the cavity due to the change in cavity loss. The oscillating laser shifts to shorter wavelength to acquire more gain to compensate for the insertion loss of the SA. With the SA, the presence of soliton is also confirmed with a weak side band at 1942.54 nm as shown in Fig. 2. It shows that this mode-locked fiber laser is operating in the anomalous dispersion regime. The lasing formation at a particular wavelength is depended on the TYDF gain profile and cavity loss, too. By optimizing the TYDF length and minimizing the cavity loss, the preeminent gain profile can be achieved as in the present work. A longer wavelength can be achieved if holmium is added to the TYDF.

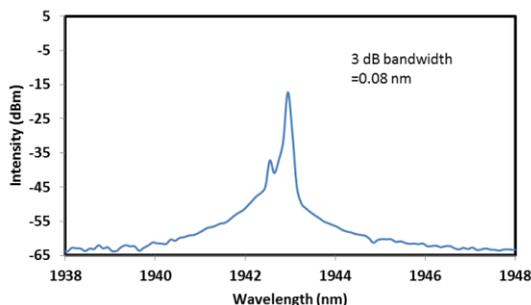


Fig. 2. Output spectrum of the mode-locked TYDFL.

The typical pulse train of the proposed graphene PVA film based passively mode-locked TYDFL is shown in Fig. 3, at a pump power of 1627mW. It has a pulse-to-pulse separation of 85ns, corresponding to a pulse repetition rate of 11.76MHz, which matches the cavity roundtrip time with a cavity length of 17m. This indicates that the well dispersed graphene in the PVA film exhibits sufficient saturable absorption for mode-locking operation. The modulation of the pulse amplitude is an artifact caused by the limited sampling points on the sampling oscilloscope, since the pulse duration is too narrow and the sampling rate of our oscilloscope is only 1Gs/s. It was observed that the repetition rate was retained at 11.76MHz as the pump power was varied from 1487 to 1964mW. The oscilloscope trace analysis indicates that the pulse width of the laser should be less than 9ns. The actual pulse width is expected to be so much smaller than 9ns due to the limitation of the oscilloscope resolution.

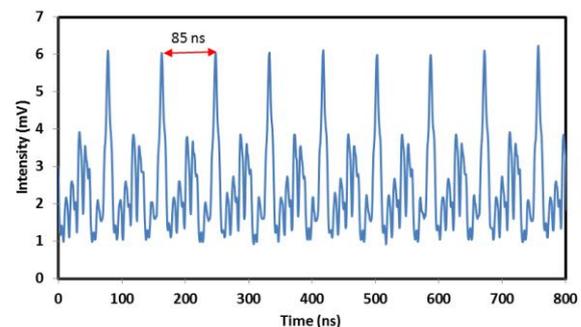


Fig. 3. Typical pulse train for the mode-locked TYDFL at pump power of 1627 mW.

The total length of the laser cavity was measured to be approximately 17m, comprising 10m long TYDF and a 7-m-long of SMF with estimated dispersions of  $-0.083\text{ps}^2/\text{m}$  and  $-0.034\text{ps}^2/\text{m}$ , respectively, at 1943nm. Therefore, the mode-locked laser is expected to operate in an anomalous dispersion regime. On the other hand, the pulse width can be measured using an auto-correlator or can be calculated mathematically using Time Bandwidth Product (TBP). Since the Auto-correlator in  $2\mu\text{m}$  range is not available, it is calculated mathematically by assuming TBP is around 0.315 for a  $\text{sech}^2$  pulse profile. The minimum pulse width possible is estimated about 51.85ps since the 3dB bandwidth of the optical spectrum is about 0.075nm (5.96GHz). We also calculate the repetition rate by using the formula  $c/1.5L$ , found to be 11.76MHz. This is equal to the observed repetition rate of this laser as shown in Fig. 3. The output power of the laser is also measured and the measurement is then used to calculate the single pulse energy at various pump power. The maximum output power of 14mW is observed at a 1750mW pump power. The pulse energy increases linearly up to a pump power of 1750mW before it decreases as shown in Fig. 4. Above a

1750mW pump power, the phase noise increases and affects the output power and pulse energy. Consequently, it degrades the pulse performance and later eliminates the pulse once the pump power reaches above 1964mW. The calculated pulse energy is in the range of 756.048 to 1190.476pJ.

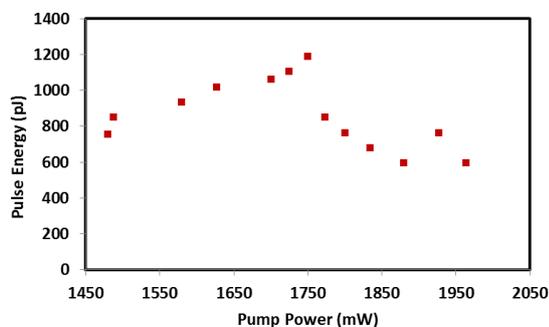


Fig. 4. The calculated pulse energy against the input pump power.

The RF spectrum of the mode-locked pulses is also measured and the result is shown in Fig. 5. Its fundamental mode peak locates at a frequency of 11.76MHz and has a signal-to-noise ratio (SNR) of 34dB, which confirms the presence of mode-locking operation in the frequency domain. Due to absorption limitation from graphene SA, the obtained SNR at 1964 mW is degraded. The peak of harmonic decreased moderately, which identifies the mode locked laser as having a narrow pulse width. At all pump power levels, no fundamental frequency is observed when the graphene SA is removed. Further work on reducing film loss and optimizing the TYDFL cavity is important especially for high power operation of the laser. The mode-locked pulses are generated since the longitudinal modes inside the cavity are forced to lock together. All the modes are either in phase or different in a multiple number of  $2\pi$ . Even though many modes are circulating in the cavity randomly, the length of the cavity is appropriate to bring them in a relationship that can produce constructive interference between different modes. Thus no extra fiber is required to lock the circulating modes in the laser cavity.

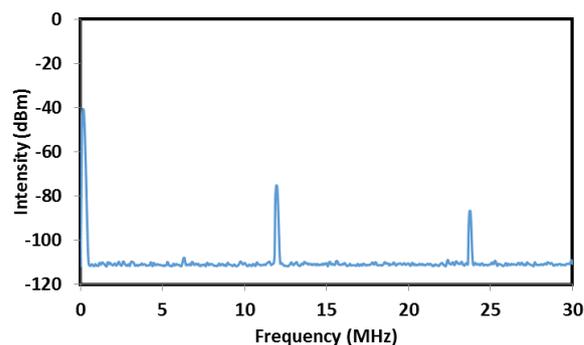


Fig. 5. RF spectrum of the mode-locked pulse train at pump power of 1964 mW.

In conclusion, a mode-locked TYDFL operating at  $2\mu\text{m}$  region is successfully demonstrated based on passive saturable absorber using an octagonal shaped double-clad nano-engineering glass based TYDF as the gain medium. The proposed laser employs a graphene PVA SA in a ring cavity with anomalous dispersion and a length of 17m to generate a mode-locking pulse. The laser operates at 1942.95nm with a repetition rate of 11.76MHz and a pulse width of around 52.85ps. The maximum pulse energy of 1190.5pJ is achieved at a multimode pump power of 1750mW.

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