Mode-Locked Thulium Ytterbium Co-Doped Fiber Laser with Graphene Oxide Paper Saturable Absorber *

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A mode-locked thulium ytterbium co-doped fiber laser (TYDFL) is proposed and demonstrated by using a commercial graphene oxide (GO) paper as saturable absorber (SA). The GO paper is sandwiched between two fiber ferrules and incorporates a ring laser cavity to generate soliton pulse train operating at 1942.0 nm at a threshold multimode pump power as low as 1.8 W. The mode-locked TYDFL has a repetition rate of 22.32 MHz and the calculated pulse width of 1.1 ns. Even though the SA has a low damage threshold, the easy fabrication of GO paper should promote its potential application in ultrafast photonics.

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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.[1,2] Nonlinear polarization rotation (NPR) is currently dominating the passive mode-locking especially in 1.5 μm region. However, it strongly depends on the polarization and phase evolution of the optical pulse in the laser cavity, thus in a long cavity it can be easily overdriven and affected by the environmentally induced fiber birefringence.[3,4] Four-wave mixing effect can also be used to govern the formation of high-repetition-rate pulses up to 1.1 THz, which has widespread applications in the fields of fiber communications, frequency comb, and optical sensing.[5] As a promising SA candidate, carbon nanotubes (CNTs) have advantages in both recovery time and saturable absorption. For instance, simultaneous picosecond and femtosecond solitons have been demonstrated by using a CNT based mode-locked all-fiber laser.[6] To achieve waveband tuning, however, CNTs with different diameters have to be mixed, resulting in extra linear losses, consequently increasing the difficulty of mode locking.[7,8] As an upcoming material in recent years, graphene has also emerged as a new saturable absorption material. It possesses favorable characteristics for SAs, similar to CNTs. As a result of gapless linear dispersion of Dirac electrons, graphene SAs would achieve wide band, tunable operation without the need of bandgap engineering or chirality/diameter control.[9–11] However, the processability is one of the main issues for the graphene based materials. Recently, a mixture of graphene and single-walled CNT was also proposed as SA in an erbium-doped fiber laser cavity for mode-locking to make use of the graphene merit and overcome its shortcomings on the stability.[12]

The structure of graphene oxide (GO) is composed of sp^2-bonded areas with variable size, which are divided by surface oxidation in the form of carboxyl, hydroxyl or epoxy groups. The synthesis of GO is relatively easier than graphene, and more importantly, can be prepared in large quantities in both water and organic solvents.[13] Furthermore, GO has good optical properties, ultrafast recovery time and strong saturable absorption, which is comparable to that of graphene.[14] GO-based SAs have been reported based on various techniques such as mirror, aqueous dispersion, and GO membrane on microfiber.[15–17] Recently, a graphene oxide paper has also been developed and is commercially available for various applications.[18]

Thulium-doped fiber lasers (TDFLs) have also 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.[19] Several approaches have been proposed so far to enhance TDF emission at 2 μm wavelength including co-doping the fiber with Yb^{3+} ions as a sensitizer to the Tm^{3+} ions.[17–21] This approach is feasible due to the fact that the Yb^{3+} emission at 1200 nm wavelength is one of the absorption bands of Tm^{3+}. The excited Yb^{3+} ions at $^2F_{5/2}$ release their energy, which is (quasi-) resonant to the Tm^{3+} energy level of $^3H_5$. In addition, the high absorption of Yb^{3+} ions and the uniqueness of the energy level of Yb provide sufficient contribution to the high power laser application. The low quantum defect of the Yb enables pumping at high power. In this Letter, a soliton mode-locked thulium ytterbium co-

doped fiber laser (TYDFL) is demonstrated by using a commercially available GO paper as an SA for the first time. The SA is constructed by sandwiching the GO paper between two fiber connectors.

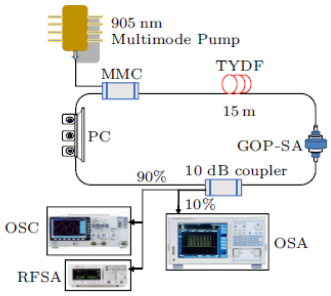

Fig. 1. Experimental setup for the soliton mode-locked TYDFL with a GO paper SA.

The GO paper can be prepared by mixing graphite oxide in water. The oxygen atoms of graphite oxide repel water molecules, thus undergoing complete exfoliation in water, producing a colloidal suspension of almost entirely individual graphene oxide sheets. After filtering the exfoliated mixture by using a membrane, these graphene oxide sheets could be made into paper-like material under a directional flow. A free-standing GO paper is obtained after drying. The fiber-type SA device was constructed by inserting this paper between two ferules. The experimental setup for mode-locked TYDFL is schematically shown in Fig. 1. The active fiber in the ring oscillator is a homemade double-clad thulium ytterbium co-doped fiber (TYDF) with an octagonal shaped pump inner cladding with a core diameter of 5.96 µm and an NA of 0.23. The selected fiber length of 15 m provides >90% pump absorption. A 905 nm multimode laser diode was used to pump the TYDF through a multimode combiner (MMC). The pulses are coupled out of the oscillator by using a 10 dB coupler, which allows 90% of the light to oscillate in the ring cavity. The length of total cavity is set at around 22.4 m so that the net cavity dispersion was anomalous for mode locking. The polarization controller (PC) was used to adjust the polarization state of the oscillating light and thus facilitate the self-starting laser. For the measurements of the laser output, an InGaAs photodetector with a response time of approximately 28 ps connected to a 500 GHz 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).

Figure 2 shows the result of Raman spectroscopy on graphene oxide paper, which was performed by using a 532 nm laser. The exposure time was set to 20 s. As shown in the spectrum, two distinctive peaks are observed at 1349 cm^{-1} and 1588 cm^{-1}, which correspond to D-band and G-band, respectively. The peak at D-band is caused by the hybridized vibrational mode related to graphene edges and it also reveals that there is disorder to the graphene structure. The G-band, also known as the graphite or tangential band, is due to the energy in the sp^2 bonded carbon in planar sheets. The in-plane optical vibration of the bond resulted in Raman spectrum at the frequency. A bump at 2700 cm^{-1}, also known as G′ or 2D band, is barely observable due to the fact that the laser power is low. Due to the fact that the intensity of G′ band is lower than the G band, it also shows that the GO paper has more than one graphene layer.

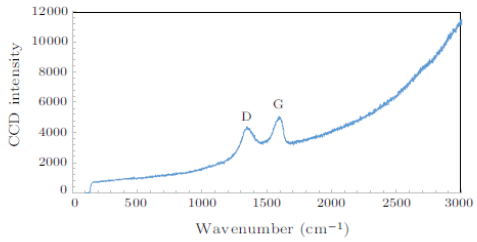

Fig. 2. Raman spectroscopy result of the graphene oxide paper.

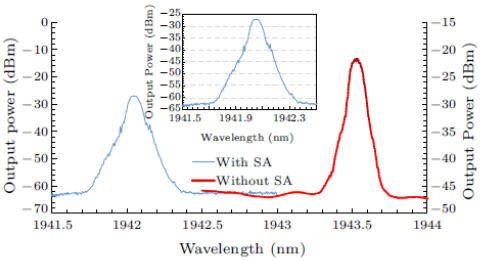

Fig. 3. Output spectra of the ring TYDFL with and without SA. Inset: the enlarged spectrum of the mode-locked TYDFL.

Mode-locking was self-started by fine tuning the PC, when pumping at the threshold pump power of 1.8 W. The output spectrum of the laser when the laser was first mode-locked is shown in Fig. 3. The output spectrum of the cw TYDFL, which was obtained by removing the SA, is also presented for comparison. As shown in Fig. 3, the spectra were centered at about 1942.0 nm and 1943.5 nm as the TYDFL is configured with and without the SA, respectively. It is observed 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 weak Kelly side bands at 1941.96 and 1942.15 nm as shown in the inset of Fig. 3. It shows that this mode-locked fiber

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