Graphene passively Q-switched two-micron fiber lasers

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Abstract: We demonstrate a passively Q-switched thulium fiber laser, using a graphene-based saturable absorber. The laser is based on an all-fiber ring cavity and produces ~2.3 μs pulses at 1884nm, with a maximum pulse energy of 70 nJ.

OCIS codes: (320.7090) Ultrafast lasers; (160.4330) Nonlinear optical materials

1. Introduction

There are growing interests in compact Q-switched laser sources that operate in the mid-Infrared spectral region, around 2 micron, mainly driven by applications in spectroscopy, sensing, medicine and nonlinear optical research [1-4]. Unlike active Q-switching, passive Q-switching is a more convenient and cost-effective way to achieve high energy pulses because it does not require additional switching electronics [5]. Compared with lasers based on bulk gain media, a fiber format offers distinct advantages including small footprint, robust beam confinement and environmental stability [5]. Thulium (Tm)-doped silica fiber is a promising two-micron gain material. It exhibits high quantum efficiency as well as a broad gain spectrum extending from 1.8 to 2.1 μm [6]. Passive Q-switching of Tm fiber lasers has so far been realized by a number of techniques including multiple quantum wells [7], Cr:ZnS or Cr:ZnSe crystals [8,9]. However, all of these implementations require the use of additional bulk components such as mirrors or lens pairs, thus compromising the key benefits of fiber lasers, i.e. their compactness and alignment-free operation [5].

Both carbon nanotubes (CNTs) and graphene are promising materials for saturable absorbers (SAs) [10-14]. They have key advantages such as ultrafast recovery time, wide operating bandwidth as well as easy integration with fiber-optic systems [10-14]. In particular, due to the linear dispersion of Dirac electrons [14], graphene based SAs have the potential to operate at wavelengths much longer than any other SAs. Both Q-switching and mode-locking of fiber lasers have been reported for graphene-based SAs at 1.0 micron [15] and 1.5 micron [16], but not in the very important long wavelength region around 2.0 micron.

Here, we fabricate a graphene-based SA (GSA) and use it to passively Q-switch a Tm-doped all-fiber laser. The laser generates ~ 2.3 μs pulses with a maximum pulse energy of 70nJ, and the repetition rate varying from 12 to 26kHz, depending on the pump power.

2. Experimental Setup and Results

Natural graphite flakes are exfoliated for 9 hours in a ultrasonic bath in N-Methylpyrrolidone (NMP) [17].The un-exfoliated flakes are allowed to settle for 10 minutes. Dispersions are then ultra-centrifuged at 10,000 rpm (17,000*g*) for an hour. The top 70% is decanted for characterization and composite fabrication. 200 mg Styrene Methyl Methacrylate (SMMA) polymer dissolved in NMP is mixed with 2ml centrifuged NMP-graphene dispersion as described in [18]. The mixture is then decanted on a petri dish, dried in vacuum overnight and then baked in oven at 80^{o}C for 45 minutes, resulting in a 50μm free-standing composite. Fig.1 shows the linear absorption of the Graphene-SMMA composite.

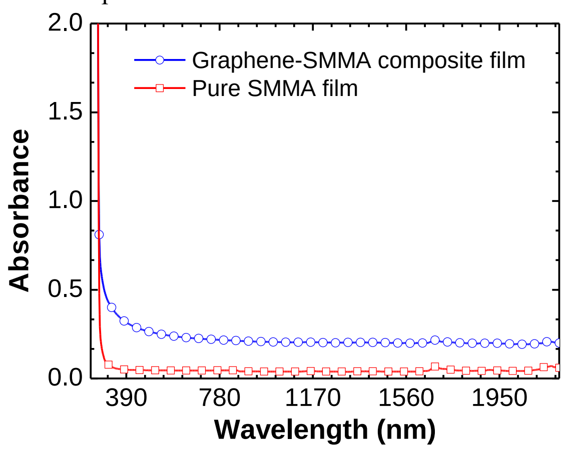

Fig.1 Linear absorption of Graphene-SMMA *film.*

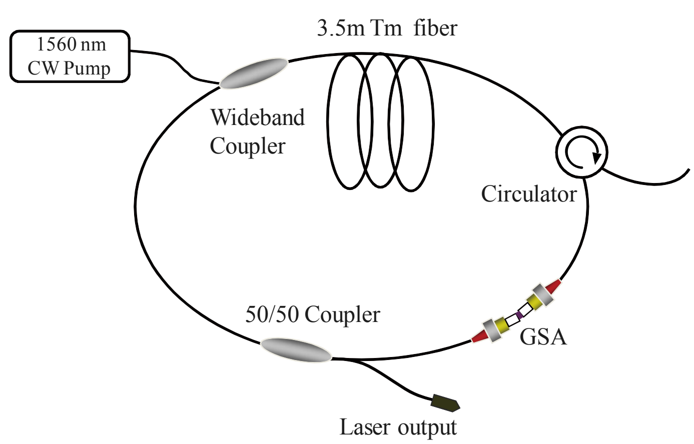

Fig.2 Q-switched thulium fiber laser setup.

Fig.2 illustrates the schematic setup for the Q-switched thulium fiber laser. The Q-switched laser is based on a ring cavity. The gain media is Tm-doped silica fiber (NUFERN) which has a 9/125 core/cladding geometry. The core absorption of the Tm fiber is ~10dB/m at the pump wavelength 1560nm. A 3.5m-span of Tm fiber is used in the cavity to provide optical gain. A diode laser emitting at 1560nm is amplified by an erbium-doped fiber amplifier (EDFA) to provide optical pumping into the core of the Tm fiber. An optical circulator is used as an optical isolator in the cavity to ensure single direction propagation. A 1550nm 50%-50% coupler is used to guide part of the circulating light out of the cavity. The total cavity length is estimated to be ~ 13m.

Q-switching operation starts at a pump power of ~ 320mW. The initial pulse repetition rate is ~ 12kHz, with an output power of 0.57mW. This corresponds to a pulse energy of ~48nJ. Q-switching can be maintained up to a pump power of 400mW, where we obtain the maximum output power ~ 1.8mW and repetition rate ~ 26kHz. At this condition, the pulse energy is increased to ~ 70nJ, larger than previously reported GSA Q-switched fiber lasers at 1.5 μm [16]. Further increase of the pump power results in unstable pulsation. Fig. 3 shows the output waveforms at 400mW pump power, using an ultrafast photo-detector (with 10GHz bandwidth). Fig.4(a-b) illustrates the pulse duration, output power and repetition rate as a function of pump power. As pump power increases, we observe increasing repetition rate and decreasing pulse duration, typically expected for Q-switched lasers [5]. The optical spectrum of the Q-switched laser is measured using a scanning spectrometer (Bristol 721B) and the spectrum exhibits a single peak at 1884nm (Fig.4c).

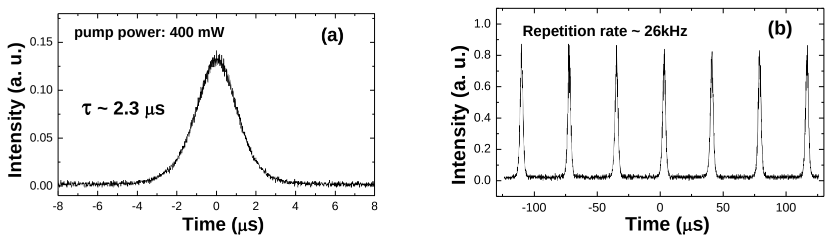

Fig.3 *Q-switched (a) pulse profile, (b) pulse train.*

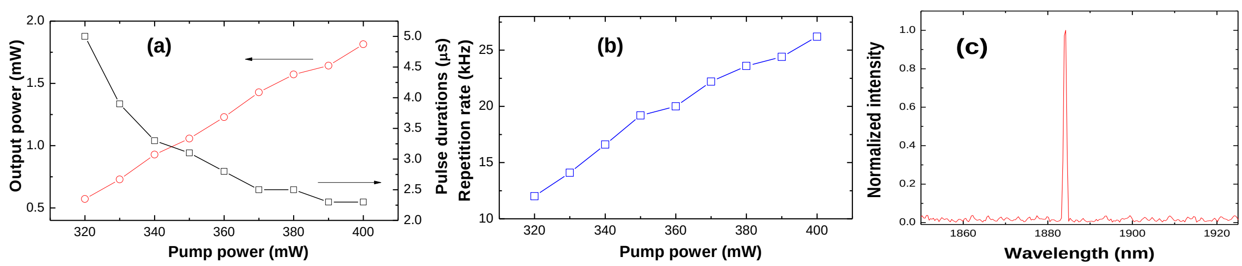

Fig.4 *Trends for (a) output power and pulse duration (b) repetition rate; (c) output spectrum*

In summary, we have demonstrated a 2.0 micron Q-switched thulium fiber laser using graphene based saturable absorber. The experimental results indicate that GSA can be used as an effective saturable absorber for mid-Infrared pulse generation.

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References

[1] B. T. McGuckin et al., Appl. Phys. Lett., **59**, 2926 (1991)
[2] M. Eichhorn et al.,Opt. Lett., **32**, 2780 (2007)
[3] J. Geng et al., Opt. Lett., **34**, 3713 (2009)
[4] Y-K. Kuo et al., Appl. Phys. Lett., **65**, 3060 (1994)
[5] O. Svelto, Principles of Lasers, 4th Ed., (Plenum, New York,1998)
[6] D. C. Hanna, R. M. Percival, R. G. Smart, A. C. Tropper, Opt. Commun., 75, 283 (1990)
[7]S. Kivisto et al., Opt. Express, **16**, 22058, (2008)
[8]F. Z. Qamar and T. A. King, Opt. Commun., **248**, 501 (2005)
[9]Y. Tang et al., Opt. Commun., **281**, 5588 (2008)
[10] F. Wang et al., Nature Nanotech. **3**, 738 (2008).
[11] Z. Sun et al.,ACS NANO, **4**, 803 (2010)
[12] T. Hasan et al., Adv. Mat. **21**, 3874 (2009).
[13] Z. Sun et al., Nano Res, **3**, 653 (2010)
[14]F. Bonaccorso et al., Nature Photonics, **4**, 611 (2010)
[15] X-L. Li et al., Opt. Express, **19**, 9950 (2011)
[16] D. Popa et al., Appl. Phys. Lett., **98**, 073106 (2011)
[17] T. Hasan et al., Phys. Stat. Sol. B, **247**, 2953 (2010)
[18] F. Torrisi et al., submitted (2011)