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# 1.61 $\mu\text{m}$ high-order passive harmonic mode locking in a fiber laser based on graphene saturable absorber

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**Abstract:** We demonstrate a passive mode-locked Er:Yb doped double-clad ring fiber laser based on graphene saturable absorber. By adjusting the polarization controller and minimizing the cavity loss, the laser can operate at hundreds of harmonics of the fundamental repetition frequency of the resonator with the central wavelength of 1.61  $\mu\text{m}$ . Up to 683rd harmonic (which corresponds to 5.882 GHz) of the fundamental repetition frequency was achieved.

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**OCIS codes:** (060.4370) Nonlinear optics, fibers; (060.3510) Lasers, fiber; (140.4050) Mode-locked lasers; (140.3500) Lasers, erbium.

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## 1. Introduction

High repetition rates ultrashort pulses are very important since they can be utilized to high bit rate optical communication [1], arbitrary wave form generation [2] and biological imaging [3], etc. In net negative dispersion fiber laser ( $\beta_2 < 0$ ), when the pump power increases beyond a certain value, multipulses will form in the cavity because of the energy quantization effect [4]. Under certain conditions they can self-arrange to create a stable and well-organized pulse

train with repetition rates far beyond the fundamental cavity frequency (free spectral range of the cavity) [5]. This technology is an efficient method to get high repetition rates ultrashort pulses, and is called high-order passive harmonic mode-locking (HML). Although HML has been observed since many years, some fundamental properties are still pointed out. As a matter of fact, it has been recently demonstrated that an external continuous wave can force a multipulse laser to operate in HML regime [6]. Moreover, the origin of pulse shortening mechanism in HML fiber lasers has also been studied [7]. Many high-order passive HML erbium-doped fiber lasers based on different mode locking patterns have been reported: 140th HML (1.2 GHz) [8], 322nd HML (3.079 GHz) [9], 634th HML (10 GHz) [10] and 337th HML (1.80 GHz) [11] in nonlinear polarization rotation (NPR) mode-locked fiber laser; 61st HML (1.692 GHz) in carbon nanotube (CNT) mode-locked fiber laser [12]; 46th HML (0.49 GHz) [13], 21st HML (2.22 GHz) [14] and 101st HML (555 MHz) [15] in graphene mode-locked fiber laser; 418th HML (2.04 GHz) in topological insulator mode-locked fiber laser [16]; 369th HML (2.5 GHz) in molybdenum disulfide ( $\text{MoS}_2$ ) mode-locked fiber laser [17]. Note however that all the above researches are focused on C-band (1530–1565 nm).

In modern optical communication systems, dense wavelength division multiplexed (DWDM) transmission systems are being developed to meet the rapidly growing data traffic demands. Conventional C-band is actually not enough for the current DWDM applications and systems, new wavelength ranges are being sought and investigated in order to widen the communications transmission capacity. This makes the L-band (1565–1625 nm) critical because it can be efficiently utilized to transport multi terabit traffic [18]. Further more, ultrafast lasers in L-band can also find other applications such as spectroscopy [19] and biomedical diagnostics [20], etc. In erbium-doped fiber lasers, theoretical and experimental approaches indicate that the emission wavelength depends on the cavity losses or on the active fiber length and dopant concentration [21]. Although erbium-doped fiber amplifier (EDFA) itself has a very low-gain at L-band, L-band operation have been realized in fiber lasers implement low cavity loss [22–24], a long length of erbium-doped fiber [25, 26] and higher erbium concentration [27]. Then L-band mode locked fiber lasers have attracted much attention in recent years [28–31]. We have recently shown that the control of the linear losses of the cavity in a filterless figure-of-eight laser allows to obtain continuous wave regime or mode-locked operation above 1.6  $\mu\text{m}$  [32]. Following this principle we have built a unidirectional ring cavity passively mode-locked with graphene saturable absorber (GSA) operating above 1.6  $\mu\text{m}$ . GSA has unique properties such as low losses, high modulation depth and wavelength independent, and is widely used in C-band mode-locked fiber lasers [33–37]. Based on its lower losses and wavelength independent, GSA may be helpful to realize a low loss laser cavity and achieve L-band pulsed operation by using a C-band EDFA. In this paper, we demonstrate an Er:Yb doped double-clad ring fiber laser based on graphene saturable absorber. High-order passive HML operating above 1.6  $\mu\text{m}$  in the soliton regime is reported for the first time to our best knowledge. The highest recorded repetition rate was 5.882 GHz, which corresponds to the 683rd harmonic of the fundamental cavity frequency (8.618 MHz).

## 2. Experimental setup

The experimental setup is shown in Fig. 1. We use a C-band double-clad Er:Yb doped fiber amplifier manufactured by Keopsys. Two identical laser diodes operating at 980 nm and emitting about 3 W each are used in a counter propagating geometry. The 8 m-long double-clad fiber has a second-order dispersion of  $-15 \text{ ps}^2/\text{km}$ . We use a polarization-independent isolator (PI-ISO) to force unidirectional operation of the cavity and a polarization controller (PC) to adjust the state of polarization in the cavity. The cavity length is about 23.8 m, including 15.8 m standard telecommunications single mode fibers (SMF) with GVD of  $-22 \text{ ps}^2/\text{km}$ . The net cavity dispersion was about  $-0.468 \text{ ps}^2$ . A 10% output coupler is used to extract the power from the cavity. The output beam is detected with a high-speed photodiode (Newport TIA 1200 13 GHz) and analyzed with either a high-speed oscilloscope (Tektronix TDS 6124C12 GHz, 40 GS/s) or an electronic spectrum analyzer (Rohde & Schwarz FSP

Spectrum Analyzer 9 kHz–13.6 GHz). Pulse duration is measured with an optical autocorrelator (Femtochrome FR-103 XL) with a scanning range scalable to about 170 ps, and an optical spectrum analyzer (Anritsu MS 9710C) is also used.

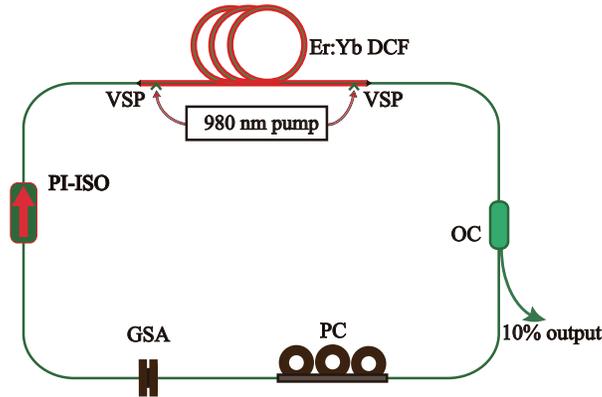


Fig. 1. Experimental setup. DCF: double-clad fiber, VSP: v-groove side-pumping, OC: output coupler, PC: polarization controller, PI-ISO: polarization-independent isolator.

The GSA with an average of 4 monolayer thickness is made by transferring a commercially available graphene film mounted on a nickel substrate onto a fiber pigtail. We purchased the graphene sample (10 mm x 10 mm graphene on nickel/SiO<sub>2</sub>/Si substrate) from the Graphene Laboratories Inc. Figure 2 shows the production process of the GSA. The detailed making process can be seen in ref. 13. The nonsaturable loss of our GSA is ~25%.

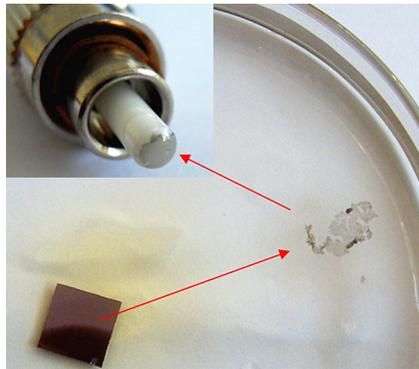


Fig. 2. Production process of the GSA.

### 3. Experimental results and discussion

In our previous works using the same EDFA in a ring cavity, only C-band output was observed [9, 38, 39]. As said in the introduction, low cavity loss maybe helpful to realize long wavelength operation. We have successfully used this approach to realize a figure-of-eight laser operating above 1.6  $\mu\text{m}$  [32]. Here, long wavelength emission at 1.61  $\mu\text{m}$  was also obtained because of the low cavity loss. With a pump power above 1.2 W, mode locking with hundred solitons is readily achieved, but most of the corresponding regimes do not consist in regularly spaced pulses. Instead, they usually formed a bunch in which many soliton pulses grouped themselves into a tight packet. Figure 3(a) shows the oscilloscope trace of the soliton bunch. The width of the bunch is 3–4 ns, and the repetition frequency shown by the inset in Fig. 3(a) is 8.618 MHz which corresponded to the fundamental cavity frequency. The spectrum with a spectral width of 0.95 nm and the corresponding autocorrelation trace are shown in Fig. 3(b). They indicate there are many solitons with the pulse width of 2.9 ps in

perpetual motion in the bunch as confirmed by the large pedestal in the autocorrelation trace. Nearly bound states of solitons in the bunch can be obtained by carefully adjusting the PC as demonstrated in Fig. 3(c). Indeed, the optical spectrum points out a modulation which suggests that coherence starts to occur between pulses. The inset in Fig. 3(c) shows the autocorrelation trace which exhibits many sharp peaks separated by 16 ps reveals that there exists some order at small scale. Soliton liquid has been used to describe this state which has been studied in our previous works [38, 39].

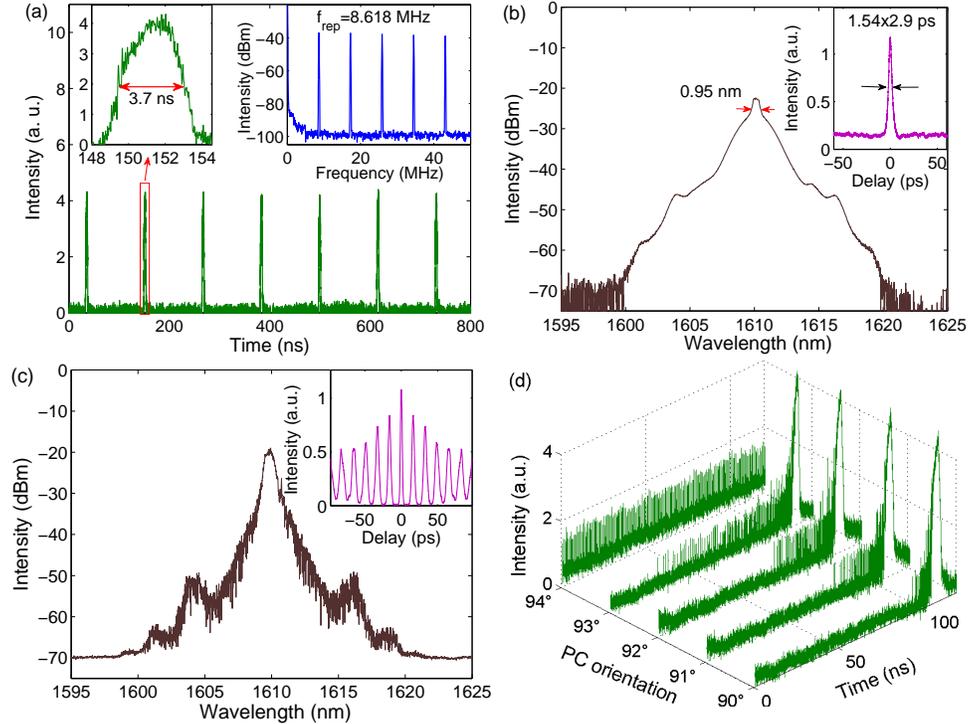


Fig. 3. (a) Temporal trace and RF spectrum (inset) of the soliton bunch. (b) Spectrum and autocorrelation trace (inset) of the soliton bunch. (c) Spectrum and autocorrelation trace (inset) of the bound states in the bunch. (d) Process from soliton bunch to high order harmonic mode locking.

Starting from the bunch state and adjusting the orientation of the PC, solitons get loose from the bunch. Further adjusting the PC, it is finally obtained high order harmonic mode locking in which all solitons are nearly identical and equidistant. Figure 3(d) shows the process from soliton bunch to high order harmonic mode locking by changing the orientation of the PC with pump power of 1.5 W. It should be noted that the last step (corresponding to the PC orientation from 93° to 94°) is sudden, i.e. during this step, very slight change of the PC will cause large number of solitons get loose from the bunch suddenly, then the bunch disappears and the harmonic mode locking is progressively formed.

Pump power does not definitely fix the repetition frequency because different repetition rates can be achieved by adjusting the PC with a fixed pump power. However, it is necessary to increase the pump power if higher repetition frequencies are desired. With increasing the pump power from 1.2 to 2.1 W, the repetition frequency is enlarged from 0.773 to 5.882 GHz. Note that each time the pump power is varied it is necessary to slightly adjust the PC to retrieve HML. Figure 4(a) shows the RF spectra of different repetition frequencies with different pump powers. Due to relatively strong competition between the fundamental and the harmonic frequency components at higher-order HML, the stability of the solitons decreases as the repetition frequency increases [7], this causes the decrease of the supermode

suppression from 35 dB to 19 dB. Indeed, for high repetition frequency the time jitter is high. Inset of Fig. 4(a) shows the RF spectrum of 5.882 GHz harmonic mode locking output measured with 110 MHz span, a supermode suppression of 19 dB is obtained. Figure 4(b) shows the temporal trace of 5.882 GHz harmonic mode locking and the corresponding optical spectrum. The spectra with different repetition frequencies have the same central wavelength of 1610 nm and comparable shapes. The pulses with different repetition frequencies almost have the same widths about 2.9 ps.

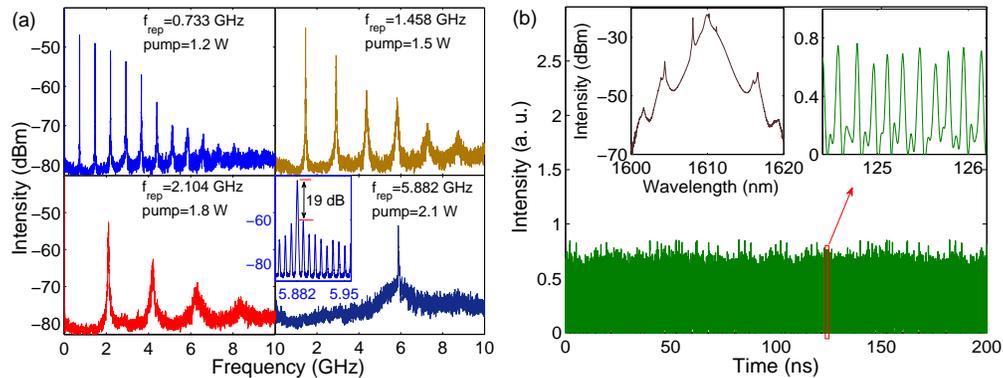


Fig. 4. (a) RF spectrum of 0.733, 1.458, 2.104 and 5.882 GHz harmonic mode locking output measured with 10 GHz span. Inset of (a): RF spectrum of 5.882 GHz harmonic mode locking output measured with 110 MHz span. (b) Temporal trace of 5.882 GHz harmonic mode locking. Inset of (b): Corresponding spectrum.

To avoid destroying the GSA in the experiment, we use the maximum pump power of 2.1 W to generate the output power of 52 mW, with a corresponding output energy of 8.8 pJ per pulse. With pump power above 2.1 W, GSAs suffer from irreversible damages. Although by using a coupler with higher output coupling ratio is helpful to protect the GSA and increase the output power, but it will result in C-band emission due to the high loss of the cavity.

#### 4. Conclusion

We have demonstrated an Er:Yb doped double-clad mode-locked fiber laser based on graphene saturable absorber. The variation of the output wavelength with the additional loss in the cavity was studied. By minimizing the cavity loss, emission wavelength above 1.6  $\mu\text{m}$  was achieved by using a C-band EDFA. Soliton bunch and bound state were observed in the fiber laser. By adjusting the PC and varying the pump power, high-order harmonic-mode-locked pulses with different repetition frequencies could be obtained. Pulses with 683rd harmonic of the fundamental repetition frequency, central wavelength of 1610 nm, duration of 2.9 ps and energy of 8.8 pJ were obtained with the pump power of 2.1 W. To our best knowledge this high-order HML is a record with GSA based mode-locked fiber lasers.

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