L-band passively harmonic mode-locked fiber laser based on a graphene saturable absorber

To cite this article: J Du et al 2012 Laser Phys. Lett. 9 896

View the article online for updates and enhancements.

Related content
- Passive harmonically mode-locked fiber laser
  Y C Meng, S M Zhang, X L Li et al.
- Graphene incorporated Q-switching
  L Zhang, J T Fan, J H Wang et al.
- Tunable Ho-doped soliton fiber laser
  A Yu Chamorovskiy, A V Marakulin, A S Kurkov et al.

Recent citations
- All-normal-dispersion fiber laser with NALM: power scalability of the single-pulse regime
  Gan Gao et al
- L-band wavelength-tunable dissipative soliton fiber laser
  Dan Yan et al
- Study on high coupling efficiency Er-doped fiber laser for femtosecond optical frequency comb
  Lihui Pang et al
Abstract: We have proposed and demonstrated an L-band passively harmonic mode-locked fiber laser based on a graphene saturable absorber (SA). By adjusting the pump power and the polarization controller, we have experimentally observed L-band fundamental and harmonic mode-locked optical pulses. The fundamental optical pulse has the duration of 1.3 ps, and the maximum average output power of 13.16 mW at the incident pump power of 98.8 mW. The order of the harmonic mode-locked optical pulses can be changed over the range from the second to the fourth. From the experimental results, we deduced that the likely origin of the harmonic mode-locked self-stabilization was the result of global and local soliton interactions induced by the instability continuous wave (CW) components.

L-band passively harmonic mode-locked fiber laser based on a graphene saturable absorber

J. Du, S.M. Zhang, H.F. Li, Y.C. Meng, X.L. Li, and Y.P. Hao

College of Physics Science and Information Engineering, Hebei Advanced Thin Films Laboratory, Hebei Normal University, Shijiazhuang 050024, China

Received: 6 March 2012, Accepted: 22 March 2012
Published online: 19 December 2012

Key words: fiber lasers; harmonic mode locking; graphene

1. Introduction

Because of their practical advantages, such as compact, inexpensive, robust, efficient heat dissipation, and so on [1], passively mode-locked (PML) fiber lasers are now exploited in long-distance communications networks. These years, with the increasing requirements of the optical communication system, people have expanded the telecommunications window from the conventional C-band (1530–1565 nm) to the long wavelength L-band (1565–1625 nm) by reason of the lowest losses of silica fibers in this region, and researchers have also paid more attention on the L-band ultrafast laser [2]. At present, semiconductor saturable absorber mirrors (SESAMs) are usually used to achieve mode locking. Though they have the intrinsical environmental stability [3], SESAMs required expensive and complex fabrication technology. Comparing with the SESAMs, single-wall carbon nanotubes (SWNTs) have subpicosecond recovery time, low saturation power, broad operation range, and easy fabrication process. By fabricating carbon nanotubes saturable absorber, Sun et al. have obtained an L-band passively mode-locked ultrafast fiber laser [4]. However, SWNTs have a low damage threshold, and tend to bundled entangled morphology.

Recently, graphene based saturable absorbers have attracted more attention due to their outstanding properties, such as continuous and independent wavelength broadband saturable absorption [5,6], ultrashort recovery time (~200 fs) [7], low saturable absorption intensity [8,9], large modulation depth [8], and high destroyed thresh-
Since Bao et al. have realized ultrafast pulses in an erbium-doped fiber laser (EDFL) using atomic layer graphene as a SA [8], large energy [12], ultrafast [13,14], and switchable and tunable [15] fiber lasers have all been studied.

In addition to expand the telecommunications window, increasing the repetition rate was other method to meet the demand of the optical communication system. On the other hand, when the pump power was increased beyond a certain value, multiple pulses would form because of the energy quantization effect [16,17]. Realizing the stability harmonic mode locking (HML) fiber lasers has attracted more attention. The harmonic mode locking dominant technology, which based on nonlinear polarization rotation (NPR) [18,19], nonlinear optical loop mirror (NOLM) [20], semiconductor saturable absorber (SESA) [21], and SWNTs [22] have all been studied. However, to the best of our knowledge, L-band passively harmonic mode-locked fiber lasers based on graphene SA have not been reported. In addition, Kutz et al. have once demonstrated that mode competition could effect the stability of the pulses [23]. Recently, Luo et al. have pointed out that highly nonlinear graphene could be helpful to mitigate the mode competition of EDFL [6], so to study the L-band passively harmonic mode-locked fiber lasers based on a graphene SA became very important.

In this paper, by using graphene as a SA, we have constructed an L-band single pulse and passively harmonic mode-locked pulses fiber laser. The single pulse has the pulse duration of 1.3 ps, and the 3 dB spectral width of 9 nm at the pump power of 98.8 mW. The order of the harmonic mode locking can be change from the second to the fourth by adjusting the pumping power and the orientation of the polarization controller (PC). Through investigated the dynamic formation process of harmonic pulses, we have found that the interaction between continuous wave (CW) component and pulses had played an important role to form the uniform distribution of pulses inside the laser cavity.

2. Experimental setup

Several technologies, such as optical deposition of graphene-polyvinyl acetate (PVA) composite [24], soaked multilayer graphene on a Ni substrate into chloride solution [5], sprayed onto the flat surface of a side-polished fiber with graphene suspension [10,25], mechanical exfoliation of graphene [26,27], and so on have been used to integrate graphene onto fiber. In this paper, we used 1 M FeCl₃ aqueous solution soaking the graphene several hours to isolate the graphene by partially etching off the surface of the Ni, the graphene has 1–7 layers structure on the Ni (300 nm)/SiO₂(300 nm)/Si substrate (10×10 mm²) composite, and then putted the soaked graphene into deionized water. Finally, few layers graphene were adsorbed onto an optical fiber pigtail end via the van der Waals forces, and the SA was manufactured.

The experiment schematic of L-band passively harmonic mode-locked fiber laser based on a graphene SA was shown in Fig. 1. A laser diode (LD) pump source with the maximum output power of 254 mW at 980 nm was used to pump the gain fiber via a wavelength division multiplexer (WDM). A section of 2.62 m high doping concentration Er-doped fiber (HDCEDF) with erbium-doping concentration Er-doped fiber, ISO – polarization independent isolator, Graphene – graphene membrane SA, PC – polarization controller, and Coupler – optical coupler with 10% output.

![Figure 1](online color at www.lasphys.com) The experimental schematic of the EDFL. WDM – 980/1550 nm wavelength division multiplexer, HDCEDF – high doping concentration erbium-doped fiber, ISO – polarization independent isolator, Graphene – graphene membrane SA, PC – polarization controller, and Coupler – optical coupler with 10% output.

3. Experimental results and discussion

In order to verify the mode locking mechanism based on the graphene, we purposely removed the graphene SA from the laser cavity at first. The CW operated steady and no mode-locked pulse was observed whatever the cavity
parameters such as the pump power and the rotation of the PC were adjusted. After we inserted the graphene-based SA into the cavity, the self-starting soliton operation was easily obtained by increasing the pump power beyond the mode locking threshold of \( \sim 56 \) mW and appropriately adjusting the orientations of the wave plates in the cavity at the same time. The pulse duration would become narrower with increasing the pump power. In order to protect the graphene thin film from thermal damage, the maximum pump power we have used in this experiment was limited to 98.8 mW. The spectrum of the output pulse at the pump power of 98.8 mW was shown in Fig. 2, the operation wavelength was 1598.2 nm and the 3 dB spectral width was 9 nm. There was CW composition in the spectrum, we thought this was because the graphene membrane had a lower number of layers than 8 – 15 layers, then it would lead to “weaker” mode locking [26]. The corresponding pulse width was 1.3 ps, if a sech\(^2\) shape pulse was assumed. The time-bandwidth product was 1.37, indicated the output pulse possessed of frequency chirp.

The output pulse train as shown in Fig. 3 corroborated that the laser operated at its fundamental period of 15.63 MHz. The stable mode-locked pulse could maintain several hours, without any amplitude variation and timing jitter. Fig. 4 showed the varying of the output power with the pump power, the maximum output power was 13.16 mW at the pump power of 98.8 mW. The slope efficiency of 13% was higher than previous work about L-band EDFL [11], which demonstrated the admirable performance of our EDFL.

In the experiment, further increasing the pump power and adjusting the PC, multi-pulses would generate because of the energy quantization effect. These pulses randomly distributed in the cavity at first. By carefully adjusting the PC, until a CW lasing position was set in an appropriate position in the soliton spectrum, and when the CW lasing became unstable, we obtained L-band harmonic mode-locked pulses. In which, all solitons distributed along the cavity with equal space. At different pump power and different position of the PC, we have obtained from the 2nd to 4th order harmonic mode-locked pulses shown in Fig. 5. It could be deduced that the unstable CW lasing and its position in soliton spectrum may played an important role for the formation of the harmonic mode locking. This was because the unstable CW lasing would cause all solitons in the cavity start to move, when the CW lasing was in a right position, a phase locking between one of the dynamical modes of the solitons and the CW lasing might fix
automatically. In this way, the phases of all the solitons in the laser cavity could be synchronized to those of the CW lasing except for an arbitrary phase constant. Then the harmonic mode locking was formed.

4. Conclusion

We have experimentally achieved L-band passively mode-locked and harmonic mode-locked pulses by employing graphene as a SA. The single pulse duration was 1.3 ps at 1598.2 nm, which was in L communication band. The output power increased linearly with the pump power with a slope efficiency of 13%. Under the advisable pumping power and the suitable rotation position of the PC, 2nd–4th order harmonic mode-locked pulses were achieved. It is a foundation for a possibility to realize high repetition rate pulses in L-band.

Acknowledgements This research was supported by grants from the National Natural Science Foundation of China (11074065), Hebei Natural Science Foundation (F2009000321, F2012205076, and A2012205023), Specialized Research Fund for the Doctoral Program of Higher Education of China (20101303110003), and Technology Key Project of Colleges and Universities of Hebei Province (ZH2011107).

References