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Generation of soliton and bound soliton pulses in mode-locked erbium-doped fiber laser using graphene film as saturable absorber

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We report an observation of soliton and bound-state soliton in passive mode-locked fibre laser employing graphene film as a passive saturable absorber (SA). The SA was fabricated from the graphene flakes, which were obtained from electrochemical exfoliation process. The graphene flakes was mixed with polyethylene oxide solution to form a polymer composite, which was then dried at room temperature to produce a film. The film was then integrated in a laser cavity by attaching it to the end of a fibre ferrule with the aid of index matching gel. The fibre laser generated soliton pulses with a 20.7 MHz repetition rate, 0.88 ps pulse width, 0.0158 mW average output power, 0.175 pJ pulse energy and 18.72 W peak power at the wavelength of 1564 nm. A bound soliton with pulse duration of ~1.04 ps was also obtained at the pump power of 110.85 mW by carefully adjusting the polarization of the oscillating laser. The formation of bound soliton is due to the direct pulse to pulse interaction. The results show that the proposed graphene-based SA offers a simple and cost efficient approach of generating soliton and bound soliton in mode-locked EDFL set-up.

Keywords: graphene; electrochemical exfoliation; saturable absorber; passive mode-locking; bound soliton

1. Introduction

Passively mode-locked erbium-doped fibre lasers (EDFLs) particularly have gained remarkable interest in recent years due to their simple and compact design and high-quality pulse generation [1–3]. To date, several types of pulses have been experimentally observed with the mode-locked EDFLs such as soliton [4], stretched pulse [5], noise like pulse [6] and square pulse [7]. Among all of these pulses, soliton pulse offers a platform to explore various nonlinear phenomena such as the formation of conventional soliton [8], vector soliton [9], bound-state soliton [10], dissipative soliton [11] and dissipative soliton resonance [12]. The solidarity of soliton in ultrafast laser ranging from femtosecond to microsecond is beneficial in increasing resolution in metrology [13], high-accuracy spectroscopy [14] and suppressed phase noise in high-speed fibre optic communication [15]. In the higher pump power regime, a soliton is most likely to operate in multi-pulse operation. Depending on the parameters of the experimental settings, the multi-pulse solitons can either rearrange themselves in a fixed position to form the harmonic mode-locking or the bound-state pulses. After Molomed [16] theoretically predicted on the bound-state solitons, bound-state soliton has become an attractive topics among researchers in both theoretical and experimental fields [10,17,18].

Up to date, bound-state solitons have been demonstrated based on various techniques such as nonlinear polarization rotation (NPR) with figure-of-eight configuration [19], carbon nanotube [20] and graphene [21]. Lately, graphene has gained a tremendous interest for mode-locking applications owing to its exceptional optical properties, such as fast saturable absorption, broadband wavelength tunability and short carrier relaxation time [22–24]. Several approaches known to date to synthesize graphene for saturable absorber (SA) application are micromechanical cleavage, liquid-phase exfoliation and chemical vapour deposition (CVD) [25]. However, these methods have proven to have some major drawbacks: the need to integrate organic solvents involves high temperature and complicated procedure to make the devices, high risk of disrupting the electronic structure of the end product of the graphene, and lastly, the process is extremely tedious and time consuming [23,26–28]. Lately, electrochemically exfoliated graphene has been demonstrated using conductive electrodes [29]. This technique emerges as one of the most desirable methods to prepare high-quality graphene on a large scale under mild conditions [30]. Compared to other techniques, the electrochemical

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The exfoliation technique is advantageous considering its simplicity, cost efficiency and easy fabrication process. This opened enormous opportunity to fabricate graphene flakes for possible optoelectronics applications particularly in ultrafast laser generation [29].

In this paper, we report an observation of soliton and bound-state soliton in passive mode-locked fibre laser by employing graphene embedded polyethylene oxide (PEO) film as passive SA. The graphene SA is fabricated using graphene flakes, which are obtained from electrochemical exfoliation process. The graphene flakes is mixed with PEO solution to form a polymer composite, which is then dried at room temperature to produce a SA film with a thickness of ~50 μm. The film is integrated in the laser cavity and the output of the generated pulse laser is characterized. Conventional soliton EDFL which produces a mode-locked regime with 0.88 ps pulses is demonstrated at the pump power of 105 mW. When the polarization controller (PC) is carefully oriented, bound soliton with two pulse separation of ~3.55 ps is recorded at the pump power of 110.85 mW. We would like to highlight that our cavity length is rather short, approximately 10 m and both conventional soliton and bound-state soliton are repeating at a fundamental frequency of 20.7 MHz.

2. Fabrication of the graphene SA

The graphene SA used in this work was produced via an electrochemical exfoliation process. This process involved the application of a certain a potential difference between two graphite rods which were immersed in an ionic fluid, sodium dodecyl sulphate (SDS) solution, until the graphite cathode underwent exfoliation process, predominantly after several hours [31–33]. The ion production inside the (SDS) solution can be written as follows:

\[ \text{H}_2\text{O} \rightarrow \text{OH}^- + \text{H}^+ \]  

\[ \text{CH}_3\text{(CH}_2)_1\text{1OSO}_3\text{Na} \rightarrow \text{CH}_3\text{(CH}_2)_1\text{1OSO}_3^- + \text{Na}^+ \]

When a certain voltage was applied to the electrodes, the negative ions moved to the anode, whereas the positive ions moved towards the cathode. Once the dodecyl sulphate ions mounted up at the anode, they reacted with the surface of the graphite rod to release graphene layers from the graphite rod [34,35]. In this experiment, we applied a voltage of ~20 V between the graphite electrodes which were immersed in an electrolysis cell. The two electrodes were separated by about 1 cm in the electrolysis cell which contained solution of 1% SDS in deionized water as depicted in Figure 1. After two hours, the solution became darker due to the accumulation of exfoliated graphene flakes. Next, the exfoliated graphene flake suspension was centrifuged at 3000 rpm for half an hour in order to eliminate large agglomerates. The supernatant portion of the suspension was removed and then the concentration of graphene was estimated from the weight of the suspension. After that, we prepared the composite solution by mixing 1 g of PEO which was dissolved in 120 ml of distilled water with the prepared graphene suspension. The ratio between the graphene and the PEO solution was 1:1. Finally, the composite was left to dry at room temperature for about seven days to form a graphene film with a thickness of ~50 μm. The insertion loss for the film is about 4.8 dB.

Raman spectrum of the fabricated film was obtained using a probe beam of 532 nm. As observed from Figure 2, the D peak indicates the existence of defects in

![Figure 1. Experimental set-up of electrochemical exfoliation of graphene. (The colour version of this figure is included in the online version of the journal.)](image1)

![Figure 2. Raman spectrum from the graphene film. (The colour version of this figure is included in the online version of the journal.)](image2)
The sample at 1351 cm\(^{-1}\). The G peak observed at 1617 cm\(^{-1}\) corresponds to the Raman active \(E_{2g}\) phonon at Brillouin zone centre of graphite [34]. The intensity ratio of the D to G band of the graphene sheets is about 1.2, as expected due to small size of the graphene sample. The existence of multi-layered graphene can be confirmed by considering the ratio of G to 2D peak which is higher than 0.5 [35]. The ratio of the G to 2D peak, as well as the shape of the weak 2D peak detected would suggest that the flakes are closer to graphite, than graphene in this case. To further characterize the linear transmission of the graphene, the transmissions with and without graphene film GSA were recorded using a broadband ASE source. The linear transmission spectrum is shown in Figure 3, which exhibits a strong resonance at around 1530 nm. This characteristic is unusual for pure graphene samples and we would suggest that this may arise from the host material or other impurities introduced in the preparation process. Figure 4 shows a modulation depth, which is obtained by using a mode-locked fibre laser with 2.38 MHz repetition rate and 330 fs pulse width as the input pump. The modulation depth is measured at 2.48\% with non saturable of 54.62\%. The modulation depth and non saturable loss obtained in this work is almost similar to the multi-layered graphene synthesized by CVD method reported by Huang et al. [36].

3. Configuration of the mode-locked EDFL

A schematic of the laser configuration is shown in Figure 5 where a graphene SA (GSA) is used as a mode-locker. The SA was prepared by cutting a small part of the graphene film (2 mm × 2 mm) and then sticking it between two FC/PC fibre connectors with the help of index-matching gel. The insertion loss of the GSA was measured to be around 3 dB at 1550 nm. The laser resonator uses 1 m long Erbium-doped fibre (EDF) as the gain medium. The EDF has an erbium concentration of 2000 ppm, a cut-off wavelength of 910 nm, a pump absorption rate of 24 dB/m at 980 nm and a dispersion coefficient of \(-21.64 \text{ ps/ nm km}\) at \(\lambda = 1550 \text{ nm}\). The remaining cavity comprises standard single-mode fibre (SMF-28) with a dispersion coefficient of 17 ps/ nm km. A 1480-nm laser diode was used to pump the EDF through a 1480/1550 nm wavelength division multiplexer (WDM). An isolator was incorporated in the laser cavity to ensure unidirectional propagation. The output of the laser was taken out from the cavity via a 95/5 fibre coupler. On the other hand, the 5\% port of the coupler was connected to the 1 × 2 3 dB coupler so that the output laser can be split into two and each part was then connected to an optical spectrum analyser (OSA) and an oscilloscope, respectively. The OSA (Yokogawa, AQ6370B) with a spectral resolution of 0.02 nm was used for the spectral analysis, whereas the oscilloscope (LeCroy, 352A) was used to observe the output pulse train of the mode-locked operation in the form of electrical signal via a 6-GHz bandwidth photodetector (Hewlett Packard, 83440B). The pulse width was measured using...
The Alnair intensity-based autocorrelator (HAC 200). The total cavity length was approximately 10 m and the estimated net group velocity dispersion was 0.1764 ps/nm at 1550 nm. The proposed laser was operating in anomalous dispersion region.

4. Results and discussions
The proposed mode-locked EDFL starts to produce CW lasing at the threshold pump power of 64 mW. As the power is further increased to around 70.2 mW, we start to observe the stable self-starting mode-locking pulse. Figure 6 shows soliton spectra of the mode-locked laser with Kelly’s sideband at various pump power. As shown in the figure, we can see that the higher the pump power, the higher the intensity of the soliton spectrum and the more prominent the Kelly sideband is. The generation of Kelly sidebands is due to the periodical perturbation of the intracavity, which confirms the realization of the soliton pulse in the anomalous dispersion region.

Figure 7 shows the output spectrum, autocorrelator trace, typical pulse train and RF spectrum of the mode-locked soliton fibre laser at the pump power of 105 mW. As shown in Figure 7(a), the central emission wavelength is approximately 1564.5 nm with full-width half maximum (FWHM) spectral bandwidth of 5 nm. Typical soliton sidebands due to periodic intracavity perturbations are also observed. Assuming a sech² temporal profile, the pulse width inferred from the measured autocorrelator trace is 0.88 ps as shown in Figure 7(b).

The calculated time-bandwidth product (TBP) is 0.539, slightly deviates from transform limited value of 0.315 for sech² pulse. This indicates that the soliton pulse is somehow chirped and the occurrence of chirping in the pulse obtained may cause by residual dispersion of the laser cavity [37]. Figure 7(c) shows a typical output pulse train with a period of 44.3 ns, which corresponds to the repetition rate of 20.7 MHz as expected from the

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Figure 6. Soliton spectrum with varying pump power (70.2, 105, 140 and 174 mW). (The colour version of this figure is included in the online version of the journal.)

Figure 7. The characteristic of the soliton EDFL obtained at pump power of 105 mW (a) OSA trace with FWHM bandwidth of 5 nm (b) Autocorrelation trace with pulse width of 0.88 ps (c) Output pulse train with a repetition rate of 20.7 MHz and (d) RF spectrum with OSNR of 41.88 dB. (The colour version of this figure is included in the online version of the journal.)
fibre cavity length. Figure 7(d) shows the optical signal-to-noise-ratio (OSNR) of the RF spectrum which is ~41.88 dB at the fundamental repetition rate of 20.7 MHz, signifying a good mode-locking stability. The recorded average output power is 0.363 mW at pump power of 105 mW and this translates to soliton peak power of 18.72 W and pulse energy of 0.175 nJ. To verify that the mode-locking operation is the result of using the graphene–PEO film, we purposely removed the SA from the cavity. No mode locking was observed subsequently, even under the maximum available pump power.

Bound solitons could also be generated by the proposed mode-locked EDFL cavity. By carefully adjusting the PC orientation and raising the pump power to about 110.85 mW, a single soliton splits into two pulses and then evolves into the bound state. The presence of the bound soliton is characterized by a dint in the central wavelength of the output spectrum [36] which can be observed in Figure 8(a). The central wavelength is 1564.2 nm at the pump power of 110.85 mW. The formation of bound soliton is due to direct pulse to pulse interaction [38]. The optical spectrum also shows a regular and evident modulation with a period of 2.0 nm. The corresponding autocorrelation trace of the bound soliton is shown in Figure 8(b). Compared to the autocorrelation trace of the conventional soliton, the autocorrelation for bound soliton has three peaks with two side peaks of the same height. This indicates that the two bound-state pulses are identical. The measured pulse separation is ~3.55 ps while the pulse duration is ~1.04 ps. According to Fourier Transform theory [39], the 3.55 ps separation between the two identical pulses in the temporal domain would lead to the 2.2 nm peak-to-peak spacing in the spectrum domain which is rather close to the experimental result in Figure 3(a). The repetition rate of bound-state soliton is maintained at 20.7 MHz. Improvement of performances of soliton and bound solitons formation are expected by further optimizing the graphene SA fabrication and reducing the loss in the laser cavity.

5. Conclusion
We have successfully demonstrated a passive mode-locked EDFL operating in soliton and bound-state soliton using graphene, which is embedded into PEO film as passive SA. The graphene was synthesized using electrochemical exfoliation technique. The fibre laser generated soliton pulses with 20.7 MHz repetition rate, 0.88 ps pulse width, 0.0158 mW average output power, 18.72 W peak power, 0.175 nJ pulse energy and 0.539 TBP. Bound soliton was observed at the pump power of 110.85 mW after carefully adjusting the PC in the laser cavity. This work offers a simple and cost-efficient approach of generating soliton and bound soliton mode-locked EDFL based on graphene SA.

Disclosure statement
No potential conflict of interest was reported by the authors.

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References