GRAPHENE BASED SOLITON MODE-LOCKED ERBIUM DOPED FIBER LASER FOR SUPERCONTINUUM GENERATION

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In this paper, we demonstrate a highly stable Soliton mode-locked Erbium-doped fiber laser (EDFL) based on graphene saturable absorber (SA). Graphene nanopowder is first converted into solution and then mixed with polyvinyl alcohol (PVA) to form a thin film. The fabricated thin film has a modulation depth and saturation intensity of 6.1 %, and 21 MW/cm^2, respectively. The proposed soliton mode locked operate with a central wavelength of 1562 nm and 3-dB bandwidth of 1.46 nm. Its repetition rate and pulse width are 1.85 MHz and 2.24 ps, respectively. At the maximum output power of 1.6 mW, the pulse energy and peak power are approximately 0.86 nJ and 363 W, respectively. The same generated mode locked pulse is observed after being sent into a 10 km single mode fiber (SMF) which conform its high stability that is required for optical communication application. Supercontinuum light is also generated using the proposed soliton mode locked with a range starting from 1300 nm to 1700 nm. The proposed supercontinuum laser can be seen as a promising frequency comb source for frequency metrology applications.

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1. Introduction

Passively mode-locked erbium-doped fiber lasers (EDFLs) have attracted much attention in past few decades owing to their advantages of flexibility, compactness, low cost. Furthermore they can provide extremely short pulse width shorter than that can be obtained from active techniques [1]. The mode-locked EDFLs have also a wide range of applications in optical frequency metrology, terahertz-wave generation, telecommunication, optical imaging and sensing, and industrial laser micromachining [2]. The mode-locking pulses can be realized by incorporating a passive saturable absorber (SA) device in the laser cavity. Generally, SAs can be divided into artificial and real types of SA. Artificial SAs such as Nonlinear Polarization Rotation (NPR) and Nonlinear Optical Loop Mirror (NOLM) have the drawbacks of ambient sensitivity or the need for long fiber to provide sufficient nonlinear phase shifts [3, 4]. On the other hand, real SAs have the advantages of robustness and more compact. Real SAs such as semiconductor saturable absorber mirrors (SESAMs), carbon nanotubes (CNTs) have been intensively investigated and used to construct mode locked fiber lasers [5, 6]. However, SESAMs are relatively expensive and operate

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in a narrow wavelength band, while CNT has complex bandgap structure and narrow operation band [7].

Ideal SA is identified by having an ultrafast recovery time, wide band absorption, adequate damage threshold, appropriate modulation depth, low saturation intensity, and simple fabrication process [8]. Recently, graphene SA perfectly fits these characteristics. Furthermore, graphene is known as a single two-dimensional (2D) atomic layer of carbon atom and it has wavelength insensitive saturable absorption at telecommunication band as it has zero bandgap [9]. Compared to CNT, graphene has no or at least less surface tension due to its unique 2D structure, therefore, it has higher damage threshold [10]. Due to all these highly valuable properties of graphene it has been widely utilized as SA for fiber lasers applications. For instance, atomic layer graphene has been used as a SA to generate a large energy mode-locked pulses at around 7.3 nJ in EDFL cavity [9] [10] [11] [12] [13]. By managing the net cavity dispersion of EDFL cavity, stretched and soliton mode locked pulses were also generated based on graphene saturable absorber [14]. Even though, afterward, other 2D materials was also reported to generate mode locked pulses such as Transition-Metal Dichalcogenides (TMDs) [15] and Topological Insulators (TIs) [16], yet, TMDs have large bandgap and require high energy, and TIs restrict itself by the difficultly of fabrication process [17]. Hence, due to limitations of TMDs and TIs, graphene is still being largely used as an efficient saturable absorber for fiber laser applications [18, 19].

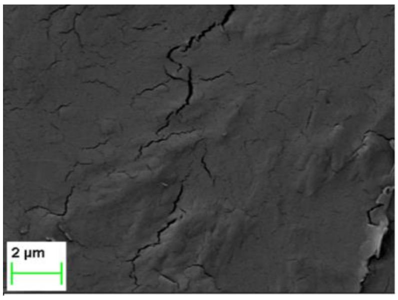
Recently, supercontinuum generation using photonic crystal fiber (PCF) got much attention by researcher and was rapidly applied into various applications including optical coherence tomography, spectroscopy, and optical frequency metrology [20, 21]. For instance, in frequency metrology applications, high frequency laser operating in supercontinuum regime is very desirable as a frequency comb source since the large mode spacing allows absolute wavelength resolution of the frequency comb [22]. In this paper, we demonstrate a highly stable soliton mode locked EDFL operating at 1562 nm using a graphene based SA as a mode locker. The fundamental frequency and the pulse duration of the constructed laser are 1.85 MHz and 2.24 ps, respectively. The maximum pulse energy and peak power were estimated to be approximately 0.86 nJ and 362.717 W, respectively. We also demonstrated a supercontinuum light source generation by using the proposed soliton mode locked fiber laser as a pump in conjunction with a spool of PCF as a nonlinear gain medium.

2. The fabrication and characterization of graphene thin film

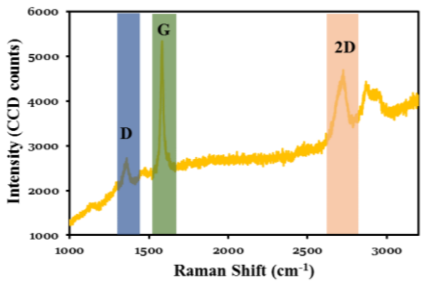
Graphene nanopowder with a specific area of 100 m^2/g, average flake purity of 99.9%, thickness of 8 nm (20-30 monolayers) and average particle (lateral) size of ~ 550 nm (150-3000) nm was purchased from graphene supermarket and used without any change to its parameters. To fabricate the graphene thin film, at first, 25 mg of graphene nanopowder was dispersed in 40 ml deionized (DI) water with the help of 1% Sodium dodecyl sulfate (SDS). The resultant solution was then sonificated for about 60 minutes. To segregate the large graphene particles, the dispersed graphene was centrifuged at 1000 rpm so that the resultant graphene suspension can be used for the film fabrication.

To prepare the host polymer, 1 g of polyvinyl alcohol (PVA) (Mw=89x10^3 g/mol, Sigma Aldrich) was dissolved in 120 ml of DI water. After that, 3 ml of the host polymer were mixed with a 2 ml of graphene suspension after the centrifuge process. The resultant mixture was poured onto a petri dishes and left for three days at room temperature till it totally dried and forms a thin film. The thickness of the thin film was measured to be around 50 µm. The fabricated graphene thin film was characterized using Field Emission Scanning Electron Microscopy (FESEM), Raman spectroscopy and twin balance technique.

Fig. 1(a) shows the FESEM image, which clearly indicates that the graphene flakes are well dispersed in the PVA matrix. Fig. 1(b) shows the Raman spectrum of the graphene SA film, which was obtained by using a 514 nm beam from an Argon-ion laser as a probe. As shown in the figure, the spectrum exhibits signature peaks at around 1353 cm^{-1}, 1585 cm^{-1} and 2724 cm^{-1} bands, which corresponds to D, G and 2D band respectively. D band is associated with the vibrations of carbon atoms with sp^3 electronic configuration of disordered graphite, while G band contributes to an E_{2g} mode of graphite and is related to the in-plane vibration of sp^2-bonded carbon atoms. However, a negligible defect existing in the graphene film was detected by the small D peak. The number of graphene layer can be estimated by the distance between G and 2D peaks or the shape of the 2D peak [23, 24]. Therefore, the obtained G/2D peak ratio of 0.6 indicates that the graphene has a multi-layer structure.



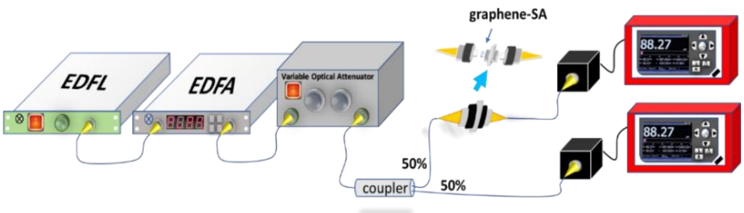
a)



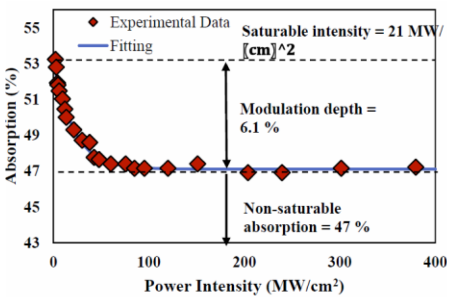
b)

Fig. 1. (a) FESEM image and (b) Raman spectrum of the fabricated graphene SA film

Finally, the twin balance technique was used to investigate the nonlinear absorption of the graphene SA, where the setup of this technique is shown in Fig. 2(a). A homemade mode-locked fiber laser was used as a seeding source. It operates at central wavelength, repetition rate and pulse width of 1550 nm, 1 MHz and 1.7 ps, respectively. The output of the mode-locked laser was amplified using Erbium doped fiber amplifier (EDFA) in order to gain a sufficient peak power to fully saturate the graphene SA. For the purpose of controlling the output power of the EDFA and changing it with a desirable range, a variable optical attenuator (VOA) was also used. The output of the VOA was connected to a 3dB coupler to measure the output power with and without the graphene-SA simultaneously. Using the readings obtained from the two power meters, the nonlinear absorption curve of the graphene SA was plotted as shown in Fig. 2(b). As shown in the figure, the modulation depth, non-saturable intensity and saturation intensity of the graphene SA are obtained at 6.1 %, 47%, and 21 MW/cm^2, respectively.



(a)



(b)

Fig. 2. Nonlinear absorption characteristic of the graphene SA (a) measurement setup based on the dual-detector technique (b) the obtained nonlinear absorption curve

3. Experimental setup

The experimental setup of the proposed supercontinuum light generation is illustrated in Fig. 3. It consists of a ring cavity mode-locked EDFL, which was designed based on the graphene SA. The EDFL used 980 nm laser diode to pump the gain medium via a 980/1550 wavelength division multiplexer (WDM). The gain medium of the laser was a 2m long EDF with erbium ions absorption of 23 dB/m at 980 nm. The EDF has a numerical aperture (NA), group velocity dispersion (GVD), and the core and cladding diameters of 0.16, 27.6 ps^2 / km, 4 µm, 125 µm, respectively. The unidirectionality of the light inside the optical resonator is ensured by using a polarization insensitive isolator which is connected to the gain medium directly. This unidirectionality of the light is essential to decrease the probability damage to the SA or LD that could be caused by the back reflection.

The graphene SA is integrated between the isolator and an optical coupler (90/10 %) of the EDFL cavity. The SA is simply formed by inserting the pre-fabricated graphene PVA film between two clean fiber ferrules. The majority of the light around 90 % was fed back to the cavity through the 1550 nm port of the WDM for the purpose of laser generation, and the remaining 10% of the oscillating photons was tapped out as an output of the laser. An additional 100 m single mode fiber (SMF-28) with GVD of -21.7 ps^2/km was added to the cavity to increase its nonlinearity and to balance total cavity dispersion, consequently, promote the mode locking action. The cavity length of the proposed laser was approximately 105 m in total. The output laser characteristics were measured using an optical spectrum analyzer (OSA) and an oscilloscope (OSC) via a photo-detector.

The mode-locked output laser was the amplified by an Erbium-doped fiber laser before it is launched into a 100m long a highly nonlinear photonics crystal fiber (HNL-PCF) for the supercontinuum generation. The spectrum of the supercontinuum source was measured by an OSA.

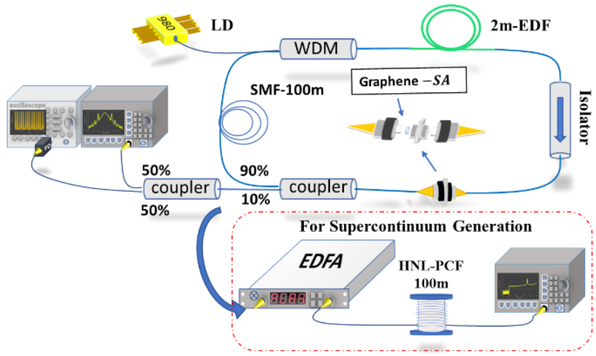


Fig. 3. Experimental setup of the supercontinuum generation setup, which consists of the graphene based soliton mode locked EDFL, an EDFA and a 100m long HNL-PCF

4. Results and discussion

The self-started soliton mode-locked EDFL was successfully generated at the threshold pump power of 36.9 mW and its operation was maintained up to the maximum pump power of 109 mW. The laser was obtained at a relatively low pump power due to the low cavity loss. **Fig. 4(a)** shows the optical spectrum of the laser at pump power of 109 mW. Based on the GVD of the EDF and SMF the total cavity dispersion is calculated to be around -2.2 ps^2 which operates in anomalous dispersion regime. This confirmed by the clear presence of the soliton with visible Kelly sidebands in the optical spectrum of the laser output. The central wavelength of the proposed soliton laser was 1562 nm and a 3-dB spectral bandwidth of 1.46 nm. Based on the 3-dB bandwidth of the optical spectrum we calculated the time–bandwidth product which was around 0.4.

Fig. 4(b) shows the oscilloscope trace of the mode-locked pulses at a pump power of 109 mW. It has a time interval of 539 ns between the pulses, which is corresponding to the total cavity length of 105 m. Because of the resolution limitation of the oscilloscope, we used an auto-correlator to measure the exact pulse width of the generated mode-locked pulse. Fig. 4(c) illustrates the corresponding autocorrelation trace. As shown in the figure, the pulse width is measured to be 2.24 ps with fitting by sech^2-pulse profile. The average output power and pulse energy as a function of the input pump power of the proposed mode locked laser were also investigated. The results of this investigation are shown in Fig. 4(d). It can be seen that the soliton mode locked pulses were started at a relatively low pump power of 36.9 mW and its operation was maintained up to the maximum pump power of 109 mW. At the maximum pump power, the output power was 1.6 mW while the pulse energy and peak power are calculated to be around 0.86 nJ and 363 W, respectively.

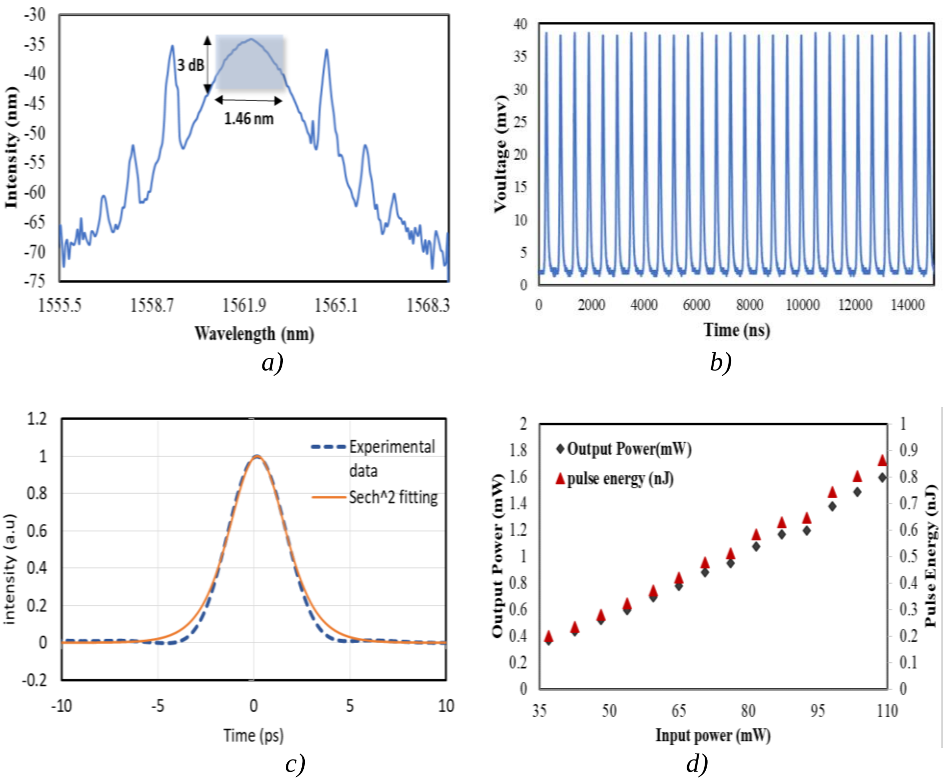


Fig. 5. Output characteristics of the soliton mode-locked EDFL (a) Output spectrum (b) Typical pulse train (c) auto-correlator trace (d) output power and pulse energy against the pump power

In order to investigate the stability of our mode locked EDFL, we have also characterized the radio frequency (RF) spectrum of the generated soliton pulses. The RF trace of the produced pulses is indicated in Fig. 5 and its inset figure which was recoded in a resolution bandwidth of 100 kHz and a span of 20 MHz, respectively. The resultant RF trace shows a high stability of the demonstrated soliton laser with a Signal to Nosie Ratio (SNR) of approximately 52 dB at the fundamental repetition rate. No addition peaks of frequency have been seen which prove no presence of Q-switching instabilities. Furthermore, the generated mode locked soliton signal was sent into a 10 km standard single mode fiber (SMF) to further examine its stability. The attenuation, dispersion, differential group delay, size of the core, and size of the cladding of the used 10 km SMF were 0.2 dB/km, 5 ps/(nm.km), 0.2 ps/km, 9 µm and 125 µm respectively. The experimental setup and the results of this stability are shown in Fig. 6. The results show only a little attenuated soliton signal with no change on the generated soliton optical spectrum or pulse width. Finally, the stability of the soliton mode locked laser was also investigated over various time periods as shown in Fig. 7. The soliton mode-locked laser was left to operate for more than three hours and no degradation of the performance has been presented.

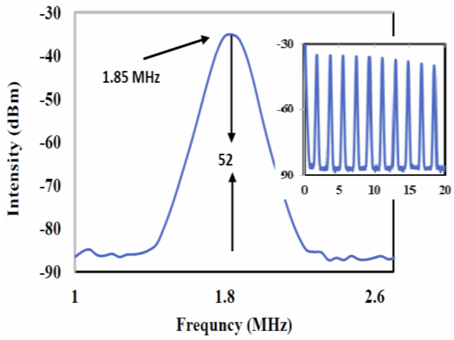


Fig. 5. RF spectrum of the mode-locked EDFL at 109 mW pump power

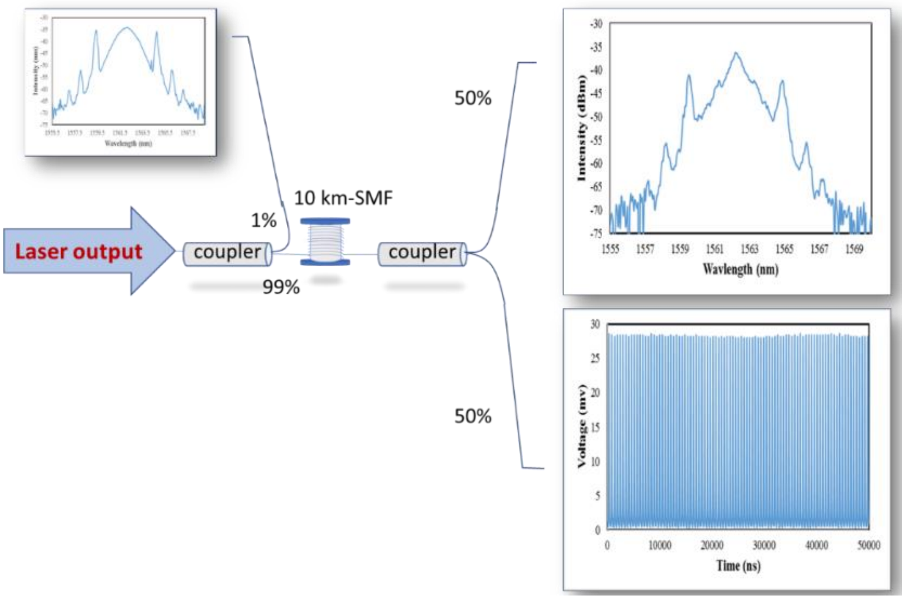


Fig. 6. The experimental setup and the results of the stability investigation using 10 km SMF

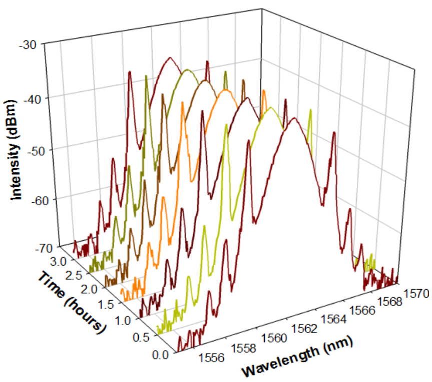


Fig. 7. The optical spectrum of the laser scanning at various periods of time

Also, in this work, we generated supercontinuum based on the proposed highly stable soliton mode locked fiber laser using graphene-SA. At first, we amplified the output of the laser to an average power of 23 dBm by using a commercial EDFA. Then the amplified ultrafast pulses were forwarded into an HNL-PCF with 100m length. Fig. 8 shows the supercontinuum spectrum with a range starting from 1300 nm to 1700 nm limited by the maximum range of the OSA.

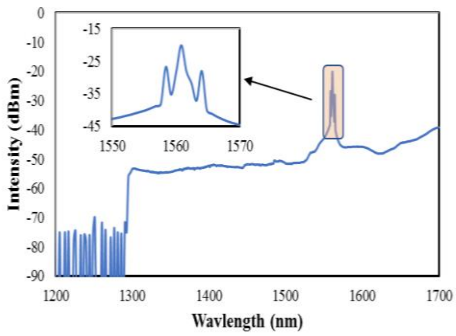


Fig. 8. The supercontinuum generation from the mode-locked laser

5. Conclusions

We used graphene-SA to construct a very stable soliton mode-locked EDFL operating at a central wavelength of 1562 nm with the fundamental frequency and pulse width of 1.85 MHz, and 2.24 ps, respectively. The maximum pulse energy and peak power of the laser were around 0.86 nJ and 363 W, respectively, at an average output power of 1.6 mW.

The stability of the generated pulses was also conformed after it being sent through 10 km SMF by observing the same soliton mode locked pulses with a little attenuation only. We also generated a supercontinuum with a range starting from 1.3 µm ending with the OSA limitation of 1.7 µm.

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