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Intracavity Optical Deposition of Graphene Saturable Absorber for Low-Threshold Passive Mode-Locking of a Fiber Laser *

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A compact, intracavity optical deposition of graphene saturable absorber (SA) for low-threshold passively mode-locked fiber laser is proposed and demonstrated. The optical deposition is implemented in the laser cavity by using a slot collimator. Utilizing the fabricated graphene SA, the fiber laser achieves self-starting, passively mode-locked operation at a low threshold of 32 mW pump power, delivering a 13.1-MHz 2.36-ps pulse train.

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Ultrashort pulsed fiber lasers have attracted much attention due to their wide applications in material processing, fiber sensing, biomedical research, and fiber optics communications.[1] Passive mode-locking is a technique that can be used to generate ultrashort pulse from a fiber laser. So far, different passive mode-locking techniques have been used for the mode-locked fiber lasers, such as the nonlinear polarization rotation,[2–5] the nonlinear amplifying loop mirror,[6,7] and the saturable absorber (SA).[8–10] Among them, the use of SA is regarded as a more efficient way to generate mode-locked pulse compared with the other two techniques. With the development of novel materials, the SA is fabricated with the materials evolving from semiconductor towards nanomaterials.

Recently, graphene, a single two-dimensional (2D) atomic layer of carbon atoms, has rapidly emerged as a novel material for fabricating SAs.[11,12] The graphene SA possesses many advantages such as wavelength-independent saturable absorbing characteristic, low saturable absorbing threshold, large modulation depth, and high damage threshold. With reference to fabricating a fiber pigtailed graphene SA, a major issue is how to fabricate a graphene SA that facilitates attaching graphene onto the fiber end. Heretofore, several methods have been proposed to fabricate nanomaterial (such as graphene and carbon nanotube) -based SA for pulsed operation of a fiber laser, such as polymer nanocomposite,[13,14] chemical vapor deposition,[15,16] self-assembly[17] and optical deposition.[18–23] Among them, the optical deposition provides a simpler approach to fabricating a graphene SA compared with the other techniques since the required equipment is conventional. However, using a conventional optical deposition method, an additional laser source should be used as input pump to deposit the graphene onto the fiber end facet. Furthermore, after deposition of graphene, the graphene SA needs to be inserted into the laser cavity to check the laser performance. This indicates that the optical deposition is generally implemented outside the laser cavity, which is un-beneficial for flexibly checking the laser performance based on the fabricated graphene SA. On the other hand, the mode-locking threshold of fiber laser based on the graphene SA using the optical deposition method is as high as ∼80 mW,[19] which is larger than that of using other types of SAs such as semiconductor saturable absorber mirror (SESAM) and carbon nanotubes (CNTs)-based SA. Therefore, it would be interesting to exploit a compact method to fabricate the graphene SA using the optical deposition method for low threshold mode-locked operation of a fiber laser.

In this Letter, we propose an intracavity method for optical deposition of graphene to achieve a low threshold, passively mode-locked fiber laser. The intracavity deposition is realized with a slot collimator. Due to the intracavity deposition design, the deposition of the graphene SA can be flexibly checked by making the two fiber ferrules close to each other in the slot collimator, which is favorable for examining whether the graphene-based mode-locking is achieved at a low threshold during the deposition process. With the fabricated graphene SA, the fiber laser achieves the passive mode-locking state at a low threshold of 32 mW pump power.

Figures 1(a) and 1(b) show the graphene-based passively mode-locked fiber laser and the photograph of the intracavity deposition using a slot collimator,

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respectively. A 5-m-long erbium-doped fiber (EDF) serves as the gain medium. A polarization controller is used to adjust the polarization state of lasing light. The unidirectional operation is ensured by a polarization-independent isolator. The output is taken by a 10% coupler. An optical spectrum analyzer (OSA) and an oscillograph are employed to record the laser spectrum and the output pulse train, respectively. Moreover, the pulse duration is measured by a commercial autocorrelator (FR-103XL).

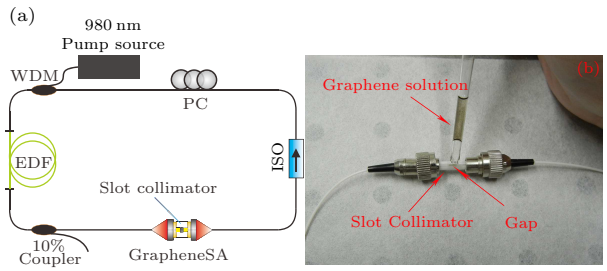


Fig. 1. (a) Schematic of passively mode-locked fiber ring laser based on graphene SA. (b) Photograph of setup for optical deposition using a slot collimator.

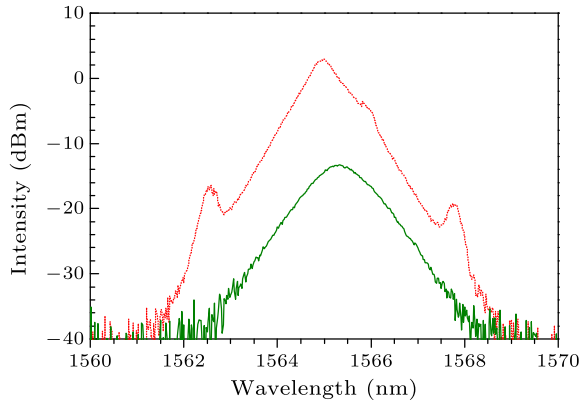


Fig. 2. Spectrum of mode-locked pulse at the pump power of 32 mW based on the fabricated graphene SA.

The intracavity optical deposition of graphene is integrated in the fiber ring laser with a slot collimator, as shown in Fig. 1(b). The gap between two fiber ferrules can be flexibly adjusted, which is about 1.5 mm in this experiment. The dimethylformamide (DMF) solution of graphene (0.1 mg/mL) is carefully dripped into the gap. Note that when the 980 nm pump power is increased to the lasing threshold, the intracavity optical deposition is carried out. Then the pump power is set to be 80 mW for optical deposition. As mentioned above, by pushing the two fiber ferrules close to each other in the slot collimator, we can flexibly check the laser performance during the deposition via increasing the pump power from 0 to about 100 mW again. Once the mode-locking pulse-train appears on the oscillograph, the 980 nm pump source is turned off to stop the optical deposition. If no pulse is shown, we could directly drip more graphene solution into the slot and repeat the deposition process described above. In this work, we find that the pulse-train appears at a low threshold of 32 mW. The deposition duration is about 25 min. After deposition, the graphene SA is evaporated at room temperature.

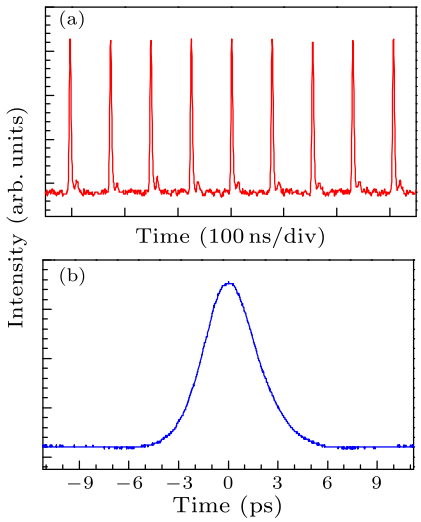


Fig. 3. (a) Mode-locked pulse-train and (b) the corresponding autocorrelation trace.

In the experiment, the cw lasing threshold is 28 mW. When the pump power is increased to 32 mW, the operation regime of the fiber laser converts from the cw lasing to the passive mode-locking operation. The mode-locked spectrum at the pump power of 32 mW is shown in Fig. 2 by the solid curve. As can be seen in Fig. 2, the central wavelength of the mode-locked pulse is 1565.3 nm with a 3-dB spectral bandwidth of 1.31 nm. Note that the soliton sidebands disappear on the mode-locked spectrum due to the low pump power. Therefore, when the pump power is further increased, the spectral sidebands could be generated as an indication of soliton operation, as shown in Fig. 2 by the red dotted curve.

The typical mode-locked pulse train is shown in Fig. 3(a). The pulse repetition is 13.1 MHz, as determined by the total cavity length. Correspondingly, we show the autocorrelation trace in Fig. 3(b). The pulse duration is measured to be 2.36 ps assuming a sech^2-pulse shape. Therefore, the time-bandwidth product is 0.378, indicating that the output pulse is slightly chirped.

In summary, we have proposed and demonstrated an intracavity deposition method using a slot collimator for the fabrication of graphene SA. With the fabricated graphene SA, a low threshold, passively mode-locked fiber laser is realized. At a relatively low pump power of 32 mW, the fiber laser achieves the self-starting mode-locked operation, delivering a 13.1-MHz 2.36-ps pulse-train. We expect to obtain shorter pulse

duration by further optimizing the quality of graphene SA and cavity dispersion.

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