Fabrication and application of a graphene polarizer with strong saturable absorption

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By transferring 100 nm gold-coated CVD monolayer graphene onto the well-polished surface of D-shaped fiber, we achieve a graphene in-line polarizer with a high polarization extinction ratio of ~27 dB and low insertion loss of 5 dB at 1550 nm, meanwhile achieving a strong saturable absorption effect of 14%. The manufacture of this graphene in-line polarizer also simplifies the graphene transfer process. To explore the potential applications of the new device, we also demonstrate noise-like pulse generation and supercontinuum spectrum generation. By launching the designed graphene device into a fiber ring laser cavity, 51 nm bandwidth noise-like pulse is obtained. Then, launching the high-power noise-like pulse into high nonlinear fiber, a 1000 nm wide supercontinuum spectrum is obtained, which is favorable for sensing and nonlinearities scientific fields.

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1. INTRODUCTION

Graphene has shown its outstanding performance as a saturable absorber (SA) in mode-locked fiber lasers, which is attributed to its wavelength-independent saturable absorption, easy combination with fiber, and low cost fabrication. Soliton [1–4], stretched pulse [5], and dissipative soliton [6], which are three main types of pulse in mode-locked fiber lasers, have been generated using a graphene-based SA. Besides, a graphene-based in-line fiber polarizer is also an attractive research interest [7]. A graphene in-line polarizer based on side-polished D-shaped fiber with a 27 dB polarization extinction ratio in the telecommunication band has been demonstrated by the strong *s*-polarization effect of graphene. However, the saturable absorption effect of the sample is not characterized. Thus, we reach a conclusion that a fine designed graphene fiber device can act as an SA and an in-line polarizer.

We propose to transfer a gold-coated chemical vapor deposition (CVD) monolayer graphene onto a moderate-polished D-shaped fiber to achieve a graphene based in-line polarizer and SA. First, by decreasing the polish depth to 6 um to the core center, the insertion loss (IL) of the D-shaped fiber itself is reduced to about 8 dB; meanwhile, the polarization dependent loss (PDL) is only 1 dB. Then, by transferring a 100 nm thick gold-coated graphene layer onto the polished surface of the D-shaped fiber, the IL is reduced to 5 dB and the PDL is increased to ~27 dB; meanwhile, the saturable absorption depth is measured to be 14%. The benefits of the solution are summarized as follows: (1) the IL of the graphene device is greatly decreased; (2) the PDL of the component is increased; (3) the in-line graphene polarizer shows strong saturable absorption effect due to the confinement of the optical field by metal cover; (4) the graphene transfer process is simplified, and the reliability of the component is also improved because no polymethyl methacrylate (PMMA) or resolvable stamp is used as in the traditional graphene transfer process.

For seeking the potential application in optical systems, we demonstrate the noise-like pulse generation using the graphene-based polarizer and SA as a multifunctional mode-locker. Besides, a demonstration of 1000 nm wide supercontinuum (SC) generation is shown by the noise-like pulse we have achieved. We hope that the new polarizing graphene SA could play versatile roles in optics fields.

2. FABRICATION OF THE DEVICE

A. Graphene Mode-Locker Fabrication and Characterization

D-shape fiber fabrication: We bent the single-mode fiber (SMF) and embedded it into a glass substrate; then, we polished the glass substrate with a resolution of 1 μm. This process ensures the polished surface is ultraflat. We monitor the IL of the D-shaped fiber to ensure a value less than 10 dB during the polishing process. The fabricated D-shaped fiber is with a polished depth of 6 μm to the core center and polished length of about 1 cm, corresponding to the IL of ~8 dB. The radius of curvature is long enough to not achieve the cut-off boundary of TE_0 mode near 1550 nm wavelength, and the disclosing part is called the evanescent field. With the graphene layer coated, the evanescent field is enhanced because of the graphene absorption. With the graphene/gold layer coated, the evanescent field becomes moderate because no $C + L$ band light beam will propagate in a gold layer, the mode distribution is suppressed in the fiber and the graphene layer; thus, the loss decreases. The side-view and cross-section of the D-shaped fiber are showed in Figs. 1(a) and 1(b), respectively. Figure 2(a)

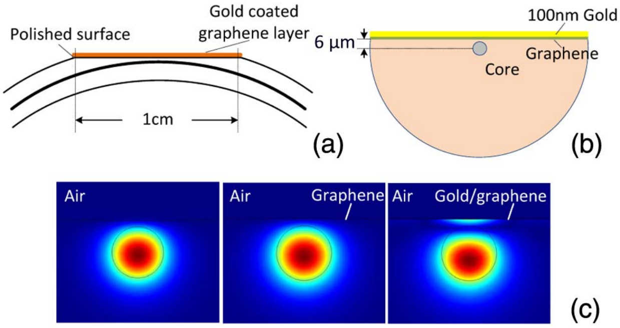

Fig. 1. (a) Side-view, (b) cross-section, and (c) mode-distribution simulation of gold-coated graphene mode-locker.

shows the curve of IL of the polished fiber versus the polished depth. We can see that, if we polished the SMF to the core, the IL increased dramatically.

Gold-coated graphene fabrication and transfer: The monolayer graphene is grown on 25 μm copper foil using a CVD method, after being characterized by Raman spectroscopy and then deposited on 100 nm thick gold film on the high-quality graphene using thermal evaporation for providing stable mechanical support during transfer process. The Raman spectrum of the CVD monolayer graphene on Cu foil is shown in Fig. 2(b), and we can judge from the narrow 2D peak and very weak D peak that the graphene is monolayer and with high quality and few defects. In the traditional graphene transfer progress, an additional layer such as PMMA, resolvable stamp, or other material is coated on the graphene layer to provide mechanical support. Further, the supporting layers need to be removed after the graphene is transferred on the substrate, but there are always some residuals on the graphene even after several cleaning processes, which will affect the performance of graphene. However, we intentionally keep the gold cover after the transfer process to make the graphene component as an in-line polarizer with high PDL and low IL. Thus, the graphene transfer process is simplified, and the device is more reliable. The transfer process is as follows: cut off a piece of gold-coated graphene and put it on the surface of 0.5 mol/L $FeCl_3$ solution; etch the Cu foil away in about 3 h; after the etching step, transfer the gold-graphene layer into deionized water (DI water) using ultrasonic processed silicon wafer as substrate to clean the residual $FeCl_3$ in 10 min and repeat the DI rinsing step three times; clean the D-shaped fiber, especially the polished surface, with alcohol or using ultrasonic processing [8], and then transfer the gold-coated graphene layer onto the polished area of the D-shaped fiber; finally, dry the gold graphene-covered D-shaped fiber in air to ensure that gold graphene layer adheres onto the polished surface firmly.

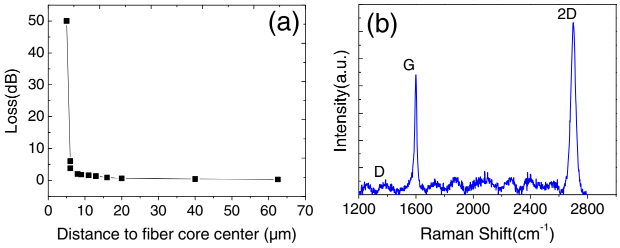

Fig. 2. (a) IL of polished fiber versus polished depth. (b) Raman spectrum of CVD monolayer graphene on Cu foil.

The cross-section mode distribution of D-shaped fiber is shown in Fig. 1(c) (simulated using the Wave Optics module of COMSOL), where we set refractive indexes of fiber core, cladding, graphene, gold as 1.468, 1.462, $2.1356 + 1.891 * i$ [9], and $0.58 + 9.81 * i$ [10], respectively. In Fig. 1(c), we can see that the surface polariton supported by the metal surface, being of the TM type, interacts with the TM-guided mode of the dielectric (fiber cladding) film through the evanescent field. As a consequence, in a short interaction length TM-guided mode of the fiber cladding is completely absorbed, whereas the TE mode is transmitted through the interaction region without significant absorption. That is to say power in the TM-like polarized HE_{11} mode of the fiber will be transferred completely to the surface polariton on the metal surface, where it is eventually absorbed [11]. It is obvious that the coupling between TM mode and surface plasmon wave is enhanced, which means the PDL of the graphene component is increased.

Graphene mode-locker (GML) characterization: We characterized the new designed device (here called GML) with IL, PDL, and saturable absorption depth. The PDL/IL and saturable absorption test setup are shown in Figs. 3(a) and 3(b) separately. The results are shown in Fig. 4.

The IL and PDL of the D-shaped fiber before graphene transfer are ~8.75 and ~1 dB at 1550 nm. After the monolayer graphene is transferred, the IL and PDL are increased to ~14 and ~2.2 dB at 1550 nm. The IL increase is originated from the graphene absorption. We assume the IL peak at 1548 nm origins from the absorption of the PMMA residuals in the traditional graphene transfer process. The PDL is not obviously increased because the fiber is not deeply polished; therefore, the evanescent field interaction with the graphene is not strong. And, after the gold-coated graphene is transferred, the IL and PDL become ~5.1 and ~26.5 dB near 1550 nm. Compared with the pure graphene-covered D-shaped fiber, the gold graphene-covered D-shaped fiber shows much lower IL and much higher PDL, which are attributed to the confinement of the TE mode and the strong attenuation of the TM mode by the metal surface.

The measurement results above proved that our design is effective, and the GML with gold coating could serve as a polarizer with low IL. The saturable absorption curve (SAC) of the GML is measured with a homemade graphene-based mode-locked fiber laser with 303 fs pulse width, 12 nJ pulse energy, and 34 mW average power [12]. The measurement method is similar with [1]. The SAC is shown in Fig. 4(c). The blue circles show the measured IL of the GML with gold coating versus the input pulses with different average power

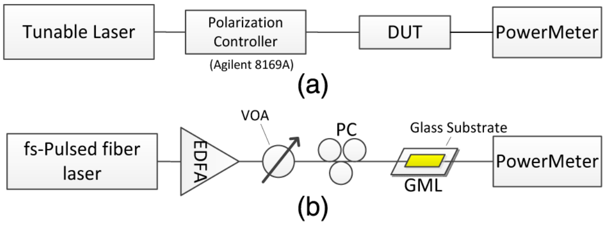

Fig. 3. (a) PDL/IL test setup for D-shaped fibers with gold-coated graphene and without graphene. Polarization controller, Agilent 8169A; DUT, device under test. (b) Saturable absorption test setup. VOA, variable optical attenuator; PC, polarization controller (three paddles).

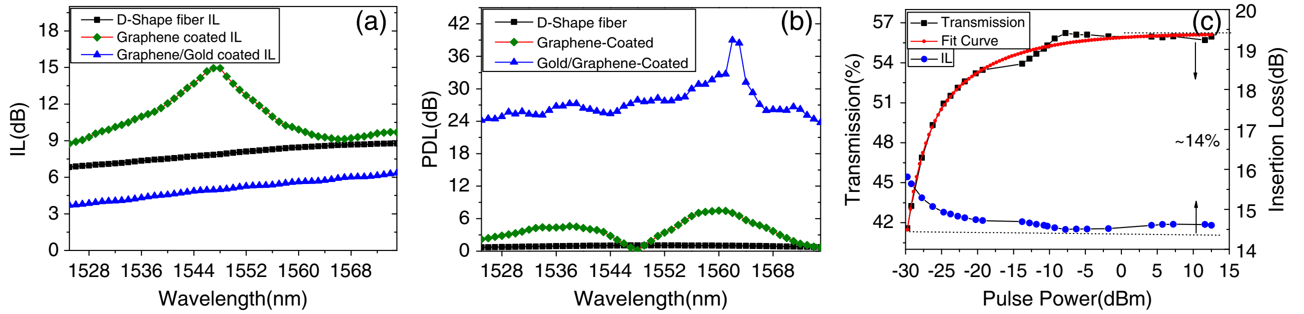

Fig. 4. (a) ILs of D-shaped fibers of different types. Blue triangles for graphene/gold coated, olive diamonds for graphene coated, and black squares for without coating. (b) PDLs. Blue triangles for graphene/gold coated, olive diamonds for graphene coated, and black squares for without coating. (c) SAC: normalized transmission (black rectangle dash line) and its fitting curve (red dash line); IL versus pulse power (blue circles).

P_{av}. The IL changes 1.2 dB as the pulse power varies. The transmission T of the GML can be expressed as

$$T(P_{\mathrm{av}}) = 10^{-\mathrm{IL}(P_{\mathrm{av}})}\cdot 100\%. \tag{1}$$

Due to the large IL of the GML at a specific input polarization state, T is always very small and changes no more than 1%. Then, we normalized T (line with black circle) and fitted normalized T with red dashed line. The corresponding modulation depth is 14%. This is the first time to simultaneously characterize the IL, PDL, and SAC of the D-shaped fiber-based GML. As we can see from the characterization above, the newly designed GML can truly be treated as polarizer and SA.

3. APPLICATIONS OF THE DEVICE

For applications such as optical coherence tomography, optical coherence radar, and fiber optical sensing systems, high power and super broadband optical sources are required. The noise-like pulses are suitable for these applications attributed to its smooth and ultrawide spectrum, high power, and low coherence [13–15]. However, until now there are seldom noise-like pulse demonstrations using graphene. In most of the previous noise-like pulse generation schemes [13–15], a polarization-dependent isolator (PD-ISO) combined with the nonlinear polarization rotation (NPR) effect of fiber are used to generate ultrashort pulses, and another polarizer is required to shape the pulse into a noise-like regime [16]. Though the noise-like scheme has not been studied thoroughly, the extra polarizer, except for the mode-locker acting as pulse shaper, is necessary during the noise-like pulse generation. Thus, our designed graphene in-line polarizer and SA is a good choice for noise-like pulse generation, where the saturable absorption characteristic is used to generate the ultrashort pulse, and the strong polarizing effect is used to shape the pulse into a noise-like regime. To achieve noise-like pulses, we insert the GML with gold coating into the fiber ring laser. The fiber laser configuration is like a traditional passive mode-locked fiber laser setup, as shown in Fig. 5, where the erbium-doped fiber (EDF) length is 18 m with group velocity dispersion (GVD) of –38 ps/nm/km. The total cavity length is 28.8 m, including the fiber pigtail. The EDF is forward pumped by a 975 nm laser diode through a fused fiber wavelength division multiplexer. A polarization controller is used to optimize the polarization state of the laser cavity. Though the spectrum width of the noise-like pulse is related with the total dispersion in the cavity, we have not optimized the cavity dispersion to achieve the widest spectrum of the noise-like pulse because our objective is just to prove the designed graphene polarizer and SA are suitable for noise-like pulse generation. In this fiber laser, the GML plays two roles: an SA to start the ultrashort pulse generation as a mode-locker and a polarizer to shape the pulse into a noise-like pulse train [16].

By adjusting the polarization state in the cavity, we can achieve a noise-like pulse with different spectrum width. The pump threshold for the mode-locking is 70 mW, and the spectrum bandwidth does not change when we increased the pump power above the threshold. Figure 6 shows the 3 dB spectral bandwidth evolution from 18 to 51 nm when we adjust the polarization state in the laser cavity at the fixed

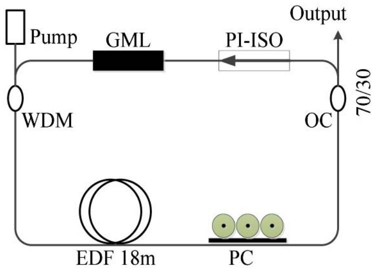

Fig. 5. Laser setup. OC, 70/30 optical coupler (30% for output); PI-ISO, polarization independent isolator.

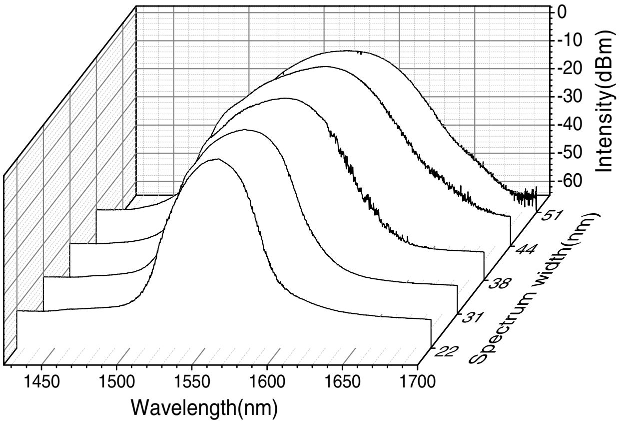

Fig. 6. Noise-like pulse spectrum evolution.

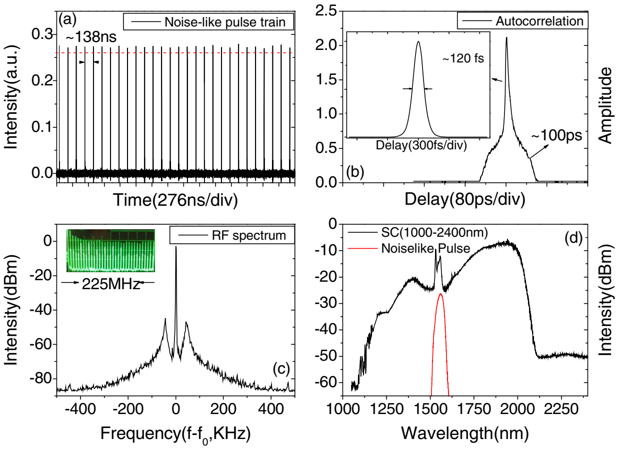

Fig. 7. Noise-like pulse measurement in time and frequency domain and SC generation spectrum: (a) pulse train in time domain; (b) autocorrelation trace; (c) radio frequency spectrum in frequency domain; (d) SC generation from the noise-like pulse.

pump power of 500 mW. Observing the spectrum evolution, it is not difficult to see that the spectrum is broadened to a long wavelength as a result of Raman self-frequency shift [14].

The generation of noise-like pulse in the fiber laser is explained in different ways. In our case, the generation of a noise-like pulse train should be the combination effects of polarizing and nonlinear effect such as four wave mixing in the GML [17]. In Fig. 7, we show the pulse train in time domain in Fig. 7(a), autocorrelation trace in Fig. 7(b), and radio frequency spectrum in frequency domain in Fig. 7(c). The pulse train amplitude is with fluctuations, and the pulse interval is 138 ns corresponding to a repetition rate of 7.238 MHz. As we can see, the trace consists of a wide pedal with 100 ps width measured by an autocorrelator and a narrow peak with 120 fs width measured by frequency-resolved optical gating as the inset shows. That indicates the noise-like pulse is the bunch of the coherent part of an ultrashort pulse and random noise. There are two obvious sidelobes on the frequency spectrum, as shown in Fig. 7(c), and the signal-to-noise ratio is only about 45 dB, which is due to the inherent instability for the noise-like operation. Both the pulse energy and the peak power of the ultrafast (fs) coherent part in noise-like pulses are much higher than that of other types of soliton. Besides, its smooth and super-wide spectrum is also a good seeding source for SC spectrum generation.

We demonstrate a super-wide SC generation by seeding the noise-like pulse with 52 mW average power, corresponding to a pulse energy of 7.2 nJ, into 500 m high nonlinearity fiber ([HNLF], with effective area of 12.4 μm^2 and nonlinear coefficient of 10.8 $W^{-1} \cdot km^{-1}$) after being boosted to 21.3 dBm. The SC spectrum covers the wavelength region from 1100 to 2100 nm, as shown in Fig. 7(d), which will be useful for optical sensor and optical coherence tomography.

4. CONCLUSIONS

We fabricated a graphene device by transferring 100 nm gold-coated monolayer graphene onto D-shaped fiber, which has a saturable absorption characteristic as an SA for mode-locking and large PDL, low IL as an in-line polarizer for pulse shaping into a noise-like region. We simulate the mode distribution of the newly made graphene device and characterized it with IL/PDL, SAC, and modulation depth. Based on such a device, we achieved a 51 nm wide noise-like pulse with 7.2 nJ pulse energy with simplified configuration. Finally, about 1000 nm SC generation is obtained by launching the noise-like pulse trains into HNLF, which will be useful for optical sensor and optical coherence tomography applications.

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