Fabrication and applications of a Graphene polarizer with strong saturable absorption

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Abstract: By transferring 100-nm gold coated CVD monolayer graphene onto the well-polished surface of D-shape fiber, we achieved a graphene in-line polarizer with high polarization extinction ratio of 27 dB, low insertion loss of 5 dB@1550nm and strong saturable absorption effect of 14%. To explore the potential applications of the dual-functional device, we demonstrate ultra-short pulse generation using the graphene device.
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1. Introduction

High-energy and high-peak-power ultra-short optical pulse has widespread applications in nonlinear optical processing, micro-machining and medical surgery fields, which has attracted much attention. Passive mode-locking in fiber laser is a main way to generate such kind of pulses. Graphene has been widely used in passively mode-locked fiber laser as the mode-locker due to its outstanding saturable absorption performance [1, 2]. Graphene saturable absorber could be achieved by transfer Graphene sample, made with oxidation reduction process, mechanically exfoliation or CVD method, to the fiber end, polished surface of D-shape fiber or the taped fiber waist. Generally speaking, graphene interacted with the evanescent field is preferred due to its longer interaction length compared to the injection case. CVD monolayer graphene has very large film size and high crystal quality, which makes it suitable for pulse generation applications. However, it is difficult to reliably transfer CVD graphene from metal substrate to the application substrate without damaging the fragile patchwork or leaving undesired residues such as PMMA or thermal release tape on the graphene surface. Such polymer residues are strong heat absorbers which would cause damage of graphene in high-energy pulse laser. So the ideal graphene transfer method requires stable mechanical support and no unnecessary residues to prevent graphene from being damaged by high energy pulse. Gold film has been used as stamp or protecting layer during the transfer of graphene/carbon nanotubes (CNT) in preparation of Si-substrate components [3], which proved that gold is a good mechanical support in graphene/CNT transfer process.

In this paper, we also used gold as a mechanical support when transferring graphene onto the polished surface of D-shape fiber as a saturable absorber, but unlike the previous work, where the gold layer was removed after supporting the transfer, we kept the gold layer for four reasons: 1) increase the polarizing effect of the device to make it a polarizer, 2) decrease the insertion loss of the polarizer in that gold film can confine the evanescent field, 3) enhance the light-graphene interaction to improve the saturable absorption, 4) simply the transfer process. By inserting such a dual-functional graphene mode locker (GML) into an Erbium-doped fiber laser as both a slow and artificial fast saturable absorber for mode-locking, an ultrafast pulse with 13.65-nJ energy, 51-kW peak power and 263-fs pulse width has been achieved. The laser is quite stable and easy to start mode-locking for the dual mode-locking scheme in the newly made graphene mode locker. Both the energy and peak power are quite high values among graphene-based Erbium-doped passively mode-locked all-fiber lasers, which are very promising in nonlinear optical processing applications.

2. Fabrication and characterization of the graphene device

We coated a 100-nm gold film on graphene rather than PMMA or release tape to provide mechanical support for large sheet of CVD graphene. The gold coated graphene fabrication process is as bellows: (1) Grow monolayer graphene on Cu foil by CVD method; (2) Graphene detection and characterization using Raman spectroscopy; (3) Coat 100-nm thick gold film on graphene by thermal evaporation. Fig. 1 shows the Raman spectrum of CVD monolayer graphene on Cu foil and we can judge from the narrow 2D peak and very weak D peak that the graphene is monolayer and with high quality and very few defects [4]. The length of the polished area of D-shape fiber was around 2 cm. To enhance the light-graphene interaction, the D-shape fiber was deeply polished to increase the interaction area where the polished surface was 6 um away from the fiber core center and the insertion loss of the D-shape fiber without graphene was measured to be 8 dB.

After the D-shape fiber was made, we transfer the gold-coated graphene onto the polished surface. The whole process is as follows: (1) Cut off a piece of gold-coated graphene and put it on the surface of 0.5mol/L $FeCl_3$ solution; (2) Etch the Cu foil away in about 3 hours; (3) 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 mins and repeat the DI-rinsing-step 3 times. (4) Clean the D-shaped fiber especially the polished surface with alcohol or using ultrasonic processing, and then transfer the gold-coated graphene layer onto the polished area of the D-shape fiber. (5) Finally, dry the gold-graphene covered D-shape fiber in air to ensure that gold-graphene layer adheres onto the polished surface firmly. The schematic side view of the gold-graphene covered D-shape fiber is shown in Fig. 2 (a). Fig.2 (e) shows the picture of the made graphene saturable absorber.

After the dual-functional graphene mode locker was fabricated, we measured the IL, polarization dependent loss(PDL) and modulation depth of the device. The decreased insertion loss of D-shape fiber with graphene/gold layer was 3 dB (from 8 dB to 5 dB). The one with graphene/PMMA layer in our previous work increased the IL to 13 dB (the bare D-shape fiber was 8dB@1550nm). The PDL was as high as 27dB@1550nm measured by electrical polarization controller and super band tunable laser source. And at the same time, we also measured the saturable absorption curve of the device by a home-made fs-pulse laser source using the same method in [1]. The modulation depth is 14%, which showed strong saturable absorption character. The measurement results further proved it was the gold film that confined the evanescent field to decrease the incremental insertion loss of GML.

The gold film made the polished fiber a polarizer, which was demonstrated in [5]. The TM mode converted surface wave was completely absorbed in a short interaction length whereas the TE mode was transmitted through the interaction region without significant absorption. So the attenuation difference of different polarization appeared. Except for the strong polarization effect, the gold film confined the evanescent field and decreased the insertion loss of the fiber device. To demonstrate the evanescent field intensity on the polished surface of D-shape fiber could be enhanced by the gold film, we first made a simulation of mode analysis using COMSOL software. Light field distributions of D-shape fiber with and without graphene/gold coating were simulated separately. Fig. 3 shows the electric field distribution of D-shape fibers in different coating cases: (a) single layer graphene and 100-nm gold coated; (b) without coating; (c) single layer graphene coated; (d) 100-nm gold coated. And it is obvious that electric field was significantly enhanced on the polished surface when the D-shape fiber was coated with gold film. The higher the electric filed intensity on the polished surface, the stronger the light-graphene interaction of the graphene mode-locker, which induced stronger saturable absorption. Simulation conditions: refractive indexes of fiber core, cladding, graphene, gold were 1.468, 1.462, 2.1356+1.891*i [7] and 0.58+9.81*i respectively.

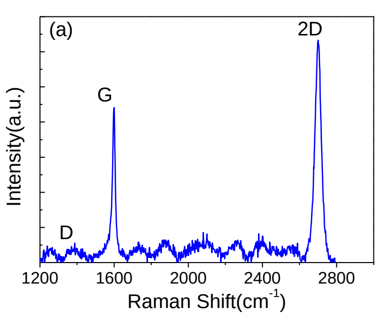

Fig. 1 Raman spectrum of monolayer graphene on Cu foil

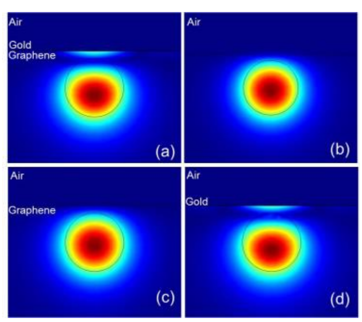

Fig. 2 Electric field distribution of different coated D-shape fibers

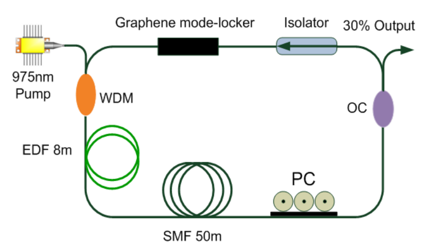

Fig. 3 The experiment setup of the fiber laser

3. Ultra-short pulse generation

By connecting the gold-graphene covered D-shape fiber into an Erbium-doped fiber laser, passively mode-locking can be achieved. The configuration of the fiber laser is shown in Fig. 3, where the Erbium-doped fiber (EDF) length was 8 m with group velocity dispersion (GVD) of -38 ps/nm/km, and the single mode fiber (SMF) length was 50 m with a GVD of 17 ps/nm/km. The total cavity length was 73 m including the fiber pigtail. The EDF was forward pumped by a 975-nm laser diode through a fused fiber wavelength-division-multiplexer (WDM). A polarization-independent isolator (ISO) was used to force the unidirectional transmission of the laser. A polarization controller (PC) was used to optimize the polarization state of the laser cavity. The 30% port of a 30/70 optical coupler (OC) was used to export the high energy pulse.

By optimizing the polarization state in the cavity, the mode-locking operation can be achieved. After achieving the mode-locked state judging from the optical spectrum analyzer (OSA), we slightly adjusted the polarization state to optimize mode-locking performance. The optical spectrum of the mode-locked fiber laser is shown in Fig. 4. The full width at half magnitude (FWHM) of the mode-locked pulse spectrum was 16.4 nm and the central wavelength was 1560 nm. There was no Kelly side band observed in the optical spectrum even the net cavity dispersion is negative.

From the real-time low-speed oscilloscope we can know that the pulse interval was 350 ns (with repetition of ~2.85 MHz), corresponding to the total ring cavity length of 73 meters. The measured output pulse train and autocorrelation trace of the femtosecond pulse using autocorrelator are shown in Fig. 5, where the black circle curve represents the measured autocorrelation trace of the pulse and we can see that the trace fit well with the Gaussian curve. The calculated FWHM of the pulse is 263 fs where the FWHM of the autocorrelation trace is 372 fs and the de-convolution factor is 1.414 for Gaussian pulse. The measured time bandwidth product was 0.539, indicating that the pulse was chirped and there is room to compress the pulse to achieve shorter pulse.

For the maximal available pump power of 610 mW, the output power was around 39 mW, corresponding to around 6.4% conversion efficiency. There was no pulse breaking observed until the pump power was increased to 610 mW. Pulse stability is important for applications and was characterized from radio-frequency (RF) spectrum of the mode-locked fiber laser [23]. In Fig. 6, The RF spectrum is with a span of 45 kHz and a resolution of 300 Hz. The measured fundamental peak to pedestal extinction was as high as 69 dB, indicating low-amplitude fluctuations of our laser. The inset of Fig. 6 showed the RF spectrum range up to 200 MHz. The fiber laser can work stably for more than 10 hours and still be in mode-locked state even when we turn off and on the pump, which also proved the stability of our made GML.

The calculated pulse energy and peak power are 13.65 nJ and 51 kW respectively, which are the highest values until now for graphene-based Erbium-doped passively mode-locked all-fiber lasers. The laser was quite easy to realize mode-locked state for the dual-functional mode locker: the graphene layer acted as slow saturable absorber to start the NPR effect mode-locking and the home-made polarizer acted as artificial fast saturable absorber to ensure the quality of the pulse. The advantages of dual mode-locking were demonstrated in [7].

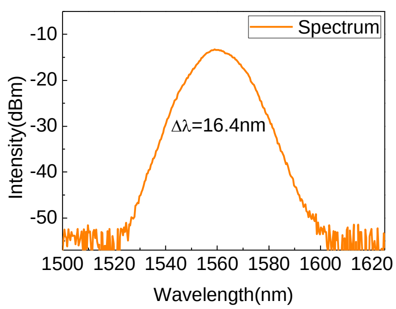

Fig. 4 Optical spectrum of the graphene based fiber laser

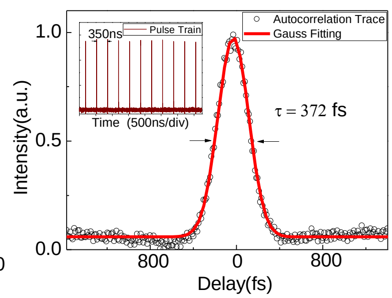

Fig. 5 Autocorrelation trace of the femtosecond pulse

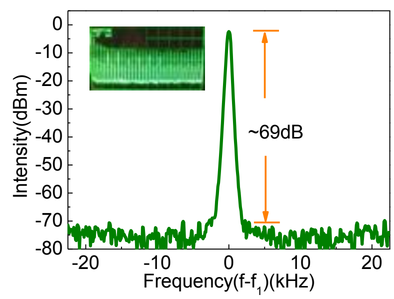

Fig. 6 The RF spectrum of the graphene based femtosecond fiber laser with 300-Hz resolution.

4. Conclusion

We transferred 100nm gold-coated graphene layer onto well-polished surface of D-shape fiber and achieved a polarizer with 14% saturable absorption. Using the newly made GML as a dual functional mode locker, high quality pulse with 13.65 nJ energy and 51 kW peak power was generated. Besides, the fiber laser was quite easy to start mode locking and super stable. The proposed fiber laser is believed to have promising applications in nonlinear optical processing and other scientific research fields.

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