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Nanosecond pulse generation in a graphene mode-locked erbium-doped fiber laser

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ABSTRACT

We demonstrate a mode-locked nanosecond erbium-doped fiber laser (EDFL) using a graphene-based saturable absorber (SA). The laser directly produces nanosecond pulses with pulse duration of 24 ns, repetition rate of 5.78 MHz and central wavelength of 1569.5 nm. The mode-locking is self-starting and the pulse train has no transient effects or signs of Q-switched behavior. The formation mechanism of nanosecond pulses emitted from the laser could be attributed to the pulse duration broadening induced by the large lumped normal dispersion of the graphene SA. Such nanosecond pulse duration as well as megahertz repetition rate makes this mode-locked all-fiber laser a suitable seed oscillator for chirped pulse amplifications and high-power applications.

1. Introduction

Passively mode-locked fiber lasers have been extensively investigated for the generation of ultrashort pulses, which have a wide range of practical applications in optical communication, metrology, medicine, and material processing, etc. [1–3]. Various techniques, e.g. the nonlinear-optical loop mirror, nonlinear polarization rotation (NPR), semiconductor saturable absorption mirrors (SESAMs), and carbon-nanotube saturable absorbers, have been employed in ultrashort-pulse fiber lasers for passive mode locking. Recently, graphene-based passively mode-locked fiber lasers have attracted considerable attention. Compared with SESAMs or single-wall carbon nanotubes (SWNTs), graphene as a saturable absorber (SA) has significant advantages, including high damage threshold, ultrafast recovery time, controllable modulation depth, and ultrabroad wavelength-independent saturable-absorption range [4]. Following the first demonstrations of graphene-based mode-locking in fiber lasers [5,6], several graphene mode-locked fiber lasers with different cavity dispersion conditions have been demonstrated [7–10]. Most of the reports were focused on ultrafast fiber lasers that emitted femtosecond and picosecod pulses.

Usually nanosecond pulses emitted from mode-locked fiber lasers are giant-chirped and have large duration and low peak power, which may induce little nonlinear phase accumulation during amplification. Therefore, a nanosecond pulsed EDFL is preferred as a better alternative seed oscillator than a femtosecond or picosecod pulsed one for chirped pulse amplification (CPA) and average power scaling systems. Recently, long-cavity mode-locked fiber lasers have attracted significant interests for the potential of producing nanosecond pulses in normal and anomalous dispersion regimes [11–14]. Wu et al. reported on the generation of nanosecond pulses directly from a mode-locked erbium-doped fiber laser (EDFL) with NPR technique [12]. The laser has a ring cavity with 163.2 m length and the generated nanosecond pulse has a pulse duration of 18.5 ns. By inserting a piece of 1200 m passive fiber into a laser cavity, Kelleher et al. demonstrated the direct generation of highly chirped 2 ns pulses in an all normally dispersive ytterbium-doped fiber laser mode-locked with a SWNT-based SA [13]. Moreover, Xu et al. reported a graphene mode-locked nanosecond EDFL producing laser pulses ranging from 3 ns to 20 ns by changing the laser cavity length from 133 to 1027 m [14]. The kilometer long cavity length, however, lowers the fundamental repetition rate of the laser to 100 kHz. Usually such low repetition rates are not desirable in applications of laser material processing, medical treatment and scientific researches. However, mode-locked fiber lasers directly producing nanosecond pulses with a megahertz repetition rate have not yet been fully explored.

In this paper, we demonstrate a mode-locked nanosecond EDFL at the fundamental repetition rate of 5.78 MHz using a graphene-based SA. The stable pulse is highly chirped with the pulse duration of 24 ns and 3 dB spectral bandwidth of 0.96 nm at the central wavelength of 1569.5 nm. The formation mechanism of

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nanosecond pulses emitted from the laser is discussed. The laser demonstrates an additional advantage of producing desired nanosecond pulses with a megahertz repetition rate, which makes this mode-locked all-fiber laser a suitable seed oscillator for chirped pulse amplifications and high-power applications.

2. Experimental setup

The experimental setup of our proposed graphene mode-locked EDFL is schematically shown in Fig. 1. It has a ring configuration and the total cavity length is approximately 35.8 m. A segment of 4.0 m erbium doped fiber (EDF, CorActive) with group velocity dispersion (GVD) parameter of −20 ps/(nm km) was employed as the gain fiber. The rest of the ring was made of standard single mode fiber (SMF), whose GVD parameter was 18 ps/(nm km). A polarization-insensitive isolator (ISO) was spliced in the cavity to ensure unidirectional operation of the laser and a polarization controller (PC) was used to fine tune the linear cavity birefringence. The laser was pumped by a commercial 980 nm laser diode (LD) through a wavelength division multiplexer (WDM). A 10% fiber coupler was used to output the signals. A assembled graphene-based SA as a passive mode-locker was placed before the optical coupler. All the components used in the cavity are polarization independent. The laser output performance was simultaneously observed using an optical spectrum analyzer (Yokogawa AQ6370C), a 500 MHz digital oscilloscope (Tektronix TDS3052C) together with a 10 GHz photodetector, and an 8 GHz radio-frequency (RF) spectrum analyzer (Advantest R3267).

The monolayer graphene film was grown on Cu foil by chemical vapor deposition (CVD) method, similar to that reported in Ref. [15]. The surface of the graphene on Cu was spin-coated with poly (methyl methacrylate) (PMMA), and the PMMA/graphene/Cu foil was baked on a hot plate at 100 °C for 3 min and then 120 °C for 5 min. Then the Cu foil was etched in an aqueous solution of 10 wt% $Fe(NO_3)_3$. After the Cu foil was completely etched, the PMMA/graphene was washed in DI water several times to remove Fe^{3+} and NO_3^-. The PMMA/graphene was transferred onto the end-face of a fiber connector, and the PMMA layer was removed by the acetone vapor. The transfer process was repeated 4 times to obtain 4-monolayer graphene onto the end-face of a fiber connector to form a graphene-based SA. The linear insertion loss of our graphene SA is about 1.5 dB. Raman spectroscopy was used to check the quality of graphene. Fig. 2 shows a typical Raman shift of the CVD-grown graphene transferred onto a 300 nm SiO_2/Si substrate. It has two bands located at ~1584 cm^{-1} (G peak) and ~2689 cm^{-1} (2D peak). The 2D band is much stronger than the G band and the 2D-to-G intensity ratio (I_{2D}/I_G) is ~2.4. In addition, the relatively

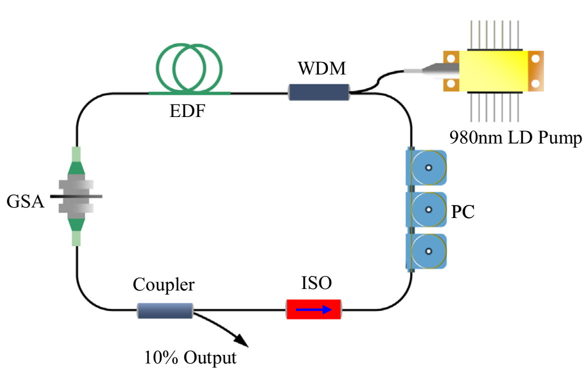

Fig. 1. Experimental setup of the proposed graphene mode-locked EDFL. 980 nm LD Pump: 980 nm diode laser pump source, WDM: 980/1550 nm wavelength division multiplexer, EDF: erbium-doped fiber, ISO: isolator, PC: polarization controller, and GSA: graphene-based saturable absorber.

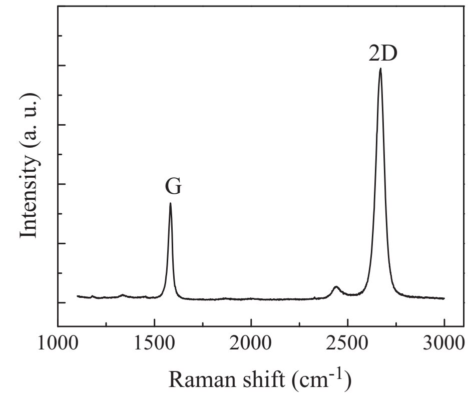

Fig. 2. Raman spectrum of the CVD-graphene transferred onto a 300 nm SiO_2/Si substrate.

weak D band at ~1350 cm^{-1} is below the Raman detection limit, indicating a low density of defects of the CVD-graphene. These observations show that the as-produced graphene has very high crystalline quality.

3. Experimental results and discussion

In this experiment, the continuous-wave (CW) operation of the proposed EDFL started at a pump power of ~70 mW. The relatively high threshold of CW operation could be attributed to large inserting loss of the assembled graphene SA. When the pump power was increased to ~93 mW, the stable pulse train was achieved with appropriate adjustment on the PC. Slightly reducing the pump power to ~87.3 mW, the pulse train remained stable. Fig. 3 shows the output characteristics of the pulsed laser. As shown in Fig. 3(a), the pulse repeats every 173 ns, matching exactly with the cavity length of 35.8 m. Experimentally, we found that the pulse repetition rate was kept to be 5.78 MHz when adjusting the value of pump power from 87.3 to 260 mW. Increasing or decreasing pump power could not destroy the pulsed state. This confirms that the laser operation is fundamental mode-locking rather than Q-switching, as the pulse repetition rate of Q-switched fiber lasers can be widely changed by increasing the pump power [16,17]. Moreover, no transient effects was observed on the oscilloscope trace of the pulse train with wide time span, indicating that the pulse train is stable and the mode-locked operation has no signs of Q-switched mode-locking behavior. Fig. 3(b) shows a nanosecond-scale single-pulse profile. The optical spectrum is shown in Fig. 3(c). The spectrum is centered at 1569.5 nm and the spectral width (FWHM) is 0.96 nm. The average output power was measured to be 12.1 mW under the maximum pump power of 260 mW, corresponding to the pulse energy of 2.1 nJ. To assure that there is no NPR effect in our laser, we have checked the laser operation by removing the graphene-based SA from the cavity. In this case, no mode locking was observed in the laser. Therefore, the mode locking obtained in our graphene-based fiber laser should be attributed to the saturable absorption of graphene in the cavity.

In order to check whether the observed mode-locked operation is a real single-pulse state, we have further measured the output pulses with a high resolution detection system (a 45 GHz photodetector, New Focus 1014, and a 40 GHz sampling oscilloscope, Agilent DCA 86100A). Fig. 4 shows the single-pulse temporal profile. The pulse duration (FWHM) was measured to be 24 ns. Experimentally, we found that no bunched pulses were observed in the pulse internal structure, thus the observed nanosecond pulse was a clean and stable single pulse. In addition, the time-bandwidth