CVD graphene based low pump threshold bidirectional mode-locked fibre laser

Kin Kee Chow

A passively mode-locked femtosecond erbium-doped bidirectional fibre laser with low pump threshold using chemical vapor deposition grown graphene saturable absorbers is demonstrated. Two synchronised and counter propagating soliton output pulse trains with a repetition rate of ~10.38 MHz and pulse widths of 660 fs and 860 fs are obtained simultaneously from the fibre laser. Simultaneous mode-locking of the fibre laser has been realised with a threshold pump power of 56 mW from a single pump laser diode, indicating a ~62% reduction in pump threshold compared to previous results.

Introduction: Graphene, a two-dimensional, single-atom thick material consisting of carbon atoms has attracted much attention because of its remarkable electrical and optical properties [1]. It possesses a unique conical band structure that converges into a single Dirac point and has zero bandgap. The Pauli blocking of electron states makes it a saturable absorber (SA) and broadband saturable absorption could be achieved because of the gapless linear dispersion of Dirac electrons. Moreover, graphene also possesses ultra-fast relaxation time, high modulation depth, low non-saturable losses and fibre-compatible nature [2]. Passively mode-locking employing a SA as a key device is a well-known technique for generating ultra-short pulses [3]. Such passively mode-locked fibre lasers attracted much attention due to their extensive range of scientific and industrial applications and are often preferred to solid state lasers, owing to their simple and compact design, reliability, efficient heat dissipation, and high-quality pulse generation [2, 3].

Conventionally, an optical isolator is generally adopted in the ring cavities in order to suppress the unwanted cavity reflections and reduce the self-starting mode-locking threshold in passively mode-locked fibre lasers. Because of the isolator, these lasers can generate pulse trains in only one direction (unidirectional mode-locking). Unlike unidirectional fibre lasers, mode-locked fibre lasers with bidirectional ring cavity configuration can simultaneously emit ultra-short pulses in opposite directions (bidirectional mode-locking) [4-6]. Such bidirectional mode-locking fibre lasers generating synchronised femo-second pulse trains have found many promising applications such as gyroscopic sensors or optical frequency beating [4, 5]. However, it has been observed that typically a high pump power is required to achieve simultaneous bidirectional passive mode-locking. Recently, we have reported a bidirectional laser utilizing a liquid-phase exfoliation prepared graphene-based SA with a pump threshold of 150 mw [6]. However, in order to obtain high-efficiency operation of a fibre laser, it is necessary to ensure a low laser threshold where a high performance SA becomes essential [7]. In order to obtain high quality graphene-based SAs, many different methodologies have been previously reported such as mechanically exfoliation from graphite, spray coating, optically-driven deposition, or chemical vapor deposition (CVD) grown graphene thin-films [2]. While each of these methods has their own merits and drawbacks, one of the main challenges falls on the repeatability and the precision of fabricating the graphene-based SA. Another concern will be the insertion loss and optical scattering of the graphene-based SAs which affect the pump threshold and performance of the mode-locked fibre laser. Among different methodologies, the CVD technique has found advantageous of precise control of the number of graphene layers thus the optical properties of the SA [2, 8].

In this paper, a relatively low pump threshold passively mode-locked bidirectional erbium-doped fibre (EDF) laser based on a graphene-based SA is presented. CVD method is utilized to fabricate the graphene thin-film to form high quality SAs. The fibre laser cavity consists of a four-port circulator, which introduces different sections of cavity for the two counter circulating pulses. By appropriately adjusting the net birefringence and loss, two synchronised stable soliton outputs with the same repetition rate in both clockwise (CW) and counter-clockwise (CCW) directions are obtained simultaneously. The results show that the laser can serve as two different femtosecond lasers simultaneously with a relatively low pump power.

Experiment and results analysis: Fig. 1 shows the experimental setup of the graphene-based passively mode-locked bidirectional fibre laser. In the experiment, the CVD graphene is fabricated on the surface of thin copper foil substrate heated up to 1000 ºC under the flow of Ar/Hydrocarbon gas/H_2 mixture [9]. Then the copper substrate covering graphene thin-film is cooled down to the room temperature, and a thin layer of polymethylmethacrylate (PMMA) is spin coated to the graphene on Cu substrate as a support layer. Subsequently, the thin Cu foil is dissolved in an aqueous solution of ammonium persulfate. The graphene thin-film is then floated on the surface of deionized water and transferred onto the facet of a fibre ferrule of a FC/APC fibre connector. Finally, the CVD graphene-based SA is formed by sandwiching the CVD graphene thin-film between another FC/APC fibre mirror through a conventional adapter. The total insertion loss of the graphene-based SA is measured to be ~1.6 dB. The saturable absorption properties of the fabricated CVD graphene-based SA are measured using a convention mode-locked fibre laser. Such laser source emits ~400 fs pulses at 1562.12 nm, with a repetition rate of 67.1 MHz and an average output power of 7 mW. The modulation depth and the non-saturable losses of the graphene-based SA are found to be ~2.5% and ~30%, respectively.

The gain medium of the laser is a 60-cm-long erbium-doped fibre (EDF, LIEKKI Er110) pumped by a 974-nm laser diode via a fused 980/1550 nm wavelength-division multiplexing (WDM) coupler. The group velocity dispersion parameter of the EDF is estimated to be 0.012 ps^2/m. A polarization-dependent fibre-pigtailed four-port circulator is adopted in the cavity to facilitate bidirectional operation of the fibre laser. A polarization controller (PC1) is employed in the common path to adjust and optimize the polarization condition of the light inside the cavity. Ports 2 and 4 of the circulator are connected to two CVD graphene-based SAs which are connected to highly reflective fibre mirrors. A 10/90 2×2 optical fibre coupler is adopted to extract 10% of the optical power from the cavity as the laser outputs. The unwanted reflected light from the laser outputs are blocked by two polarization-independent isolators.

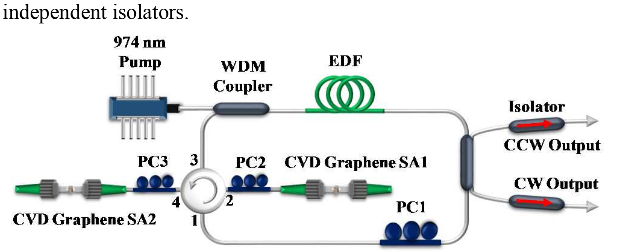

Fig. 1 *Schematic illustration of passively mode-locked bidirectional fibre laser incorporating CVD graphene-based SAs. EDF, erbium-doped fibre; SA, saturable absorber; WDM, wavelength-division multiplexer; PC, polarization controller; CVD, chemical vapor deposition.*

The total length of the main path of the laser cavity is estimated to be ~10.2 m, which includes 3.9 m of single mode fibre (SMF) pigtails from the output coupler, 1 m of HI1060 fibre pigtails from the WDM couplers, 1.3 m of polarization maintaining (PM) fibre pigtails for port 1 and port 3 of the circulator, and 4 m of SMF through PC1. Each sub-path has an extra fibre length of 9 m, which mainly consists of the fibre pigtails of the circulator, PCs, and the FC/APC connectors. Note that the main-path is always shared by the counter-propagating pulses while they pass through different CVD graphene-based SAs in their corresponding sub-paths. The net cavity dispersion of the cavity is calculated to be −0.403 ps^2 and the total length of the cavity is 19.27 m, which corresponds to a fundamental repetition rate of 10.38 MHz. The outputs of the bidirectional fibre laser are characterized with an optical spectrum analyser (OSA) and an optical autocorrelator. For both CW and CCW directions, the net cavity dispersion is anomalous so that the generated pulses have soliton-like shape with Kelly's sidebands shown in their optical spectra [3, 10]. However, distinct optical properties of the output pulses are expected as they experience slightly different optical gain and loss in the cavity.

In the experiment, mode-locking operation in the CW direction is first observed when the pump power is increased. It is believed that pulses propagating in different directions experience different cavity losses resulting in such observed mode-locking priority. However, in order to realise simultaneous bidirectional passively mode-locking of the laser, an additional loss on the CW light path is essential to balance the effective net gain of the counter-propagating light in the cavity. In order to serve this purpose, the polarisation maintaining fibre pigtails of the circulator and the PCs in the sub-paths (PC2 or PC3) can be regarded as tunable attenuators. By carefully adjusting the PC2 and/or PC3, one can introduce controllable losses in either propagating directions. Therefore, simultaneous passively mode-locking in both directions can be obtained by adjusting the imposed loss and the net birefringence of the cavity by the three PCs, in which PC1 will control the net birefringence of the cavity and PC2 and PC3 will introduce controllable loss in both counter-propagating directions to provide enough net gain for both propagating directions. With an optical pump power of 56 mW, stable single-pulse mode-locking is observed in both directions simultaneously. In comparison to the earlier results with liquid-phase exfoliation prepared graphene-based SA [6], a significant decrease of ~62% of the pump threshold is observed. The results shows that the CVD graphene SA can enable a low pump power bidirectional passively mode-locking of the fibre laser. It is worth noting that owing to the low optical scattering loss properties of the CVD graphene-based SAs, the results can be obtained with only one pump laser diode instead of two in the laser cavity [6].

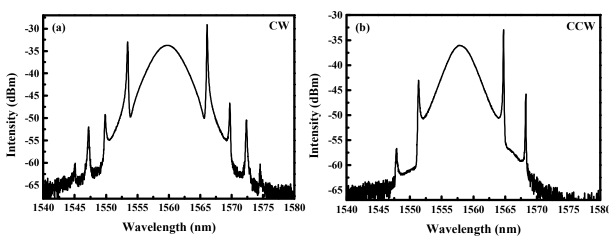

Fig. 2 *Output optical spectra of the CVD graphene-based passively mode-locked bidirectional fibre laser in (a) CW direction and (b) CCW direction.*

The output optical spectra of the two counter-propagating laser outputs are shown in Figs. 2(a) and 2(b). The center wavelengths of the CW and CCW outputs are found located at 1559.7 nm and 1558.0 nm, respectively. The 3-dB bandwidths of the two output spectra are found to be 4.6 nm and 3.9 nm. As the net cavity dispersion is anomalous, the output spectra show a soliton-like shape with Kelly's sidebands observed.

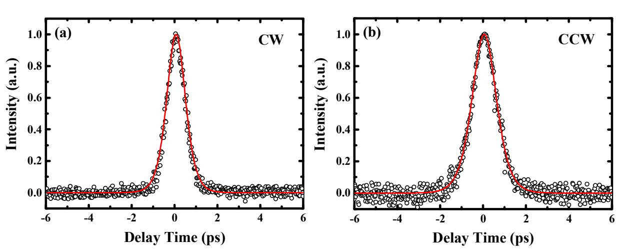

Fig. 3 *Autocorrelation traces of (a) the CW output pulses (b) and the CCW output pulses.*

Fig. 3 further depicts the output autocorrelation traces of the bidirectional passively mode-locked laser. The pulse widths of the CW and the CCW output are measured to be 660 fs and 860 fs with $sech^2$ fitting, respectively. The time-bandwidth product of the output pulses are calculated to be 0.37 and 0.41, which are close to typical values of transform-limited $sech^2$ pulses. Figs. 4(a) and (b) further show the output radio frequency (RF) spectra of the mode-locked laser measured with a resolution bandwidth of 100 Hz over a 100 kHz span. The fundamental repetition rates of the two output pulse trains are measured to be 10.379 MHz and 10.378 MHz. The peak-to-pedestal ratios of the output RF spectra are measured to be around 60 dB, indicating stable mode-locking operation has been obtained. The output average optical powers for the CW and CCW pulse trains are measured to be 150 μW and 80 μW, respectively. It is believed that such unequal output powers from the two output ports is due to the slight asymmetry of the laser cavity.

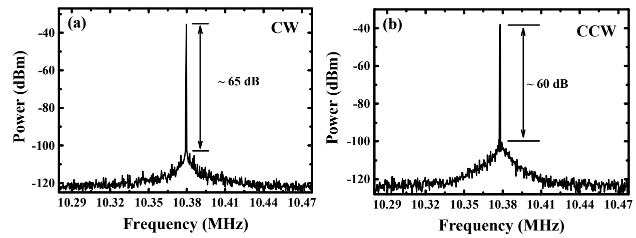

Fig. 4 *Output RF spectrum of the bidirectional fibre laser in (a) CW direction and (b) CCW direction.*

Conclusion: In summary, a low pump threshold passively mode-locked bidirectional laser with CVD graphene as saturable absorber has been demonstrated. The experimental results indicate that the fibre laser can simultaneously produce two synchronised stable output soliton pulse trains with a similar fundamental repetition rate of ~10.38 MHz at a pump power as low as 56 mW from a single pump laser diode. A polarisation maintaining circulator and a polarization controller are utilized to adjust the cavity birefringence and to introduce controllable losses as required, resulting in the simultaneous generation of counter-propagating pulse trains. The laser produces soliton pulses with a pulse width of 660 fs and 860 fs for the clockwise direction and counter-clockwise direction, respectively. The results indicates that the CVD graphene thin-film can be utilized in low pump threshold bidirectional fibre lasers for ultra-fast pulse generation.

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