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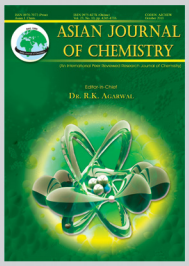

Pulse Train from Graphene Solutions

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We report on pulse train generation in an erbium-doped fiber laser with atomic layer graphene-water solutions which are fabricated from graphite by wet-chemistry techniques. Pulse trains generated from various concentration of graphene-water solutions are investigated under different laser energy. Present results show that atomic layer graphene-water solutions could be a promising saturable absorber for pulse trains due to its wavelength-independent ultrafast saturable absorption, good processbility and low cost.

Key Words: Graphene solutions, Pulse train, Wet-chemistry techniques.

INTRODUCTION

Ultrashort optical pulses have widespread applications in commercial applications and scientific researches. In passively mode-locked pulse lasers, saturable absorbers have been widely used as mode lockers which can generate repetitive ultrashort pulse trains[1]. Dyes in solutions were traditionally used as absorbers. In recent years, the development of semiconductor saturable absorber mirrors (SESAMs) has brought great benefits to solid-state and fiber lasers not only because of the ease of processing, but also the capability to self-start continuous mode locking[2-7]. Zhang *et al.*[8] first reported graphene-based mode-locked laser. Many research have been demonstrated that such optical pulses can also been directly generated by the passively atomic layer graphene mode locked fiber laser oscillators. By using the chemical vapor deposition (CVD) and electrospinning techniques, Zhang *et al.*[8-10], have demonstrated that atomic layer graphene can be used as a mode locker to produce ultrafast pulsed lasers in an erbium doped fiber (EDF) laser and Sun *et al.*[11], have generated pulses from an erbium doped fiber laser using graphene-polymer composite as mode locker through wet-chemistry techniques. Recently Tan *et al.*[12], reported a technique of using graphene which was obtained from solution graphene oxide *via* a reduction process using hydrazine as a saturable absorber making pulses in a ceramic Nd:yttrium aluminum garnet laser. The results have shown the promise of using the graphene-polymer composite to replace the SESAMs as mode locker for many practical applications. However, the report about pulse train from graphene solutions and the relationship between laser intensity and the concentration of graphene is rare. In this paper we report our studies on the pulse generation in an erbium-doped fiber laser passively mode locked with atomic layer graphene-water solutions. We show that not only the graphene-polymer composite can be used as a mode locker to mode lock fiber lasers, but also the various concentration of graphene-water solutions produce pulse train under different laser energy.

Graphene, the closest archetype of a two-dimensional (2D) atomic layer of carbon atoms arranged in a hexagonal lattice, while being very promising for future applications, represents also an extremely interesting system from the viewpoint of fundamental physics[13,14]. Distinctly, the electronic states of an isolated graphene do not obey the conventional laws of Schrödinger's quantum mechanics but are rather governed by an equation which is equivalent to the Dirac equation for massless fermions[15,16]. The "rise" of graphene dates from 2004 when it was effectively introduced into the the laboratory environment, following the clear identification of 10 μm sized graphene flakes deposited on Si/SiO_2 substrates[17] and of multi-layer epitaxial graphene thermally decomposed from silicon carbide[18,19]. Recent advances in graphene research has shown that graphene can be easily synthesized from graphite with wet-chemistry techniques[11,20-23]. Moreover, different from other graphene synthesis techniques such as chemical vapor deposition, mechanically peeling progressively finer layers from raw flakes of graphite and

reduction from graphene oxide *etc*. It is easy to obtain single or few layer "perfect" graphene by this ultrasonification and centrifugation methods from graphite. Different from the impossibility of selective growth of single walled carbon nanotubes (SWCNTs), we can get single-layer or few layer graphene from graphite by wet-chemistry techniques. Therefore, it is expected that using wet-chemistry techniques pulses could be generated from graphene solutions.

EXPERIMENTAL

All the reagents used in this work were commercial available. Dispersions were prepared by ultrasonicating 120 mg of graphite (Sinopharm Chemical Reagent Co. Ltd.) for 2 h in 10 mL of deionized (DI) water, with 90 mg of sodium deoxycholate (SDC, Sinopharm Chemical Reagent Co. Ltd.) bile salt to breaking of bundles of graphene that are formed due to the van der Waal forces. The resulting dispersion was then subjected to centrifugation in order to separate the remaining macroscopic flakes of graphite for 1 h at room temperature. Using the experimental absorption coefficient 1390 L/g at 660 nm[20,21], we estimate 0.1 mg/mL of graphitic material in the solution. Different concentration of graphene-water solutions are made by add deionized water. Only the visually homogeneous part of solution was used for the optical deposition process. In order to position graphene solutions, poly(vinyl alcohol) (PVA) was added to increase the viscosity of the solutions. The reason why we choose poly(vinyl alcohol) is that poly(vinyl alcohol) is optical transparency and easy dissolve in water.

We used our solution to build and test an ultrafast laser working at the main telecommunications window. The mode-locker is assembled by sandwiching the solution between two fiber connectors with a fiber adapter, as schematized in Fig. 1. A 5 m erbium-doped fiber (EDF) and a 12 m single mode fiber (SMF) are used. It is pumped by a 1480 nm diode laser *via* a wavelength division multiplexer (WDM). An isolator (ISO) is placed after the gain fiber to maintain unidirectional operation. A 30/70 coupler is used.

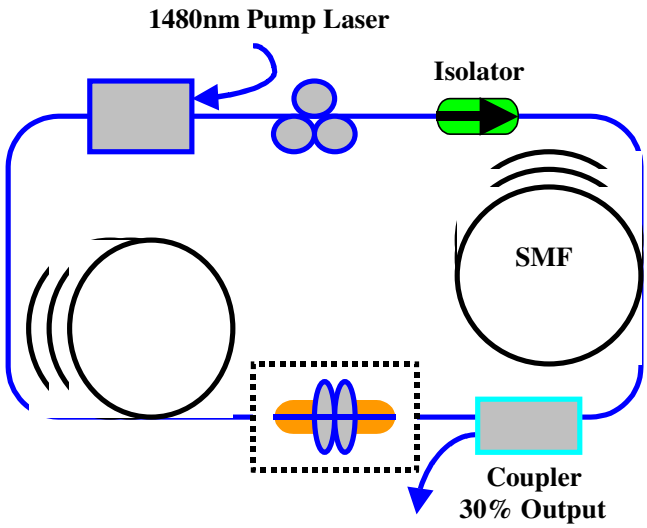
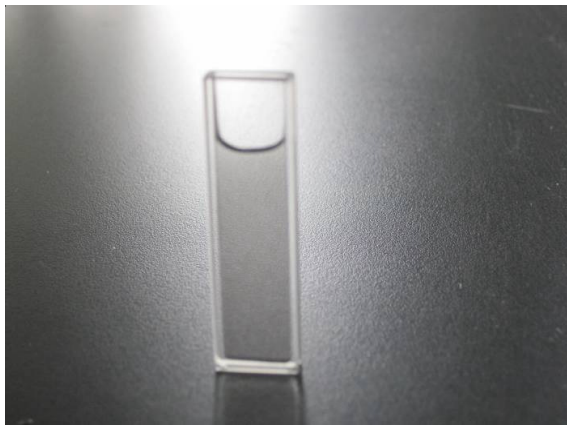


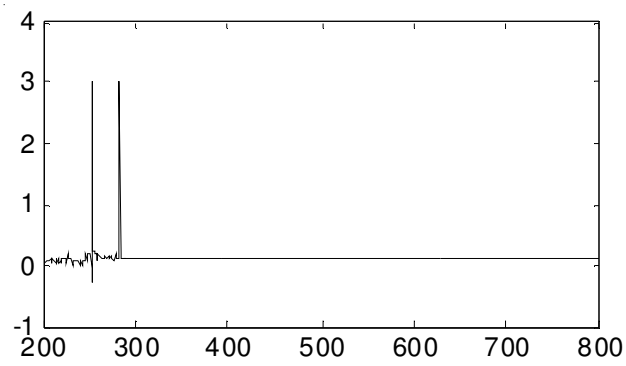
Fig. 1. Graphene mode-locked fiber laser

RESULTS AND DISCUSSION

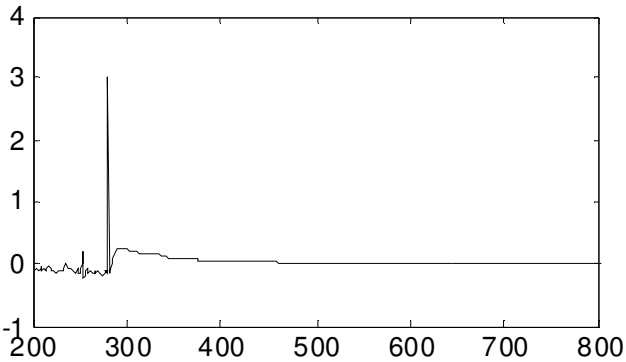
Photographs of the graphene solution and its optical absorption spectrum are shown in Fig. 2(a-c), respectively. A photograph of the dispersion of graphene in water after ultrasonification and centrifugation is shown in Fig. 2(a). The optical absorption of both graphene and graphene-poly(vinyl alcohol) solutions were measured by a spectrometer [Fig. 2(b-c)]. The 253 nm absorption peaks characteristic of the graphene are clearly observed in Fig. 2(b-c).



(a)



(b)



(c)

Fig. 2. (a) Graphene dispersion, (b) absorption spectrum of graphene dispersion, (c) absorption spectrum of graphene-PVA solution (0.1 mg/mL)

In this studies, pulses from graphene solutions were confirmed. Fig. 3 shows the measured oscilloscopes trace within nanosecond time scale. In all of the pump power range, the

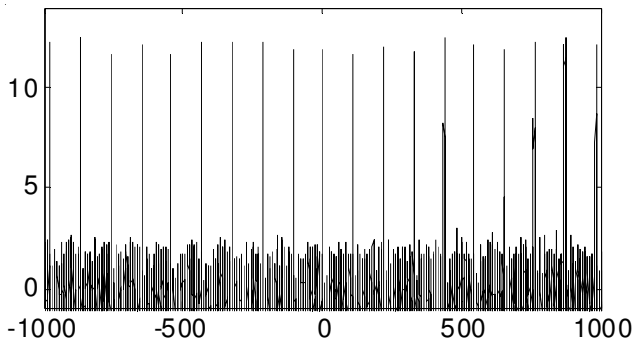


Fig. 3. Pulse train

laser always emitted single pulse, no pulse breaking or multiple pulse operation was observed with the autocorrelation trace measurement.

Table-1 shows the relationship between laser intensity and the concentration of graphene solutions. The connection between the intensity and the concentration is not linear. It is noted that the laser energy descend with increasing of the concentration of solutions.

TABLE-1
RELATIONSHIP OF THE LASER INTENSITY AND CONCENTRATION

Entry	Concentration (mg/mL)	Laser energy (pJ)
1	0.01	136
2	0.03	105
3	0.05	95
4	0.10	90

Conclusion

In summary, we have demonstrated pulse train with atomic layer graphene solutions as the saturable absorber. Laser energy descend with increasing of the concentration of graphene solutions. Present experimental results show that the atomic layer graphene solutions could be a promising saturable absorber for pulse train.

ACKNOWLEDGEMENTS

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