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Evanescent field interaction of tapered fiber with graphene oxide in generation of wide-bandwidth mode-locked pulses

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ABSTRACT

Pulses with picosecond pulse widths are highly desired for high precision laser applications. A mode-locked pulse laser utilizing evanescent field interaction of a tapered fiber with graphene oxide (GO) is demonstrated. A homemade fabrication stage was used to fabricate the tapered fiber using systematic flame brushing and a GO solution was used to coat the microfiber using optical deposition technique. Pulse trains with a pulse width of 3.46 ps, a 3 dB optical bandwidth of 11.82 nm and a repetition rate of 920 kHz were obtained. The system has substantial potential for many crucial medical, communication, bio processing, military, and industrial applications.

1. Introduction

Ultrafast and ultrashort pulses are crucial elements in many applications such as micromachining, surgery, terahertz wave generation, optical imaging and supercontinuum generation [1], in particular for communications applications in the S-band [2], C-band [3] and L-band [4]. For efficient pulse generation, the longitudinal modes in the resonator must be synchronized to generate the desired ultrafast pulses [1]. Passively ultrafast pulsed laser can be achieved using two methods: i) by integrating a saturable absorber (SA) in the cavity, or ii) by taking the advantages of nonlinear effects occurring in the fiber [1] such as the nonlinear polarization rotation technique or by using a nonlinear amplification loop mirror [5]. Since fine-tuning of the polarization state is not required, using the SA inside the cavity is seen as the most effective technique to generate the pulse train [6]. Various nano materials can be used to create the SAs, and the most common approach is to deposit the SA on the fiber ferrules on the connector, allowing light to penetrate the SA directly. Another viable approach is to deposit the SA on the tapered waist of the microfiber or side polish fiber as a coating, allowing the interaction between the evanescent field and the SA to generate a pulse. Direct depositing of the SA material onto the fiber ferrule has its limitations, including thermal damage probability, weak optical absorption and parasitic reflection [7–9]. Thermal damage in particular would occur when light passes directly through the SA layers, possibly hindering safe and robust SA application. On the other hand, the evanescent field based SAs such as SA coated tapered fibers and side polish fibers require only a small portion of light to interact with thin layer of SA in the waist diameter, thus allowing for a faster cooldown and reducing the probability of thermal damage in high optical power applications [7]. Unfortunately, there are some drawbacks to the use of side polished fiber based SAs, such as difficulties in obtaining a perfect smooth surface structure and high unavoidable sensitivity because of the asymmetric structure [7]. Thus, a tapered fiber based SA seemed a better choice which can generate pulse employing evanescent field interaction.

Many types of SA have been tested for ultrafast generation such as graphene [10–19], MoS_2 [20], WS_2 [21], CNT [15], topological insulator [22] and black phosphorus [23]. Among these SAs, graphene has become the focus of interest of many researchers because of its exceptional electrical and electronics properties [1,24–26] including outstanding nonlinear optical response. There are many features of graphene such as large Kerr nonlinearity, ultrafast carrier dynamics, easy integration with optical system, ultrafast recovery time (200 fs), very low saturable absorption threshold, and a wide operating range covering even the telecom band [9,27] that make it highly desirable for wavelength dependent nonlinear signal generation [28] and broadband nonlinear saturable absorption for mode locking [9]. Bao et. al [29] first demonstrated the mode locked fiber laser using multilayer graphene, and this was quickly followed by various similarly designed systems [10–19]. Most of the SAs in these works were fabricated using the direct deposition technique either by putting layered graphene [10–14,29] or graphene flake-polymer composites [1,15–19] onto a fiber ferrule that is then joined using connectors. The very first mode locked fiber laser exploiting evanescent field interactions with a based graphene SA [27] managed to generate a pulse train output with a repetition rate of 6.99 MHz and a cavity length of 28 m. In this case,

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the interaction of a side polished fiber (SPF), or also known as D-shaped fiber, and graphene suspension was observed. Nam Hun et. al. also reported an efficient mode-locked fiber laser using SPF and uniform monolayer graphene interaction where a repetition rate of 37.72 MHz was achieved in cavity length of 5.49 m [9].

Nano-and micro-fibers are already seeing tremendous applications in the field, include the detection of micro and nano-based particles [30,31]. However, only limited work based on the interaction of tapered fiber and graphene solution to generate mode-locked fiber laser have been found [7,8,32]. This limitation leaves a big gap in this field that further research work could prove substantial and useful results. A mode locked fiber laser has been reported based on reduced graphene oxide and evanescent field interaction [7]. Although the measured repetition rate of 3.33 MHz complied with their cavity length of 62 m, the spectral 3 dB bandwidth was very narrow and the pulse width was broad [7], which is undesirable. A passive harmonic mode locked (HML) fiber laser using microfiber-based Graphene SA was also demonstrated with up to the 101st HML operation attained [32]. In this case, a fundamental repetition rate of 5.46 MHz was recorded with a cavity length of 38 m, but the spectral bandwidth was narrow [32], indicating broad pulse width. He et. al. demonstrated mode-locked fiber laser using microfiber and reduced graphene interaction [8] where spectral properties was narrow and the pulse width was wide.

Currently, most of the work have been focused on the interaction of reduced graphene oxide (RGO) and tapered fibers to produce mode-locked lasers [7,8,32]. However the mode locking behavior of graphene oxide (GO) SA on tapered fiber is yet to be explored widely. We choose GO because of simple and minimized fabrication process that reduced a step of RGO fabrication. This work aims to produce mode lock pulse laser with shorter pulse width and larger bandwidth. Therefore, a mode locked fiber laser utilizing tapered fiber and GO evanescent field interaction is presented in this paper. A tapered fiber was fabricated by homemade fabrication stage and GO was deposited using optical coating deposition technique. Then the tapered fiber based GO SA was inserted in the ring cavity to generate mode-locked pulse. The details of the work is presented in later part of the paper.

2. Fabrication of microfiber and characterization of SA

2.1. Fabrication of microfiber

The microfiber was fabricated from single mode fiber (SMF) using a systematic flame brushing technique [33–36]. Approximately 4 cm length of the coating was stripped out from the SMF and was cleaned using isopropyl alcohol. The SMF was then placed in a homemade linear fabrication stage where a set up was used is depicted in Fig. 1(a). The set up consisted of two fiber holders, moveable torch, two stepper motors and an Arduino-based motor controller. One fiber holder was fixed and another holder was used to pull the fiber during the tapering process. The torch moved left and right periodically and heated through the desired length of the fiber to soften the glass fiber. The taper was made by pulling the fiber using movable holders. Butane and Oxygen mixture flame was used and the pressure of the gas mixture was controlled by adjusting the gauge valves to achieve a stable flame. During the experiment, the fiber waist was tapered to a diameter of 11 μm, as in Fig.1(b).

with less than 2.5 dB of the insertion loss was recorded in 1.5 μm region. This is to ensure sufficient evanescent field induced by the tapered fiber and to assure the durability of the tapered fiber.

2.2. Characterization of graphene oxide

The GO sample has been characterized before the experiment. Fig. 2(b) shows the Raman spectrum of the GO. Three main peaks from the characteristic curve were observed. The peak D appears at 1353 cm^{-1} due to stretching of C–C bond from the doubly resonant disorder-induced mode. The G peak, a doubly degenerate phonon mode due to the first order scattering of E_{2g} phonon of sp^2 C atoms [37] is located at the Brillouin zone center (1605 cm^{-1}); and the 2D overtone peak is found at 2715 cm^{-1} [38–41]. The GO sample indicated significant structural disorder by showing a prominent D peak which caused by O-incorporation. The 2D band at 2715 cm^{-1} originated from two phonon double resonance Raman process, indicating that crystalline graphite materials are highly sensitive to number of graphene layers. Based on the estimation of I_G and I_{2D} intensity, the synthesized GO is found in a multi-layer GO form [42–44].

2.3. Deposition of graphene oxide in microfiber

While keeping the microfiber intact on the translational stage, the GO solution was dropped on a glass slide and the glass slide was placed on the top of a 2 dimensional (Y-Z) translational stage. The stage can be moved in the Y axis and Z axis and it is possible to reach microfiber's height by adjusting the axis micrometer as shown in Fig. 2(c). The stage was adjusted to the microfiber's height to make sure that the waist diameter of the microfiber immersed completely in the drop of the GO solution. The setup of deposition is shown in Fig. 2(a).

The ASE source with output power of 13 dB was launched through the fabricated microfiber waveguide and a strong evanescent field was created around the waist region. When the ASE source was turned on, the presence of strong evanescent field across the waist region attracted nano-sized particles of the GO and eventually created a thin layer of GO surrounding the microfiber. This deposition process was observed by monitoring the transmitted ASE power using optical power meter (OPM). The initially transmitted ASE power started to decrease after ASE source was turned on, indicating the deposition has been started. Deposition was stopped after 15 min figuring out that the insertion loss of 6 dB due of the deposition process. The 6 dB loss is to assure the graphene oxide is attached to the tapered fiber and induced sufficient saturable absorption to produce mode locked pulses. When the insertion loss is higher than 6 dB, it effected the cavity efficiency and lower down the pulse energy. In the experiment, we have deposited the GO for a total length of approximately 40 μm. A microscopic image,

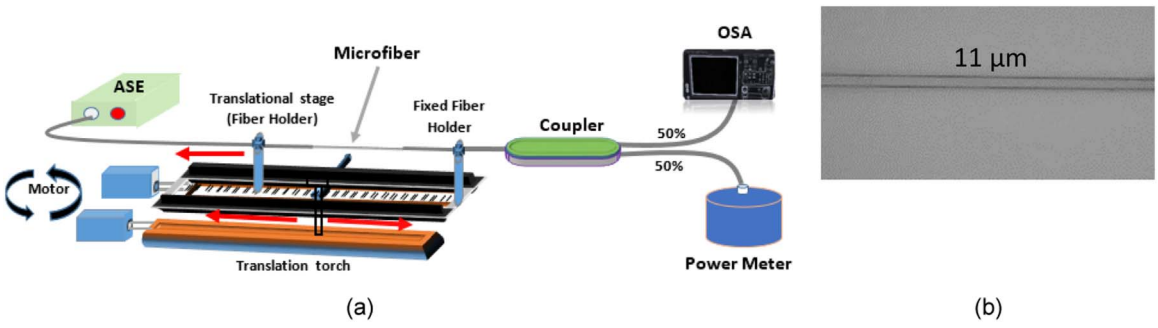

Fig. 1. (a) Microfiber fabrication set up; (b) microfiber after fabrication.