Carbon nanotube and graphene photonics for ultrafast pulse generation and signal processing

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***Abstract*—We review the nonlinear photonic properties, saturable absorption and third-order nonlinearity, of one and two dimentional forms of nano-carbon, Carbon nanotube (CNT) and graphene, and their applications to mode-locked lasers and nonlinear functional devices.**

Optical pulsed fiber lasers offer a broad-range of applications in various fields, such as optical communications, optical signal processing, fiber sensings, laser surgery etc. Passively mode-locked fiber lasers can generate transform-limited optical very short pulses by introducing a saturable absorber (SA) in the laser cavity. We are developing new types of passively mode-locked fiber lasers for telecom and sensing applications, using carbon nanotube (CNT) or graphene as a SA. We are also investigating the nonlinear functional devices using them. Here we review our recent progress of these mode-locked fiber lasers and nonlinear functional devices [1].

Graphene and semiconducting CNTs absorb photons corresponding to their band structure. This absorption is exicitonic and saturable, and its recovery time is inherently fast, <1ps, which is fit for the laser mode locker for fs-pulse generation [1][2]. Typical saturable absorption (SA) fluence is comparable to that of conventional semiconductor-based saturable absorber (SESAM). It has been known that they also have high third-order nonlinearity ($n_2 \sim 2\times10^{-12}$ m^2/W). We usually use the thin (~1μm) layer of CNTs on substrates or optical fiber ends as a SA, either by the spray, the CVD, or the optical deposition method [3]. The CNT thin film is normally placed perpendicular to the light path. For the high power applications, however, we have a problem of optical damage. We proposed a new configuration based on the evanescent field interaction of the propagating light with CNTs using overcladding-less waveguide, D-shaped fiber, and so on [1].

We have applied the CNT-based SA in many kinds of passively mode-locked fiber lasers. CNT-based SA can operate in transmission, reflection, and even bi-directional modes. Therefore, it is applicable to any laser configurations, such as a ring- and a linear-cavity lasers. We have demonstrated that these lasers can easily generate high-quality nearly transform-limited pulses with pulsewidths as short as a few hundred femtosecond, regardless of the laser configurations [1]. Compared with other SAs, CNT-based SA is small, low-loss, and compatible to fibers. Thus we can apply it to mode lock very short cavity fiber lasers to generate very stable pulse trains at high repetition rate. By using high-gain Er:Yb fiber together with high finesse fiber cavity and CNT-based SA, we have succeeded in generating pulses at 5GHz repetition rate from a 2cm-long fiber laser [4]. We made a further improvement recently to achieve up to 20GHz repetition rate from down to 5mm-long fiber lasers, and also demonstrated in supercontinuum (SC) generation spanning from 1.4μm to 1.7μm in highly nonlinear fiber (HNLF) using the 10GHz fiber laser as a seed source [5]. We also realized a high-power mode-locked fiber laser by using CNT-coated D-shape fiber as the SA. We achieved the average power as high as 250mW and the pulse energy as high as 6.5 nJ with the repetition rate of 38.9 MHz [6].

Graphene is more attractive than CNT because of its wavelength independence. We demonstrated that the optical deposition is also possible and that the mode locking properties are quite similar to the CNT-based one [7]. We also realized short-cavity (1cm) high-repetition-rate (10GHz) graphene-based mode-locked fiber laser [8].

As for the nonlinear functional devices, we succeeded in wavelength conversion of 10Gb/s NRZ signal through nonlinear polarization rotation (NPR) [9] and four-wave mixing (FWM) [10] in the CNT-coated D-shaped fiber.

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