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Invited Paper

Short pulse fiber lasers mode-locked by carbon nanotubes and graphene

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ABSTRACT

One and two dimensional forms of carbon, carbon nanotubes and graphene, have interesting and useful, not only electronic but also photonic, properties. For fiber lasers, they are very attractive passive mode lockers for ultra-short pulse generation, since they have saturable absorption with inherently fast recovery time (<1 ps). In this paper, we review the photonic properties of graphene and CNT and our recent works on fabrication of fiber devices and applications to ultra-short pulse mode-locked fiber lasers.

1. Introduction

Short pulse lasers having sub-ps pulse durations can have very high pulse peak power. For example, a 100 fs pulse with 10 nJ pulse energy have a peak power exceeding 100 kW. Thus, these lasers offer a broad-range of promising applications in various fields, such as micro-machining, nonlinear microscopy, spectroscopy, metrology, laser surgery, etc. Passive mode locking (Fig. 1) is a technique used to generate such short pulses. Mode locking can be achieved using a fast saturable absorber (SA). This SA requires a fast, intensity-dependent loss (loss is smaller at higher intensity) to favor optical pulse formation from noise over continuous-wave lasing.

Conventionally, intense pulses in the 100 fs range have been generated by large mode-locked solid-state lasers, typified by the Ti:Sapphire lasers mode-locked by the Kerr-lens phenomena [1]. However, these solid state lasers are bulky requiring large space and energy consumption. Recently, passively mode-locked fiber lasers have been growing very rapidly, and catching up with these solid-state lasers in terms of pulse duration and energy [2]. Compared to solid-state lasers, fiber lasers have higher beam quality, better wall-plug efficiency, more efficient and passive heat dissipation, smaller footprint, and higher reliability and portability.

SAs for the passively mode-locked fiber lasers are classified into three types. The first one is the semiconductor-based reflection-type SA, ordinary called semiconductor saturable absorbing mirror (SESAM) [1,3]. It is a semiconductor multiple quantum well (MQW) Bragg reflector device utilizing the SA property of semiconductor material. It requires a complex and costly fabrication process, and also needs extra optics to couple the light into the optical fiber. The second one is the fiber-based SA, such as nonlinear polarization rotation (NPR), nonlinear loop mirror (NOLM), nonlinear amplifying loop mirror (NALM) [2,4]. NPR is sometimes termed as nonlinear polarization evolution (NPE). They are not a natural but artificial SA, in which nonlinear phase shift by self-phase modulation (SPM) and interference of two modes (two polarization modes in the case of NPR, and two opposite direction modes in the case of NOLM and NALM) makes the loss to be a periodic function of input light intensity. It is a very fast SA, and modulation depth can be high. Also, it is very much suitable for fiber lasers since they are all-fiber devices composed of a length of nonlinear fiber and an inline polarizer (NPR), or a fiber coupler (NOLM, NALM), which can be made in an ordinary optics laboratory. However, they are polarization-dependent, and the device length tends to be long, typically longer than a few meters, which sometimes causes instability due to polarization fluctuation. Also, lack of slower (>a few ps) recovery from saturation, that exists in natural SAs, can make the self-starting of mode locked operation difficult in many cases.

We have been working on a third type of SAs from an early stage, based on nano-carbon SAs, such as carbon nanotube (CNT)-based SA (CNT-SA) and graphene-based SA (G-SA) [5–8]. These devices offer several key advantages such as: ultra-fast plus slow recovery from saturation, small size, low background loss, polarization independence, ability to operate both in transmission, reflection and bi-directional modes, and compatibility to optical fibers.

In this paper, we will review the basic properties of graphene and CNT and our works on the application to the short-pulse mode-locked fiber lasers. We will start by discussing the fundamental properties, the electronic band structures, and linear and saturable optical absorption properties of graphene and CNT. Then, we move onto how the CNT-SAs and G-SAs are fabricated, especially in the form of fiber devices. Finally, we will review our recent work on the application to the mode-locked fiber lasers.

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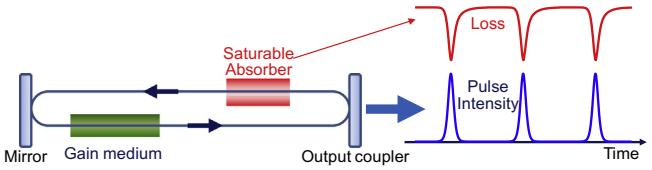

Fig. 1. Passively mode-locked laser using saturable absorber (SA).

2. Fundamentals of graphene and CNT

2.1. Electrical and optical properties of graphene

A single-layer graphene consists on a flat monolayer of carbon atoms tightly packed into a 2D honeycomb lattice by sp^2 hybridization (Fig. 2(a)). Originating from its 2D honeycomb lattice structure, graphene is known to have a unique band structure. In ordinary materials, semiconductor for example, momentum P and energy E of electrons are expressed as $P = \hbar k = m_c v$ and $E = m_c v^2/2$, respectively, where k is the wave number, v is the speed and m_c is the effective mass. As a result, energy E and wave number k has a relation (dispersion relation) $E = P^2/2m_c = \hbar^2 k^2/2m$. Thus, in ordinary materials, the band shape becomes parabolic.

In graphene, on the other hand, it is known that the dispersion relation is not parabolic, but linear, and it can be expressed as shown in Eq. (1):

$$E^{\pm} = \pm \hbar v_F |\kappa|, \tag{1}$$

where $\boldsymbol{\kappa} = (\kappa_x, \kappa_y)$ is the 2D wave vector around K points in the hexagonal Brillouin zone, and $v_F \sim 10^6$ m/s ($\sim c/300$ where c is the speed of light) is the electronic group velocity [9]. Eq. (1) means that the valence and conduction bands form conic shapes, and touches at the vertexes (=K point) as shown in Fig. 3(a). The zero-gap linear band structure shown in Fig. 3(a) is referred as "Dirac cones," and the K point as "Dirac point." Calculations indicate that the density of state (DOS) of graphene is also linear around the Dirac point, which is identical to the Fermi level in pristine graphene without doping, as shown in Fig. 3(b). Thus, graphene has a semi-metallic, or zero-gap semiconducting nature. Eq. (1) also implies that $E = v_F P$, which is similar to that of photons, $E = cP$. Therefore, electrons propagating through the 2D graphene behave as massless Dirac fermions, or, in other words, like 'photons', at the velocity of v_F, which is 1/300 of the light speed c.

Graphene exhibits a variety of unique and unusual electric transport phenomena that are characteristic of 2D Dirac fermions, such as extremely high mobility (μ) of up to 10^6 cm^2 V^{-1} s^{-1} due to ballistic transport of electrons in graphene, 'minimum' conductivity of $\sim 4e^2/h$ even with zero carrier concentration, anomalous quantum Hall effects [10].

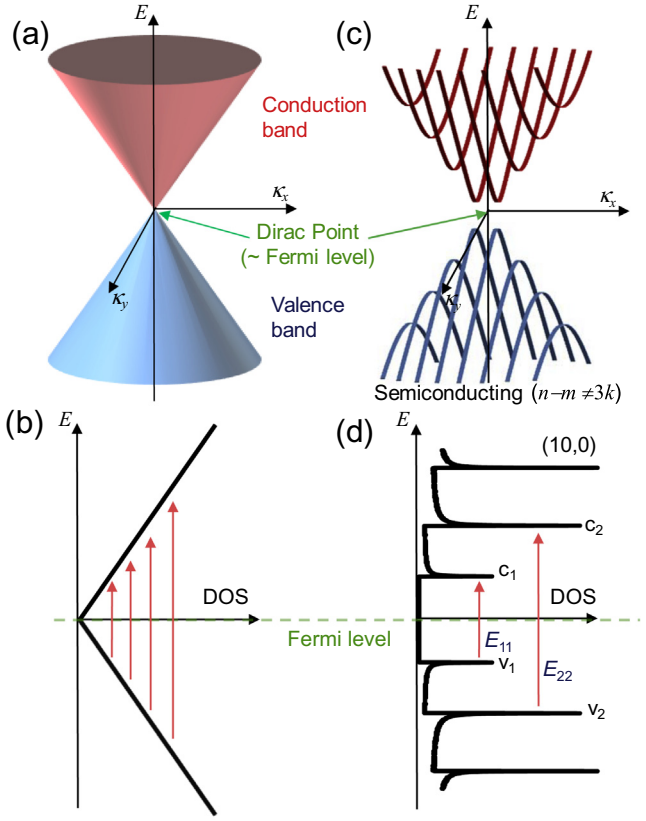

Fig. 3. Band structures and density of states (DOS) of (a,b) graphene and (c,d) semiconducting CNT (s-CNT).

But the interesting features of graphene do not end with its electrical properties, graphene also exhibits a variety of unique and unusual optical properties. Despite being only one atom thick, graphene absorbs a significant fraction of incident light, as a consequence of its unique electronic properties. The transmittance of single-layer graphene is calculated to be

$$T = (1 - 0.5\pi\alpha)^{-2} \sim 1 - \pi\alpha \sim 97.7\%, \tag{2}$$

where α is the fine structure constant ($\alpha = e^2/\hbar c \sim 1/137$) [11]. Because of the linear dispersion relation and DOS in graphene (Fig. 3(a and b)), absorption is wavelength independent (Fig. 4(a)). Also, in few-layer graphene optical absorption increases linearly with the number of layers N (inset of Fig. 4(a)), which indicates that the number of the layer can be estimated by observing the optical contrast in the sample.

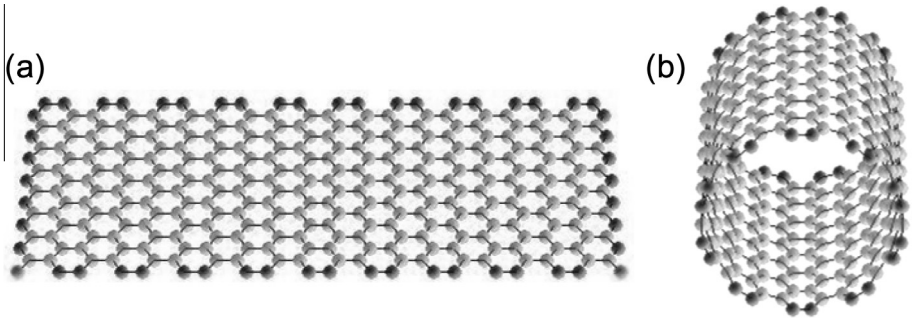

Fig. 2. (a) Graphene, and (b) carbon nanotube (CNT).