Application of Carbon Nanotubes for Mode-Locked Fiber Lasers and Nonlinear Devices

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Abstract

We review our studies on passively mode-locked fiber lasers and nonlinear optical devices using carbon nanotube (CNT). CNT-based devices offer several key advantages such as: ultra-fast response, robustness, tunability of wavelength, and compatibility to fibers.

Introduction

Carbon nanotube (CNT) has attracted researchers' attention in the field of photonic technology since we recently proposed and demonstrated a saturable absorber (SA) incorporating CNT [1]-[22]. CNT-based SA offers several key advantages such as: ultra-fast recovery time, polarization insensitivity, high optical damage threshold, mechanical and environmental robustness, chemical stability, tunability to operate at wide range of wavelength bands, and compatibility to optical fibers. Using the CNT-based SA, we have realized femtosecond fiber pulsed lasers at various wavelengths, as well as the very short-cavity fiber laser having high repetition rate. Besides the saturable absorption, CNT has been known to have high third-order nonlinearity, which is attractive for realization of compact and integrated functional photonic devices, such as all-optical switches and wavelength converters.

In this paper, we review our studies on CNT-based mode-locked fiber lasers, and our recent research progresses of nonlinear photonic devices using evanescent coupling between optical field and CNT.

Optical properties of CNTs

CNTs are classified into multi-walled and single-walled nanotubes (MWNT and SWNT), and interesting optical properties are in SWNTs. SWNT is an enrolled two-dimensional graphene honeycomb sheet, whose typical diameter is ~1nm and length is ~1μm, thus it is a one-dimensional material. Structure of SWNTs is determined by a single parameter, called chirality. Depending on the chirality, SWNTs exhibit two different electrical properties, metallic or semiconducting. Semiconducting SWNTs has energy bandgaps like in ordinary semiconductors, and photons having corresponding wavelength are absorbed by the SWNT. This absorption is exicitonic and saturable, and its recovery time is quite fast, <1ps. The bandgap energy in semiconducting SWNTs can be controlled by the tube diameter. A tube diameter of ~1.2nm gives absorption at wavelength around 1550nm [1][2]. However, it is not yet possible to synthesize only one chirality selectively in any method. Therefore, the sample is a mixture of several types of SWNTs.

The CNT-based saturable absorbers have been fabricated through several processes. First, the SWNTs were synthesized. There are several synthesis methods of SWNTs. After a series of purifying processes, the high-purity SWNTs were dispersed in ethanol and then sprayed onto the surface of quartz substrate. As the result, the CNTs are randomly oriented and entangled. We recently demonstrated a new fabrication technique based on the low-temperature alcohol catalytic CVD method [3]. It can synthesize high-quality SWNTs directly onto the quartz substrates, and even onto the single-mode fiber (SMF) ends. It is also possible to synthesize the vertically aligned SWNTs with this technique [4].

CNT-based mode-locked fiber lasers

Typical saturable absorption property is comparable to that of conventional semiconductor-based saturable absorber (SESAM). A rather low CNT loss of ~0.3dB is sufficient to mode-lock a laser [1][2]. And, CNT-based SA is compatible to optical fibers, since it can be sandwiched in between two fiber ends.

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. The first mode-locked fiber laser using CNT-based SA was demonstrated in the ring laser configuration [1]. 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]-[22].

Compared with other SAs such as SESAM or NOLM, 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 [5]. We also realized an ultrashort-cavity mode-locked SOA-based laser whose repetition rate is as high as 17.2GHz [6].

Typical absorption bandwidth of CNT sample is ~100nm. By controlling the fabrication condition, it is possible to extend it to be >500nm. Using this kind of wideband CNT sample, we have demonstrated mode-locked fiber lasers not only at 1.5μm but also at 1.3μm and 1μm by changing the gain medium [7][8].

As for the high-power laser applications, CNT thin film suffers from the optical power induced thermal damage. For high-power fiber lasers, we proposed a new configuration based on the evanescent field interaction of the propagating light with CNTs. In the scheme, since only a part of the optical power of the propagating mode interacts with CNTs, higher intracavity power can be introduced for higher energy pulse formation. By using CNT-sprayed D-shape fiber as the SA, We have 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 [9].

CNT-based nonlinear optical devices

Besides the saturable absorption, CNT has been known to have high third-order nonlinearity [10]. To apply the nonlinearity to the functional devices, longer interaction length between the CNT and optical field is required. We applied the evanescent coupling technique described in Sec.5 to obtain longer interaction length. We have used evanescent coupling in over-cladding-less waveguides, D-shaped fibers, or tapered (etched) fibers [11]-[14]. We realized several kinds of all-optical nonlinear devices using these CNT devices. By using the waveguide-type CNT device in NOLM configuration, we observed optical switching as in the normal NOLM device [11][12]. The nonlinear coefficient of the CNT device is estimated to be as high as $10^6 W^{-1} km^{-1}$. Similar all-optical wavelength converter based on the nonlinear polarization rotation was realized by using the CNT-coated D-shaped fiber [13][14]. We have also succeeded in converting 10Gb/s NRZ signal to other wavelength using the CNT device [15]. We have also realized a novel optical fiber blocker, in which a FBG is etched to the vicinity of the fiber core and CNT layer is formed around the etched region. When the pump light is incident to the CNT-FBG, the Bragg wavelength shifts due to the refractive index change, thus it can be used as an optical blocker or limiter [16].

New fabrication methods of CNT-based photonic devices

We have had two major fabrication techniques of the CNT-based photonic devices, spray method and direct CVD synthesis method. In both methods, however, most part of CNTs are left unused since only the CNTs on the core regions interact with the light. We recently proposed and demonstrated a novel and simple method to deposit CNT onto the core of optical fiber ends using a light [17][18]. By simply immersing the cleaved fiber onto the CNT solution and input the high-power light, we found that the CNTs are deposited only on the core regions of the cleaved fiber end. We have confirmed that the optically deposited CNT can work as the SA for the mode locked fiber laser. The mechanism of the optical deposition technique is considered to be a combination of the optical tweezer effect and the convection in the solution. We also found that the CNTs can also be optically deposited around the tapered fiber [19], which is useful for evanescent coupled CNT devices.

Another research direction is the realization of CNT-doped waveguide or fibers. We have succeeded in fabricating CNT-doped PMMA composites [20], and also realizing the CNT-doped PMMA fibers for the first time [21], and confirmed the mode locking of fiber lasers. We also realized fibers having CNT-filled micro-channel/slot for laser mode locking and nonlinear devices [22].

Conclusions

We believe that CNT is an emerging new materials with various promising photonic applications. We are developing waveguide- and fiber-type CNT devices for laser mode locking and nonlinear integrated devices.

Acknowledgements

The authors acknowledge support from Strategic Information and Communications R&D Promotion Programme (SCOPE) of The Ministry of Internal Affairs and Communications (MIC), Japan.

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