Carbon nanotube/polymer composite coated tapered fiber for four wave mixing based wavelength conversion

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Abstract: In this paper, we demonstrate a nonlinear optical device based on a fiber taper coated with a carbon nanotube (CNT)/polymer composite. Using this device, four wave mixing (FWM) based wavelength conversion of 10 Gb/s Non-return-to-zero signal is achieved. In addition, we investigate wavelength tuning, two photon absorption and estimate the effective nonlinear coefficient of the CNTs embedded in the tapered fiber to be 1816.8 $W^{-1}km^{-1}$.

OCIS codes: (160.4330) Nonlinear optical materials; (190.4380) Nonlinear optics, four-wave mixing.

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1. Introduction

Over the last decade, Carbon nanotubes (CNTs) have received much attention due to their exceptional nonlinear optical properties, such as their ultrafast, broadband, saturable absorption [1–3] with broad applications in the mode locking of fiber lasers [4] and their very high third order susceptibility [5]. Since 2003, CNT-based mode-locked lasers have been applied to a wide variety of laser configurations and operational wavelengths [4, 6–10].Besides, CNTs can be employed as an optical nonlinear medium due to the predicted ultrahigh third order nonlinearity [5] which is corresponding to the Kerr nonlinearity, Re($\chi^{(3)}$). Similar to other highly nonlinear organic materials, in which the Kerr nonlinearity originates from π-electron conjugation, π-electrons in CNTs are localized to their 1D structure, enhancing their Kerr nonlinearity response. The Kerr nonlinearity for CNTs under the resonance condition has been theoretically predicted to be as high as ~10^{-6} esu, which corresponds to the nonlinear refractive index $n_2 \sim 2 \times 10^{-8}$ cm^2/W [5], although this value is highly dependent on the wavelength. Such nonlinearity for CNTs can be utilized to realize various nonlinear functional devices for telecommunications, such as optical switches, wavelength converters, and signal regenerators. In 2006, based on nonlinear interference in a nonlinear optical loop mirror (NOLM) by Kerr nonlinearity, optical switching was reported by Kashiwagi et al. using a planar waveguide type optical device coated with CNTs [9]. In the same year, Song et al. realized optical switching using a D-shape fiber coated with CNTs, and then Chow et al. went on to demonstrate Four wave mixing (FWM)-based wavelength conversion [11,12]. Recently, we have reported FWM generation in CNT and graphene thin films optically deposited onto fiber ends [13], and then we also demonstrated FWM based wavelength conversion in mechanically exfoliated graphene sample [14]. When assuming the pump wavelengths are close enough and the propagation length is short, the conversion efficiency η of FWM can be approximately expressed as [15]

$$\eta(L) = (\gamma p_p^2 L) \tag{1}$$

where L is the light propagation distance, γ is the effective nonlinear coefficient, and p_p is the pump power. Therefore, the longer interaction length L is the key to achieve the higher conversion efficiency.

The evanescent field configuration is particularly suitable to exploit the nonlinear properties of CNTs because it allows strong electric field, long interaction length and relative low-loss transmission. From these properties, the evanescent coupling structure offers not

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only high third order nonlinearity [16] but also high optical damage threshold. For example, FWM based wavelength conversion using a CNT-deposited D-shaped fiber [12] demonstrated the feasibility of using CNT-based nonlinear devices for real applications. However, the structure of D-shaped fiber is polarization sensitive and therefore the FWM generated in the planar waveguide type optical device based CNTs has a strong polarization dependence [17]. In addition, the process of manufacturing such devices is fairly complex. A suitable candidate to overcome these drawbacks is using CNT-coated taper fibers. Such a taper fiber - based CNT device has low polarization sensitivity and allows control over the interaction between the CNTs and the propagating light and the nonlinearity of the device by adjusting parameters such as the interaction length, the taper waist, and the CNT concentration. Our group has previously proposed an optical deposition method of CNTs around a tapered fiber; both passive mode-locked lasing [18] and FWM based wavelength conversion [19] have been demonstrated using the CNT-light interaction in this fiber device. Nevertheless, the tapered fiber optically deposited with CNTs degrades rapidly due to being exposed directly to the environment [20]. Moreover, it exhibits significant losses caused by scattering and the damage threshold of optically deposited CNTs onto fiber tapers is low because the CNTs are not evenly distributed but agglomerate in a small region around the waist. This leads to increased scattering and linear losses and reduces the nonlinearity of the device and its damage threshold. By spraying the CNTs onto the fiber taper the CNTs can be evenly distributed, but the taper still suffer environmental damage and high scattering losses since the CNT are in direct contact with the taper surface. In order to fully utilize the nonlinear optical properties of CNTs, polymers have been identified as an optimum host material since they are transparent at optical communications wavelengths and have a structural composition that allows uniform dispersion of the CNT [21]. Passively mode locked lasers have been demonstrated using fiber tapers embedded in CNT/polymer composites [22, 23]. CNT/polymer coated tapered fiber devices have more potential in their FWM based wavelength conversion applications because the CNTs can be evenly dispersed in the polymer and thus interact with the evanescent field of the taper fiber without being in direct contact with the taper surface. Such CNT-polymer coated taper devices have higher third-order optical nonlinearity, longer and controllable interaction length, lower transmittance loss, and higher damage threshold. In addition, the polymers have the role of protecting the taper from environmental degradation improving the damage threshold and long term durability of the device.

In this work, we demonstrate an experimental observation of FWM based wavelength conversion of a 10 Gb/s Non-return-to-zero (NRZ) signal with a CNT-polymer tapered fiber. Moreover, wavelength tuning properties are investigated and its effective nonlinear coefficient is estimated. The CNT-polymer tapered fiber device exhibits significant performance improvements over previous fiber-type devices [12, 17, 19] on higher FWM conversion efficiency, higher damage threshold, lower insertion losses and longer stability.

2. Fabrication of CNT-polymer tapered fiber

We created the fiber tapers coated with CNTs-poly 2,2,2-trifluoroethyl methacrylate (PTFEMA) composite. Specifically we focused on the interaction length between the light wave and CNTs and the CNT concentration, and aimed to fabricate the fiber taper with low insertion loss. At first, we prepared a fiber taper from a standard single-mode silica fiber using the method proposed in [24]. The primary coat of the fiber was partially-removed from a 1 m long fiber and the fiber was fixed between two motor-driven transition stages for elongation. Then the naked part of the fiber was heated with a 40 mm ceramic heater at 1600 °C, and then a tension was loaded to the fiber in axial direction by the two transition stages. Here, by adjusting the heating time and the speed of transition stage, a high reproducibility of the diameter of the tapered region was realized as shown in Fig. 1. The fabricated tapered fiber has about 10 cm taper length, 1µm diameter and 0.2 dB transmittance.

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Next, the tapered regions were coated with the CNTs-PTFEMA composites. There are two reasons why we chose a partially fluorinated polymer, PTFEMA for the composite: one is lower inherent absorption loss due to Carbon-Hydrogen bond at a wavelength of 1550 nm compared to PMMA and other polymers. The other reason is its lower refractive index than that of the cladding of silica fiber taper. Thus, CNTs-PTFEMA composite can interact with the evanescent field with a low radiation loss. The CNT-PTFEMA composite is fabricated using the same way as that introduced in [20, 25].

We dissolved the CNTs-PTFEMA composite with 1-ppm-CNT concentration in a solvent. Then, the solution was deposited over the waist part of the silica fiber taper with a diameter of 1 μm placed on a glass plate. Subsequently, the glass plate was removed from the fiber taper. The coated length was approximately 10 cm. After vaporizing the solvent, a fiber taper device was obtained. The propagation loss of the fiber was monitored during the above fabrication process. In this way, the 1μm diameter of the fiber taper (1-ppm-CNT concentration) was obtained with an insertion loss of 5.0 dB.

Fig. 1. Optical micrograph of a single-mode silica fiber taper region with a diameter of 1 μm.

3. Experiment and results

Figure 2 shows our experimental setup on FWM based wavelength conversion using the tapered fiber coated with CNT/polymer composite. The structure of embedded fiber taper is illustrated in the inset of Fig. 2. The continuous wave (cw) output from the external cavity laser (ECL1) served as the signal light for the FWM, and was modulated with a 2^{31}-1 bits pseudorandom NRZ signal at 10 Gb/s. The modulated light was then amplified by a low noise Erbium-doped Optical Fiber Amplifier (EDFA) with Amplified Spontaneous Emission (ASE) filtering. Afterwards, the 10 Gb/s signal was combined with the other cw light from the ECL2 which served as pump light through a 3 dB coupler and amplified together with the 2nd high power EDFA, and launched into the CNT/polymer coated tapered fiber. The launched pump power into the embedded tapered fiber was estimated to be + 32 dBm (Considering the better FWM performance, the damage threshold of sample and the reproducibility of the FWM experiment, we chose the optimal value of being launched pump power into the embedded tapered fiber as + 32 dBm). The amplified pump and signal lights generate new light though FWM in the CNT/polymer fiber.

Figure 3(a) shows the output FWM spectrum obtained after the CNT-polymer coated tapered fiber device. In our experiment the pump was fixed at 1550.0 nm and different converted wavelengths were obtained by tuning the signal wavelength. Significant converted signal at 1547.8 nm was observed corresponding to the signal light wavelength at 1552 nm. Figures 3(b) and 3(c) depict the close-up views of the converted light and the signal light, respectively. From Fig. 3(b), it is observed that the generated converted signal is spectrally broadened due to 10 Gb/s modulation which confirms the generation of the converted signal is the result of wave mixing between the input signal and the pump light. The insets of Fig. 3(b) and Fig. 3(c) show the 10 Gb/s eye diagrams of the converted signal and the input signal. The eye-diagram of the converted signal is obtained after the optical filter as shown in Fig. 2 followed by a low noise EDFA with suitable ASE filtering in order to enhance the optical power for measurements. The background noise on the weak converted signal and inhomogeneous parts of dispersed CNT in CNTs-PTFEMA composites mainly affect the eye opening and lead to deterioration of the converted signal. The same experiment was repeated

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with the bare polymer tapered fiber without CNT, an 8 dB lower conversion efficiency of FWM effect compared to the CNT-polymer tapered fiber one was obtained due to the nonlinearity from the bare polymer tapered fiber. We can get the conclusion that the conversion efficiency in the system comes from the FWM of CNTs-polymer coated tapered fiber sample.

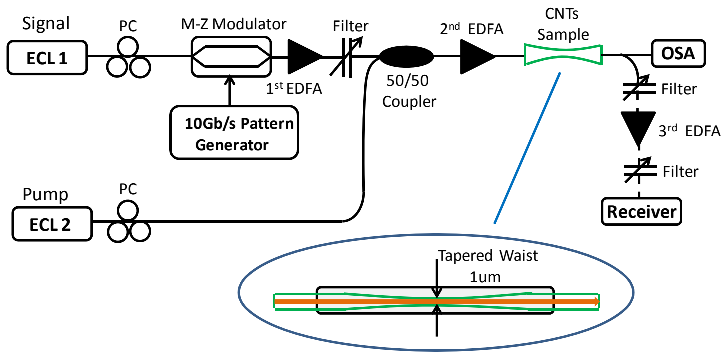

Fig. 2. Experimental setup on FWM based wavelength conversion. Inset: diagram showing an embedded tapered fiber used as a nonlinear optical device.

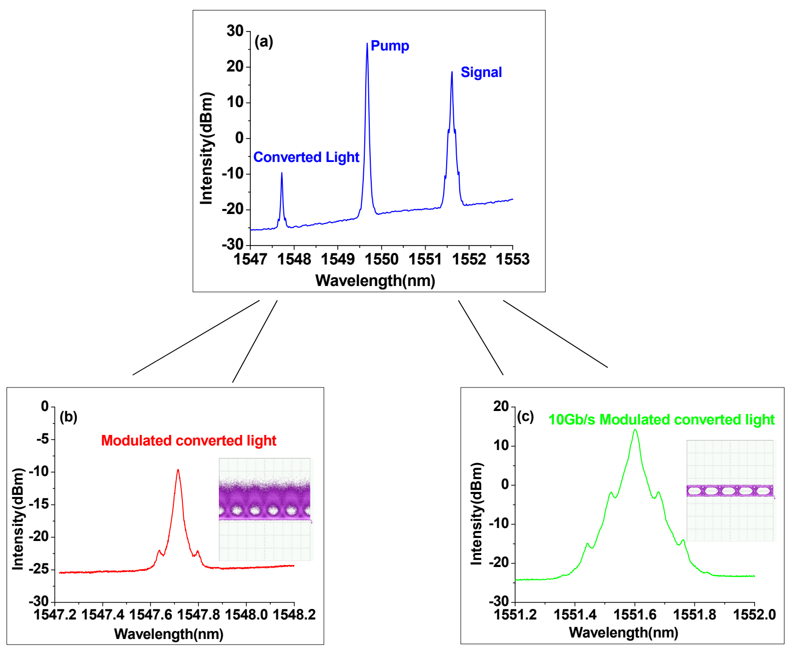

Fig. 3. (a) Four-wave mixing spectrum obtained after the CNT-polymer tapered fiber sample with input signal modulated at 10 Gb/s and the corresponding close-up views of (b) converted signal and (c) input signal. Inset (left) and (right) show the 10 Gb/s eye-diagrams of the converted and the input signal, respectively.

We define the conversion efficiency as the ratio of the converted light power to the signal power inside the CNTs-polymer coated tapered fiber. The converted signal tunability is further investigated and the relationship between the conversion efficiency and the signal light wavelength detuning against the fixed pump light is plotted in Fig. 4(a). A tuning range of around 9 nm corresponding to the 1ps response time of CNTs is obtained with a peak conversion efficiency of –27 dB. In the experimental setup, the intensity modulator is

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incorporated and very sensitive to the polarization status. The fluctuation (>5 dB) of the conversion efficiency in the Fig. 4(a) comes from the mismatching of polarization status.

Basing on Eq. (1), there is a directly proportional relationship between η and p_p^2, such linear relationship is also followed by the CNTs-polymer tapered fiber sample here studied at the lower pump power. However, due to two-photon absorption, η tends to saturates at the high pump power and the effect of two-photon absorption can be observed in Fig. 4(b). Because the pump power level for taking place the saturable absorption effect is lower than the pump power level which is responsible for the obvious FWM phenomenon (conversion efficiency >-35dB). So, the range of pump power shown in Fig. 4(b) is already in saturable absorption region, and the impacts of saturable absorption effect is linear and isn't taken into account here. Furthermore, the effective nonlinear coefficient of the CNTs in the embedded tapered fiber in our experiment is calculated to be 1816.8 $W^{-1}km^{-1}$ from the Eq. (1). The corresponding n_2 of the composite is 1.36×10^{-16} m^2/W in case of 50 μm^2 effective core area A_{eff} considering the 98% of input pump power serving as interaction power of the evanescent field using the Eq. (2) [15], where γ_{CNT} is calculated effective nonlinear coefficient of the CNTs-polymer composite coated tapered fiber, c is the velocity of light and $\omega_0 \approx 2\times10^{14}$ in the 1550nm region.

$$n_2 = \frac{\gamma_{CNT} c A_{eff}}{\omega_0} \tag{2}$$

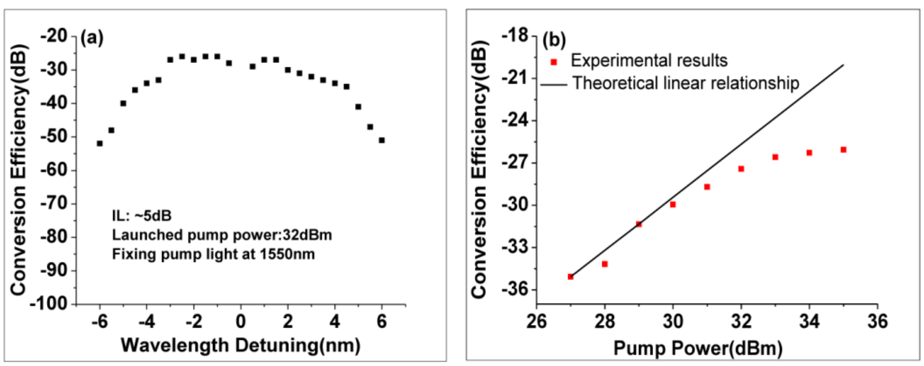

Fig. 4. Conversion efficiency against probe wavelength detuning (a) and two photon absorption(b) in CNT polymer tapered fiber sample.

4. Discussion and conclusion

The CNT-polymer coated tapered fiber device here proposed offers long-term stability and high power endurance. We did not observe any obvious degradation in the sample which was fabricated several months before and no significant damage when the launched power was as high as 36 dBm, whereas optically deposited devices degrade rapidly over time at those power levels [19]. In addition, longer interaction length of the evanescent field and lower insertion losses were achieved in the CNTs-polymer coated tapered fiber device by using the method described in section 2 and the uniformly dispersed CNTs in PTFEMA polymer as the host material [24]. Therefore, the FWM conversion efficiency of CNTs-polymer tapered fiber sample was significantly improved. Table1 shows the comparison of performances among polymer tapered fiber without CNT and CNT-polymer coated tapered fiber here discussed and previous optically deposited CNTs tapered fiber device.

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Table 1. Performances in Three Different Tapered Fiber Samples

	Polymer coated tapered fiber	CNTs-polymer coated tapered fiber	OD CNTs tapered fiber
Interaction length	5 cm	5 cm	100 μm
Insertion loss	2.2 dB	5 dB	9 dB
FWMconversion efficiency	–35 dB	–27 dB	–48 dB
Environmental stability	Stable	Stable	Easily damaged

(OD: Optically deposited)

In conclusion, FWM-based wavelength conversion of 10 Gb/s NRZ signal in tapered fiber coated with a CNTs-polymer composite has been demonstrated. Wavelength detuning was also investigated. The performance of FWM conversion efficiency, insertion loss and environmental stability were significantly improved compared with previous similar works. We believe that taper fiber type-CNT based devices are very promising for further practical wavelength conversion applications. By optimizing the CNTs concentration, polymer characteristics and taper parameters, we expect to further improve the device performance.

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