Carbon-Nanotube-Deposited PLC Waveguide for Four-Wave Mixing based Wavelength Conversion

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Abstract: We demonstrated a novel carbon-nanotube-deposited PLC waveguide for four-wave-mixing-based wavelength conversion. Tunable wavelength converted 10-Gb/s NRZ signal is achieved with 3-dB power penalty. This is the first demonstration of CNT-technology-based device for integrated photonic applications.

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

1. Introduction

Owing to its unique optical properties, single-walled carbon nanotube (CNT) technology has drawn much research attention [1-3]. Applications and studies including mode-locked lasers [4-6], ultra-fast optical response [7], and optical noise suppression [8] had been investigated. In particular, CNTs can be employed as an optical nonlinear medium due to the theoretically estimated ultra-high third-order nonlinearity [2, 4]. Recently, our group had reported four-wave mixing (FWM) based wavelength conversion using a CNT-deposited D-shaped fiber [9] as well as a CNT-deposited tapered fiber [10], which initiated the possibilities of practical nonlinear CNT devices. However, the D-shaped fiber configuration is difficult for device integration or to construct different waveguide structures. In this paper, we demonstrate FMW-based wavelength conversion using a CNT-deposited planar lightwave circuit (PLC) waveguide. Such PLC waveguides can have much flexibility of integration and fabricating special waveguide structures. As a material for generating nonlinear effects, CNTs are deposited on the over-cladding removed PLC waveguide for CNT-light interaction. Tunable FWM-based wavelength conversion is obtained with the device and a power penalty of 3 dB at 10^{-9} level is measured for 10 Gb/s non-return-to-zero (NRZ) wavelength converted signal in the bit-error-rate (BER) measurements.

2. Fabrication of CNT-deposited PLC waveguide

The CNT-deposited PLC waveguide works with the interaction between CNTs and the evanescent field of propagating light in the over-cladding removed core of the waveguide. The nonlinearity of CNTs is believed to be originated from the inter-band transitions of the π-electrons causing nonlinear polarization. In this respect the CNTs are similar to other organic optical materials such as polyacetylene or polydiacetylenes which exhibit extremely high nonlinearity [2]. Fig. 1(a) shows the schematic illustration of the adopted PLC waveguide. The waveguide is fabricated by standard silicon-based PLC fabrication process and a number of straight waveguides can be fabricated on the same PLC device. During the fabrication process, the over-cladding of the waveguides can be removed for CNT deposition on the core. In our experiment, we have adopted a PLC waveguide with 10 cm in length, 5 cm

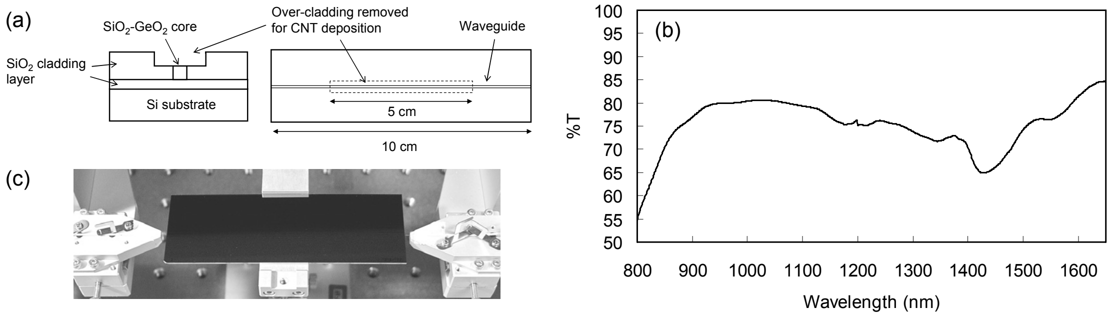

Fig. 1 (a) Schematic illustration of PLC waveguide with over-cladding removed for CNT deposition in cross-view (left) and top-view (right); (b) absorption spectrum of the deposited CNTs measured by a spectrophotometer; and (c) photo of CNT-deposited PLC waveguide with fiber coupling.

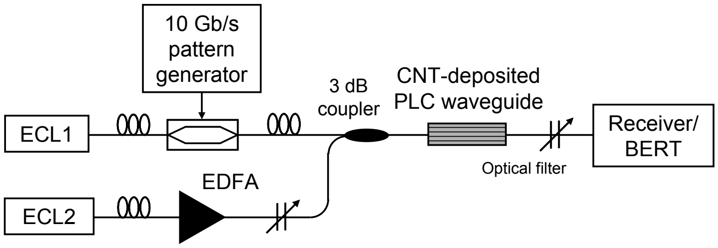

Fig. 2 Experimental setup on four-wave mixing in a CNT-deposited PLC waveguide. ECL: external cavity laser; EDFA: erbium-doped fiber amplifier; OSA: optical spectrum analyzer; BERT: bit-error rate test set.

over-cladding removed region, and a waveguide width of 7 μm. The CNTs in our experiment are made by a bulk production method called high-pressure CO conversion (HiPCO). Since the isolation of individual CNT is critical, the diameter and the diameter distribution of the CNTs are well controlled to obtain maximum nonlinearity. The CNTs are then dispersed in dimethylformamide (DMF) and only the homogeneous part is taken after the centrifugal separation. Fig. 1(b) shows the absorption spectrum of the CNTs measured by a spectrophotometer. By controlling the HiPCO process thus the nanotube diameters and the diameter distribution, the CNTs show a desirable absorption peak near 1550 nm. The device is finished by evenly spraying the prepared CNTs on the over-cladding removed region of the PLC waveguide. Fig. 1 (c) is the photo of the finished CNT-deposited PLC waveguide. The waveguide is free-space coupled to cleaved dispersion-shifted fibers with index-matching gel and the overall fiber-to-fiber insertion loss is 19 dB mainly due to the large absorption of the deposited CNTs.

3. FWM-based wavelength conversion using CNT-deposited PLC waveguide

The experimental setup on FMW in CNT-deposited PLC waveguide is shown in Fig. 2. The continuous-wave (cw) output of the wavelength tunable external cavity laser (ECL1) is modulated to be a 2^{31}-1 bits pseudorandom NRZ signal (S) at 10 Gb/s. Another cw output (P) from the ECL2 is amplified with a high power erbium-doped fiber amplifier (EDFA) with suitable ASE filtering and combined with S through a 3-dB coupler. Then the combined light is launched into the CNT-deposited PLC waveguide through free-space coupling as shown in Fig. 1(c). The launched pump (P) power into the fiber is estimated to be +25 dBm. In our experiment the pump (P) is fixed at 1550 nm and different converted wavelengths (C) are obtained by tuning the signal wavelength (S). Fig. 3(a) shows the output FWM spectrum obtained after the CNT-deposited PLC waveguide where Fig. 3(b) and 3(c) depict the close-up views of the converted signal and the input signal, respectively. From Fig. 3(b) it is observed that the generated converted signal is spectrally broadened to have a 10 Gb/s modulation characteristics corresponding to the input signal, thus confirming the generation of the converted signal is the result of wave mixing between the input signal and the pump. We define the conversion efficiency as the ratio of the idler (C) power to the signal (S) power inside the CNT-deposited PLC waveguide. Assuming the pump wavelengths are close enough and the propagation length is short, the conversion efficiency η can be approximately expressed as [11]:

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

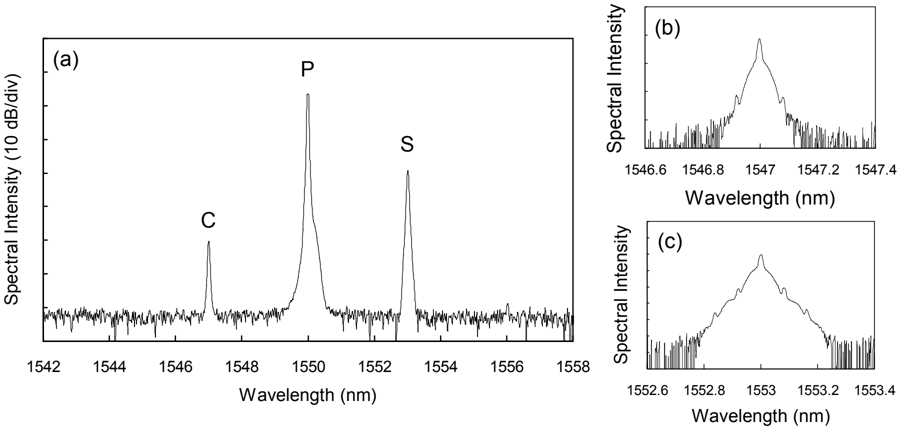

Fig. 3 (a) Four-wave mixing spectrum obtained after the CNT-deposited PLC waveguide and the corresponding close-up views of (b) converted signal and (c) input signal.

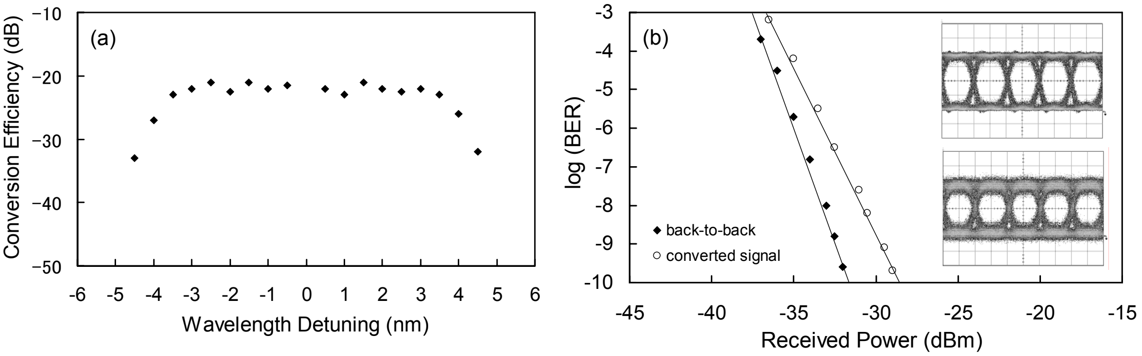

Fig. 4 Plot of (a) conversion efficiency against wavelength detuning and (b) bit-error rate against received optical power; inset (upper) and (lower) show the 10 Gb/s eye-diagrams of the input and the converted signal, respectively.

where L is the light propagation distance, γ is the effective nonlinear coefficient, and P is the pump (P) power. Form Eq. (1) the effective nonlinear coefficient of the CNT-deposited PLC waveguide in our experiment is calculated to be as high as 5.64×10^3 $W^{-1}km^{-1}$.

The relation between the conversion efficiency and the S wavelength detuning against the fixed P is plotted in Fig. 4(a). A 3-dB tunning range of around 7 nm is obtained. The performance of the FWM-based wavelength converter is further investigated by performing BER measurements. Fig. 4(b) plots the output BER against the received optical power with the inset showing the 10 Gb/s eye diagrams of the input signal and the converted signal. In this measurement the wavelengths of S and C are the same with those in Fig. 3. Note that the converted signal is obtained after the optical filter shown in Fig. 2 followed by a low noise EDFA with suitable ASE filtering in the receiver. The figure shows the results of a 3-nm down-conversion and the power penalty is measured to be around 3 dB at 10^{-9} BER level.

4. Conclusion

We have demonstrated four-wave mixing based wavelength conversion using a PLC waveguide with carbon nanotubes deposited. A power penalty of 3 dB at 10^{-9} level in the 10 Gb/s BER measurements is obtained. Due to the design fexiblity of the PLCs, future work on CNT-deposited PLCs with different waveguide structures including Mach-Zehnder interferometer is foreseeable. Since the intrinsic response time for CNT is in the order of <500fs, we expect this technology to be developed into a practical and compact all-optical functional device platform, for applications in future ultra-highspeed applications such as all-optical signal processing and optical logic gates.

5. References

[1] S. Iijima and T. Ichihashi, “Single shell carbon nanotubes of one nanometer diameter,” *Nature*, vol. 363, pp. 603-605, 1993.

[2] Vl. A. Margulis, E. A. Gaiduk, and E. N. Zhidkin, “Optical third-harmonic generation from an array of aligned carbon nanotubes with randomly distributed diameters,” *Diamond Relat. Mater.*, vol. 10, pp. 27-32, 2001.

[3] Ph. Avouris, M. Freitag, and V. Perebeinos, “Carbon Nanotube Optics and Optoelectronics”, *Nature Photonics*, vol.2, No. 6, pp. 341-350, 2008.

[4] S. Y. Set, H. Yaguchi, Y. Tanaka, and M. Jablonski, “Ultrafast fiber pulsed lasers incorporating carbon nanotubes,” *J Select. Top. Quantum Electron.*, vol. 10, No. 1, pp. 137-146, 2004.

[5] S. Yamashita, Y. Inoue, S. Maruyama, Y. Murakami, H. Yaguchi, M. Jablonski, and S. Y. Set, “Saturable absorbers incorporating carbon nanotubes directly synthesized onto substrates/fibers and their applications to mode-locked fiber lasers,” *Optics Lett.*, vol. 29, No. 14, pp. 1581-1583, 2004.

[6] J. W. Nicholson, R. S. Windeler, and D. J. DiGiovanni, “Optically driven deposition of single-walled carbon-nanotube saturable absorbers on optical fiber end-faces,” *Opt. Express*, vol. 15, pp. 9176-9183, 2007.

[7] Y. C. Chen, N. R. Raravikar, L. S. Schadler, P. M. Ajayan, Y. P. Zhao, T. M. Lu, G. C. Wang, and X. C. Zhang, “Ultrafast optical switching properties of single-walled carbon nanotube polymer composites at 1.55 μm,” *App. Phys. Lett.*, vol. 81, No. 6, pp. 975-977, 2002.

[8] S. Y. Set, H. Yaguchi, Y. Tanaka, and M. Jablonski, “A noise suppressing satiable absorber at 1550 nm based on carbon nanotube technology,” *OFC 2003*, paper FL2, Atlanta, Georgia, USA, 2003.

[9] K. K. Chow and S. Yamashita, “Four-wave mixing in a single-walled carbon-nanotube-deposited D-shaped fiber and its application in tunable wavelength conversion,” *Opt. Express*, vol. 17, pp. 15608-15613, 2009.

[10] K. K. Chow, M. Tsuji, and S. Yamashita, “Four-wave mixing based wavelength conversion in a carbon nanotubes deposited tapered fiber,” *ECOC 2009*, paper P1.13, Vienna, Austria, 2009.

[11] G. P. Agrawal, *Nonlinear Fiber Optics*, 3rd ed. New York: Academic, pp. 210-216, 2001.