AIP | Applied Physics Letters

Four-wave mixing in carbon nanotube-coated optical fiber gratings

Li-Yang Shao, Michael B. Jakubinek, Tingting Sun, Benoit Simard, and Jacques Albert

Citation: Applied Physics Letters **100**, 071108 (2012); doi: 10.1063/1.3687170
View online: http://dx.doi.org/10.1063/1.3687170
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/100/7?ver=pdfcov
Published by the AIP Publishing

APPLIED PHYSICS LETTERS **100**, 071108 (2012)

Four-wave mixing in carbon nanotube-coated optical fiber gratings

Li-Yang Shao,[1,a] Michael B. Jakubinek,[2] Tingting Sun,[1] Benoit Simard,[2]
and Jacques Albert[1]
[1]*Department of Electronics, Carleton University, 1125 Colonel By Drive, Ottawa, Ontario, K1S 5B6, Canada*
[2]*Steacie Institute for Molecular Sciences, National Research Council Canada, 100 Sussex Drive, Ottawa, Ontario K1A 0R6, Canada*

(Received 4 November 2011; accepted 24 January 2012; published online 16 February 2012)

The observation of four-wave mixing (FWM) in single-walled carbon nanotubes (SWCNTs) deposited around a tilted fiber Bragg grating (TFBG) has been demonstrated. A thin, floating SWCNT film is manually wrapped around the outer cladding of the fiber and FWM occurs between two core-guided laser signals by TFBG-induced interaction of the core mode and cladding modes. The effective nonlinear coefficient is calculated to be $1.8 \times 10^3\,\mathrm{W}^{-1}\,\mathrm{Km}^{-1}$. The wavelength of generated idlers is tunable with a range of 7.8 nm. [doi:10.1063/1.3687170]

Single-wall carbon nanotubes (SWCNTs) have drawn considerable interest and research activity due to their nonlinear properties.[1–3] Many applications have been reported with SWCNTs as nonlinear optical materials, including passively mode-locked lasers, optical noise suppression, and wavelength conversion.[4–7] In particular, SWCNTs exhibit an extremely high third-order nonlinearity which is believed to be due to interband transitions of π-electrons.[4] Such effects would be desirable in guided wave configurations and much effort has been made towards devices where SWCNTs interact with guided light through evanescent field coupling, including D-shaped fibers,[5] tapered fibers,[6] and cladding-removed planar waveguides.[7] All these devices require physical modifications of the waveguiding geometry and hence the degradation of their mechanical strength (as well as increased fabrication complexity and cost per device). Recently, our group has reported on the deposition of SWCNT on standard optical fiber claddings and investigated their ultrafast optical response using a 4° tilted fiber Bragg grating (TFBG). The TFBG couples the launched light into cladding modes, which interact with the outer SWCNT coating.[8] Here, we investigate four wave mixing (FWM) in a similar configuration where two core-guided pump waves generate idler waves that are recoupled into the core of the fiber in the forward direction. The wavelength tunability and efficiency of the conversion process are reported for this grating-based device.

A TFBG is a variant of the normal fiber Bragg grating (FBG) whose grating planes are not perpendicular to the fiber axis. This subtle variation allows the TFBG to couple the light from the single core mode to counter-propagating cladding modes. Consequently, the grating transmission response becomes highly structured with numerous cladding mode resonances in addition to the core mode resonance.[9] Figure 1 demonstrates the working principle of SWCNT-coated TFBG for FWM generation. Two laser sources (λ_1 and λ_2) are launched into the TFBG and coupled out to the fiber cladding. The evanescent fields of the two laser waves reach into the SWCNT layer, where they interact with each other and generate two new wavelengths (λ_{FWM1} and λ_{FWM2}) through the high third-order nonlinearity of the SWCNT layer. Then, the FWM signals are coupled back into the fiber core by the TFBG and appear in the transmission spectrum.

In this experiment, 1-cm-long TFBGs with a tilt angle of 10° were inscribed in hydrogen-loaded Corning SMF-28 fibers using a pulsed KrF excimer laser and the phase mask technique. For the wrapping deposition technique, a floating SWCNT film was prepared as previously described.[10] Briefly, 2 mg of purified SWCNTs were dispersed in 500 ml of 2 wt. % aqueous sodium cholate solution using sonication. SWCNT films were then produced by vacuum filtering 10 ml of suspension through cellulose acetate filter membranes (Nalgene, 47 mm diameter, 0.22 μm pore size). In this case, a rectangular mask (~7 mm× 20 mm) was placed beneath the filter membrane to produce films for wrapping. Immediately after filtration, the films are detached by submerging the filter membrane in a nanopure water bath.

The transmittance of such a film, collected on a glass slide, is shown in Figure 2. The floating films were wrapped around TFBGs by lifting the film with the optical fiber and rotating the fiber to wrap the film around the TFBG. After drying, additional SWCNT films can be wrapped around the first coating. Following this approach, a TFBG was wrapped with two films to provide a thicker coating. The inset of Figure 2 shows a scanning electron microscopy image of the edge of a cleaved fiber wrapped with a similar film. The average thickness SWCNT film used in our experiments was measured to be 60 nm by atomic force microscopy.

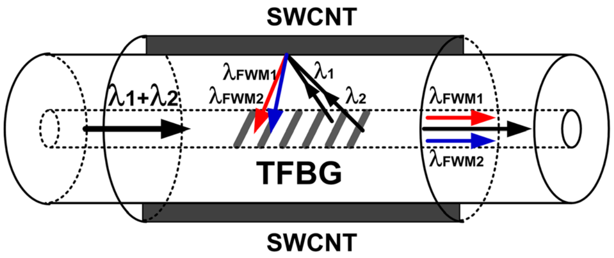

FIG. 1. (Color online) Schematic illustration of the FWM process in a SWCNT-coated TFBG.

---

[a] Author to whom correspondence should be addressed. Electronic mail: liyangshao@gmail.com.

0003-6951/2012/100(7)/071108/3/$30.00

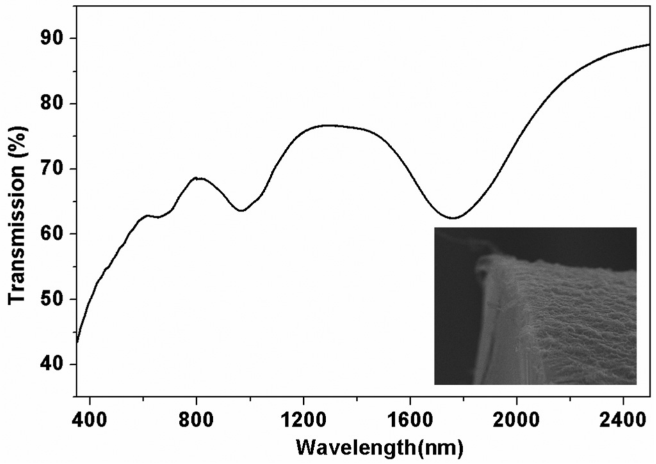

FIG. 2. Vis-NIR spectrum of a rectangular SWCNT film produced under the same conditions as the films used for TFBG wrapping. The inset depicts the SEM image of a cleaved fiber with wrapped SWCNTs.

Figure 3 depicts the spectra of a 10° TFBG without/with wrapped SWCNTs. The SWCNT layer attenuates the high order cladding mode resonances (at shorter wavelengths) because of the high refractive index of SWCNTs and the small linear absorption. The maximum insertion loss is around 5 dB near 1550 nm, indicating strong interaction of the guided light with the coating. The experimental setup for FWM in a SWCNT-wrapped TFBG is shown in Figure 4.

Two CW tunable lasers (TLS 1 and 2; λ_1 and λ_2) serve as a pump and a probe light, respectively, which were combined through a 3 dB coupler. The combined light is then launched into a high power erbium-doped fiber amplifier (EDFA, Amonics Ltd, HK) followed by two narrow band optical filters, a polarization controller (PC), and the SWCNT film-wrapped TFBG. The optical filters were employed to suppress unwanted amplified spontaneous emission (ASE) noise introduced by the EDFA. The polarization of the amplified light was adjusted by the PC to align with the TFBG. The output of the device is measured with an optical spectrum analyzer (OSA, ANDO 6137B using 0.05 nm spectral resolution).

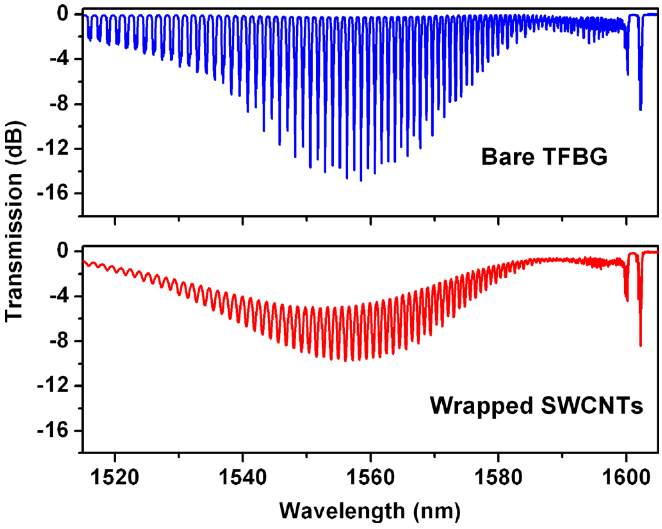

FIG. 3. (Color online) Spectra of a 10° TFBG without/with wrapped SWCNTs.

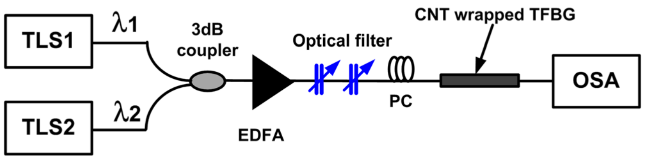

FIG. 4. (Color online) Experimental setup for FWM in a SWCNT-wrapped TFBG (see text for details).

Figure 5 shows the transmitted FWM spectrum through the SWCNT-wrapped TFBG. In the experiment, the first laser (λ_1) is fixed at 1548.6 nm and different FWM wavelengths are obtained by tuning the other laser wavelength (λ_2). The FWM conversion efficiency is defined as the ratio of the FWM signal power to the input pump laser power inside the nonlinear device. Assuming the two input laser wavelengths are close enough, the FWM conversion efficiency η can be approximately expressed by[11]

$$\eta = (\gamma P L_{eff})^2, \tag{1}$$

where L_{eff} is the effective length of the device (shorter than the physical length of the coated TFBG because of absorption), γ is the effective nonlinear coefficient, and P is the power of each pump (with equal power here). The measured pump power of the tunable laser #2 incident on the SWCNT-wrapped TFBG is 160 mW. From the grating length and propagation loss induced by the wrapped SWCNTs, L_{eff} is calculated to be 0.87 cm. The coupling efficiency of $\lambda_{\rm FWM1}$ is higher than that of $\lambda_{\rm FWM2}$, which may be caused by the ASE noise. The intensity of $\lambda_{\rm FWM1}$ is higher than that of $\lambda_{\rm FWM2}$ in the ASE spectrum of EDFA, and the optical filter cannot suppress all the ASE noise out of the wanted band. η is measured to be -52 dB based on $\lambda_{\rm FWM2}$ of the FWM spectrum shown in Figure 5. From Eq. (1), the effective coefficient of the SWCNTs wrapped TFBG is then calculated to be $1.8 \times 10^3\ \mathrm{W^{-1}\,Km^{-1}}$. Finally, the wavelength tunability of FWM spectrum is also investigated. Figure 6 shows the relationship between conversion efficiency and the input wavelength detuning of the second pump against the fixed pump. A 3 dB tuning range of around 7.8 nm is obtained.

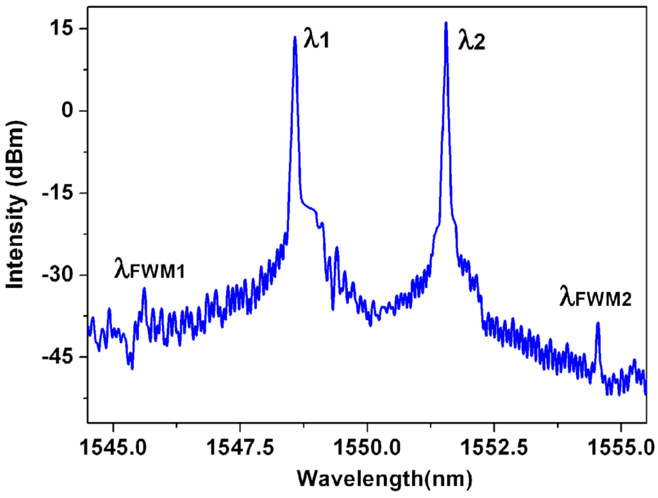

FIG. 5. (Color online) Output FWM spectrum obtained from the SWCNT-wrapped TFBG.

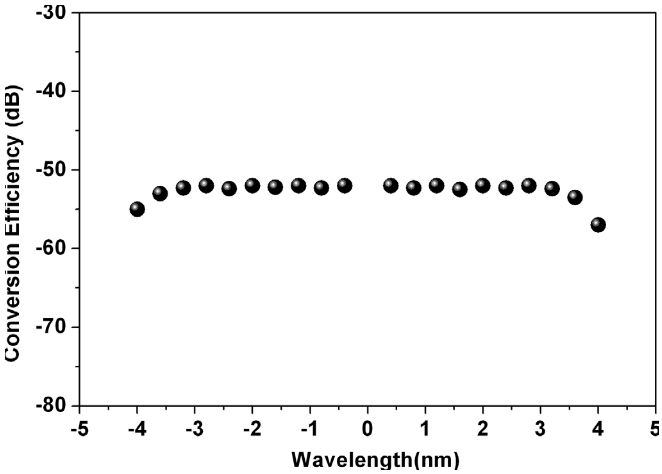

FIG. 6. FWM efficiency against detuning of one pump relative to the other.

The efficiency obtained is remarkable considering the fact that the SWCNTs are randomly oriented (but mostly tangential to the surface of the cladding) and that the generated light from the thin coating must be recoupled back into the core by the grating. Furthermore, the visible and near-infrared reflectance (VIS-NIR) spectrum shows that our SWCNTs have some diameter distribution which lowers the effective nonlinearity. It will be possible to further enhance the effective nonlinear coefficient by adopting CNTs with more precisely engineered average tube diameter (1.35 nm on average here).

In conclusion, FWM generation of core-guided light in SWCNTs wrapped around the undisturbed cladding of conventional single mode transmission fiber has been demonstrated. Up to 0.2 μW of wavelength converted light was produced with two pumps at 160 mW each, along with a 3 dB wavelength tuning range of 7.8 nm. Further work on improving the grating design and optimizing the thickness, tube diameter distribution and alignment of the SWCNTs on fiber cladding are required to allow the enhancement of FWM efficiency but these preliminary results show the significance of the TFBG technology in ultrafast wavelength conversion with nonlinear claddings.

This work is supported by the Natural Sciences and Engineering Research Council of Canada, the Canada Foundation for Innovation, the Canada Research Chairs program (J. Albert), LxDATA, the National Research Council Canada, and the National Natural Science Foundation of China under Grant No. 61007050.

[1] S. Tatsuura, M. Furuki, Y. Sato, I. Iwasa, M. Tian, and H. Mitsu, Adv. Mater. **15**, 534 (2003).
[2] S. Y. Set, H. Yaguchi, Y. Tanaka, and M. Jablonski, IEEE J. Sel. Top. Quantum Electron. **10**, 137 (2004).
[3] Y. Chen, N. Raravikar, L. Schadler, P. Ajayan, Y. Zhao, T. Lu, G. Wang, and X. Zhang, Appl. Phys. Lett. **81**, 975 (2002).
[4] A. Martinez, K. Zhou, I. Bennion, and S. Yamashita, Opt. Express **18**, 11008 (2010).
[5] K. K. Chow and S. Yamashita, Opt. Express **17**, 15608 (2009).
[6] K. K. Chow, M. Tsuji, and S. Yamashita, Appl. Phys. Lett. **96**, 061104 (2010).
[7] K. K. Chow, S. Yamashita, and S. Y. Set, Opt. Lett. **35**, 2070 (2010).
[8] G. E. Villanueva, M. B. Jakubinek, B. Simard, C. J. Oton, J. Matres, L.-Y. Shao, P. Pérez-Millán, and J. Albert, Opt. Lett. **36**, 2104 (2011).
[9] C.-F. Chan, C. Chen, A. Jafari, A. Laronche, D. J. Thomson, and J. Albert, Appl. Opt. **46**, 1142 (2007).
[10] M. B. Jakubinek, M. B. Johnson, M. A. White, J. Guan, and B. Simard, J. Nanosci. Nanotechnol. **10**, 8151 (2010).
[11] G. P. Agrawal, *Nonlinear Fiber Optics*, 3rd ed. (Academic, New York, 2001).