# Experiment study of wavelength conversion in a dispersion-flattened photonic crystal fiber

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Received February 27, 2007

Wavelength conversion based on four-wave mixing (FWM) has been demonstrated using a 40-m dispersion flattened highly nonlinear photonic crystal fiber (HNL-PCF). A conversion efficiency of −26 dB for a pump power of 19.5 dBm and a conversion bandwidth of 28 nm have been obtained, which are limited by the continuous wave (CW) laser wavelength range and tunability of optical band pass filters (OBPFs).

*OCIS codes:* 190.2620, 190.4380, 060.0060, 060.2330.

With the recent interest in phase-modulated signals for optical communication systems, a suitable wavelength conversion techniques should be found. Wavelength conversion can be achieved by using either cross-phase modulation (XPM)[1] or four-wave mixing (FWM)[2] within optical fibers. Arguably, FWM is more flexible and attractive than XPM because of its relative transparency to both bit rate and modulation format. FWM in a fiber is a phase and intensity modulation preserving process that is furthermore independent of the bit rate owing to the virtually instantaneous response of the Kerr nonlinearity of fused silica, therefore satisfying the major requirements for transparent wavelength conversion in all-optical systems[3]. In recent years, photonic crystal fibers (PCFs) have received a lot of attention owing to their exceptional properties. In contrast with conventional optical fibers, the PCFs have three main merits. Firstly, their cross-section can be optimized to obtain single-mode operation over a wide wavelength range[4]. Secondly, PCFs with a very small core can exhibit very high nonlinear properties[5]. Finally, dispersion characteristics in PCFs can be easily shaped due to the flexibility of varying air-hole size and the position in the photonic cladding[6].

In this letter, we demonstrate wavelength conversion using FWM in a 40-m-long dispersion-flattened highly nonlinear photonic crystal fiber (HNL-PCF) in internal. We measure a conversion efficiency of −26 dB and a conversion bandwidth of 28 nm respectively only limited by the continuous wave (CW) laser wavelength variety range and tunability of optical band pass filters (OBPFs).

The conversion efficiency is defined as the ratio of the converted signal power to the input signal power, which can be expressed in decibel units as

$$\text{Conversion efficiency [dB]} = 10\log(P_\mathrm{c}/P_\mathrm{s}),$$

where $P_\mathrm{c}$ and $P_\mathrm{s}$ are the powers of converted signal and the input signal, respectively. The formula used for FWM estimation was originally derived by Hill *et al.*[7] and was later reformulated to include the phase-matching dependent on efficiency by Shibata *et al.*[8],

$$\begin{aligned} P_\mathrm{c} = {} & \eta(1024\pi^6/n^4\lambda^2c^2)(3\chi_{1111})^2 \\ & \times(L_\mathrm{eff}/A_\mathrm{eff})^2P_\mathrm{p}^2P_\mathrm{s}\exp(-\alpha L). \end{aligned} \tag{1}$$

To evaluate the degenerated FWM, Eq. (1) can be written as[9]

$$P_\mathrm{c} = (\gamma P_\mathrm{p}L_\mathrm{eff})^2\cdot P_\mathrm{s}\mathrm{e}^{-\alpha L}\cdot\eta, \tag{2}$$

where $L$ is the fiber length, $n$ the refractive index of the core, $c$ the light velocity in free space, $\chi_{1111}$ the third-order nonlinear susceptibility, $\lambda$ the wavelength, $A_\mathrm{eff}$ the effective area, $\alpha$ the fiber attenuation coefficient, $P_\mathrm{p}$ and $P_\mathrm{s}$ are the powers of pump and signal, respectively. The $L_\mathrm{eff}$ is the effective interaction length given as

$$L_\mathrm{eff} = (1-\mathrm{e}^{-\alpha L})/\alpha. \tag{3}$$

And the optimum fiber length is[10]

$$L_\mathrm{opt} = \ln(3)/\alpha. \tag{4}$$

Furthermore, $\eta$ is the FWM efficiency, which can be expressed as

$$\eta = \frac{\alpha^2}{\alpha^2+\Delta\beta^2}\left(1+\frac{4\mathrm{e}^{-\alpha L}}{(1-\mathrm{e}^{-\alpha L})}\sin^2\left(\Delta\beta\frac{L}{2}\right)\right), \tag{5}$$

here $\Delta\beta$ is the propagation constant difference written as

$$\Delta\beta = \beta_\mathrm{c}+\beta_\mathrm{s}-2\beta_\mathrm{p}. \tag{6}$$

Applying Eqs. (2), (4), and (5), we can get the $P_\mathrm{c}$ and then the conversion efficiency can be written as[9]

$$\begin{aligned} & \text{Conversion efficiency} \\ & = \frac{P_\mathrm{c}}{P_\mathrm{s}} \approx \frac{4}{27}\left(\frac{c^2\cdot n_2\cdot P_\mathrm{p}}{\lambda_\mathrm{s}^5A_\mathrm{eff}\cdot\Delta f^3\cdot \mathrm{d}D/\mathrm{d}\lambda}\right). \end{aligned} \tag{7}$$

The experimental setup is shown in Fig. 1. An optical transceiver served as pump and a wavelength-tunable CW laser served as signal. The pump wavelength was set to 1552 nm. In order to suppress stimulated Brillouin scattering (SBS), the pump spectrum was broadened by a phase modulator (PM). Then the pump was amplified by a high power conventional erbium-doped fiber amplifier (EDFA), with 30-dBm maximum output power. The fiber we used is a dispersion flattened HNL-PCF with a nonlinear coefficient of $\gamma = 11\ \mathrm{W^{-1}\cdot km^{-1}}$, and

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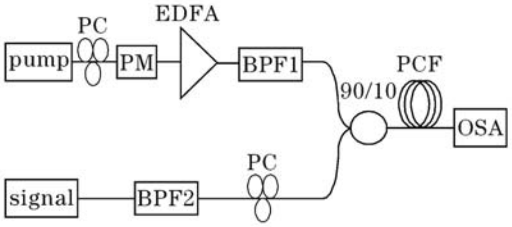

Fig. 1. Experimental setup for the wavelength conversion. PC: Polarization controller; PM: phase modulator; EDFA: erbium-doped fiber amplifier; BPF1 and BPF2: band-pass filters; PCF: dispersion flattened photonic crystal fiber; OSA: optical spectrum analyser.

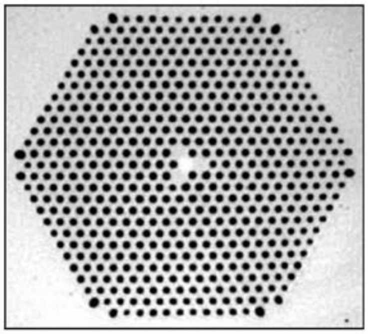

Fig. 2. Electromicrograph of the fiber.

the dispersion slope is 0.03 ps/(nm$^2$·km). The electromicrograph of the fiber is shown in Fig. 2. The attenuation of the 40-m HNL-PCF is < 19 dB/km, using Eq. (3), the $L_{\rm eff}$ is about 35 m or longer, so the length of the fiber used is suitable for our experimental setup. Signal and pump were combined by a 90/10 coupler with 0.46-dB insertion loss for the pump and 9.8-dB insertion loss for the signal. The states of polarization of both the signal and the pump were optimized by adjusting the PC in order to ensure the highest conversion efficiency. At the output of the PCF, we can get the spectra of the signal, pump, and the converted wavelength from the optical spectra analyser (OSA).

The observed wavelength conversion spectrum is shown in Fig. 3. The pump wavelength is 1552 nm. The pump power before being lunched into the PCF is measured to be about 19 dBm. The signal wavelength and power are 1562.2 nm and −15 dBm, respectively.

As shown in Fig. 3, the converted signal wavelength is 1541.8 nm. Then we adjust the polarization controller to change the polarization states of the signal and the pump. We find that the converted peak power fluctuates evidently with the tuning of the polarization controller, when the converted peak power is the maximum, a −26-dB conversion efficiency is obtained, and sometimes, the converted peak even disappears. Therefore, this wavelength conversion is polarization sensitively.

Figure 4 shows the relationship between the conversion efficiency and the converted output wavelength. As shown in Fig. 4, 3-dB tuning range over 28 nm is obtained from 1539 to 1567 nm, and the fluctuation in the conversion efficiency is less than 2 dB. It shows that the peak conversion efficiency is about −26 dB and is flat over a 28-nm bandwidth.

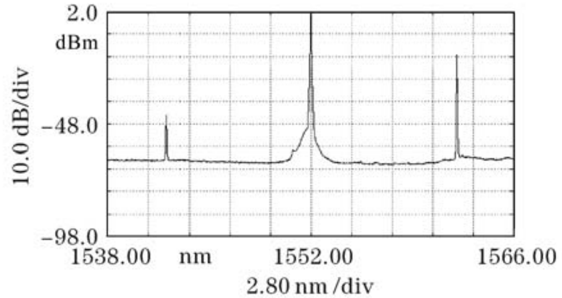

Fig. 3. Wavelength conversion spectrum. Pump wavelength is set to 1552 nm, while the signal wavelength is 1562.2 nm.

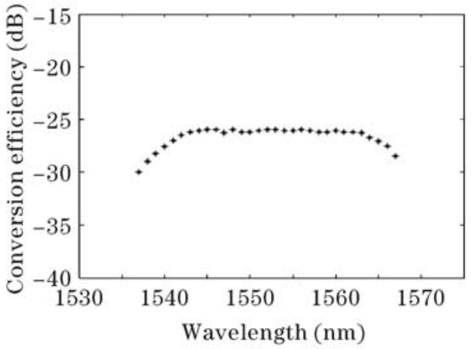

Fig. 4. Measured conversion efficiency versus the signal wavelength.

In this paper, wavelength conversion in a HNL-PCF based on FWM is demonstrated. The conversion efficiency is measured to be about −26 dB and the 3-dB conversion bandwidth is about 28 nm. Furthermore, the converter has a polarization sensitive property.

This work was supported by the National Natural Science Foundation of China (No. 60678043) and Beijing Education Committee Common Build Foundation (No. XK100130637). Q. Wang's e-mail address is wangqiuguo0101@sina.com.

## References

1. B.-E. Olsson, P. Öhlén, L. Rau, and D. J. Blumenthal, IEEE Photon. Technol. Lett. **12,** 846 (2000).
2. O. Aso, S. Arai, T. Yagi, M. Tadakuma, Y. Suzuki, and S. Namiki, Electron. Lett. **36,** 709 (2000).
3. K. Inoue and H. Toba, IEEE Photon. Technol. Lett. **4,** 69 (1992).
4. T. A. Birks, J. C. Knight, and P. St. J. Russell, Opt. Lett. **22,** 961 (1997).
5. R. Hainberger and S. Watanabe, IEEE Photon. Technol. Lett. **17,** 70 (2005).
6. L. P. Shen, W.-P. Huang, G. X. Chen, and S. S. Jian, IEEE Photon. Technol. Lett. **15,** 540 (2003).
7. K. O. Hill, D. C. Johnson, B. S. Kawasaki, and R. I. MacDonald, J. Appl. Phys. **49,** 5098 (1978).
8. N. Shibata, R. P. Braun, and R. G. Waarts, IEEE J. Quantum Electron. **23,** 1205 (1987).
9. B. Batagelj, in *Proceedings of 2nd International Conference on Transparent Optical Networks* 179 (2000).
10. K. Kihuclii and C. Lorattanasane, IEEE Photon. Technol. Lett. **6,** 992 (1994).