

All-optical regeneration based on highly nonlinear photonic crystal fiber

Yongzhao XU¹, Yanfen WEI (✉)², Xiaomin REN³, Xia ZHANG³, Yongqing HUANG³

¹ Department of Electronic Engineering, Dongguan University of Technology, Dongguan 523808, China

² Tianjin Mobile Corporation Company, Tianjin 300021, China

³ Key Laboratory of Optical Communication and Lightwave Technologies, Ministry of Education, Beijing University of Posts and Telecommunications, Beijing 100876, China

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Abstract An all-optical regeneration based on self-phase modulation in a highly nonlinear photonic crystal fiber is proposed. The dispersion and nonlinearity properties of a series of photonic crystal fibers are analyzed, and the results show that the nonlinearity coefficient is closely related to the structure of the fiber. In this paper, the nonlinearity coefficient is increased by reducing the effective mode area, and a highly nonlinear photonic crystal fiber with a large air-filling fraction is used as nonlinearity medium in optical regeneration. The numerical results show that good optical regeneration results can be obtained by using a relatively short fiber length due to the high nonlinearity of the fiber. The input peak power launched into the photonic crystal fiber and the parameters of the filter have much influence on optical regeneration. To achieve good optical regeneration, those parameters need to meet certain requirements. Furthermore, the transfer characteristic of the regenerator is also discussed. By adjusting the input peak power and filter parameters, the regenerator can deal with input pulses of different pulse widths.

Keywords fiber optics and optical communications, photonic crystal fiber, optical regeneration, self-phase modulation

1 Introduction

Photonic crystal fibers (PCFs), also called holey fibers, have attracted significant attention [1–6] in recent years. They commonly consist of a fused silica core surrounded by a regular array of air holes running along the fiber length. PCFs have advantages of design flexibility in

controlling dispersion and nonlinearity by altering the size and arrangement of air holes. These fibers also have extraordinary properties [7–10] such as special dispersion and high or low nonlinear effects. Therefore, PCFs already have important applications in nonlinear fiber optics, optical communication and many other fields [11–17].

In optical communication, signal gets distorted because of noise, dispersion and other factors, and the distortion accumulates with the transmission distance. To restore the quality of the signal, the distorted signal needs to be regenerated. The conventional way of regenerating is to convert optical signal to electric signal, and then regenerate the distorted signal in an electrical domain and convert it back to optical form. However, this technology is not transparent to optical signal due to the limitation of the electronic processing speed. All-optical regeneration, or regenerating signals in an optical domain, can avoid such a problem, which makes it a promising technology in the next generation of all-optical networks.

In this paper, a highly nonlinear PCF is used as the nonlinear medium, and the feasibility of all-optical regeneration based on self-phase modulation (SPM) in the PCF is studied.

2 Fiber characterization

The nonlinearity of a fiber is commonly measured by its nonlinearity coefficient γ , defined as

$$\gamma = 2\pi n_2 / \lambda A_{\text{eff}}, \quad (1)$$

where n_2 is the nonlinearity coefficient of the fiber, A_{eff} is the effective mode area, and λ is the optical wavelength. A_{eff} depends on fiber parameters such as the core radius and the core-cladding index difference. One way in which the nonlinearity of PCFs can be enhanced is to reduce the effective mode area by using a smaller diameter core.

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E-mail: yanfenwei@gmail.com

High nonlinearity can be obtained by using PCF with a particular arrangement of air holes and defects.

A triangular lattice silica-air PCF, one of the most commonly used air-hole patterns with the hole diameter d and pitch Λ , is considered. The absence of the air hole in the center forms the fiber core at which light can be confined. PCFs with the pitch $\Lambda = 2.3 \mu\text{m}$ and different air-filling factor d/Λ are simulated. The finite difference time domain method (FDTD) [18] is used to analyze the properties of the PCFs. Figure 1 shows the calculated dispersion as a function of wavelength for d/Λ ranging from 0.2 to 0.8. It indicates that the dispersion curve moves upwards when d/Λ increases. Figure 2 shows the calculated A_{eff} and nonlinearity coefficient γ as a function of d/Λ at a wavelength of 1550 nm. It is noted that with d/Λ increasing, A_{eff} decreases and correspondingly the nonlinearity coefficient γ increases. That is because for the large air-filling fraction pattern, the field is strongly confined to the region of the fiber core and decays rapidly inside the first row of holes. When d/Λ is 0.8, γ is

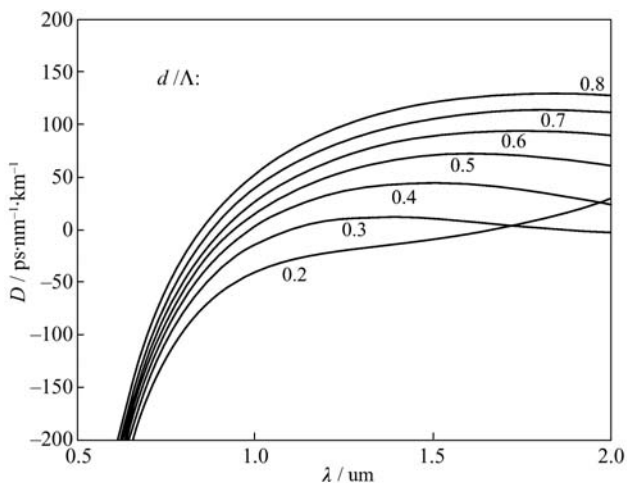


Fig. 1 Dispersion as a function of wavelength for $\Lambda = 2.3 \mu\text{m}$ and d/Λ ranging from 0.2 to 0.8

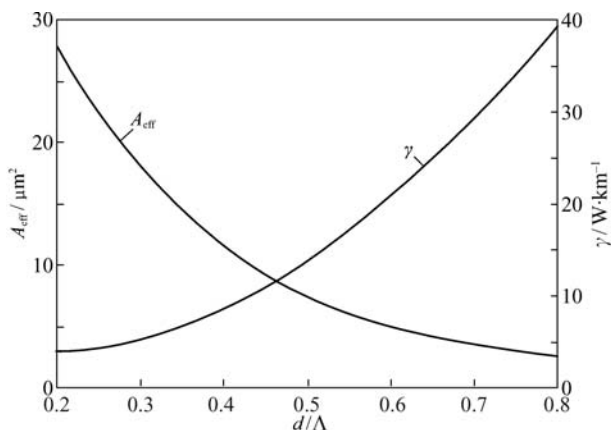


Fig. 2 Effective mode area A_{eff} and nonlinearity coefficient γ as a function of d/Λ

calculated to be $40 \text{ W}^{-1}\cdot\text{km}^{-1}$, and the corresponding dispersion is $123 \text{ ps}/(\text{nm}\cdot\text{km})$ at 1550 nm . This PCF is thus used as the nonlinear medium, and SPM-based all-optical regeneration in the PCF is studied.

3 All-optical regeneration based on SPM in highly nonlinear PCF

3.1 Principle

The principle of all-optical regeneration based on SPM is shown in Fig. 3. The distorted return to zero input signals passes through a PCF after being amplified. It is then filtered by a band-pass filter (BPF) which is offset from the input center wavelength. The signal spectrum broadens due to the SPM effect. Since low power noise experiences only limited SPM-induced spectral broadening, it is filtered out by the BPF, whereas pulses experiencing sufficient spectral broadening can be partially transmitted through the BPF. This leads to a noise reduction, suppression of the amplitude fluctuations and a restoration of the signal pulses.

3.2 Results and discussion

Here the regeneration of 10 ps (FWHM) Gaussian pulses at 1550 nm with a bit rate of 10 Gbit/s is considered. The fiber used in the optical regeneration is an anomalous dispersion PCF with dispersion $D = 123 \text{ ps}\cdot\text{nm}^{-1}\cdot\text{km}^{-1}$, $\gamma = 40 \text{ W}^{-1}\cdot\text{km}^{-1}$ and fiber length $L = 10 \text{ m}$.

Figures 4(a) and 4(b) show the waveform and spectrum of the initial signal respectively, and Fig. 5 shows the damaged signals after transmission. It indicates that the signal is badly damaged with its fluctuating amplitude and distorted shape.

To regenerate the optical signal, the damaged signal is first amplified to 10 W by an erbium-doped fiber amplifier (EDFA) and then launched into the PCF. After passing through the PCF, the signal experiences a large spectral broadening due to SPM as shown in Fig. 6. Then it is filtered by a Gaussian BPF which is offset by 1 nm from the input center wavelength. As for an unchirped Gaussian pulse of any width, the product of its spectral width and temporal width $\Delta\nu\cdot\Delta t$ approximately equals 0.44 [19]. So the bandwidth of the BPF should be set to 0.35 nm (44 GHz) to regenerate a 10 ps Gaussian pulse. Figure 7 shows the regenerated signal with an FWHM bandwidth of 9.98 ps , which is very close to that of the initial signal. It is evident that the noise in the signal is significantly suppressed and amplitude fluctuations are also eliminated.

3.3 Effect of filter parameters on all-optical regeneration

The parameters of the filter have a great influence on the performance of all-optical regeneration. For a Gaussian

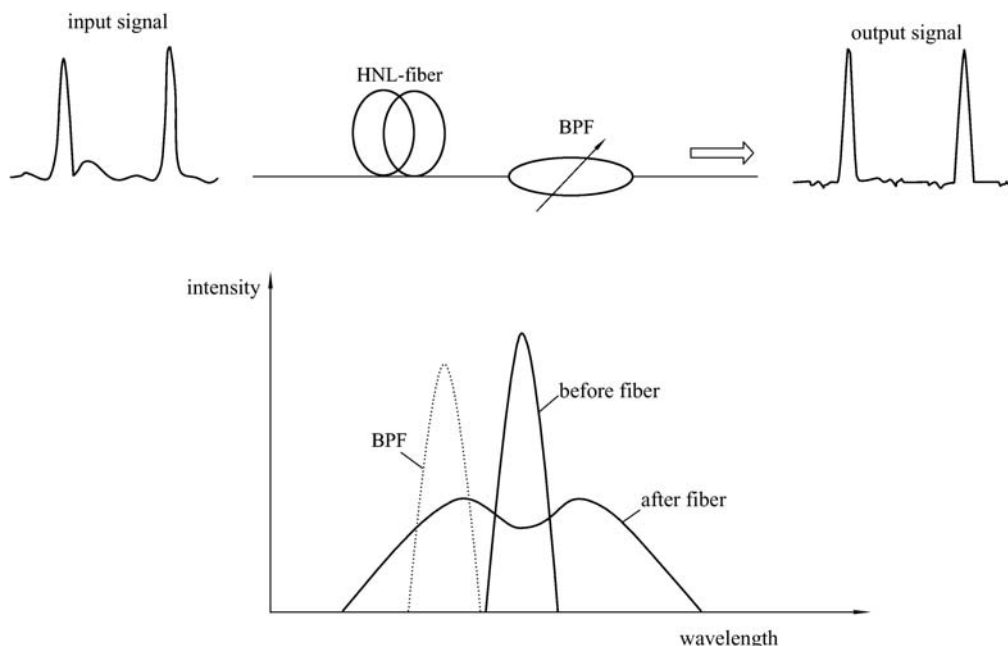


Fig. 3 Principle of self-phase modulation based optical regeneration (BPF: band-pass filter, HNL-fiber: high nonlinear fiber)

type BPF, its transfer function is $H(\omega) = \exp[-(\omega - \omega_0)^2 / \delta\omega^2]$, where the center frequency ω_0 and bandwidth $\delta\omega$

are the two parameters that can be chosen to optimize regeneration performance.

For a transform-limited pulse [20], the pulse width of the regenerated signal is determined by the filter bandwidth. Thus only the center frequency ω_0 is adjustable for a given input pulse width.

Figure 8 presents the regeneration of 10 ps signals with different filter offsets when the peak power into the fiber is fixed. It shows that the regenerated signal is bad when filter offset is smaller than 0.3 nm, as noisy signals enter the filter and cannot be filtered out when the filter offset is too small. As filter offset increases, the amplitude fluctuation and the pedestal of the regenerated signal become smaller. When filter offset exceeds 0.8 nm, the amplitude fluctuation can be neglected and the pulse pedestal disappears. To get the regenerated signal, the

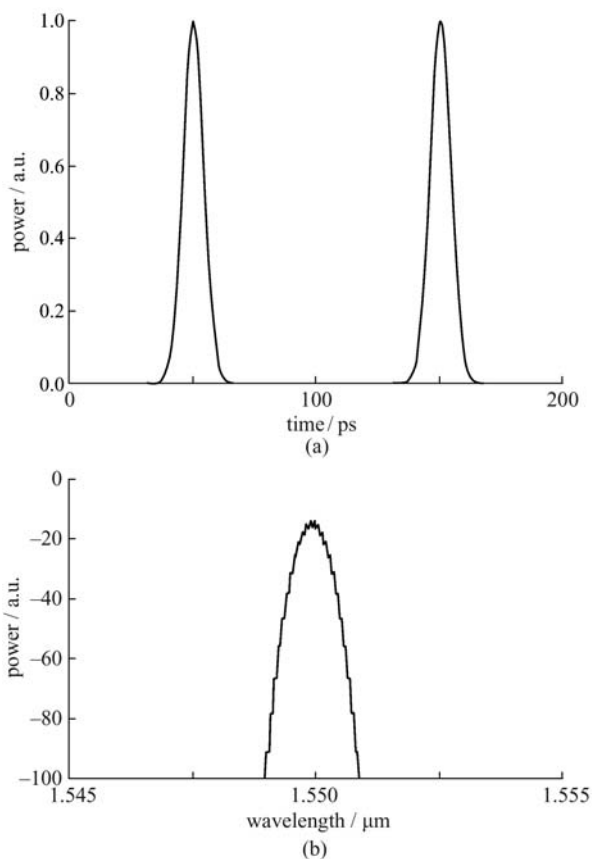


Fig. 4 Waveform and spectrum of initial signal. (a) Waveform of the initial signal; (b) spectrum of the initial signal

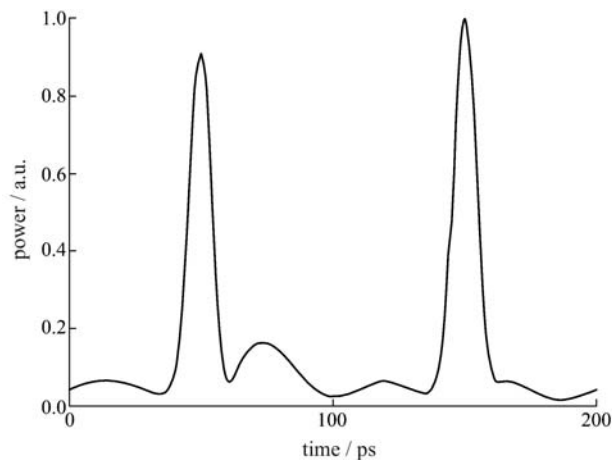


Fig. 5 Damaged signals after transmission

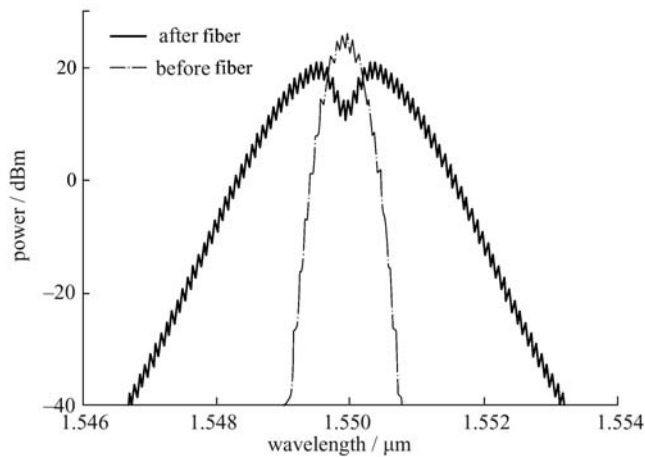


Fig. 6 Broadened spectrum due to SPM after passing through PCF

filter offset thus needs to exceed a critical value. However, if the filter offset is tuned outside the broadened spectrum, no regenerated signals can be transmitted through the BPF.

To regenerate the pulses with a different width, the bandwidth of the filter needs to be changed correspondingly.

3.4 Transmission characteristics of the regenerator

When pulse width is kept with $T_{FWHM} = 10$ ps, filter center wavelength $\lambda_0 = 1551$ nm, filter bandwidth $\delta\lambda = 0.35$ nm, and the transfer characteristics of the regenerator are studied. Figure 9 shows the power transfer function of the regenerator as a function of input peak power. It shows that the output peak power is close to zero when the input peak power is very small. This is because the SPM-broadened spectrum is not broad enough to transmit through the BPF. Figure 10 shows the broadened spectra and the regenerated signals for the input peak powers of 10 mW and 1.5 W respectively. When the input peak

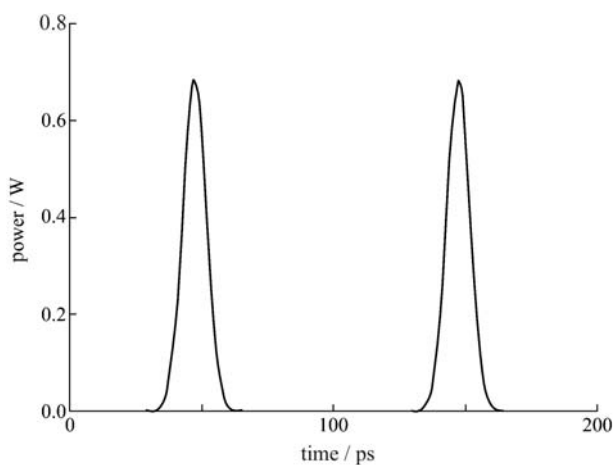


Fig. 7 Waveform of regenerated pulses

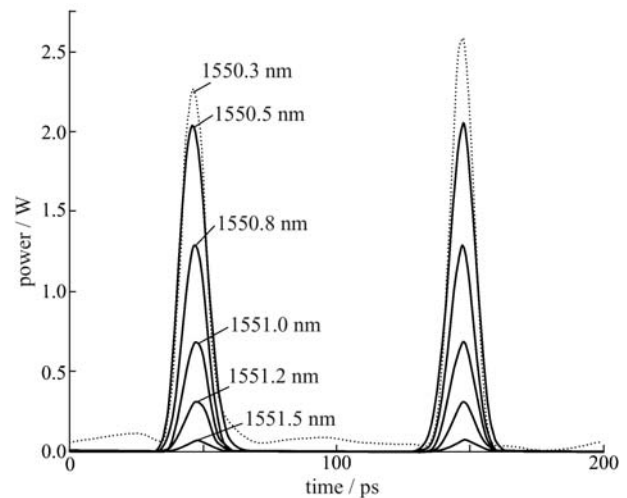


Fig. 8 Regenerated pulses with different filter offsets

power is 10 mW, the regenerator performance is bad, and when the input peak power reaches 1.5 W, good regenerator performance can be achieved.

From Fig. 9 it is also noted that the output peak power increases rapidly when the input peak power reaches a certain value. With the input peak power increasing, there is an intense oscillation in the transfer function curve, since spectrum broadening is accompanied with an intense oscillatory structure (Fig. 11).

4 Conclusions

The effects of fiber structure parameters on fiber dispersion and fiber nonlinearity in a series of PCFs have been analyzed. A highly nonlinear PCF with a large air-filling ratio is used as the nonlinear medium in SPM-based all-optical regeneration. The results show that a better

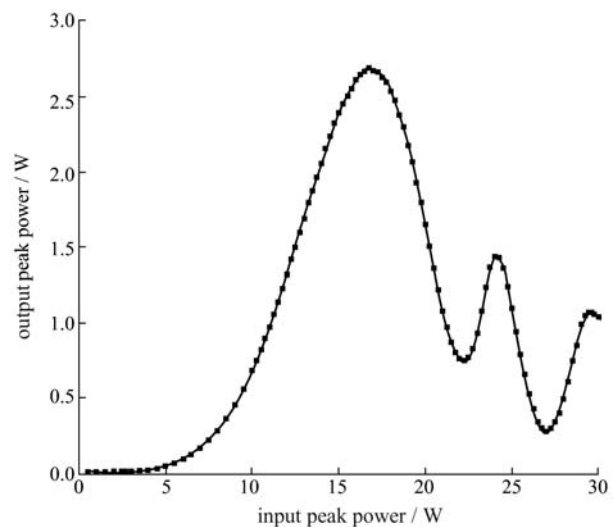


Fig. 9 Transfer function of optical regenerator

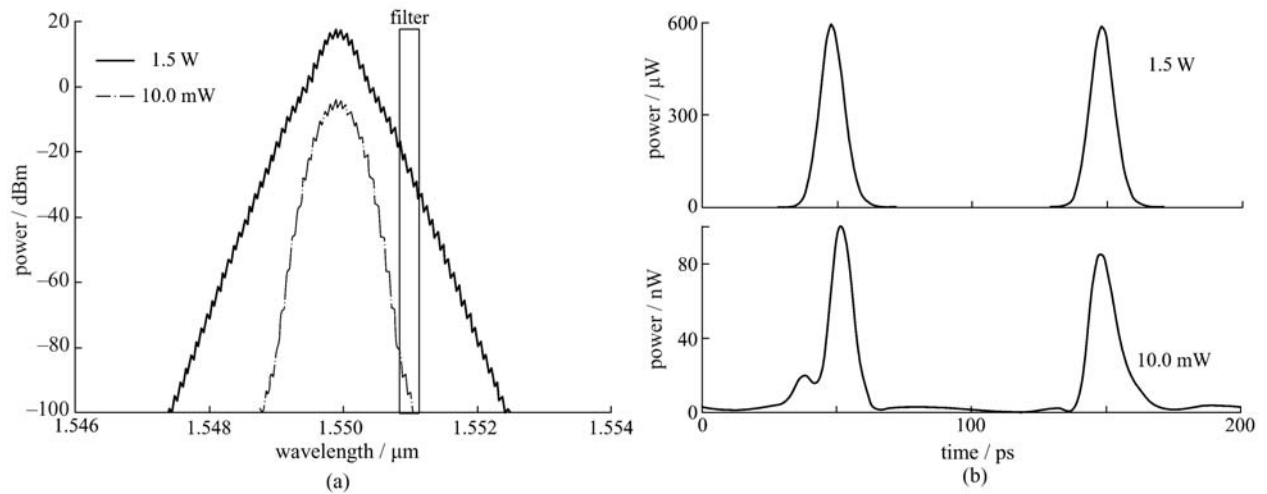


Fig. 10 Comparison of two regeneration results for input peak powers of 10 mW and 1.5 W. (a) Broadened spectra; (b) regenerated signals

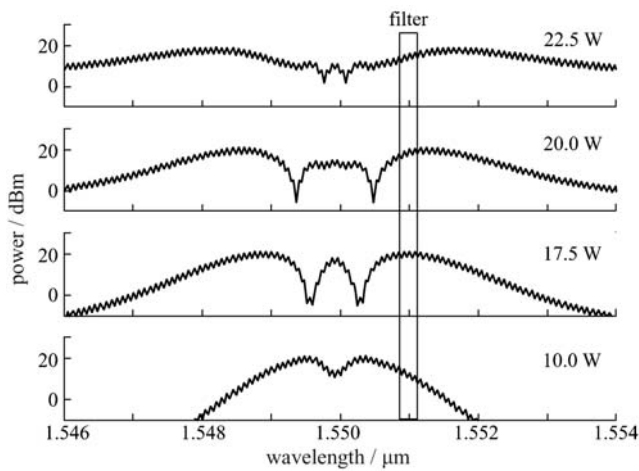


Fig. 11 Broadened spectra entering the filter with increased input peak powers

regeneration result can be achieved with a relatively short fiber length because of the high nonlinearity of the PCF. The filter center wavelength, filter bandwidth and input peak power have great influence on regeneration performance. To achieve a better regeneration result, the right filter parameters need to be chosen and the input peak power must meet certain requirements at the same time. By adjusting input peak power and filter parameters, the regeneration of input pulses with different widths can be achieved.

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References

1. Russell P. Photonic crystal fibers. *Science*, 2003, 299(5605): 358–362
2. Zhang C S, Kai G Y, Wang Z, et al. Influence of lateral pressure on phase and group modal birefringence in

microstructure fiber. *Acta Optica Sinica*, 2006, 26(2): 171–175 (in Chinese)

3. Zhang X, Wang Z N, Yang G Q, et al. Birefringence in squeezed hexagonal lattice microstructure fiber. *Acta Optica Sinica*, 2006, 26(1): 25–28 (in Chinese)
4. Wu J Q, Xue W R, Zhou G S. Dispersion property analysis of square-lattice varying microstructured optical fiber. *Acta Optica Sinica*, 2005, 25(2): 174–178 (in Chinese)
5. Liu Y Y, Hou L T, Li Q J, et al. Measurement of photon localization in micro-structure optical fibers using coherent back scattering. *Chinese Journal of Lasers*, 2006, 33(3): 343–346 (in Chinese)
6. Zhou Q L, Lu X Q, Qiu J R, et al. Beam-shaping microstructure optical fiber. *Chinese Optics Letters*, 2005, 3(12): 686–688
7. Lou S Q, Wang Z, Ren G B, et al. Polarization properties of elliptical core photonic crystal fiber. *Journal of Optoelectronics · Laser*, 2004, 15(9): 1021–1025 (in Chinese)
8. Birks T A, Knight J C, Russell P. Endlessly single mode photonic crystal fiber. *Optics Letters*, 1997, 22(13): 961–963
9. Knight J C, Arriaga J, Birks T A, et al. Anomalous dispersion in photonic crystal fiber. *IEEE Photonics Technology Letters*, 2000, 12(7): 807–809
10. Broderick N G R, Monro T M, Bennett P J, et al. Nonlinearity in holey optical fibers: measurement and future opportunities. *Optics Letters*, 1999, 24(20): 1395–1397
11. Zhang X, Yang G Q, Huang Y Q, et al. Researches on all-optical wavelength conversion in highly nonlinear microstructure fibers. *Journal of Optoelectronics · Laser*, 2005, 16(10): 1211–1213 (in Chinese)
12. Song X P, Chen B, Lin J F, et al. Supercontinuum generation in multi-core microstructure fiber. *Chinese Journal of Lasers*, 2006, 33(8): 1066–1068 (in Chinese)
13. Abedin K S, Kubota F. Wavelength tunable high-repetition-rate picosecond and femtosecond pulse sources based on highly nonlinear photonic crystal fiber. *IEEE Journal of Selected Topics in Quantum Electronics*, 2004, 10(5): 1203–1210
14. Abedin K S. Nonlinear optical loop mirror with highly birefringent polarization-maintaining photonic crystal fiber for walk-off free wavelength conversion over 150 nm. In: *Proceedings of Conference on Lasers and Electro-Optics (CLEO2004)*, 2004, 2: 16–21

15. Andersen P A, Tokle T, Geng Y, et al. Wavelength conversion of a 40-Gb/s RZ-DPSK signal using four-wave mixing in a dispersion-flattened highly nonlinear photonic crystal fiber. *IEEE Photonics Technology Letters*, 2005, 17(9): 1908–1910
16. Her T H, Raybon G, Headley C. Optimization of pulse regeneration at 40 Gb/s based on spectral filtering of self-phase modulation in fiber. *IEEE Photonics Technology Letters*, 2004, 16(1): 200–202
17. Li Y F, Hu M L, Wang Q Y. Supercontinuum generated from photonic crystal fiber and its applications. *Journal of Optoelectronics · Laser*, 2003, 14(11): 1240–1243 (in Chinese)
18. Qiu M. Analysis of guided modes in photonic crystal fibers using the finite-difference time-domain method. *Microwave Optics Technology Letters*, 2001, 30(5): 327–330
19. Agrawal G P. *Nonlinear Fiber Optics & Applications of Nonlinear Fiber Optics* (in Chinese, trans. Jia Dongfang, Yu Zhenhong, Tan Bin, et al.). Beijing: Publishing House of Electronics Industry, 2002, 42–59
20. Mamyshev P V. All-optical data regeneration based on self-phase modulation effect. In: *Proceedings of the 24th European Conference on Optical Communication (ECOC'98)*, Madrid Spain. 1998, 1: 475–476