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REVIEW ARTICLE

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Enhanced nonlinear effects in photonic crystal fibers

Abstract Photonic crystal fibers are a new class of single-material optical fibers with wavelength-scale air holes running down the entire fiber length. Photonic crystal fibers were first developed in 1996 and have subsequently been the focus of increasing scientific and technological interest in the field of fiber optics. The manufacturing, principles, basic properties, and some applications of photonic crystal fibers are briefly described in this paper. A review of our recent work on the nonlinear effects in photonic crystal fibers is presented, and special emphasis is placed on such effects as supercontinuum generation, frequency conversion, and solitons observed when femtosecond light pulses propagate in these fibers.

Keywords photonic crystal fiber, holey fiber, microstructure fiber, nonlinear effects, femtosecond light pulses

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1 Introduction

Photonic crystal fibers (PCFs) , also know as holey fibers (HFs) or microstructure fibers (MFs), are a new class of single-material optical fibers with wavelength-scale air holes running down the entire fiber length. The idea of arranging periodic air holes in the fiber cladding originated from the concept of photonic crystals proposed by Yablonovitch [1] and John [2] in 1987. It is known that due to Bragg-like diffraction the periodic potential induced by the periodic arrangement of atoms in electronic crystals creates electronic bandgaps for electrons. Various electronic devices result from the control of the motion of electrons by the energy bands and bandgaps. Similarly, by light scattering, photonic crystals, which are periodic dielectric media, can present photonic bandgaps for photons. Photons whose frequency range is within the bandgap are forbidden to propagate in the periodic medium. When a defect is introduced into the otherwise periodic structure, light can be localized at the defect or propagate down the defect, and thus the behavior of light can also be manipulated [3]. PCFs as two-dimensional photonic crystal waveguides were first proposed by Russell's group at the University of Bath in 1995 [4] and realized in 1996 [5]. However, in spite of the fact that the first reported PCF did not guide light by the photonic bandgap effect and the first photonic bandgap fiber was not demonstrated until 1998 [6], some intriguing properties different from and even superior to those of conventional optical fibers (COFs) have been found from PCFs and used to advantage [7]. Therefore, PCFs are currently of increasing scientific and technological interest in the field of fiber optics [8, 9].

In this review, the nonlinear effects in PCFs are highlighted and the paper is organized as follows. In Section 2, we briefly describe the manufacturing, principles, basic properties, and some applications of PCFs. The experimental setup we adopted is shown in Section 3. In the next three sections, we report on our recent work on supercontinuum generation, frequency conversion, and soliton effects in PCFs, respectively. Comments are made on the applications of these nonlinear effects in Section 7. Section 8 concludes this paper.

2 Manufacturing, properties, and applications of photonic crystal fibers

The first reported PCF was based on a two-dimensional triangular lattice with a solid defect, which did not guide light by the photonic bandgap effect but by modified total

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internal reflection (MTIR) because the periodic air holes effectively lowered the refractive index of the cladding as compared to the solid core [5]. The PCF was produced by the so-called stack-and-draw method, which typically involves stacking capillary tubes and rods into the desired preform and subsequent drawing of the preform into the fiber. This method first adopted in Ref. [5] has become a standard technique for drawing air-silica PCFs. Other techniques [10] like extrusion have also been developed for producing PCFs based on other materials such as soft glass [11] and polymer [12]. The manufacturing techniques available have made PCFs with different structures possible. In particular, it was found that PCFs with a random hole distribution can also guide light by MTIR [13]. Thus, alternative names for PCFs like HFs and MFs were also coined. From an operating principle point of view, however, these fibers are either index-guiding or bandgap-guiding. Fig. 1 shows typical examples of these two types of PCFs. In the present paper, we just concentrate on the first type, namely, PCFs that guide light by MTIR.

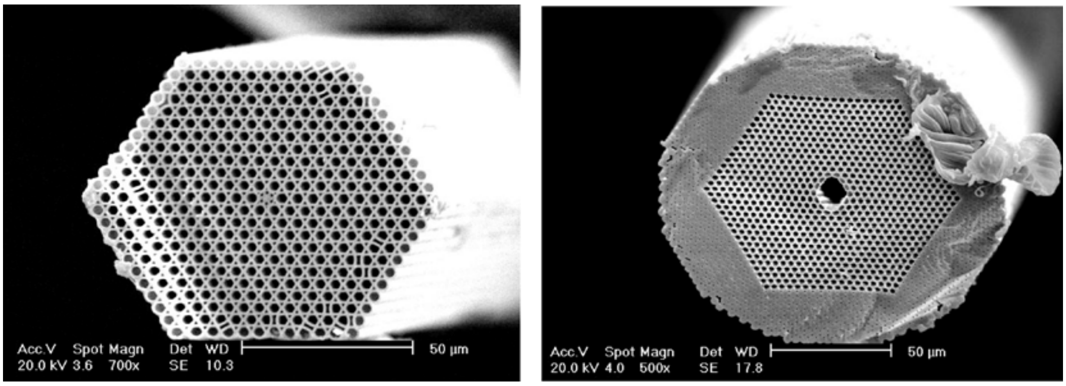

Fig. 1 Typical index-guiding (*left*) and bandgap-guiding (*right*) PCF

As have been shown by intensive research activities [8, 9], the holey structure in PCFs can bring about novel properties unimaginable with COFs: endless single mode operation [14], anomalous dispersion at visible and near-infrared wavelengths [15], tailorable mode area [16, 17], and high birefringence [18], just to name a few.

As is well known, in a COF the normalized frequency V must not exceed 2.405 for the fiber to be single mode. Likewise, a similar effective V value V_{eff} is defined for a PCF, where a wavelength-dependent cladding index is used. It is found that V_{eff} tends to constant values when the wavelength λ approaches the high frequency limit ($\lambda \to 0$) and that below a certain ratio of the air hole diameter D to the air hole pitch Λ (about $d/\Lambda \leqslant 0.4$) [7] the fiber is single mode. This is due to the fact that more light is confined in silica regions when $\lambda \to 0$ and therefore the effective cladding index increases, counteracting the effect of the decrease of λ. This property is highly desirable in a wide variety of applications including optics communications, high power delivery, and so on.

In a COF, the normal waveguide dispersion leads to the total dispersion being normal below $1.3\ \mu\text{m}$, whereas in a PCF with a large air filling fraction strong light confinement to a small core region can be achieved by the large index difference between air and glass and this results in very high waveguide dispersion, which can act to cancel even the large negative dispersion of silica glass that exists at visible wavelengths. By tailoring the hole spacing and air filling fraction in the cladding, the zero-dispersion wavelength can be unprecedentedly tuned to a required wavelength [19]. This feature has been, as we will show below, exploited to advantage to enhance nonlinear phenomena in PCFs.

By the stack-and-draw process, PCFs with tailorable mode area can be fabricated. On the one hand, PCFs with extremely large cores [16, 17] while maintaining single-mode operation are favorable for high-power operation [20]. On the other hand, extremely small-core PCFs can be fabricated with enhanced nonlinearity [17]. In combination with controllable dispersion, the enhanced nonlinearity makes small-core PCFs ideally suited as nonlinear media [21], as will be exemplified in detail in this review.

The current research focuses on both the theoretical and experimental aspects of PCFs. On the theoretical side, how to numerically, by various methods, design PCFs with the expected properties and the correct parameters is an area of intensive and active study [10, 22]. On the experimental side, the fabrication and applications of PCFs receive the most attention. The research on fabrication techniques [10, 12, 23] is intended to draw fibers with more precision, to produce fibers of new variety, or to reduce loss. The applications are diverse and broad [24, 25] but are mainly in such areas as PCF fiber lasers and amplifiers [26] , signal processing devices [27], gratings and other devices, etc [28, 29].

3 Nonlinear effects in photonic crystal fibers–experimenttal setup

The dispersion of PCFs can be tailored to such a degree that when ultrashort light pulses propagate in PCFs the nonlinear effects can be controlled and enhanced more than those in COFs [30]. In what follows, we will show our experimental results on nonlinear effects in PCFs conducted with femtosecond light pulses, including supercontinuum generation, frequency conversion, and soliton effects, which are well-known phenomena in nonlinear fiber optics [31].

Figure 2 shows the typical setup used in our experiments. A home-made self-mode locking Ti: sapphire oscillator, running at a central wavelength of around 800 nm, generated femtosecond light pulses of about 30 fs with an average output power of 600–800mW. The pulse repetition rate was 80 or 100 MHz, depending on the particular system used. A Faraday isolator was placed just behind the Ti: sapphire oscillator to prevent retroreflected radiation from disturbing the operation of the laser oscillator. The femtosecond pulses were coupled into the PCF with an objective lens (typically×40). The spectral properties of the output pulses were measured by an optical spectrum analyzer. The coupling and output were monitored by CCD cameras.

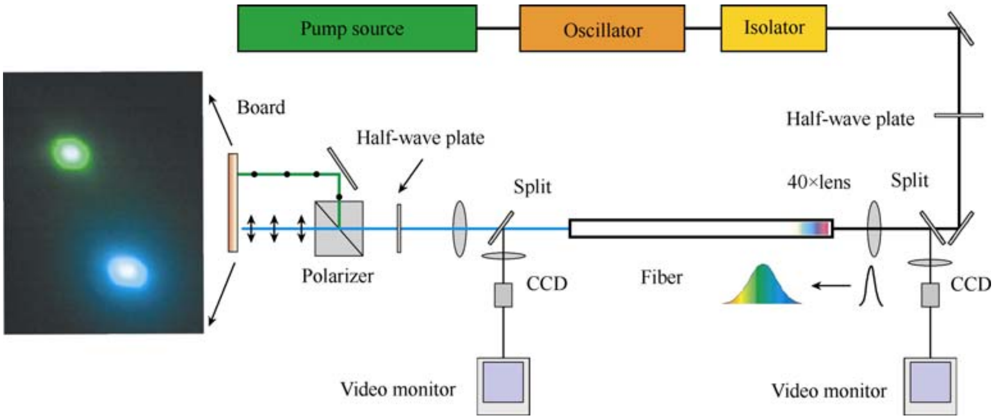

Fig. 2 Schematic of the experimental setup

4 Nonlinear effects in photonic crystal fibers–supercontinuum generation

The term supercontinuum refers to the phenomenon of dramatic spectral broadening of optical pulses and thereby potentially octave-spanning output, see Fig. 3. Supercontinuum generation (SG) through propagation of ultrashort picosecond or femtosecond high-power light pulses in nonlinear media was first discovered in the 1970 and the first observation of SG in PCFs was reported by Ranka *et al.* in 2000 [32]. Since then, SG in PCFs has been studied extensively and the results show that a number of linear and nonlinear effects that are well-known in conventional nonlinear fiber optics [31] like group-velocity dispersion (GVD),third and higher-order dispersion, self-phase modulation (SPM), cross-phase modulation (XPM), four-wave-mixing (FWM), stimulated Raman scattering (SRS), higher-order soliton formation, self-steeping, birefringence all can come into play [21, 33].

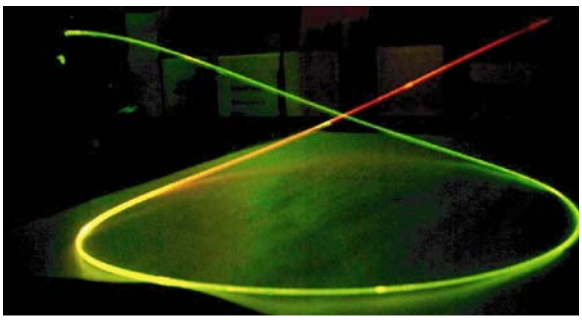

Fig. 3 Supercontinuum generation in a PCF

Nevertheless, depending on the pumping in the normal or anomalous dispersion regime, different effects may dominate [34]. In the case of picosecond pumping, the primary mechanism of spectral broadening is identified as the combined action of stimulated Raman scattering and parametric FWM, while the role of SPM is negligible [35]. In the case of femtosecond pumping, when light pulses lie in the anomalous dispersion region of the PCF, SG can be caused by spectral broadening through fission of higher-order solitons into red-shifted fundamental solitons and blue-shifted dispersive wave radiation and subsequent spectral smoothing through FWM [36–38]. When femtosecond light pulses lie in the anomalous dispersion region of the PCF, SG can be generated through SPM and FWM [34]. Here, we show some results on SG we got by propagating femtosecond light pulses in PCFs.

In Fig. 4, we show how the spectrum can be broadened in a PCF by increasing the pump power of the light pulses of 35 fs at a central wavelength of 825 nm [39]. The PCF used in the experiment was shown in the inset to Fig. 4, which was made by Crystal Fibre and whose zero dispersion is at 780 nm. The role of anomalous dispersion and FWM is evident. In the anomalous dispersion regime, solitonic features are observed and by FWM phase-matched blue components are generated to smooth the spectrum. By tuning the wavelength of the input pulses, the phase-matching process can be tuned, and thus the output spectra are correspondingly changed, as shown in Fig. 5 [39]. Furthermore, it has been shown that the output spectra from PCFs are sensitive to the input pulse parameters and noise [40, 41]. This is also observed in our experiments. As shown in Fig. 6 [39], when the spectra of the input pulses contain DC components, the output spectra are more extended in the blue side and are broader but more complex than when there are no DC component in the spectra of the input pulses.

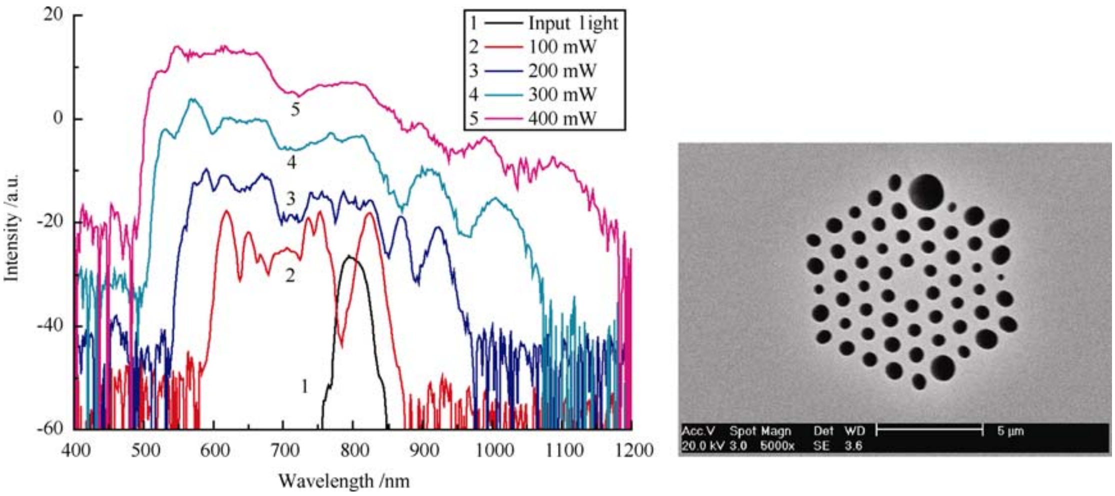

Fig. 4 Output spectra for different pump powers by coupling pulses of 35 fs at 825 nm into a PCF as shown in the inset.

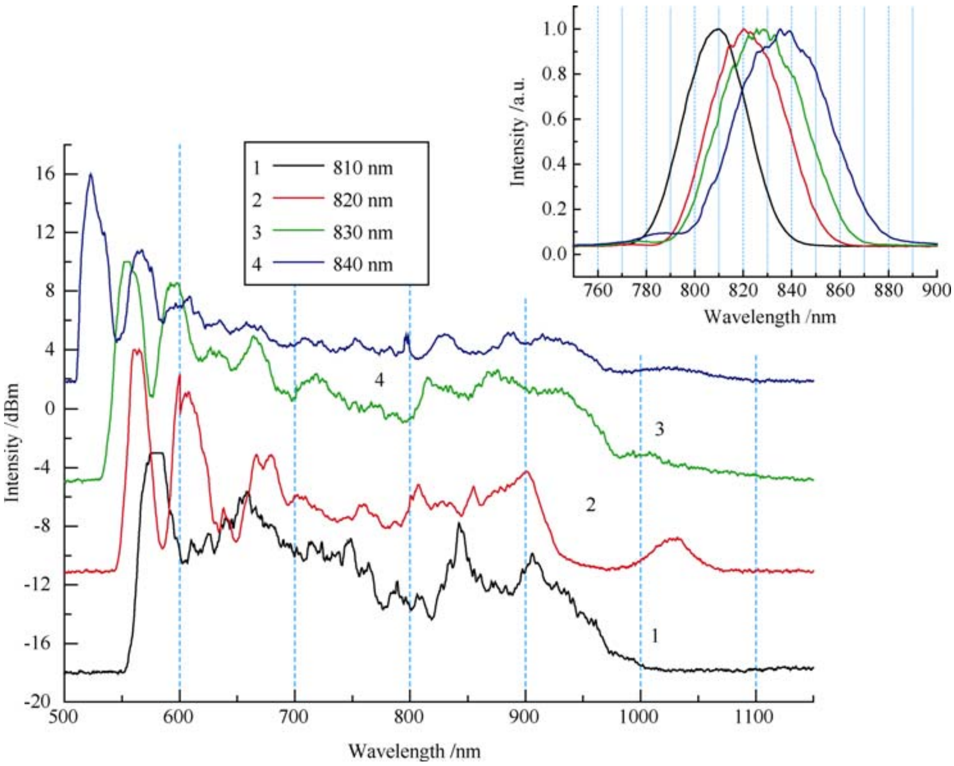

Fig. 5 Output spectra for different pump wavelengths by coupling pulses of 35 fs and 450 mW into the same fiber as in Fig. 4. The corresponding spectra of the input pulses are shown in the inset.

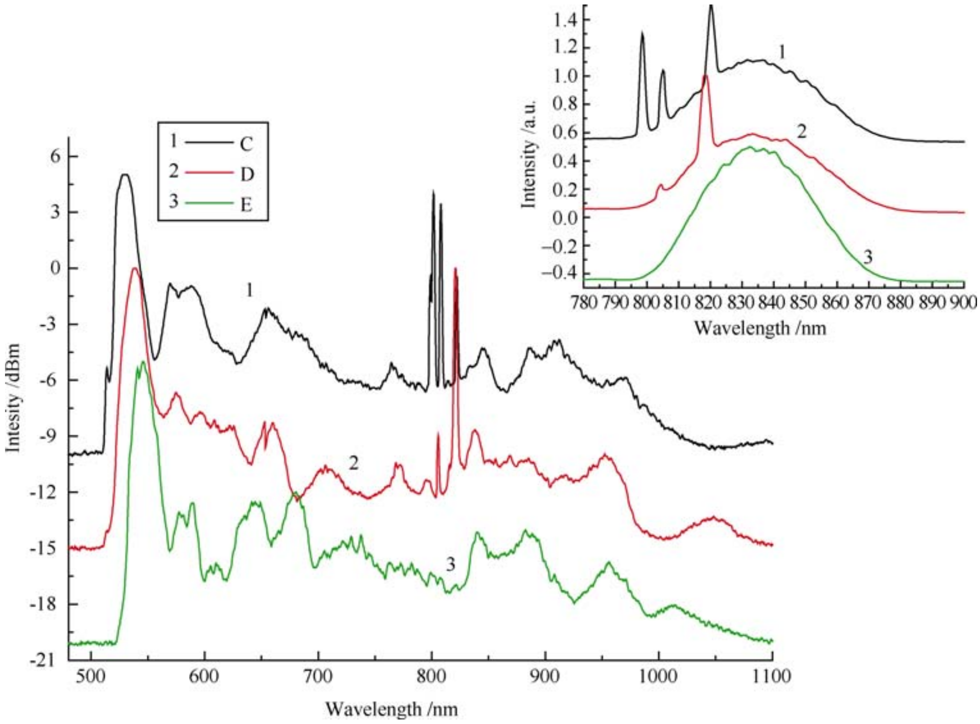

Fig. 6 Output spectra for pulses containing (1) multiple DC components (2) one DC component and (3) no DC component. Spectra of the input pulses (35 fs and 550 mW at 835 nm) are shown in the inset. Fiber is the same as in Fig. 4.

PCFs with a random hole distribution (better called HF here) can also confine light by MTIR [13]. Extremely small cores can also be formed by irregularly arranged air holes (see the inset to Fig. 7) and thus similar SG can also happen due to enhanced nonlinearity [42]. Due to the random hole arrangement, this HF is birefringent and the modes along the two polarization axes have different dispersion properties, and thus SG processes can be further controlled by the combined effects of dispersion and nonlinearity [31], as shown in Fig. 7. When the generated supercontinuum propagates in such a birefringent HF, beating of the two polarization modes is observed, see Fig. 8 [43].

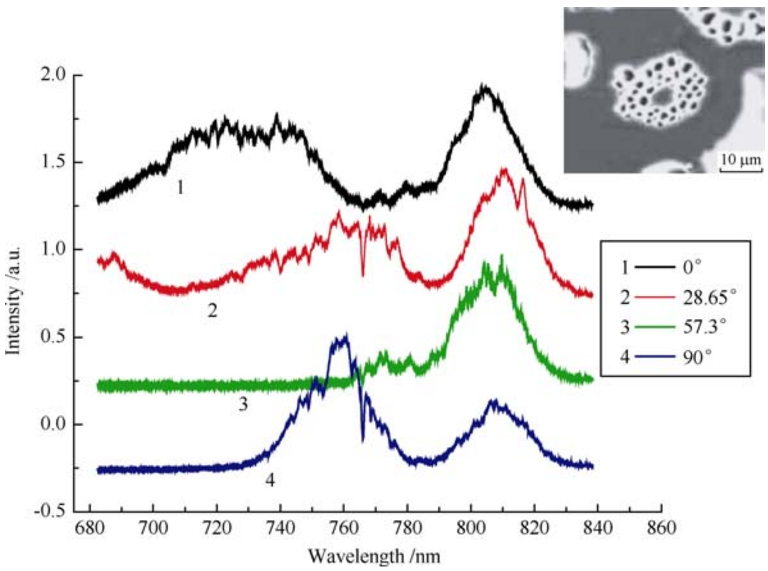

Fig. 7 Output spectra for different polarization angles with respect to the fast axis of the fiber by coupling pulses of 35 fs and 600 mW into the HF as shown in the inset.

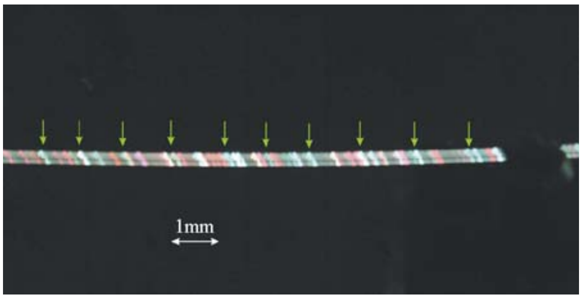

Fig. 8 Beating in a birefringent HF. The arrows indicate the same color.

Finally, we show how SG is tuned in a high-index-step PCF with a comma-shaped core [44]. The fiber (shown in the inset to Fig. 9) supports two different types of guided modes with bell- shaped intensity profiles. The GVD curves and the field intensity profiles of the two modes (labeled as 1 and 2, respectively) are shown in Fig. 9. The central wavelength of the input pulses is 800 nm and falls in the anomalous dispersion regime, no matter whether modes of type 1 or type 2 are excited. The zero dispersion wavelengths are 783 nm and 630 nm for the first type and second type of modes, respectively. Two different physical mechanisms lead to different features in the output supercontinuum spectra: the supercontinuum emitted by the modes of type 1 is smooth covering from 450 to 1 400 nm, while the modes of the second type generate supercontinuum with an enhanced short-wavelength wing, dominated by intense spectral lines centered at 400–450 nm, as shown in Fig. 10. When the modes of the first type are excited, FWM around the zero dispersion wavelength plays an important role in the initial stages of SG and leads to the depletion of the pump field. When the modes of type 2 are excited, phase matching processes involving the red-shifted soliton and dispersive wave results in the pronounced short-wavelength wing. The two regimes of supercontinuum generation and the two types of output spectra can be switched by displacing the input end of the fiber with respect to the laser beam in the transverse direction, see Fig. 11.

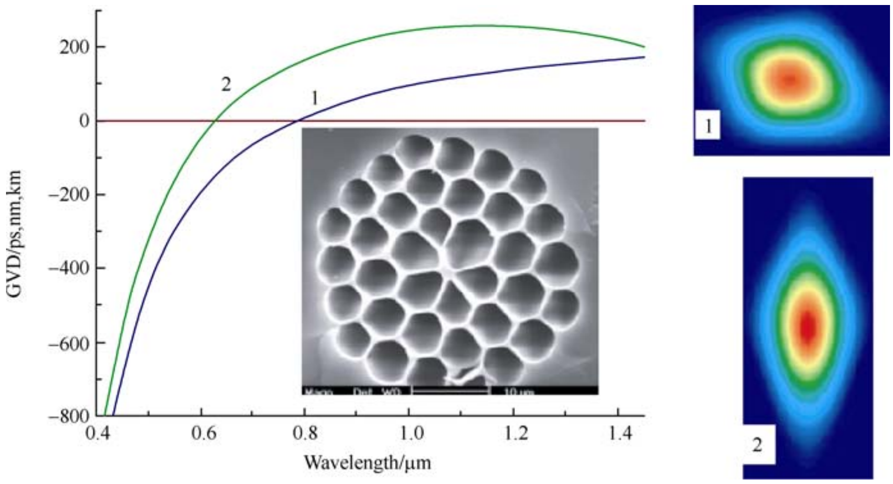

Fig. 9 GVD curves and field intensity profiles of the two modes (labeled as 1 and 2, respectively)supported by the PCF with a comma-shaped core (inset).

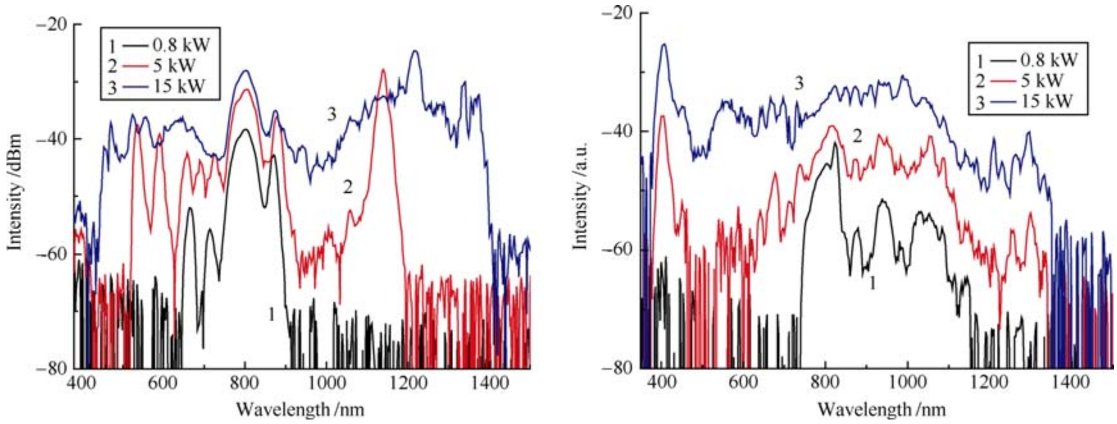

Fig. 10. Output spectra by coupling 30 fs laser pulses into the first (*left*) and second (*right*) type mode of the fiber. The initial peak power of laser pulses is (1) 0.8 kW, (2) 5 kW, and (3) 15 kW.

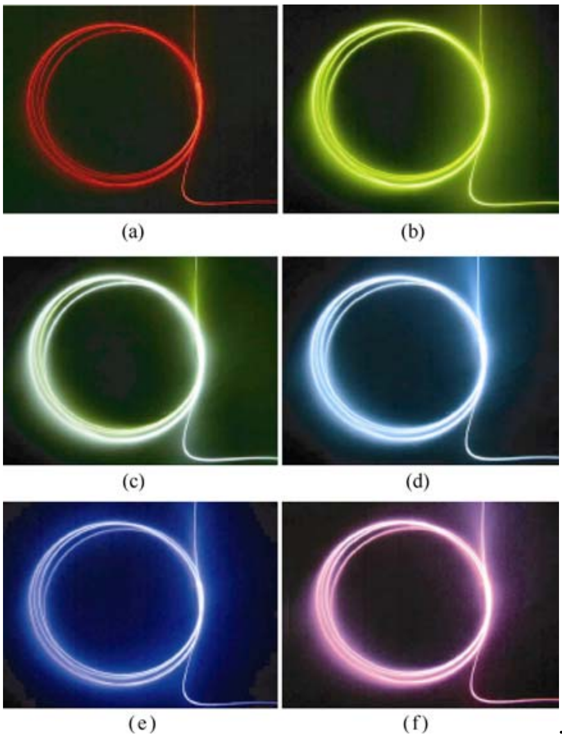

Fig. 11. Side images of the PCF generating supercontinuum in the first (**a**, **b**, **c**) and second (**d**, **e**, **f**) type modes with a peak power of the input field of (**a**, **d**) 8 kW, (**b**, **e**) 11 kW, and (**c**, **f**) 14 kW.

5 Nonlinear effects in photonic crystal fibers-frequency conversion

In nonlinear fiber optics, an important nonlinear effect is four-wave mixing [31], which occurs when photons from one or more waves are annihilated and new photons are created at different frequencies. In PCFs, degenerate FWM is common which through phase matching creates stokes and anti-stokes components by depletion of the pump waves. The phase-matching condition of FWM is dispersion-sensitive and thus is also sensitive to the polarization state of the mode. In addition, the condition can be mode-selective. Our work on frequency conversion in PCFs is shown in this section.

Intense blue-shifted lines centered at 490 and 510 nm, respectively, are generated at the output of a birefringent PCF [45, 46] when the pump laser pulses of 35 fs at 820 nm are polarized along the fast or slow axis of the fiber core, due to the different GVD properties of the two eigenmodes of the PCF. This is shown in Fig. 12, and the PCF used is shown in the inset. The outputs are observed as bright blue and green emission, as shown in Fig. 13. This anti-stokes line generation is mode-selective, and modes of higher-order and very high order can be involved in the phase-matching process[47, 48]. Using a different PCF (shown in the inset to Fig. 14) and pulses with similar parameters, we can excite the first doublet of higher-order modes and the second multiplet of higher-order modes [49, 50], as shown in Fig. 14. This mode-selective vectorial nonlinear process can be controlled by varying the tilt angle of the input beam and rotating the polarization of the input field [51]. The result is illustrated in Fig. 15, where the laser pulses are 30 fs at a central wavelength of 800 nm and the input average power of laser pulses is 300 mW.

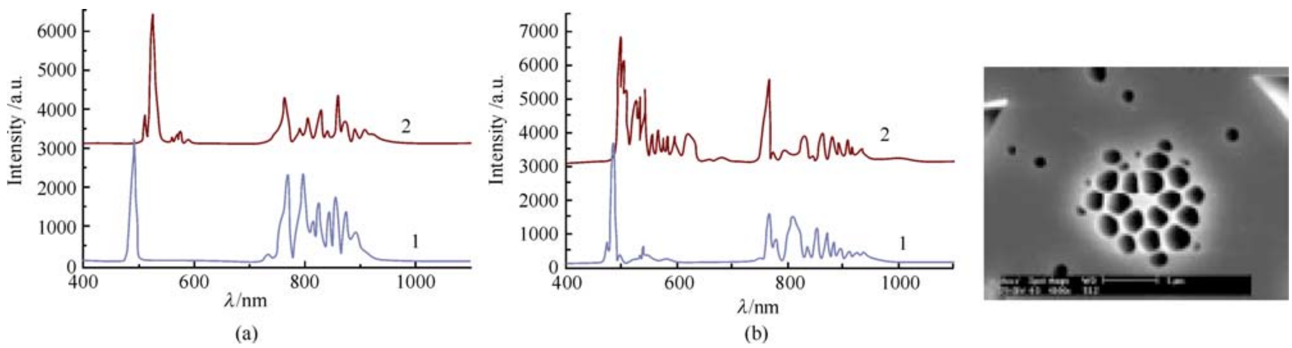

Fig. 12 Generation of anti-Stokes line emission in a PCF by pump pulses polarized along (1) the fast and (2) the slow axis of the fiber core. The average power of pump radiation is (**a**) 100 mW and (**b**) 200 mW. The fiber is shown in the inset.

Adding polarization-separating devices to the experimental setup in Fig. 2, we can demultiplex the two-color frequency conversion shown in Fig. 13 by accurately polarizing the pump field along one of the principal axes of the elliptically deformed fiber core [52]. This is demonstrated in Fig. 16. Interestingly, when 30 fs light pulses are coupled into a random-hole HF, phase-matched multiplex frequency conversion occurs at an array of waveguiding channels formed in this fiber [53]. Fig. 17 shows a close-up view of the HF and the corresponding output mode patterns.

6 Nonlinear effects in photonic crystal fibers-soliton effects

Soliton refers to special kinds of wave packets that can propagate

Fig. 13 Output of anti-Stokes line emission in a PCF by pump pulses polarized along (*left*) the fast and (*right*) the slow axis of the fiber core.

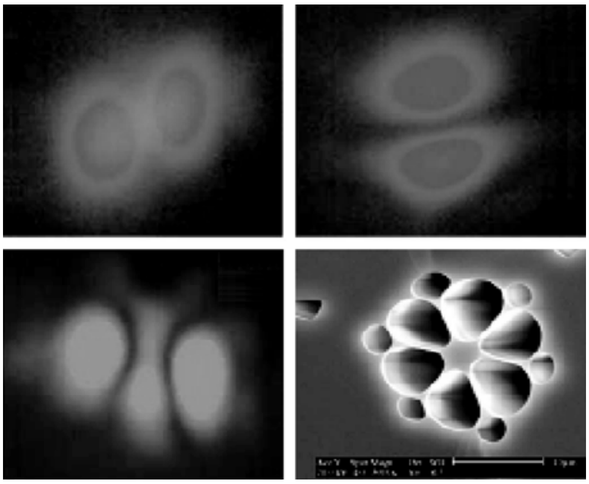

Fig. 14 Output mode patterns of anti-Stokes line emission in a PCF shown in the inset:first doublet (*left*) and (*middle*) and the second multiplet (*right*) of higher-order modes

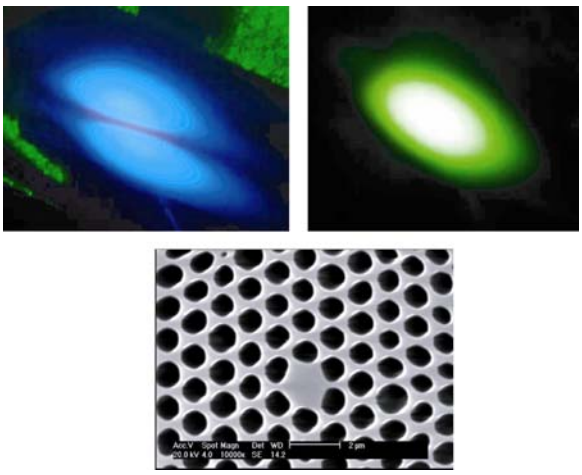

Fig. 15 The output mode profiles of the frequency-shifted PCF (shown in the inset). The angle between the input beam and the PCF axis is 10^{o}. The angle between the polarization vector of the input field and the slow axis of the fiber core is (*left*) 10^{o} and (*right*) 90^{o}, respectively.

undistorted over long distances [31]. They are not only of fundamental interest but also of practical application significance in nonlinear fiber optics and fiber optic communications. The GVD of PCFs can be shifted to the visible and near-infrared wavelengths, thus making it possible for solitons to occur at wavelengths previously inaccessible. There have been many experiments on soliton effects in PCFs [54–58]. By tuning the input pulse energy, the solitons generated have covered the spectral range from 0.78 μm to 1.677 μm. Here we show some of our recent results on soliton generation in PCFs.

Although solitons have already been seen to play a significant role in SG processes in Section 4 (e.g., see Fig. 4), we can observe distinct solitonic features by carefully choosing the fiber and pulse parameters. Fig. 18 shows the observed evolution of the soliton self frequency shift as the pulse energy is increased when light pulses of 30 fs at 820 nm are coupled into the same PCF as in Fig. 12 [59]. Due to birefringence, when the input light is polarized along the two polarization axes, different features are observed [60], see Fig. 19.

7 Applications of nonlinear effects in photonic crystal fibers

The enhanced nonlinear effects in PCFs as shown above have found and are still finding wide applications in fiber optics and other fields. Particularly, the octave-spanning supercontinuum generated from PCF is now used in precision frequency spectroscopy [61, 62], carrier-envelope phase control of femtosecond mode-locked lasers [63, 64], optical coherence tomography [65, 66], and other spectroscopic and microscopic applications [67–69]. Besides, the supercontinuum is also possible for compression to yield ultrashort light pulses [70, 71] or as WDM sources for communications [29, 72]. As efficient frequency converters, PCFs can generate frequency-tunable ultrashort pulses, allowing the creation of new sources of

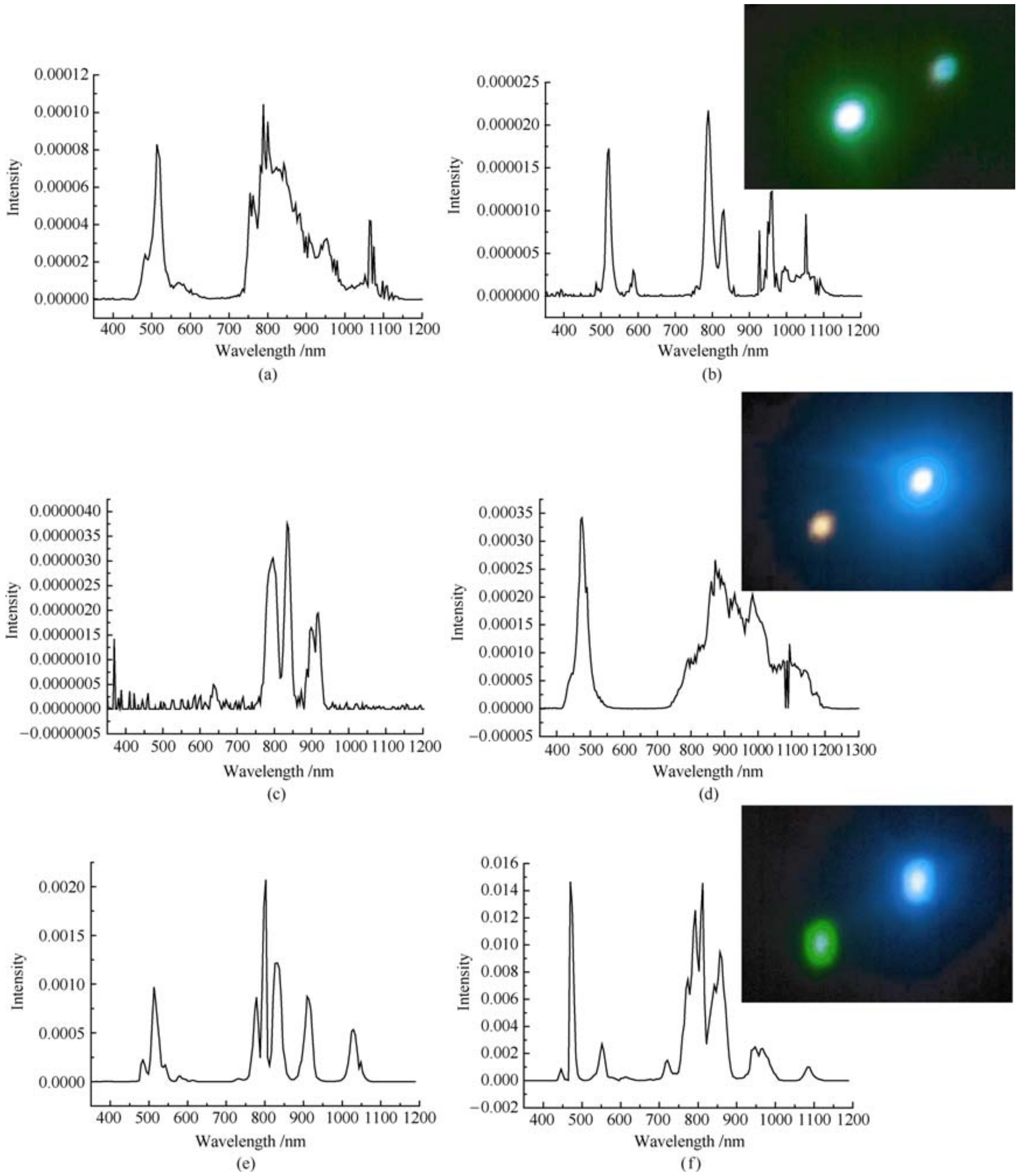

Fig. 16 Polarization-demultiplexed output of a birefringent PCF. The pump field is polarized at an angle of (**a**, **b**) 90°, (**c**, **d**) 0°, and (**e**, **f**) 45° with respect to the x-axis. The polarization analyzer selects radiation polarized along (**a**, **c**, **e**) the *y*-axis and (**b**, **d**, **f**) the *x*-axis. Respective beam images are shown in the insets.

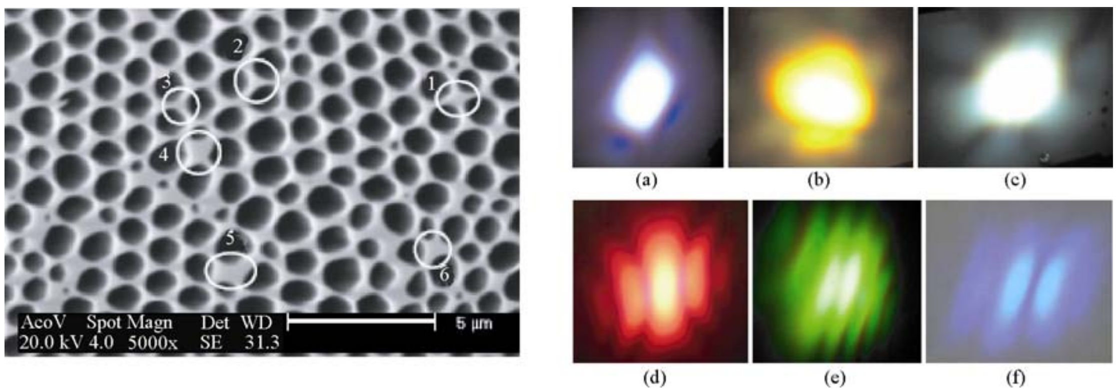

Fig. 17 Left: a close-up view of the random-hole HF used. Right: output beams patterns of anti-stokes emission from channels 1–6[(a)–(f)] of the random-hole HF

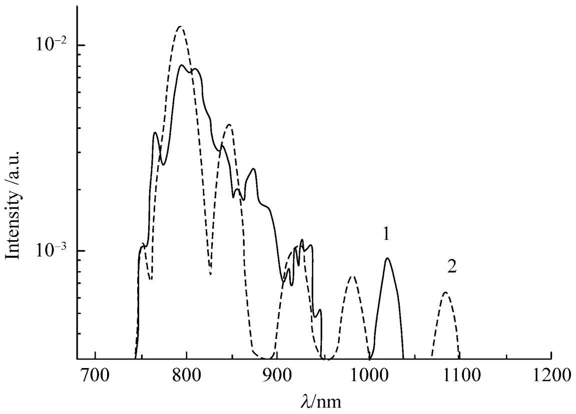

Fig. 18 Spectra of laser pulses transmitted through the PCF with a length of 7 cm. The initial pulse duration is 30 fs. The initial pulse energy is (1) 340 and (2) 540 pJ.

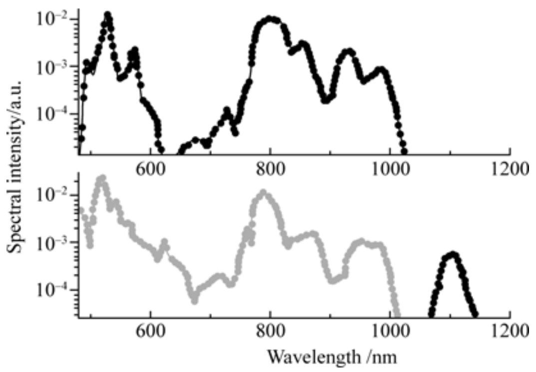

Fig. 19 Spectra of laser pulses transmitted through the PCF for two orthogonal polarizations of the linearly polarized input field. The initial pulse duration is 30 fs. The initial pulse energy is 0.5 nJ.

tunable radiation for applications in spectroscopy, photochemistry, optical metrology, photobiology, biomedicine, quantum optics and so on [73–77]. Solitons generated from PCFs are not only potential sources for communications, but they also provide a good means for the generation of tunable light sources [55, 78–80].

At the same time, other nonlinear effects not covered here like SPM, XPM, SRS can all be utilized to make PCF-based devices like amplifiers, lasers, gratings, signal-processing units [26–28], which are essential components in fiber optics and fiber optic communications.

8 Summary and outlook

Photonic crystal fibers were developed ten years ago, but have shown in many ways their unique properties that cannot be obtained with conventional optical fibers. In this work, we presented a review of our efforts made in the understanding of the nonlinear effects of these fibers. These effects studied are supercontinuum generation, frequency conversion, and soliton effects. The properties of photonic crystal fibers and the phenomena observed in photonic crystal fibers are, however, much more diverse and colorful than we can shown here. The enhanced nonlinearity in photonic crystal fibers has found wide and important applications. The most persuasive example may be the development of precision spectroscopy based on supercontinuum generation from photonic crystal fibers (or the optical frequency comb technique), which has been recognized as one of the important contributions by J.L. Hall and T.W. Hänsch, two of the laureates of the Nobel Prize in Physics in 2005. The photonic bandgap effects, although not covered here, have equally important properties and applications. We have enough reason to believe that with the further development of the technology and a better understanding of the properties offered by photonic crystal fibers, the filed of fiber optics stands ready to be transformed.

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