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REVIEW ARTICLE

Photonic crystal fibers for supercontinuum generation

Xian ZHU, Xinben ZHANG, Jinggang PENG, Xiang CHEN, Jinyan LI (✉)

Wuhan National Laboratory for Optoelectronics, Huazhong University of Science and Technology, Wuhan 430074, China

Abstract Photonic crystal fibers (PCFs) present a wavelength-scale periodic microstructure along their length. Their core and two-dimensional photonic crystal might be based on varied geometries and materials, allowing supercontinuum (SC) generation due to nonlinear effects in an extremely large wavelength range. In this paper we have reviewed PCFs utilized for SC generation. Fiber fabrication for SC generation is present. Spectral broadening mechanisms are also described in brief. Particular attention is as well as paid to PCFs including uniform PCFs, cascaded fibers, tapered fibers and PCFs with special material doped, which are commonly used to generate SC.

Keywords photonic crystal fibers (PCFs), supercontinuum (SC), PCF fabrication, nonlinear optics, tapered PCF, cascaded PCF, Ge-doped core

1 Introduction

Supercontinuum (SC) generation has attracted much attention since it was first reported in 1970 by Alfano and Shapiro [1–3]. They observed the generation of a white light spectrum covering the entire visible range from 400 to 700 nm after propagating picosecond pulses at 530 nm. Bulk borosilicate glass was used as a nonlinear medium in the pioneering work [1]. SC generation in optical fibers was first observed in 1976 by Lin and Stolen for pumping in the normal group velocity dispersion (GVD) regime of standard silica fiber [2]. Philip Russell, the inventor of photonic crystal fibers (PCF) technology, worked on PCFs from 2001, realizing the renaissance of interest in optical fibers and their uses. His work marked the start of a new era in SC generation in PCFs [3]. In the 20th century PCFs gradually make a great difference to efficient octave-spanning SC. It has been a subject of intense research since Ranka reported an optical continuum 550 THz in width, extending from the violet to the infrared, by propagating pulses of 100 fs duration and kilowatt peak powers through a PCF near zero-dispersion wavelength (ZDW) [4]. The nonlinear effects responsible for the spectral broadening require a high light intensity. It is spatial nonlinear effects resulting in self-focusing of the beam that closely connect with SC generation in bulk glass. In contrast, PCFs who have subtle variations in the refractive index can tightly confine the beam in a small core. Thus, it is to a large degree possible to engineer the dispersion of PCF by proper design of the structural parameters and high beam intensity can be sustained over larger propagation distances. This reduces the requirement of high laser power for efficient broadband generation [5]. In parallel with these developments, the availability of PCF was leading to a dramatic revolution in the broad spectra's realized and potential applications. The SC spectrum is not only broad, but is also spatially coherent, contrary to light from, e.g., a tungsten lamp, and consequently has higher brightness. These properties has opened up new applications in fields such as optical frequency metrology, optical coherence tomography, pulse compression, chemical and bio-medical system, modern military, space industry, etc. [2].

2 PCFs fabrication

Solid core PCFs have been in practical existence as low-loss waveguides since early 1996 [6]. The initial demonstration took four years of technological development, and since then, the fabrication techniques have become more and more sophisticated [7]. Generally, PCFs are fabricated by the conventional stack-and-draw technique as displayed in Fig. 1. Silica capillaries with given outer diameter and inner diameter are stacked together to form an ideal hexagonal structure with perfect regularity, air holes embedding within a pure silica fiber strand. The stack is bound with wire before being inserted into a jacketing tube, and the whole assembly is then mounted in perform feed unit (it is usually called drawing tower) for

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E-mail: ljy@mail.hust.edu.cn

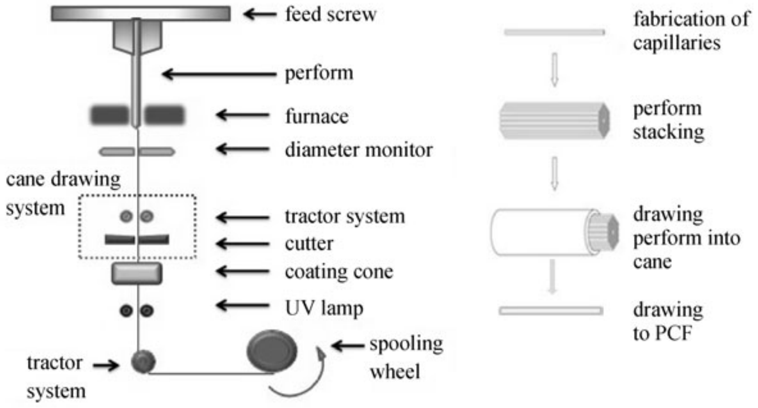

Fig. 1 Process of PCFs fabrication

drawing down to fiber. During the fiber drawing, the overpressure applied into the holes should be specially controlled to achieve the inflation of air holes [8]. Judicious use of pressure and vacuum allows some limited control over the final structural parameters, for example, the d/Λ value [7].

3 Spectral broadening mechanisms

As is well established, effects such as self-phase module (SPM), four wave mixing (FWM), soliton self-frequency shift (SSFS), the generation of dispersion wave and cross phase module (XPM) should be responsible for the SC generation. When pumping using femtosecond pulses in the anomalous GVD regime of the fiber, SC generation is dominated by soliton-related propagation effects. The most importance of these in the initial stages is the soliton fission process, whereby a pulse with sufficient peak power to constitute a higher-order soliton is perturbed and breaks up into a series of lower-amplitude sub-pulses. Each of these pulses is, in fact, a constituent fundamental soliton. The process is followed by the Raman shifting of constituent ejected solitons and the associated generation of dispersive waves from each ejected fundamental soliton due to the effect of higher-order dispersion. It is the phase-matching condition that determines the spectral position of dispersive wave [1]. Afterwards, the soliton self-frequency shift extends the broadening to the infrared side of the spectrum while trapped dispersive waves into short-wavelength region [3]. SC generation with long pulses in the anomalous GVD regime involves similar soliton-related dynamics as in the femtosecond regime. However, in contrast to the femtosecond case, solitons play a relatively minor role during the first step of propagation. Recent numerical studies by Travers et al. [9,10], Mussot et al. [11] and Cumberland et al. [12] have provided further insight into this dynamics, and explicitly demonstrated that four-wave mixing and/or Raman scattering dominate the initial steps of SC generation with long pulses, leading to symmetrical broadening of the pump spectrum. Subsequent soliton formation and breakup which are subject to the peak power and dispersion values takes place, and Raman self-scattering can then lead to a long-wavelength soliton continuum [10,13].

4 PCFs utilized to generate SC

In this section, we provide an overview of the PCFs of two types to generate SC. One type of PCFs has changes in geometry. Uniform PCFs, tapered fibers and cascaded fibers are included. While the other type of PCFs is modulated in material. Doping material like germanium or fluorine, even water is used in the central rod to modulate the PCF's dispersion and nonlinear properties.

4.1 PCFs with different geometry

Uniform PCFs may be the most conventional optical fiber and has attracted much attention. Ranka et al. [4] generated an ultrabroadband continuum extending from 390 to 1600 nm by injecting pulses of 100 fs duration, 800 pJ energy, and a center wavelength of 790 nm into a 75 cm section of fiber in 2000. Here the combined nonliner effects including self-phase modulation, soliton propagation, efficient four-wave mixing and Raman scattering result in a broad, flat spectrum. In 2002, Dudley et al. [14] studied the generation of SC in these fibers. In the femtosecond experiments, a continuum from 450 to 1250 nm has been generated in a 1 m length of fiber pumped at 780 nm by 100 fs pulses from a Kerr-lens model-locked Ti: sapphire laser.

In 2008, the work by Mussot et al. provided a comprehensive description of the dynamics involved [11]. They used a randomly polarized CW Yb fiber laser with 12 W and spectral width of 1 nm, centered at 1066 nm. By injecting 6 W inside 500 m long PCF, they obtained a SC ranging from 1 to 1.3 μm with total 1 W output power. It is worthy to note that the output spectrum is very flat and, in particular, majority of the pump power is converted into the SC.

Ghosh et al. latest work in 2011 [15] have confirmed that by injecting 600 ps pulses from a Nd:YAG Q-switched microchip laser of 1064 nm and 8 kHz repetition rate, a 10 m of PCF generated SC from about 400 to above 1800 nm as shown in Fig. 2. It should be noted that, the short wavelength side of the continuum is more affected by the pump power than the long wavelength. When the pump peak power increases to 14.3 mW, the spectrum expands the most obviously.

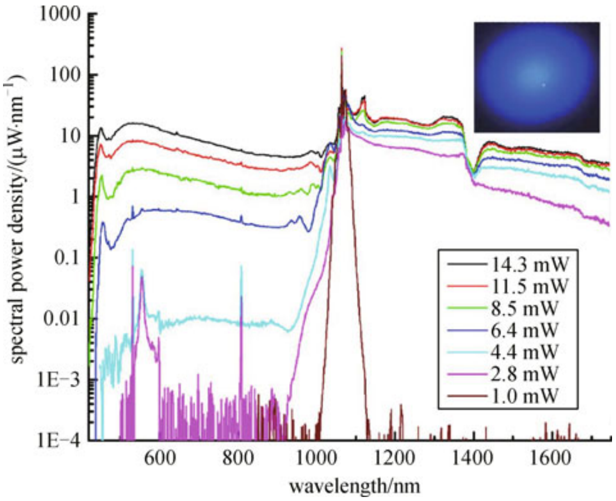

Fig. 2 Evolution of SC spectra in PCF with varied pump power with output mode shape in extreme blue region showing in the inset

Although uniform PCFs have been experimented for many times, there are some apparent shortcomings such as the SC can not be broadened to shorter visible wavelengths with pump sources at 1.06 μm because the requirement of a short ZDW for the phase matching of parametric processes in the visible will compete with the necessity of pumping in the low-anomalous dispersion region of the HF for modulation instability and a long-wavelength Raman-soliton continuum [10]. Cascaded fibers have recently been used in an attempt to resolve this problem. In May 2010, Guo et al. [16] obtained a SC spanning from 1055 to 1475 nm. It is achieved by cascading a long ZDW high-nonlinearity fiber with the output photonic crystal fiber.

In October 2010, Travers [17] reported their work on this kind fiber as shown in Figs. 3 and 4. The broadening process in cascaded fibers can be roughly separated into two stages. Raman-soliton and the simultaneous excitation of dispersive waves make contribution to the initial stage. It is noted that the pump power should be sufficient and the wavelength of pump locates at the anomalous dispersion region, approaching ZDW. In the second stage, the light that is obtained in the first stage possessed a relative broad

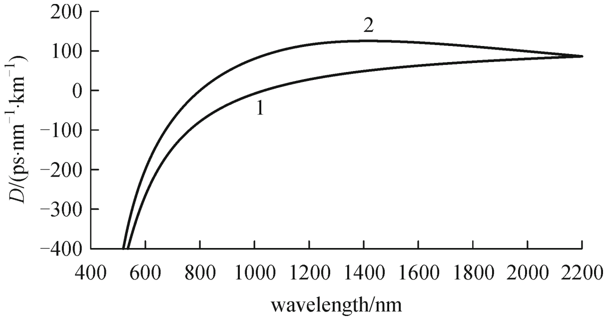

Fig. 3 Dispersion curves for the first- and second-stage fibers in cascaded set-up

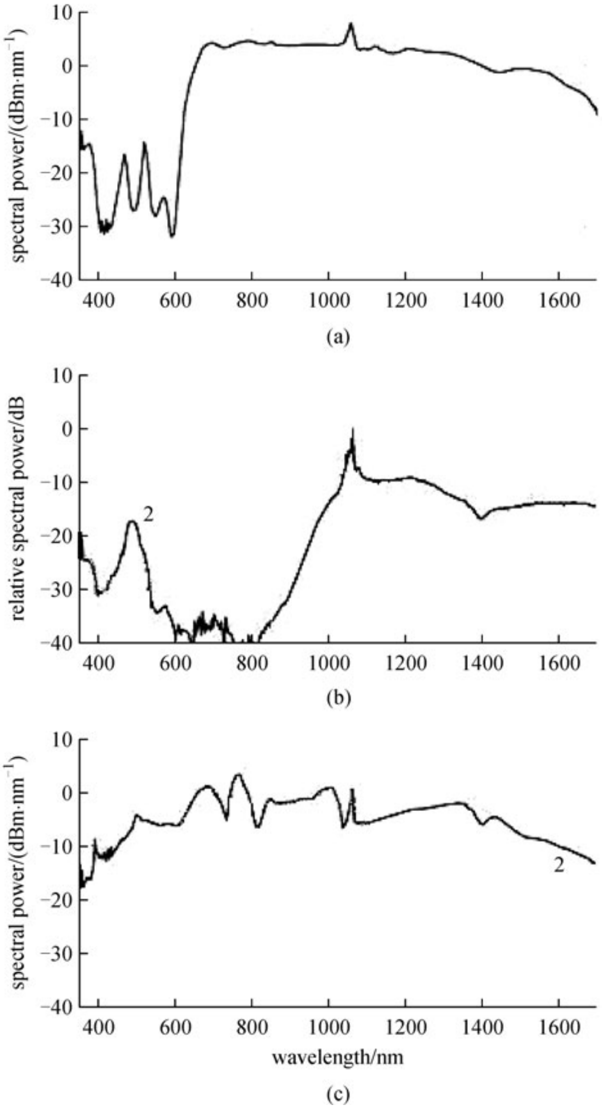

Fig. 4 (a) Output of the first stage; (b) spectrum obtained when pumping the second stage fiber with pump laser; (c) spectrum achieved when pumping the second fiber with the output of first stage

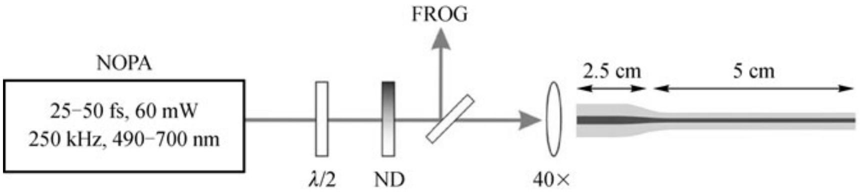

Fig. 5 Experimental setup: NOPA, non-collinear optical parametric amplifier; λ/2, half-wave-plate; ND, neutral-density filter; 40×, in-coupling lens

Table 1 Comparison between when respectively pumped at 1064 nm from Yb doped fiber laser

parameters	L/m	$C_R/(W^{-1}\cdot km^{-1})$	$\gamma/(W^{-1}\cdot km^{-1})$	spectrum/nm	output/W
GeO_2	300	17	37	570–2040	3.5
Si	400	2.6	10	850–1350	3.7

spectrum, especially the short-wavelength part. The light may behave as pump for the second stage and satisfy broad group velocity matching to the shortest wavelength. Consequently, the short wavelength extent of the continuum gets extended. They demonstrated that, by controlling the cascaded fibers, one can generate either a strong blue enhanced continuum.

The natural progression from using discrete cascaded fibers is to attempt a continuous longitudinal variation of dispersion and nonlinearity. Fibers tapered at the drawing tower can be as long as the fiber drawing equipment permits — up to kilometers [17]. This allows for slower and more controlled transitions and changing the fiber characteristics as the SC develops. However, what limit their application may be the fabricate techniques. Recently, Travers [17] had confirmed that the use of tapered fibers can greatly improve the cascaded results and dramatically enhances the soliton trapping process. As far back as in 2006, Kudlinski et al. [18] and his colleagues also did similar work of this kind and generated SC spanning from 372 to more than 1750 nm.

It's worthy to note that, in 2009, Stark et al. studied on this kind of PCFs. The fiber had ZDW at 509 and 640 nm, and the excitation wavelength was at 523 nm. The experimental setup is shown in Fig. 5. They found that when pumping with higher powers, extremely wide spectral broadening of the input pulse occurs within the first few millimeters of fiber. The spectral spanning of 300–470 nm has been observed [19].

4.2 PCFs with special material doped

Silica is intrinsically not a particular highly nonlinear material. The presence of materials such as germanium or fluorine in silica will significantly enhance the Kerr and Roman responses, which is important for efficient SC generation. In 2009, Kudlinski et al. [20] has compared 300 m-PCFs doped GeO_2 with 400 m-ones made of pure silica [20,21], as shown in Table 1. Kerr and Roman coefficient is greatly enhanced in GeO_2 case. The pump power launched in PCFs is 13 W. ZDWs for PCFs doped GeO_2 and ones made of pure silica are respectively 1060 and 1062 nm.

Then they carried on another comparison. The benefits of GeO_2 doping were highlighted in the context of SC generation. Figure 6(a) shows experimental spectra when 13 W's pump power was injected in a 400 m-long pure silica PCF and in a 300 m-long GeO_2-doped-core PCF. The short and long ends of the SC depend on a velocity matching condition between soliton and trapped dispersive waves just as shown in Fig. 6(b). We can clearly observe that in GeO_2-doped-core PCF case, the spectrum is greatly broadened. Moreover, Cascante et al. [8] reported experi-

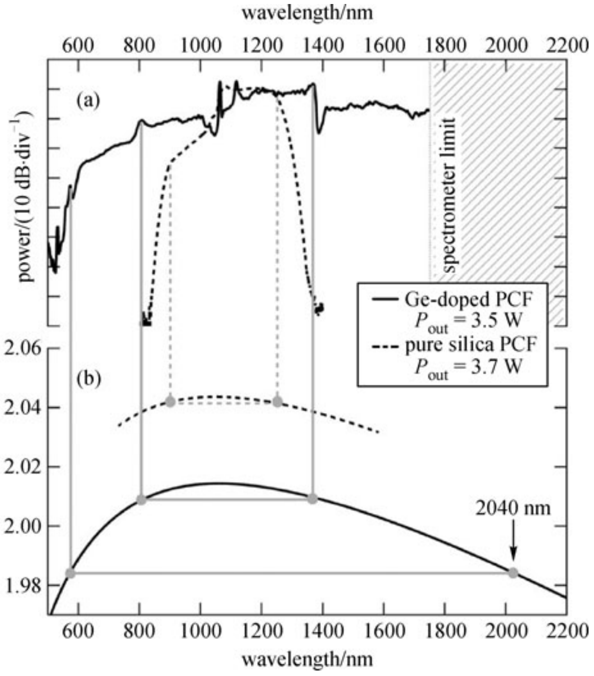

Fig. 6 Spectra recorded for (a) launched power of 13 W in GeO_2-doped-core PCF (solid curve), and pure silica PCF (dashed curve); (b) corresponding group-velocity curves

mental results on SC generation in a highly Ge-doped core Y-shaped PCF using pump pulses of 9 ns duration at 1064 nm in 2010. Although the fiber was pumped in normal dispersion and relatively far from the ZDW, flat and smooth SC in the fundamental mode from 550 to beyond 1750 nm was generated. In 2010, SC generation by Bethge et al. [21] in a water-filled photonic crystal fiber was reported. By only filling the central hollow core of this fiber with water, the fiber properties were changed. Using a pump wavelength of 1200 nm and few-microjoule pump pulses, the generation of SC with two-octave spectral coverage from 410 to 1640 nm was experimentally demonstrated.

5 Conclusions

We have reviewed the PCFs used to generate SC and briefly analyzed the physical mechanisms enabling this process. PCFs have been creating new ways of thinking about light guidance in optical fibers, which happens not only in silica cores, but also in germanium or fluorine, liquids and even gases. To obtain a wanted continuum, we should carefully choose the fiber parameters, pump conditions and other conditions. Further optimization of the fiber design and the use of cascaded or tapered fibers should allow extension to the visible spectral region.

References

1. Dudley J M, Genty G, Coen S. Supercontinuum generation in photonic crystal fiber. Reviews of Modern Physics, 2006, 78(4): 1135–1184
2. Genty G, Coen S, Dudley J M. Fiber supercontinuum sources. Journal of the Optical Society of America B, Optical Physics, 2007, 24(8): 1771–1785
3. Cerqueira A S Jr. Recent progress and novel applications of photonic crystal fibers. Reports on Progress in Physics, 2010, 73(2): 024401–024422
4. Ranka J K, Windeler R S, Stentz A J. Visible continuum generation in air-silica microstructure optical fibers with anomalous dispersion at 800 nm. Optics Letters, 2000, 25(1): 25–27
5. Frosz M H. Supercontinuum Generation in Photonic Crystal Fibres: Modelling and Dispersion Engineering for Spectral Shaping. Department of Communications, Optics & Materials. Technical University of Denmark, 2006
6. Moselund P M. Long-Pulse Supercontinuum Light Sources. Department of Photonics Engineering. Technical University of Denmark, 2009
7. Russell P St J. Photonic-crystal fibers. Journal of Lightwave Technology, 2006, 24(12): 4729–4749
8. Cascante J V, Torres P S, Diez A, Andres M V. Supercontinuum generation in highly Ge-doped core Y-shaped microstructured optical fiber. Applied Physics. B: Lasers and Optics, 2010, 98 (2–3): 371–376
9. Travers J C, Rulkov A B, Cumberland B A, Popov S V, Taylor J R. Visible supercontinuum generation in photonic crystal fibers with a 400 W continuous wave fiber laser. Optics Express, 2008, 16(19): 14435–14447
10. Travers J C, Popov S V, Taylor J R. Extended blue supercontinuum generation in cascaded holey fibers. Optics Letters, 2005, 30(23): 3132–3135
11. Mussot A, Kudlinski A, Beugnot J C, Sylvester T, Gonzalez H M, Bouwmans G. Extended blue side of flat supercontinuum generation in PCFs with a CW Yb fiber laser. In: IEEE/LEOS Winter Topical Meeting Series, 2008, 178–179
12. Cumberland B A, Travers J C, Popov S V, Taylor J R. Toward visible cw-pumped supercontinua. Optics Letters, 2008, 33(18): 2122–2124
13. Skryabin D V, Gorbach A V. Colloquium looking at a soliton through the prism of optical supercontinuum. Reviews of Modern Physics, 2010, 82(2): 1287–1299
14. Dudley J M, Provino L, Grossard N, Maillotte H, Windeler R S, Eggleton B J, Coen S. Supercontinuum generation in air-silica microstructured fibers with nanosecond and femtosecond pulse pumping. Journal of the Optical Society of America. B, Optical Physics, 2002, 19(4): 756–771
15. Ghosh D, Roy S, Pal M, Leproux P, Viale P, Tombelaine V, Bhadra S K. Blue-extended sub-nanosecond supercontinuum generation in simply designed nonlinear microstructured optical fibers. Journal of Lightwave Technology, 2011, 29(2): 146–152
16. Guo C Y, Ruan S C, Yan P G, Pan E, Wei H F. Flat supercontinuum generation in cascaded fibers pumped by a continuous wave laser. Optics Express, 2010, 18(11): 11046–11051
17. Travers J C. Blue extension of optical fibre supercontinuum generation. Journal of Optics, 2010, 12(11): 113001–113020
18. Kudlinski A, George A K, Knight J C, Travers J C, Rulkov A B, Popov S V, Taylor J R. Zero-dispersion wavelength decreasing photonic crystal fibers for ultraviolet-extended supercontinuum generation. Optics Express, 2006, 14(12): 5715–5722
19. Stark S P, Podlipensky A, Joly N Y, Russell P S J. Ultraviolet-enhanced supercontinuum generation. Journal of the Optical Society of America B, Optical Physics, 2009, 27(3): 592–598
20. Kudlinski A, Bouwmans G, Vanvincq O, Quiquempois Y, Rouge A L, Bigot L, Melin G, Mussot A. White-light cw-pumped supercontinuum generation in highly GeO_2-doped-core photonic crystal fibers. Optics Letters, 2009, 34(23):3631–3633
21. Bethge J, Husakou A, Mitschke F, Noack F, Griebner U, Steinmeyer G, Herrmann J. Two-octave supercontinuum generation in a water-filled photonic crystal fiber. Optics Express, 2010, 18(6): 6230–6240