Cascaded PCF tapers for flat broadband supercontinuum generation

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We report the fabrication of cascaded photonic crystal fiber (PCF) tapers in monolithic design. Flat broadband supercontinuum (SC) generation in cascaded PCF tapers pumped by sub-nanosecond pulses from a 1 064-nm microchip laser is demonstrated. The spectral width (20 dB) extends from 0.47 to 1.67 μm. In the optimal configuration, an ultraflat (3 dB) spectrum from 500 to 1 000 nm is achieved.

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Flat broad supercontinuum (SC) is of interest in quite diverse applications, including the realization of compact sources for wavelength division multiplexing[1], optical coherence tomography, ultrashort pulse generation[2], optical frequency metrology[3], and so on. Typically, SC generation in photonic crystal fibers (PCFs) is realized by introducing a short pump pulse into the anomalous dispersion region of the fiber, near the zero dispersion wavelength (ZDW). However, the output SC spectrum commonly suffers from lack of spectral flatness (i.e., considerable spectral fluctuations around 20 dB) and low-coherence properties that restrain practical applications. One method to avoid spectral vibration is pumping in the normal dispersion regime. It prevents modulation instability (MI) and soliton fission and, thus, improves coherence and spectral flatness, but with the disadvantage of a narrow spectrum[4].

The report on flat broadband SC attracted much attention because of the diverse applications. Wide (1.1–2.2 μm) and very smooth SC spectra in soft glass PCF, pumped with femtosecond pulse, were theoretically identified[5]. A broad (1 000–1 700 nm) and flat (5 dB) SC with low pump pulse energy (69-pJ, 740-fs pulses at 1 540 nm) at telecom wavelengths in a lead-silicate fiber was demonstrated[6]. A long ZDW high nonlinearity fiber spliced with a 200-m-long PCF was used to address the insufficient energy conversion from the pump region to the long wavelength region of the SC, thus achieving a broad flat CW-pumped SC with a 3-dB spectral range of 340 nm[7].

Tapered PCFs have been used successfully as a nonlinear medium for various studies on SC generation. Tapered PCFs are attractive options for SC generation because of their manageable dispersion and enhanced nonlinearity. In many SC generation experiments, short tapered fibers can be adequate to obtain broadband spectra. SC generation confined to the visible 15-cm-long tapered SMF28 and tapered PCF pumped by femtosecond pulses centered at 540 nm were achieved[8]. SC generation, extending from 375 to 1 750 nm, was observed in the tapered PCFs, with 11-m-long transition for both nanosecond and picosecond 1.06-μm pump sources[9]. An ultra-broad SC (down to 280 nm in deep UV) was formed by pumping sharply tapered (5–30 mm

taper lengths) solid-core PCFs at 130-fs and 2-nJ pulses at 800 nm were obtained[10]. However, all the spectra generated in the tapered PCF lack spectral flatness (i.e., considerable spectral fluctuations around 20–40 dB), thus restricting the applications.

In this letter, we fabricated cascaded PCF tapers based on two kinds of PCFs to achieve a monolithic design. This technique can address the limitation of the tapering rig and, thus, enhance the length of nonlinear interaction. The cascaded tapers have been used to generate broadband SC, spanning almost two octaves and extending an ultraflat (3 dB) spectrum from 500 to 1 000 nm with sub-nanosecond pump pulse. Enhanced continuum flatness will widen potential applications in biomedical imaging, microscopy, and spectroscopy systems.

The experimental setup is shown schematically in Fig. 1. All fibers are pumped using a microchip laser at 1 064 nm and delivering 0.7-ns pulses (FWHM) at a repetition rate of 7 kHz. The light is shone to the PCFs or tapers with a×25 microscope objective. The pump peak power effectively launched into the fiber was 8kW (corresponding to an average power of 40 mW). The output spectra were recorded using an optical spectrum analyzer (OSA, AQ6315A) with spectral resolution of 10 nm.

Initially, our approach can fabricate cascaded two PCF tapers to achieve a monolithic design, consisting of two tapered sections within one PCF (i.e., the tapers are connected by the untapered section, rather than by splicing). To improve the spectral broadening and flattening, cascaded three PCF tapers and four PCF tapers within one PCF were used. By adjusting the tapering parameters, a series of low loss (<0.1 dB) cascaded PCF tapers were obtained. The schematic of the cascaded PCF tapers is shown in Fig. 2.

The PCFs used in this work consisted of pure silica and were prepared through the stack-and-draw technique by YOFC and FIBERHOME. Figures 3(a) and 4(a) show the cross sections of the untapered PCFs, with ZDW values of 1.01 and 1 μm, respectively. The flame-brush technique was used to taper the PCFs by adjusting the tapering parameters to reduce the outer diameter, while keeping the air-filling fraction almost unchanged. All the tapered samples have untapered sections at each end, allowing launch efficiencies. The outer diameter of the
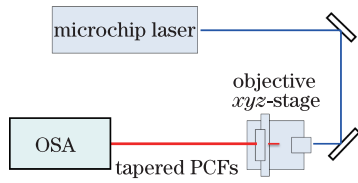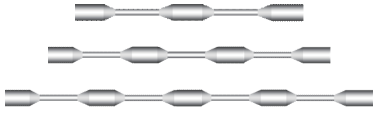
Fig. 1. Experimental setup.

Fig. 2. Schematic of the cascaded PCF tapers (the number of tapered sections increased from 2 to 4).
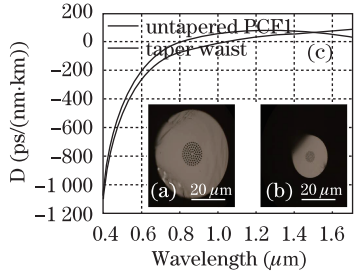

Fig. 3. Cross sections and calculated GVD values of (a) PCF 1, $d = 2.05$ μm, $\Lambda = 3.35$ μm, (b) tapered PCF1, $d = 0.984$ μm, $\Lambda = 1.6$ μm; (where d and Λ are the hole diameter and the hole-to-hole distance, respectively), and (c) calculated GVD of untapered and tapered PCF1.

tapered PCF1 was reduced from 125 to ∼60 μm along a 12-cm length, resulting in core size reduction from 4.2 to ∼2 μm. On the other hand, the outer diameter of the tapered PCF2 was reduced from 125 to 45 μm along a 16-cm length, resulting in core size reduction from 4.5 to 1.6 μm. The cross sections of the taper waists of PCF1 and PCF2 are shown in Figs. 3(b) and 4(b).

The dispersion properties of the tapered PCFs were modeled using the finite element method (with the COMSOL software). Calculations were made using the untapered fibers and the structure of the taper waist. The calculated group velocity dispersion (GVD) curves are shown in Figs. 3(c) and 4(c). For the tapered PCF1, the ZDW value decreased from 1.01 to 0.8 μm, and another ZDW appeared at 1.89 μm. These values were similar to those of the tapered PCF2 (i.e., the ZDW value was 1 μm at the input end, and two ZDWs appeared at 0.73 and 1.26 μm at the taper waist).

Apparently, all the SCs were generated in the fundamental mode. Their spectra were plotted on a logarithmic scale.

The output spectra generated by the tapers were measured and then compared with that of the untapered fiber. The untapered PCF1, tapered PCF1, and cascaded two PCF1 tapers had the same lengths (70 cm). The average launched power was ∼40 mW, in all cases. The results of measurements are summarized in Fig. 5(a). Compared with that of the untapered PCF1, the spectra of the tapered PCF1 and the cascaded two PCF1 tapers showed continuous broadening toward both sides of the pump wavelength. The same phenomenon was observed in the cascaded three and four PCF1 tapers,

compared to the equally long untapered fiber, as shown in Figs. 5(b) and (c). The changes in nonlinear interaction length clearly resulted in strong variations in the output spectrum. The transfer of energy from the pump wavelength to the continuum gradually became more and more efficient, and the generated SC sequentially broadened on the visible side. The widest spectrum (more than 1 100 nm at the –20 dB level) was observed in the cascaded four PCF1 tapers, from 520 to 1 650 nm.

It is an interesting challenge to check whether a substantial broadening is achievable simply by choosing a "suitable" waist and increasing the interaction length as much as possible. Thus, we prepared cascaded two PCF2 tapers, consisting of two tapered sections, each with 45-μm waist diameter and 16-cm waist length.

The development of SC in the cascaded PCF2 tapers was studied by cutting the fiber back at a fixed pump power. The fiber was cut from the output end of the first tapered section, and the spectrum was recorded. We also compared the output spectra with equally long untapered PCF2. The results of the measurements are summarized in Fig. 6. The output power was nearly indistinctive, which demonstrates that cascaded tapers will not reduce the throughput considerably. Strikingly, significant broadening already started at one taper. In fact, with an output power of 20 mW, the generated SC of the tapered PCF2 covered almost two octaves. The
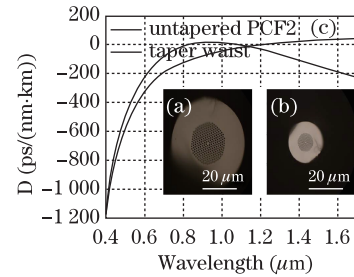

Fig. 4. Cross sections and calculated GVD values of (a) PCF 2, $d = 2.03$ μm, $\Lambda = 3.27$ μm, (b) tapered PCF 2, $d = 0.73$ μm, $\Lambda = 1.18$ μm, and (c) calculated GVD for untapered and tapered PCF 2.
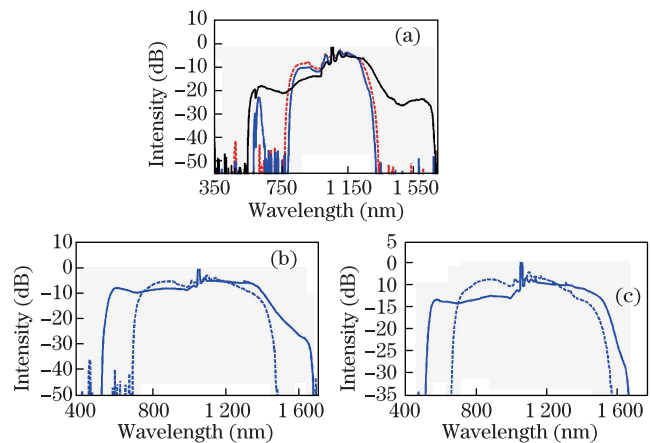

Fig. 5. (Color online) (a) Output spectra of the tapered PCF1 (blue), cascaded two-PCF1 tapers (black), and untapered PCF1 (red). Output spectra of the cascaded (b) three- and (c) four-PCF1 tapers (solid) and untapered PCF1 (dashed). Each tapered section has a waist diameter of 60 μm and a waist length of 12 cm.

broadening was also extended to the visible region, producing a spectrum that ranged from 470 to 1 670 nm (at –20 dB level).

In Fig. 7, the cascaded two PCF2 tapers did not alter the spectrum significantly. However, they had better flatness and showed an ultraflat (3 dB) spectrum from 500 to 1 000 nm. This result suggests that increasing the length of the tapers improves the spectral flatness.

In our experiments, all tapered samples have untapered sections at each end. The piece of untapered fiber ensures that the pulse breakup and the soliton generation began before the tapering.

Subsequently, the spectral broadening in the taper can be comprehended in three steps (i.e., the generations along the input taper transition, the taper waist, and the output transition). The decreasing ZDW along the input transition allows the four-wave mixing (FWM) phase-matching condition to be satisfied. A cascaded FWM process along the taper transition was enabled[11]. Simultaneously, Raman soliton self-frequency shifted (SSFS) propagating in the taper transition contributed to the generation toward long wavelengths[12]. The broadband light generated during the taper transition pumped the uniform taper waist. As we all know, the long wavelength edge of the SC is shaped by the spectral redshift of solitons that occur in the Raman-active media[11]. The second ZDW of the tapers dropped to wavelengths below 2 400 nm, where it limits the red shift caused by soliton recoil from the dispersive waves generated above the ZDW. The cascaded PCF tapers ensured the appropriate interaction length, by which modified phase-matching conditions are satisfied. As the fiber diameter started to increase in the output transition region, the solitons accelerate. The dispersive waves that they had trapped fall behind and do not interact further with the solitons. Further
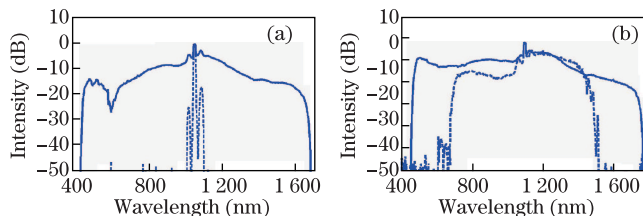

Fig. 6. Output spectra of (a) the tapered PCF2 (solid) and (b) cascaded two PCF2 tapers and untapered PCF2 (dashed). The waist diameters of tapered sections are 45 μm and the lengths are 16 cm each.
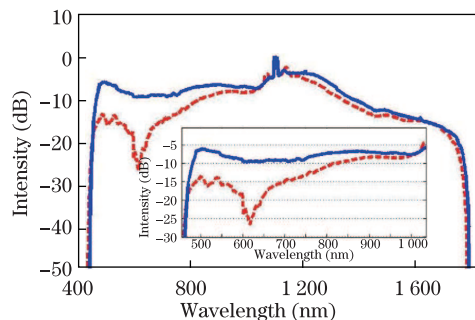

Fig. 7. Output spectra of the tapered PCF2 and cascaded two PCF2 tapers, and the far field pattern of the output beam of the cascaded tapers (inset).

changes in the spectrum were small.

In our experiments, the variation in diameter of the tapered PCFs can be used as a new degree of freedom to tailor the spectrum. The next step is cascading PCF tapers with different diameters in an attempt at a continuous longitudinal variation of dispersion and nonlinearity. The reason is that soliton trapping of dispersive waves to extend the short wavelength of the continuum requires a broad group velocity that matches the shortest wavelength possible[4].

In conclusion, we demonstrate the generation of almost two octave-spanning ultraflat SC in cascaded PCF tapers. The generated SC has a spectral width extending from 0.47 to 1.67 μm, with 3-dB spectral range of 500 nm (from 500 to 1 000 nm). Adequate spectral amplitude shaping can be achieved, because the freedom in PCF parameter control offered by the tapers, as well as other post-processing techniques, leads to some new considerations. The proposed concept of cascaded PCF tapers can be extended toward long interaction lengths, high nonlinearity, and manageable dispersion, so that the presented superb SC quality can be even increased further.

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