

# Build-up of supercontinuum in heated and unheated photonic crystal fibers using a chirped femtosecond laser

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## Abstract

The build-up of supercontinuum in a photonic crystal fiber (PCF) has been investigated experimentally as a function of pump power using chirped 100-fs pulses from a Ti:sapphire laser. As compared with the PCF at room temperature, a new blue-shifted spectral component is observed in the initial steps of supercontinuum (SC) generation when the central part of PCF is heated to 120 °C by a hot plate. In addition, the slope efficiency of SG is slightly improved with the slightly extension of supercontinuum spectrum in blue edge at high pump powers. The change in dispersion property as well as the effective cascading of nonlinear photonic crystal fibers for heated PCF would be the main attributions.

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## 1. Introduction

Recently, photonic crystal fibers (PCFs) have attracted great research interests [1–3]. Various fiber designs are proposed and even commercially available. PCFs commonly consist of a central fused-silica core surrounded by a regular array of air holes running along the fiber length. By varying the arrangement and size of the holes, the dispersion of the fiber can be tailored in broad wavelength ranges [4,5]. In contrast to the conventional single-mode fiber (SMF) which has zero dispersion around 1310 nm, the zero dispersion wavelength of PCF can be designed toward shorter wavelengths; therefore, many interesting nonlinear optical effects can be observed in the near infrared as well as in the visible ranges. The unique dispersion and nonlinear properties of PCFs show potential applications in fiber optic communication, sensor technology, frequency metrology, and laser physics [6–8]. For sensor applications, dependences of PCF properties on temperature, tension, etc. are usually recorded to reflect the environmental

changes [8]. For example, increased environment temperatures could cause the size and spacing of PCF holes to change due to thermal expansion. In addition, the refractive index of fused-silica would also change because of thermo-optical effect. The combined thermal effects might add up to lead to complicated dependences of dispersion and nonlinearity on temperature of the PCFs.

Generation of broadband supercontinuum (SC) from the injection of femtosecond laser pulses into photonic crystal fibers had been studied by several groups [9–17]. These attentions originate both in scientific curiosity and in many applications, such as metrology, optical coherence tomography, novel light sources, etc. [18–21]. Different nonlinear mechanisms were observed depending on whether the pump is located in the normal or anomalous dispersion region. The combination of the unique dispersion properties and enhanced nonlinearities benefit efficient generation of SC radiation when the center wavelength of ultrashort pulse laser is located in the vicinity of the zero dispersion wavelengths of the PCFs. However, the roles of PCFs properties under controlled temperature in the SC generation process have not been reported in the literatures.

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In this paper, we experimentally investigate the influence of the thermal effects of nonlinear PCF on the initial stage of spectral broadening as well as the overall spectral range and conversion efficiency of SC generation with chirped femtosecond laser pulses. At very low pump powers, a blue-shifted nonsolitonic radiation is observed for unheated PCF. When the central part of PCF is heated to 120 °C by a hot plate, a new blue-shifted spectral component is observed. At high pump powers, the slope efficiency of SC generation is slightly improved with the blue edge of SC spectrum occurring at a shorter wavelength as compared with the unheated PCF. The observed phenomena might be attributed to the change in dispersion property as well as the effective cascading of nonlinear photonic crystal fibers for heated PCF.

## 2. Experimental setup

Fig. 1 shows the schematic of our experimental setup. Femtosecond pulses from a chirped Kerr-lens mode-locked Ti:sapphire laser were coupled into the PCF through a 40× microscope objective. For maximum coupling efficiency, the input side of PCF was mounted on a high resolution 3-axis translation stage, and the optical axis of microscope objective was aligned parallel to the fiber. The pump power was measured just before the microscope objective. The output spectrum from PCF was recorded by a spectrometer with 200–850 nm spectral range (Ocean Optics S2000) and an optical spectrum analyzer with 350–1750 nm spectral range (Advantest Q8347). The PCF used in our SC generation is a 1-m long highly nonlinear fiber, whose core diameter is 1.7 μm with symmetrical mode-field guidance (Crystal Fibre NL-1.7-790). There are two zero dispersion wavelengths of 790 nm and 1400 nm for this fiber, and its cutoff wavelength of single mode is 680 nm. For heating the fiber, the central part of this fiber is kept in contact with a hot plate, whose temperature is tunable from the room temperature 20–300 °C. Although the used equipment allows increasing the temperature up to 300 °C, we do not heat the fiber to higher temperature than 150 °C to avoid melting of the fiber coating, which might induce uneven stress on the PCF.

## 3. Results and discussion

At the beginning, we set the center wavelength of the pump Ti:sapphire laser to about 830 nm (Fig. 2(a)), corre-

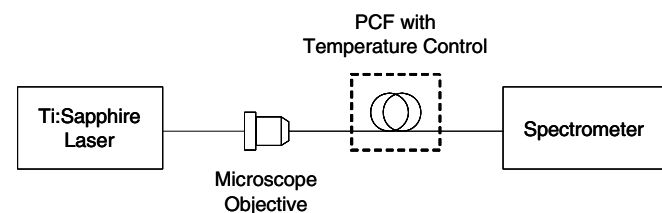


Fig. 1. Experimental setup of SC from the PCF.

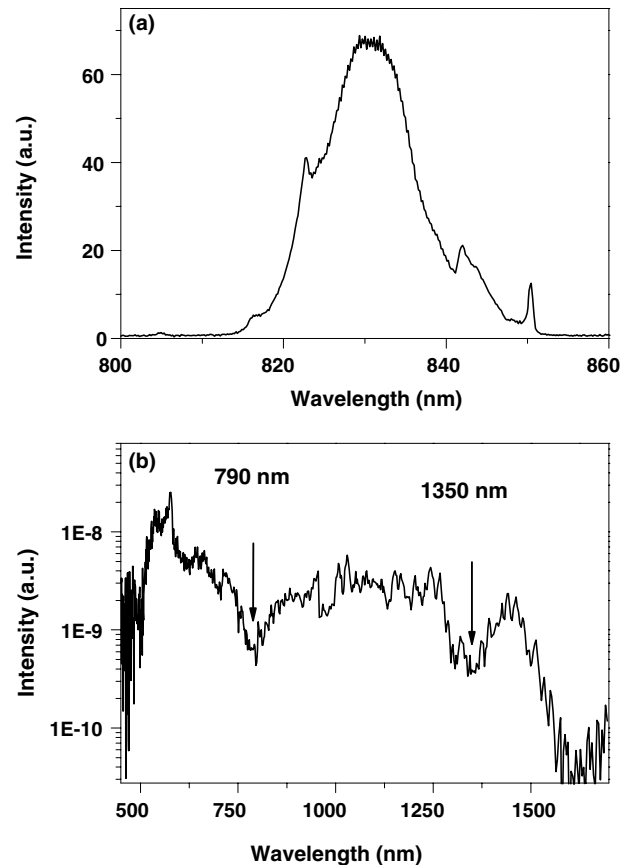


Fig. 2. (a) Spectrum of the chirped 100-fs Ti:sapphire laser with center wavelength of 830 nm. (b) SC generation from PCF for 350 mW pump power.

sponding to the anomalous dispersion region of fiber, and the average power of laser pulses is 350 mW. The chirped pulse has the full-width at half-maximum (FWHM) about 14 nm and the pulsewidth about 100 fs. The time-bandwidth product of the chirped pulse is 0.61, which is larger than that of transform-limited  $\text{sech}^2$  pulse (0.315). The SC spectrum in Fig. 2(b) extends from 480 to 1600 nm, spanning over 1100 nm. As reported previously [22], two spectral dips at 790 and 1350 nm are obviously observed, which is very close to the two zero dispersion wavelengths of this fiber (790 and 1400 nm in the specification).

Then, the laser power and the ambient temperature of PCF are tuned independently to observe their influences on the SC generation. In Fig. 3, output spectra from PCF were recorded for various pump powers when the ambient temperature of PCF is set at room temperature. At very low pump power (Fig. 3(a)), the output spectrum is slightly broadened around 830 nm due to self-phase modulation (SPM). When the pump power is increased to 6 mW, a new wavelength begins to build up around 695 nm. As the pump powers are further increased to 8 and 10 mW, the build-up wavelengths are shifted to 690 and 680 nm, respectively, as shown in Fig. 3(b) and (c). In Fig. 3(d) and (e), the output spectrum becomes broader and extends further toward shorter wavelength as the

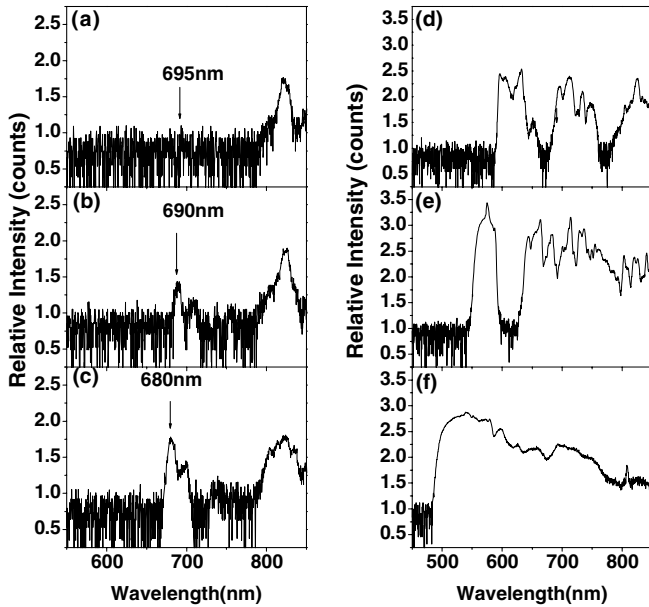


Fig. 3. Output spectra of PCF for pump powers of: (a) 6 mW, (b) 8 mW, (c) 10 mW, (d) 30 mW, (e) 100 mW, and (f) 350 mW, respectively (the relative intensities are in log scales). The ambient temperature of PCF is 20 °C. For 350 mW pump power, the short wavelength edge of SC generation located at 480 nm.

pump power is further increased. When the central wavelength of the pump laser is tuned slightly longer than the wavelength of zero dispersion, one would expect the build-up of new wavelength shorter than the wavelength of zero dispersion as a result of four-wave mixing (FWM) or Cerenkov radiation [10,17]. Therefore, shorter build-up wavelengths would be observed if longer central wavelengths of laser pulses were applied for pumping the PCF. At high pump power, additional nonlinearity including FWM process [10] and cross phase modulation (XPM) [17] results in more wavelengths generating. As shown in Fig. 3(f), the blue edge of SC has been extended to 480 nm for 350 mW pumping. The spectral dip near 790 nm is not obvious due to the deteriorated near IR responsivity of this spectrometer. However, the shift of spectrum toward shorter wavelength is terminated if we further increase the pump power above 350 mW.

To study the thermo-optical properties of PCF in the nonlinear regime, the central part of this PCF (about 60 cm in length) is heated to 120 °C by a hot plate. Again, various power levels of ultrashort pulse were launched into the PCF in order to observe the build-up and spectral broadening of SC generation. As shown in Fig. 4(a), two distinct spectral peaks around 680 and 740 nm begin to build up at the onset of spectral broadening for pumping with 830 nm central wavelength and 18 mW pump power. Following, additional peaks would be seen and the spectra show the continual result as the power increase at 30 mW (Fig. 4(b)) and 100 mW (Fig. 4(c)). Under high pump power of 350 mW, the blue edge of SC for heated PCF (at 120 °C) is extended to a shorter wavelength at 470 nm (Fig. 4(d)) as compared to the unheated one. The blue-shifted spectral

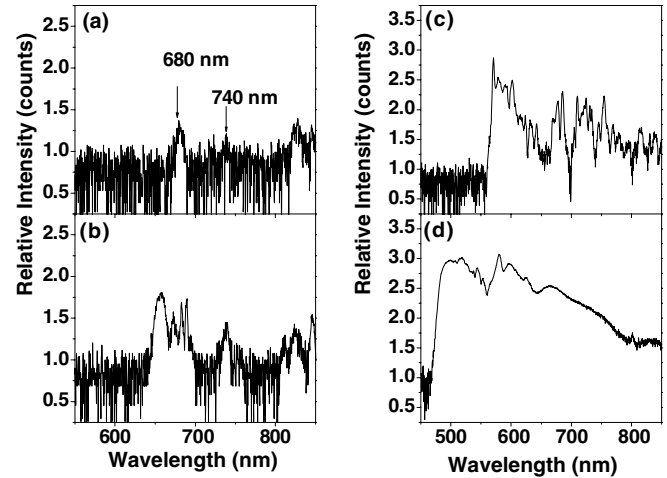


Fig. 4. Output spectra of PCF for pump power of: (a) 18 mW, (b) 30 mW, (c) 100 mW, and (d) 350 mW, respectively (the relative intensities are in log scales). The central part this PCF (60 cm) is heated to 120 °C by a hot plate. For 350 mW pump power, the short wavelength edge of SC generation located at 470 nm.

component might be attributed to the change of the total dispersion curve in the heated section of PCF that would be described in the following text, but quantitative studies still have to be done for further understandings of the temperature influence on SC generation. The slope efficiency of SC generation is also improved slightly for the 120 °C heated PCF, especially within the 550 ~ 650 nm wavelength range. However, further increasing the temperature to 150 °C will deteriorate slightly both the spectral range and conversion efficiency of SC. This should result from the proper compensation of the pulse chirping for the 120 °C heated PCF.

Since the core diameter of heated part in PCF increases as a result of thermal expansion, the cutoff wavelength and mode field should be changed in the heated part. The linear expansion of the fiber can be expressed by

$$\Delta L = \alpha \Delta T,$$

where  $\Delta L$  could be core diameter, air-hole diameter, pitch or fiber length,  $\alpha$  is the thermal expansion coefficient of the fiber material, and  $\Delta T$  is the temperature change of the heated PCF. In addition, the thermo-optical index change of the fiber material can be expressed by

$$\frac{dn}{dT} = \zeta n,$$

where  $n$  and  $\zeta$  are refractive index and thermo-optic coefficient of the fiber materials, respectively. The thermal-expansion coefficient for silica glass is around  $5 \times 10^{-7}/^\circ\text{C}$ , and the thermo-optic coefficient is around  $7 \times 10^{-6}/^\circ\text{C}$  [23]. Thermal expansion effect will change the waveguide dispersion of PCF, while thermo-optic effect will change the material dispersion. Ferrando et al. [4] have shown the effect of scaling simultaneously the pitch ( $\Lambda$ ) and the air-hole radius ( $r$ ) while keeping the  $r/\Lambda$  ratio constant. The dispersion curves shift upwards and broaden

slightly as the scaling factor increases (this is equivalent to increasing  $A$ , or thermal expansion). This effect shifts the short zero dispersion wavelength  $\sim 50$  nm toward the shorter wavelength even for flattened chromatic dispersion PCF (smaller dispersion slope with separation of zero dispersion wavelengths  $< 90$  nm). The amount of shift of short zero dispersion wavelength would depend upon the designed structure of PCF (waveguide dispersion of larger dispersion slope, with separation of zero dispersions  $\sim 600$  nm in our case). On the other hand, temperature-dependence of Sellmeier coefficients for silica glass must also be considered in estimating the zero dispersion wavelength and dispersion slope. As calculated by Ghosh et al. [24], the zero dispersion wavelength  $\lambda_0$  ( $1.273 \mu\text{m}$  at  $26^\circ\text{C}$ ) for bulk silica glass varies linearly with temperature, and  $d\lambda_0/dT$  is  $0.025 \text{ nm}/^\circ\text{C}$ . Therefore, the thermo-optic effect will shift the short zero dispersion wavelength toward longer wavelengths that should be all the same for various silica glass fibers including PCFs. As a result, thermal expansion and thermo-optic effects compete in the determination of zero dispersion wavelengths and total dispersion curve. Thus, the observed blue-shifted spectral component appearance should be attributed to the change of the dispersion curve, which is governed by the waveguide dispersion due to the thermal expansion effect in the heated section of PCF. Kato et al. [25] have examined the temperature dependence of chromatic dispersion for various types of fiber. Its coefficient has been found to depend strongly on the dispersion slope. Therefore, temperature may affect the dispersion as well as the SC in conventional high nonlinear single mode fiber, depending on the design of fibers.

The zero-dispersion wavelength could be different for the heated and unheated section of PCF because of their differences in physical dimensions, such as core diameter or pitch, etc. Therefore, the heated nonlinear PCF in our experiment has two zero-dispersion wavelengths in the near IR spectral range, corresponding to unheated and heated portions of the fiber, which is equivalent to cascading two highly nonlinear PCFs with slightly different physical dimensions. This may also explain why a higher pump power ( $18 \text{ mW}$ ) is required to initiate new wavelengths than that at room temperature ( $6 \text{ mW}$ ), since the effective interaction length for certain nonlinear process has been reduced. In addition, the spectral broadening is less obvious in heated PCF at lower pump powers, which can be observed by comparing the spectrum in Fig. 4(b) with that of Fig. 3(d). However, the above situation is reversed at higher pump powers. By comparing the spectra in Fig. 3(e) and 4(c) for  $100 \text{ mW}$  pump power, as well as the spectra in Figs. 3(f) and 4(d) for  $350 \text{ mW}$ , we observed that the spectra is more continual and slightly broadened for the heated PCF.

In comparison with the result by using transform-limited Ti:sapphire laser pulses, we find that the generated SC for both heated and unheated PCFs are nearly the same. In a recent paper [26], Champert et al. has demonstrated that the simultaneous launching the fundamental

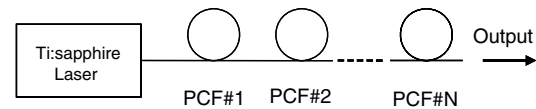


Fig. 5. A proposed scheme for tailoring both the PCF nonlinearity and dispersion in the SC generation process.

and second harmonic signals of a passively Q-switched microchip laser in the normal and anomalous dispersion regimes of photonic crystal fiber leads to a homogeneous SC in the visible range. Hu et al. [27] also showed that a disordered PCF with randomly distributed transverse sizes allowed a highly efficient broadly tunable frequency conversion of low energy ultrashort laser pulses. Although the improvement of spectral range for SC generation is not dramatic by using the sectional PCF-heating method, we believe that by proper cascading of highly nonlinear PCFs may help to further broaden and flatten the SC spectrum. A proposed scheme is shown in Fig. 5, where several PCFs (PCF#1 through PCF#N) are connected in series to enhance the cascading effect as well as to tailor the overall nonlinearity and dispersion. The cascading of fiber nonlinearity would be helpful in the SC generation process.

#### 4. Conclusion

We have generated supercontinuum spectra by coupling chirped Ti:sapphire laser pulses into nonlinear photonic crystal fibers and found that the threshold pump power for initial build-up as well as the spectral range of supercontinuum depend on the ambient temperature of fibers. In comparison with the unheated PCF, the heated PCF shifts the blue edge of supercontinuum spectrum toward the shorter wavelength and slightly improve the slope efficiency of supercontinuum generation. This should result from the proper compensation of the pulse chirping for the heated PCF. We believe that by effective cascading of highly nonlinear photonic crystal fibers, either by sectional heating or by physical connecting, could help to broaden and flatten the supercontinuum spectrum.

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