High stability supercontinuum generation in lead silicate SF57 photonic crystal fibers*

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We report supercontinuum (SC) generation in a lead silicate SF57 photonic crystal fiber by using a 1550 nm pump source. The effective nonlinear coefficient of the SF57 fiber is simulated to be 111.5 $W^{-1}\cdot km^{-1}$ at 1550 nm. The fiber also shows ultraflat dispersion from 1700 nm to 2100 nm. Our results reveal that with an increase of the average power of the incident pulse from 10 mW to 90 mW, the SC of the SF57 photonic crystal fiber is generated from 1300 nm to 1900 nm with high stability and without significant change in spectral broadening.

Keywords: photonic crystal fiber, nonlinear optics, supercontinuum generation

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1. Introduction

Supercontinuum (SC) generation in a photonic crystal fiber (PCF) has attracted a lot of attention in recent years.[1–5] In those fibers, the high linear refractive index contrast between the background material and the air holes leads to tight modal confinement. One of the most important features of PCF is the flexibility to control their dispersion profiles. Generally speaking, the PCF's dispersion is determined by the material and the waveguide dispersion. In this paper, we use a PCF whose background material is a high index lead silicate SF57 soft glass and fiber structure which can be designed to give rise to a very strong waveguide dispersion.

The use of high index PCF for SC generation is cutting-edge research in the field of photonics.[6,7] Many unusual properties can be achieved, including the range of transmission extending to mid-infrared,[8] the zero dispersion wavelength (ZDW) up to 2.0 μm,[9] and the ultraflat SC generation.[10] SC generation provides a broadband optical source for the optical frequency metrology,[11] frequency comb generation,[12] and optical coherence tomography.[13]

In our previous studies,[14] a broad SC generation was realized in a silica PCF by using a pulsed laser whose wavelength was in the anomalous dispersion region of a PCF. The SC spectra showed an unstable spectral structure and low coherence properties. One way to prevent fluctuation in SC spectra is to tune the wavelength of the pump pulse to the normal dispersion region of the fiber. This suppresses the modulation instability (MI) and soliton fission and improves the coherence and spectral flatness. However, there is a drawback: the spectral broadening is reduced.[10,15] Recently, there are studies that use optimized dispersion profiles and the nonlinear response of the PCF to generate broadband continuums.[16] Omenetto *et al.* demonstrated a spectrally smooth SC spectrum ranging from 350 nm to 3000 nm in a soft-glass PCF with the pump wavelength at the anomalous dispersion regime.[17] Hundertmark *et al.* reported an all fiber diode-pumped erbium-fiber oscillator–amplifier system as an optical source for SC generation in a PCF at 1560 nm. When the pulse energy was about 200 pJ, an octave-spanning SC from 400 nm to beyond 1750 nm was generated.[18] A transmission experiment was performed using a birefringent PCF, when the center wavelength of the incident pulse was in the normal dispersion regime, it would produce an SC spectrum with a significant blue sift.[19] Zhang *et al.* presented a genetic algorithm based approach to design the PCF for high coherence and large bandwidth SC generation. The SC of their PCF showed a larger bandwidth and an increased coherence compared to those of a fiber with a single ZDW at 2 μm.[20]

In this paper, we study SC generation in a soft glass (SF57, a high index lead silicate glass) PCF, which was fabricated by the Institute of Photonics & Advancing Sensing at the University of Adelaide, Australia. We numerically simulate the basic properties of the SF57 PCF by using the finite element method (FEM), and experimentally measure the spectral evolution of the generated SC when the average pump power is varied from 10 mW to 90 mW. We demonstrate the SC generation with spectrum spanning from 1300 nm to 1900 nm using ultrafast pump pulses at 1550 nm in a 60 cm length fiber with

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its ZWD at 1610 nm. The SC shows high stability and no significant changes in spectral broadening with the increase of the average power of the incident pulse.

2. Theory

The refractive index of the SF57 glass can be obtained by the Sellmeier equation as

$$n(\lambda)=\sqrt{1+\frac{B_1\lambda^2}{\lambda^2-C_1}+\frac{B_2\lambda^2}{\lambda^2-C_2}+\frac{B_3\lambda^2}{\lambda^2-C_3}}, \tag{1}$$

where B_1=1.81651371, B_2=0.428893641, B_3=1.07186278, C_1=0.0143704198, C_2=0.0592801172, and C_3=121.419942.[21] Due to the combination of the highly nonlinear refractive index of the lead silicate SF57 glass and the strong mode confinement possible in the small core PCF, the SF57 PCF is a suitable nonlinear medium with a strong nonlinear effect. The nonlinearity coefficient γ can be defined as

$$\gamma(\lambda)=\frac{2\pi n_2}{\lambda A_{\rm eff}}, \tag{2}$$

where $A_{\rm eff}$ is the effective mode field area, and can be expressed as

$$A_{\rm eff}=\frac{\left(\iint_{-\infty}^{\infty}|F(x,y)|^2\,{\rm d}x{\rm d}y\right)^2}{\left(\iint_{-\infty}^{\infty}|F(x,y)|^4\,{\rm d}x{\rm d}y\right)}. \tag{3}$$

The nonlinear refraction index n_2 is 4.1×10^{-19} m^2/W[22] (measured at 1.06 μm), which is an order of magnitude higher than that of the fused silica. The $F(x,y)$ is the distribution of the fundamental mode field. Since the refractive index is dependent on the wavelength, the chromatic dispersion is considered. The dispersion $D(\lambda)$ can be defined as

$$D(\lambda)=-\frac{\lambda}{c}\frac{{\rm d}^2n_{\rm eff}(\lambda)}{{\rm d}\lambda^2}, \tag{4}$$

where $n_{\rm eff}(\lambda)$ represents the effective index of the guided mode that can be calculated by the FEM, and c is the speed of light in a vacuum.

The beam propagation is described by the nonlinear Schrödinger equation (NLSE), which can be expressed as[23]

$$\begin{aligned}&\frac{\partial A(z,t)}{\partial z}-\sum_{n\geq2}\frac{{\rm i}^{n+1}}{n!}\beta_n\frac{\partial^nA}{\partial T^n}\\&={\rm i}\left(\gamma_0+{\rm i}\gamma_1\frac{\partial}{\partial T}-\frac{\gamma_2}{2}\frac{\partial^2}{\partial T^2}\right)\\&\times\left(A(z,T)\int_{-\infty}^{T}R(T')|A(z,T-T')|^2\,{\rm d}T'\right),\end{aligned} \tag{5}$$

where $A(z,T)$ represents the optical field envelope of the propagating pulse, β_n is the n-th derivative of the propagation constant at the center frequency ω_0, γ is the nonlinear coefficient that can be calculated according to Eq. (2), and $T=t-z/v_{\rm g}$. The nonlinear response function $R(t)$ includes both the electronic and the vibrational (Raman) contributions. It can be written as $R(t)=(1-f_{\rm R})\delta(t)+f_{\rm R}h_{\rm R}(t)$. In our simulations, $f_{\rm R}=0.1$, and the Raman response function is

$$h_{\rm R}(t)=\frac{T_1^2+T_2^2}{T_1T_2^2}\exp\left(-\frac{t}{T_2}\right)\sin\left(\frac{t}{T_1}\right),$$

with $T_1=5.5$ fs, $T_2=32$ fs for the SF57 glass.[22,24] This NLSE is solved by using the split-step Fourier method considering the effects of higher-order fiber dispersion up to the fifth order, and the loss of the fiber is neglected.

3. Basic fiber properties

In this section, we numerically simulate the basic properties of the SF57 PCF by using scanning electron microscopy (SEM) images of the actual fiber structure shown in Fig. 1. The PCF used has six small holes uniformly distributed in the inner ring at the core region. These sub-wavelength holes are introduced to provide a control of the fiber dispersion. The diameter of the small holes is approximately 0.5 μm. The light confinement is enabled by the six larger air holes that surround the core region. The core has a diameter of about 9 μm, the large air holes of the outer ring have a diameter of approximately 6–7 μm. Based on the fiber structural parameters measured by the SEM image, we numerically simulate the nonlinearity, dispersion, and effective mode area of this fiber.

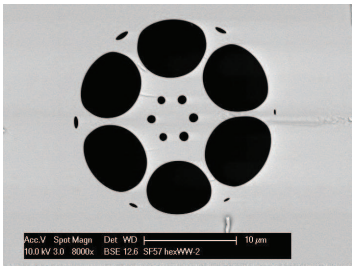


Fig. 1. The SEM image of the cross section of the actual fiber structure.

The dispersion profile of the fundamental mode is shown in Fig. 2. This calculation ignores the fiber birefringence. The fiber shows large negative (normal) and positive (anomalous) dispersion profiles at the short and long wavelengths, respectively. The ZDW is at 1610 nm. A relatively flat dispersion region is obtained from 1600 nm to 2100 nm.

Figure 3 shows the dependences of nonlinearity and effective mode area of the SF57 PCF on wavelength. We can see that the effective nonlinear coefficient decreases but the effective mode area increases with increasing wavelength.

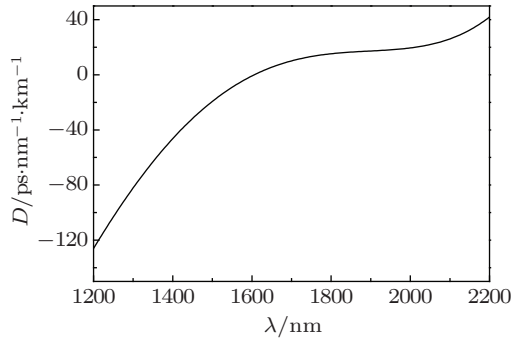


Fig. 2. Dispersion profile of the fundamental mode as a function of wavelength.

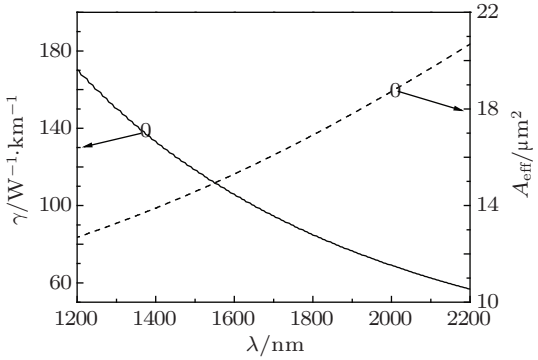


Fig. 3. Dependences of nonlinearity and effective mode area of the PCF on wavelength.

4. Experiments and results

The propagation loss spectrum of the PCF is measured using the cut-back method. Light from a tungsten halogen lamp source is coupled into the fiber. The output signal of the fiber is measured using an optical spectrum analyzer (OSA). Figure 4 shows the measured loss spectrum from 600 nm to 2200 nm. It can be seen that this PCF exhibits a reasonably low loss of 2.2 dB/m at 1550 nm and a larger loss in the visible region, which is similar to that of the bare SF57 fiber.[25] At wavelengths shorter than 1500 nm, the loss is attributed to the Rayleigh scattering and the bulk material loss. The loss at long wavelengths is mainly dominated by the confinement loss and water in glass.[21] The minimum loss is 1 dB/m at the wavelength of 1200 nm.

The setup used for the SC generation in the SF57 PCF is depicted in Fig. 5. A commercial laser system (FPL-04TTYSU11 Calmar Optcom, Inc.) provides fs pulses in the near-infrared (NIR) with a pulse duration of 150 fs and a repetition rate of 50 MHz. The operating wavelength in the experiments is 1550 nm. The output of the laser is coupled into the SF57 PCF using a 40× objective with a numerical aperture (NA) of 0.65. Neutral density filters are used to control the average input power. The pulse average power is changed from 10 mW to 90 mW. The output power of the SF57 PCF is coupled to an NIR optical spectrum analyzer (Avaspec-NIR256-NIR-2.5) with a multi-mode (MM) fiber. The power meter is used to measure the average power of the output and the input of the PCF.

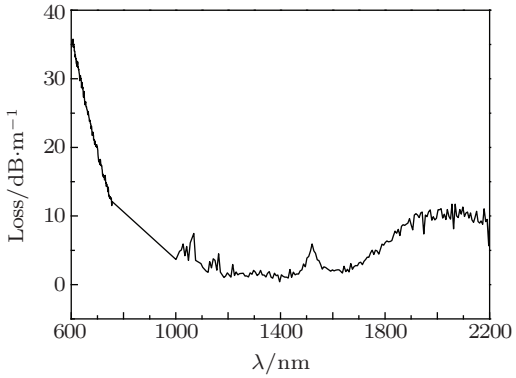


Fig. 4. The loss spectrum of the PCF measured using the cut-back technique.

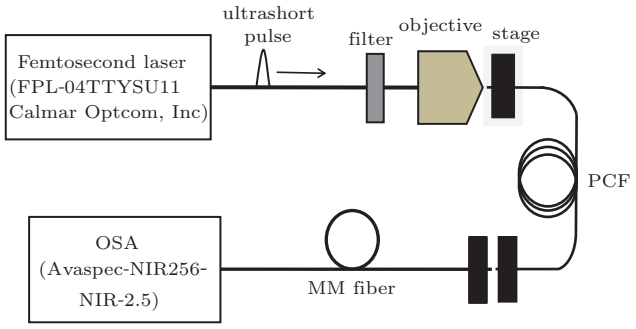


Fig. 5. (color online) Diagram of the experimental setup.

The SF57 PCF used in these experiments has a core diameter of 9 μm, a length of 60 cm, and a ZDW at 1610 nm. The 1550 nm laser pulses are propagating in the normal dispersion region of the PCF (Fig. 2). Figure 6 shows the measured relative spectral intensity at the output end of the SF57 fiber for different average input power in a logarithmic scale. The spectrum of the 1550 nm pump laser is also displayed in the same figure for comparison. The relative intensity of the output spectrum increases with the increasing incident pulse power, but the spectral broadening is little affected. As the pulse propagates in the PCF, the high-frequency (blue-shifted) components of the pulse travel slower than the low-frequency (red-shifted) components of the same pulse in the normal dispersion regime. By contrast, the opposite occurs in the anomalous dispersion regime, and the pulses in different dispersion regimes interfere. A lower relative spectral intensity is shown from 1600 nm to 1700 nm. In our previous studies,[26] we have known that the spectral broadening factor for fs pulses is given by $N = \sqrt{\gamma p_0 T_0^2/\beta_2}$ in the normal dispersion regime. The spectrum is rapidly broadened due to the self-phase modulation (SPM) in the initial distance. As the pulse further propagates along the fiber length, the spectrum becomes asymmetric due to self-steepening, and the spectral broadening is prevented because the rapid broadening of a pulse results in the

decrease of the peak power of the pulse.[5] Thus a broad SC is generated from 1300 nm to 1900 nm.

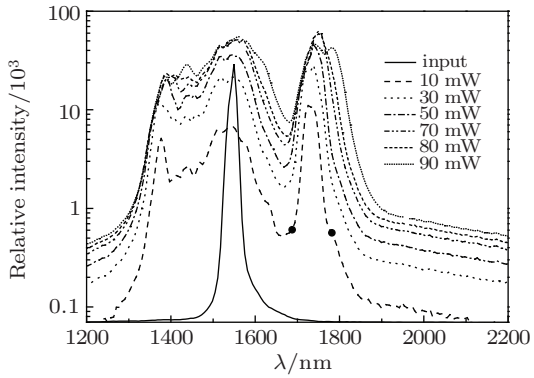


Fig. 6. Relative spectral intensity measured with average power varied from 10 mW to 90 mW, and the solid curve represents the input spectrum of the SF57 fiber.

A numerical simulation of the SC from the SF57 fiber is also performed at the input power of 80 mW and shown in Fig. 7 together with the experimental spectrum. The modeled and the measured spectra display remarkable agreement at wavelengths above 1300 nm. In our numerical simulation, the loss of the fiber is neglected. In the short wavelength region, as the loss of the actual fiber is high, the intensity density of light is too low to produce nonlinear effects, thus the measured intensity is significantly lower than the modeled values.

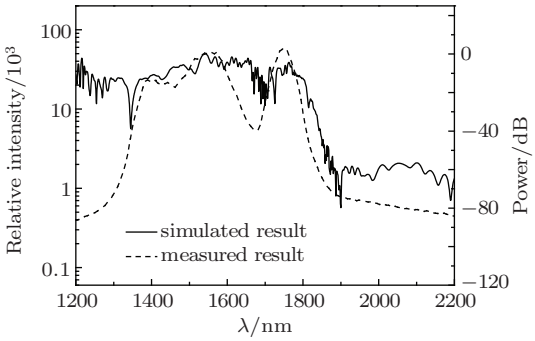


Fig. 7. The measured and simulated results vs wavelength at 80 mW input power.

5. Conclusion

In this paper, we report the propagation loss spectrum of a lead silicate SF57 PCF measured by using the cut-back method. We numerically simulate the basic fiber properties of the fiber. An SC is experimentally measured by employing a fiber laser as the source, which delivers 150 fs pump pulses at a central wavelength of 1550 nm. The experimental results are in excellent agreement with the numerical simulations in the NIR region. The SC spectra demonstrate no significant changes with the launched pulse average power changing from 10 mW to 90 mW, and the spectral spanning is from 1300 nm to 1900 nm. In the future, the use of mid-infrared transmitting glasses would enable the generation of SC at longer wavelengths.

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