19-fs pulse generated by supercontinuum compression

Hua-Qiang Zhang(张华强)[1], Peng Wang(王鹏)[2], Wen-Jun Liu(刘文军)[2,†], Yi-Lei Yao(姚翳蕾)[2], Zhi-Jing Xu(徐志敬)[1], and Jian Li(李健)[3]

[1] *School of Information and Electrical Engineering, Harbin Institute of Technology at Weihai, Weihai* 264209, *China*
[2] *Department of Optoelectronic Science, Harbin Institute of Technology at Weihai, Weihai* 264209, *China*
[3] *School of Physics and Electronic Science, Shandong Normal University, Jinan* 250014, *China*

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Supercontinuum generation and compression in a length of 50-mm photonic crystal fiber with pulse of nanojoule energy are investigated theoretically and experimentally. Chirped mirror pair is used for dispersion compensation and pulse compression. Pulse characteristics are measured by frequency-resolved optical gating. And 19-fs pulse is generated.

Keywords: femtosecond phenomena, multilayer mirror, phase compensation, photonic crystal fiber

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1. Introduction

Generation of femtosecond laser pulses is highly important in time-resolved studies of fundamental processes in physics, chemistry and biology. Various techniques for generating of few-cycle pulses were proposed based on the direct generation from the laser or employing parametric processes.[1–3] Ultrashort laser amplifiers can easily provide pulse energies in millijoule level but with pulse durations longer than several tens of femtoseconds. External compression of supercontinuum (SC) is another effective way to generate ultrashort pulse.[4] The advantages of this approach are the preserving of a single pulse in the time domain, perfect temporal coherence and spectral properties suitable for efficient external recompression. External compression of SC generated in 1.7-mm piece of all-normal dispersion photonic crystal fiber (PCF) allows producing high-quality sub-two cycle pulses.[5] Jocher *et al.* demonstrated nonlinear compression in a solid-core PCF, and pulse shortening by more than one order of magnitude to 23-fs pulses was achieved with chirped mirror compression.[6] Pulse with few-cycle duration could be achieved through gas-filled hollow core fibers and filamentation.[7–9] Planar waveguides were allowed to generate few-cycle pulses with higher energies.[10,11] Chen *et al.* generated pulses of 12-fs duration with 2-mJ energy.[12] Multi-octave self-compressions in a solid and dielectrics are reported.[13,14]

To compress self-phase modulation (SPM) induced SC in PCF is attractive technique due to the large achievable compression factor and high efficiency. SPM and positive group velocity dispersion in the fiber result in a spectrally broadened and temporally stretched output pulse. The phase accumulated by SPM is linear and positive in the time domain. By introducing appropriate amount of negative dispersion to the chirped pulse, a pulse substantially shorter than the original one can be obtained. The input chirps and the SC spectral widths for various pump pulse conditions in PCF were numerically investigated.[15,16] Mcconnell and Riis reported an order of magnitude reduction of the pulse width to 25 fs by using a short section of PCF.[17] Compression factors of three orders of magnitude and output pulses of 5 fs have been reported.[18]

In gas-filled hollow core fibers and filamentation pulse compression experiments, μJ or even mJ seed pulse was used. Using PCFs for SC generation was also possible with pulse of nanojoule energy at the oscillator repetition rate. 16 fs, 350-nJ pulses were generated by chirped pulse compression in fibers.[19] 5.5-fs pulses were generated by compressing a supercontinuum generated with 15-fs pulses from a Ti:sapphire oscillator in a 5-mm-long PCF, but double-chirped mirrors and active phase control method were used.[20]

In this paper, a Ti:sapphire oscillator with 60 fs at 80 MHz and a length of 50-mm PCF with zero-dispersion wavelength at 940 nm is used to generate SC. The spectral bandwidth and the transmitted average power of the SC are measured. The generated SC is stable due to low pulse energy of laser oscillator. 19-fs pulse is generated by using chirped mirrors to compensate for spectral phase of SC. Pulse characteristics are measured by frequency-resolved optical gating. Pulse traces at fiber output are obtained. Pulse shape and phase in spectral and temporal domains are shown in detail.

2. Supercontinuum generation simulation

In order to show the spectral and temporal characteristics at the output end of the fiber, we first conduct theoretical simulation. The generalized nonlinear Schrödinger equation (GNLSE) is widely used to simulate the dynamics of supercontinuum generation and it can be written in its normalized

†Corresponding author. E-mail: liuwenjun68@siom.ac.cn

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form as[21,22]

$$\frac{\partial A}{\partial z}+\frac{\alpha}{2}A = \mathrm{i}\sum_{m=1}^{\infty}\frac{\mathrm{i}^m\beta_m}{m!}\frac{\partial^m A}{\partial t^m}+i\gamma\left(1+\frac{\mathrm{i}}{\omega_0}\frac{\partial}{\partial t}\right) \times\left(A(z,t)\int_0^{\infty}R(t')\left|A(z,t-t')\right|^2\mathrm{d}t'\right), \quad (1)$$

where α represents the fiber losses and γ is defined as the nonlinear parameter. Assuming that the electronic contribution is nearly instantaneous, the functional form of $R(t)$ can be written as

$$R(t)=(1-f_R)\delta(t)+f_R h_R(t), \quad (2)$$

where $f_R=0.245$, the first and the second term correspond to the electronic and Raman responses, respectively. The Raman response function can be expressed in the form

$$h_R(\tau)=(f_\mathrm{a}+f_\mathrm{c})h_\mathrm{a}(\tau)+f_\mathrm{b}h_\mathrm{b}(\tau), \quad (3)$$

where the functions $h_\mathrm{a}(\tau)$ and $h_\mathrm{b}(\tau)$ are defined respectively as

$$h_\mathrm{a}(\tau)=\frac{\tau_1^2+\tau_2^2}{\tau_1\tau_2^2}\exp\left(-\frac{\tau}{\tau_2}\right)\sin\left(\frac{\tau}{\tau_1}\right),$$
$$h_\mathrm{b}(\tau)=\left(\frac{2\tau_\mathrm{b}-\tau}{\tau_\mathrm{b}^2}\right)\exp\left(-\frac{\tau}{\tau_\mathrm{b}}\right), \quad (4)$$

where $\tau_1=12$ fs, $\tau_2=32$ fs, $\tau_\mathrm{b}=96$ fs, the coefficients $f_\mathrm{a}=0.75$, $f_\mathrm{b}=0.21$, and $f_\mathrm{c}=0.04$ quantify the relative contributions of the isotropic and anisotropic parts of the Raman response.

We perform a numerical simulation on the propagation of 60-fs input pulses with a repetition rate of 80 MHz at a wavelength of 800 nm through 50 mm of a PCF with zero-dispersion wavelength at 940 nm, as this is also the case in our experiment. The other parameters are $\gamma=0.28\ \mathrm{W^{-1}\cdot m^{-1}}$, $\beta_2=1.830\times10^{-26}\ \mathrm{s^2/m}$, $\beta_3=-12.1038\times10^{-41}\ \mathrm{s^3/m}$, and $\beta_4=9.525\times10^{-56}\ \mathrm{s^4/m}$. The simulated output pulse shape and spectrum at the end of the fiber with 50-mW input average power are shown in Figs. 1(a) and 1(b), respectively.

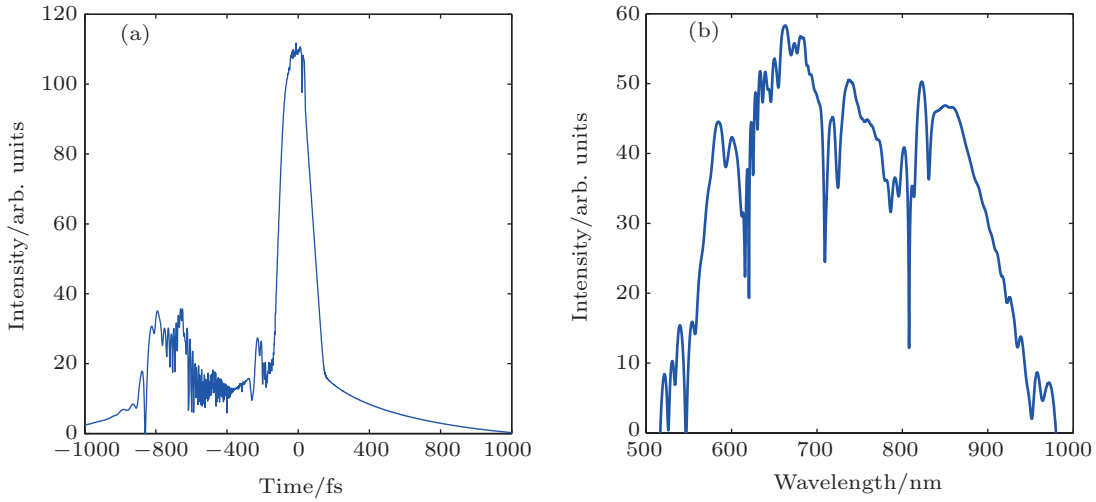


Fig. 1. (color online) Simulated output pulse shape (a) and spectrum (b) at the end of the fiber with 50-mW input average power.

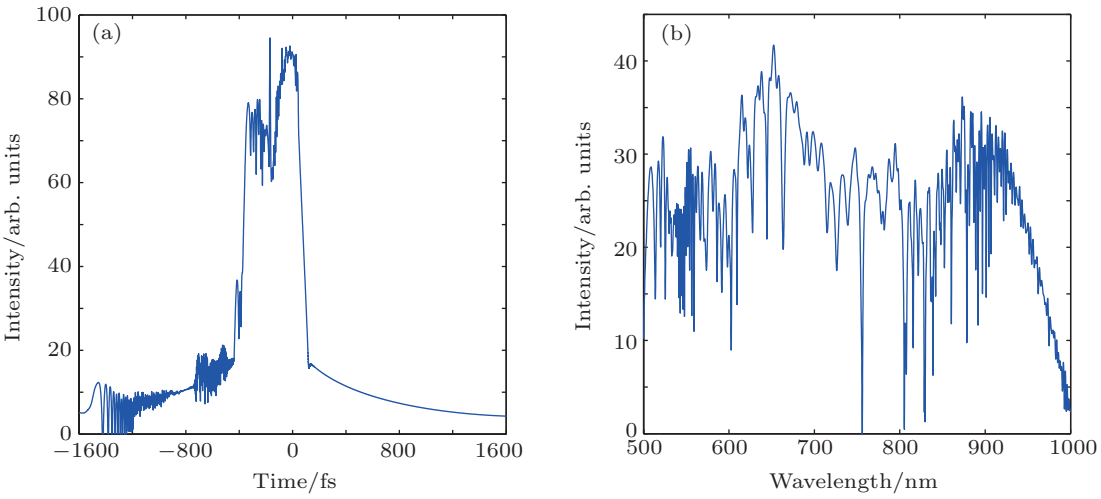


Fig. 2. (color online) Simulated output pulse shape (a) and spectrum (b) at the end of the fiber with 100-mW input average power.

In the following simulation, input average power is increased continuously. Figure 2(a) shows the simulated output pulse shape at the end of the fiber with 100-mW input average power, and figure 1(b) displays the simulated output spectrum.

3. Experiments

Schematic diagram of experiment is shown in Fig. 3. In experiment, a commercial Ti:sapphire oscillator produces 60-fs pulses at a central wavelength of 800 nm with a repetition rate of 80 MHz. The beam is focused into a length of 50-mm PCF. The polarization of the laser beam entering the fiber is set by a polarization rotator. The output of the fiber is collimated and passed through a dispersion compensating stage consisting of chirped mirror (CM) pair. The CMs are produced by VENTEON Laser Technologies GmbH. The dispersion compensating for wavelength range of the CM pair is of 600 nm–1200 nm. The mirror pair can provide a negative GVD of -120 fs^2 per bounce at 800 nm. The PCF in experiment has a hexagonal structure of air holes to guide the light in a 2.6-μm diameter core, and the distance between adjacent air holes is 1.8 μm. The zero dispersion wavelength (ZDW) point is around 940 nm. The experiment operates in the region of normal dispersion. The output pulse of the fiber is measured by frequency-resolved optical gating.

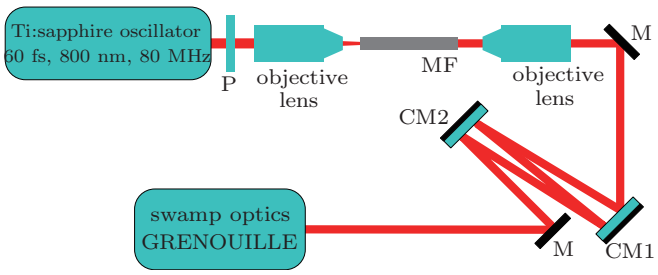


Fig. 3. (color online) Schematic diagram of experiment.

4. Experimental results and discussion

At low energy, the spectrum of 60-fs pulse is unchanged in the fiber. At high energy, spectral broadening is observed. Figure 4(a) shows the generated SC spectra with different input powers. The spectral bandwidth broadens with the increasing of input power. SPM is the dominant mechanism for spectrum broadening; this is justified by the typical spectral shapes observed in broadened spectrum. The spectrum becomes unstable as soon as the first Raman soliton is created when the broadened spectrum exceeds the ZDW. This happens at about 85 mW coupled into the fiber. The first soliton is formed just around the ZDW and is subsequently self-frequency shifted to longer wavelengths as the pump power is further increased. The spectral bandwidth and the transmitted average power of the measured SC are shown in Fig. 4(b).

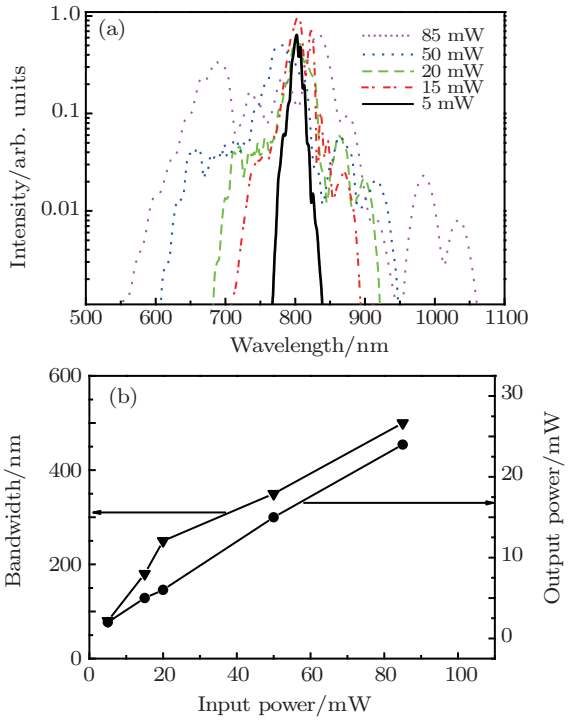


Fig. 4. (color online) (a) SC spectra generated with different input powers; (b) SC bandwidth and output power vary with input power.

As the pulse propagates through the fibre and the spectrum broadens, the temporal profile of the pulse also broadens. The phase accumulated by SPM in the fiber is positive in the time domain corresponding to a positive group delay dispersion (GDD) in the spectral domain. The large spectral bandwidth obtained through SPM in the fiber makes it possible to compress the pulse with CMs. A well-compressible SC and short pulse can be obtained only if the input pulse and the full spectrum of the SPM pulse are in the positive dispersion range of the fiber in order to avoid solitonic and Raman processes that can make the output incompressible. In the following compression experiment, 50 mW of input power is used to pump the fiber because of its SC in the normal dispersion region. Figure 5(a) shows the measured trace of fiber output with a pump power of 50 mW. The reconstructed spectrum and spectral phase are shown in Fig. 5(b). Figure 5(c) shows the reconstructed output pulse shape and temporal phase. The temporal full width at half maximum (FWHM) width of the output pulse is 223 fs and positive chirp develops across nearly its entire width. The reconstructed temporal profile shows a main sharp peak with wide pedestal due to dispersion.

The output of the fiber is collimated and passes through a CM pair to compensate for the spectral phase dispersion. In experiment, four bounces off CM are used. After passing through the CM pair, the compressed pulses are characterized by frequency-resolved optical gating. The measured trace is shown in Fig. 6(a). Figure 6(b) is a reconstructed spectrum and

spectral phase of the compressed pulse. The spectral phase is nearly flat in the spectral range. Figure 6(c) shows a reconstructed temporal profile and phase of the compressed pulse. The pulse duration is 19 fs. A nearly flat temporal phase covers the main pulse. The temporal profile shows weak pedestal which may come from uncompensated high-order dispersion.

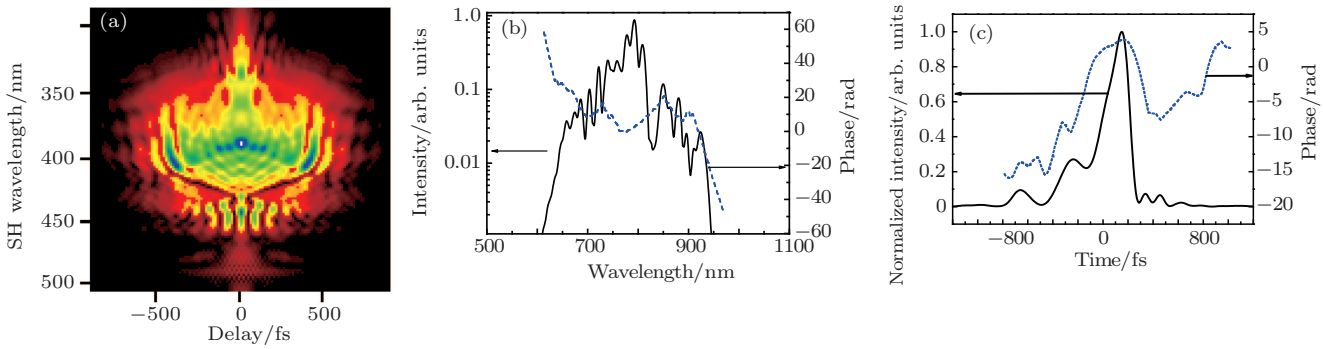


Fig. 5. (color online) Measured outputs of the fiber pumped with 50-mW input power: (a) measured traces, (b) retrieved spectral intensity and spectral phase, and (c) retrieved temporal profile and temporal phase.

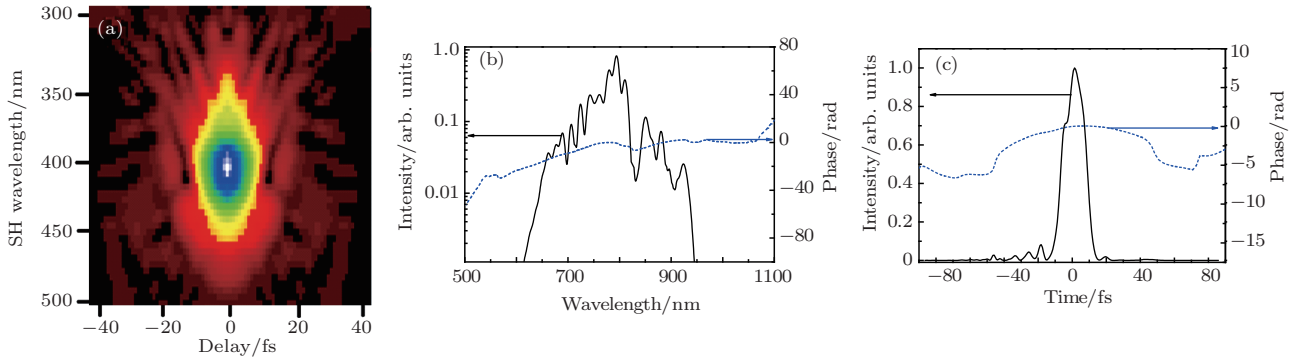


Fig. 6. (color online) Measured results of the compressed pulse: (a) measured trace, (b) reconstructed spectrum and spectral phase, and (c) reconstructed temporal profile and phase.

5. Conclusions

Supercontinuum generation in a length of 50-mm photonic crystal fiber pumped with nJ pulse is investigated theoretically and experimentally. Chirped mirror pair is used to compensate for dispersion and compress the broadened pulse. The wavelength range of compensating for dispersion of the CM pair is of 600 nm–1100 nm. The 19-fs pulse is generated.

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