Enhanced Femtosecond Optical Pulses Compression in Highly Nonlinear Photonic Crystal Fibers at 850 nm

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Abstract— In this letter, we numerically investigate the soliton-effect compression of femtosecond optical pulses in highly nonlinear silica-core photonic crystal fiber (HN-PCF) at near-infrared region of the spectrum (specially at 850 nm) using full-vector finite element method and split-step Fourier method. We propose a novel photonic crystal fiber structure featuring a anomalous group velocity dispersion ($\beta_2 = -50.698\,\mathrm{ps}^2/\mathrm{km}$), small higher-order dispersions and enhanced nonlinearity ($\gamma = 268.4191\,\mathrm{w}^{-1}/\mathrm{km}$) for efficient soliton-effect compression of femtosecond optical pulses. We numerically investigate the effect of the high-order soliton compression of Gaussian pulses in HN-PCF. It shows that high-quality ultrashort optical pulses with little pedestal energy can be obtained.

1. INTRODUCTION

Utrashort optical pulses have potential applications in ultrafast optical communication, optical signal processing, optical machining, sensing technology and other fields. Fiber-based pulse compression technology is one of effective ways for obtaining ultrashort optical pulse. However, the conventional fiber has been restricted by its geometric parameters and it's not easy to get a good pulse compression effect. Highly nonlinear photonic crystal fibers effectively overcome the deficiency of conventional fiber, and greatly improve the efficiency of pulse compression. Thus, the photonic crystal fiber-based pulse compression technology has become a hotspot in the research of pulse compression technologies.

Highly nonlinear photonic crystal fiber has important applications in various areas such as ultrashort laser pulse frequency conversion, spectrum broadening, pulse compression, wave breaking and so on. The effect of high nonlinearity can be achieved by minishing the area of core, increasing the air filling fraction or using the background material with large nonlinear refractive index. The development of optical communication system has experienced the process from the short wavelength (850 nm) to the long wavelength (1310 nm and 1550 nm), considering the communicating cost of the short wavelength of 850 nm is lower than the long wavelength, we numerically investigate the compression of femtosecond optical pulses in HN-PCF at 850 nm.

In recent years, pulse compression at near-infrared region of the spectrum were extensively investigated. In 2010, Abobaker et al. [1] investigated a new design of PCF in order to achieve efficient pulse compression at length at 850 nm, that compression factor is 21.49 which is almost 13.02 times greater than adiabatic pulse compression. Fedotov et al. [2] investigated the 20 fs pulses in the near-infrared by pulse compression in the regime of normal dispersion using a large-mode-area all-silica photonic band-gap fiber, whose central wavelength is 1140 nm. Abobaker et al. [3] designed a pulse compressor using a tapered PCF wherein dispersion as well as nonlinearity varies along the propagation direction, and discussed the generation of pedestal free ultrashort pulses around 850 nm. Olupitan et al. [4] designed a pulse compressor using a tapered PCF, and studied the possibility of generating pedestal-free ultrashort pulses around 850 nm using eight chirped cosine pulses. In 2014, Ghanbari et al. [5] proposed a novel nano-size silica PCF structure and investigated the dynamics of soliton-effect compression of femtosecond optical pulses in silica-core PCF at 850 nm.

In this paper, we designed a novel silica-core photonic crystal fiber structure, simulated the index of the fundamental guided mode using full-vector finite element method, the results show the PCF has a minimum anomalous group velocity dispersion, small higher-order dispersions and enhanced nonlinearity for efficient soliton-effect compression of femtosecond optical pulses at 850 nm. We investigated the Gaussian pulses and investigate the effect of the high-order soliton compression in HN-PCF using split-step Fourier method. It shows that high-quality ultrashort optical pulses with little pedestal energy can be provided. The parameters, such as the fiber length, chirp parameter or the soliton order, have significant influence on the pulse compression properties, such as compression ratio and peak power.

2. THEORETICAL ANALYSIS

The total dispersion of photonic crystal fibers includes waveguide dispersion and material dispersion [6]. Due to the photonic crystal fiber is generally composed of a single material such as pure silica, so the material dispersion is unchanged. The waveguide dispersion is related to the geometrical arrangement, hole pitch (Λ), wavelength (λ), and normalized air holes diameter (d/Λ) are the main factors on which the waveguide dispersion of photonic crystal fibers depends. The total dispersion is given by

$$D\left(\lambda\right)=-\frac{\lambda}{c}\frac{d^2\mathrm{Re}\left[n_{\mathit{eff}}\left(\lambda\right)\right]}{d\lambda^2}+D_m\left(\lambda\right) \tag{1}$$

where c is the velocity of light in a vacuum, λ is the wavelength, $\mathrm{Re}[n_{\mathit{eff}}(\lambda)]$ is the real part of the effective refractive index, The material dispersion (D_m) which is represented by Sellmeier equation.

We consider a PCF with a triangular lattice of holes as shown in Figure 1, where d is the hole diameter, Λ is the hole pitch, an air hole is omitted to form a central high index defect serving as the fiber core [7].

The dispersion parameter, D which is commonly used in fiber optics, is related to the group velocity dispersion (GVD) parameter β_2 given by

$$\beta_2=-\frac{\lambda^2}{2\pi c}D \tag{2}$$

The nonlinear coefficient γ is defined as

$$\gamma=\frac{n_2\omega_0}{cA_{\mathit{eff}}} \tag{3}$$

where A_{eff} is the effective mode area, c denotes the speed of light, n_2 is the nonlinear refractive index.

We use the generalized nonlinear Schrödinger equation which describes the propagation of femtosecond pulses in photonic crystal fibers. In the normalized coordinates commonly used for describing optical solitons, the Equation (3) takes the form

$$\begin{aligned}\frac{\partial U}{\partial\xi}=&-\frac{i\,\mathrm{sgn}\left(\beta_2\right)}{2}\frac{\partial^2U}{\partial\tau^2}+\frac{\beta_3}{6\left|\beta_2\right|T_0}\frac{\partial^3U}{\partial\tau^3}+\frac{i\beta_4}{24\left|\beta_2\right|T_0^2}\frac{\partial^4U}{\partial\tau^4}-\frac{\beta_5}{120\left|\beta_2\right|T_0^3}\frac{\partial^5U}{\partial\tau^5}\\&-\frac{1}{2}\alpha L_DU+iN^2\left[\left|U\right|^2U+\frac{i}{\omega_0T_0}\frac{\partial}{\partial\tau}\left(\left|U\right|^2U\right)-\frac{T_R}{T_0}U\frac{\partial\left|U\right|^2}{\partial\tau}\right]\end{aligned} \tag{4}$$

where U is normalized amplitude, the parameter α represents the fiber's intrinsic loss, which is given by $0.02\,\mathrm{dB/m}$, β_2, β_3, β_4, β_5 are GVD, TOD, FOD, and fifth-order dispersion, respectively. γ states as the nonlinear coefficient, ω_0 is the central angular frequency, $T_R=3\,\mathrm{fs}$ is the slope of Raman gain profile at the carrier frequency [8]. The last three were self-phase modulation (SPM), self-steepening (SST) and intrapulse Raman scattering (SRS), respectively.

To generate N-th order soliton, the following equation should be satisfied

$$N^2=\frac{L_D}{L_{NL}}=\frac{\gamma p_0T_0^2}{\left|\beta_2\right|} \tag{5}$$

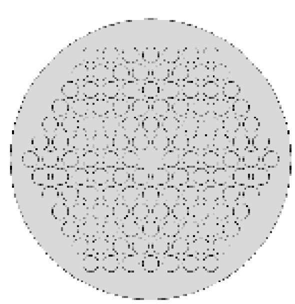

Figure 1: The model of PCF.

where P_0 is the peak power of the incident pulse, the normalized distance ξ ($\xi = z/L_D$), the dispersion length L_D ($L_D = T_0^2/|\beta_2|$), the nonlinear length $L_{NL}(L_{NL} = 1/\gamma p_0)$.

The obtained pulse compression is characterized by the compression factor F_c defined by:

$$F_C = \frac{T_0}{T_C} \tag{6}$$

where T_0 and T_c are the half-width (at $1/e$-intensity point) of input and output compressed pulse, respectively.

3. NUMERICAL SIMULATION

3.1. Dispersion of Photonic Crystal Fibers

The effective refractive index can be calculated by using full-vector finite element method, suppose the normalized air holes diameter ($d/\Lambda = 0.8$). Figure 2 shows the group velocity dispersion (GVD) varies with a function of wavelength. It can be seen in Figure 2, there is a minimum and nearly flat region of negative GVD, the nearly flat region is shifted to higher wavelengths by changing the pitch (Λ). By choosing the proper pitch (Λ), this region can be centered at desired wavelengths. As can be seen in Figure 3 by choosing the values $\Lambda = 0.9\,\mu$m and $d/\Lambda = 0.8$, the minimum and nearly flat region can be centered at 850 nm, β_2 is $-50.698\,\text{ps}^2/\text{km}$.

For the propagation of pulses with femtosecond duration, it is necessary to include the higher-order dispersions. Therefore, we use the generalized nonlinear Schrödinger equation which included the third-, fourth- and fifth-order dispersion. the result is that β_3, β_4 and β_5 are $0.01982\,\text{ps}^3/\text{km}$, $2.463 * 10^{-4}\,\text{ps}^4/\text{km}$ and $-8.0362 * 10^{-7}\,\text{ps}^5/\text{km}$ at 850 nm, respectively.

3.2. Soliton Propagation in Photoniccrystal Fiber

Figure 3 shows the effective mode area of the PCF for $d/\Lambda = 0.8$ and $\Lambda = 0.9\,\mu$m. A_{eff} is $0.881\,\mu\text{m}^2$ at 850 nm, γ is $268.41908\,\text{W}^{-1}/\text{km}$, so this fiber is a highly nonlinear photonic crystal fiber.

Equation (4) is solved numerically by using the split-step Fourier method, the numerical simulations taking into account SPM, GVD, TOD, FOD, fifth-order dispersion, SST, SRS. The input pulses are assumed to be chirp free and have Gaussian shapes with initial width of $T_{\text{FWHM}} = 100$ fs, $U(0, T) = \exp(-0.5\tau^2)$.

To change the soliton order N, we conduct the numerical simulation of optical pulse compression. Figure 4 shows that the compression factor F_c as a function of soliton number N, respectively. F_c reach the maximum when $N = 8$, it has a good pulse compression effect while the peak power of

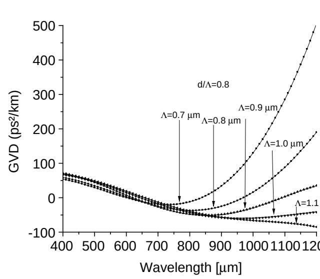

Figure 2: GVD of the PCF as a function of wavelength for different pitches and $d/\Lambda = 0.8$.

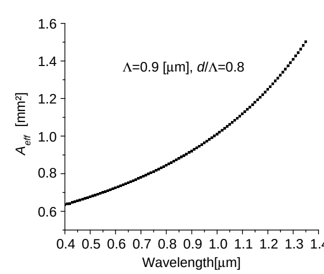

Figure 3: The effective mode area of the PCF for $d/\Lambda = 0.8$ and $\Lambda = 0.9\,\mu$m.

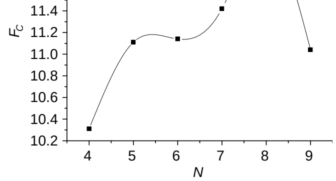

Figure 4: The compression factor F_c.

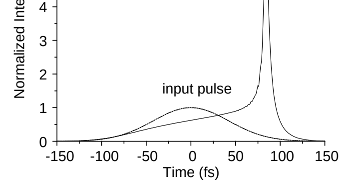

Figure 5: The input and output compressed pulse.

initial pulse P0=3357.8 W. It can be seen in Figure 5 that we get an output compressed pulse of $T_0 = 4.96$ fs at the propagation distance of 5.66 mm.

4. CONCLUSION

Due to the flexible design of photonic crystal fiber structure, it has the highly nonlinear parameter and adjustable dispersion characteristics, we can obtain a high-quality compressed pulse using a shorter fiber. We propose a novel photonic crystal fiber with the normalized air holes diameter $d/\Lambda = 0.8$ and the hole pitch $\Lambda = 0.9\,\mu$m, the photonic crystal fiber structure shows a anomalous group velocity dispersion, small higher-order dispersions and enhanced nonlinearity at 850 nm, a compressed pulse of $T_0 = 4.96$ fs can be obtained using a 5.66 mm highly nonlinear photonic crystal fiber.

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REFERENCES

1. Abobaker, A. M., R. V. J. Raja, et al., "Efficient pulse compression in photonic crystal fibre at 850 nm," *IEEE 2010 International Conference on Computer and Communication Engineering (ICCCE)*, 1–4, 2010.
2. Fedotov, I. V., A. A. Lanin, et al., "Generation of 20 fs, 20 MW pulses in the near-infrared by pulse compression using a large-mode-area all-silica photonic band-gap fiber," *Journal of Modern Optics*, Vol. 57, No. 19, 1867–1870, 2010.
3. Abobaker, A. M., S. Olupitan, et al., "Dynamics of 850 nm optical pulses upon compression in a tapered photonic crystal fiber," *IEEE 2011 Saudi International Electronics, Communications and Photonics Conference (SIECPC)*, 1–4, 2011.
4. Olupitan, S., P. R. Babu, et al., "Generation of a train of ultrashort pulses near-infrared regime in a tapered photonic crystal fiber using raised-cosine pulses," *IEEE Photonics Journal*, Vol. 4, No. 5, 1420–1437, 2012.
5. Ghanbari, A., A. Sadr, et al., "Modeling photonic crystal fiber for efficient soliton-effect compression of femtosecond optical pulses at 850 nm," *Arabian Journal for Science and Engineering*, Vol. 39, No. 5, 3917–3923, 2014.
6. Ferrando, A., E. Silvestre, et al., "Nearly zero ultraflattened dispersion in photonic crystal fibers," *Optics Letters*, Vol. 25, No. 11, 790–792, 2000.
7. Saitoh, K. and M. Koshiba, "Empirical relations for simple design of photonic crystal fibers," *Optics Express*, Vol. 13, No. 1, 267–274, 2005.
8. Agrawal, G. P., *Nonlinear Fiber Optics*, 5th Edition, Academic Press, 2013.
9. Ma, W. W., S. G. Li, et al., "High efficiency pulse compression in tapered microstructure fibers in anomalous dispersion region," *Acta Physica Sinica*, Vol. 59, No. 7, 4720–4725, 2010.