Supercontinuum generation in optimized photonic crystal fiber at 1.3 μm for optical coherence tomography

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Abstract. In this paper, we have designed a high nonlinear photonic crystal fiber (HN-PCF) based on square-lattice geometry with the zero dispersion wavelength (ZDW) around 1300 nm. The exploitation of different nonlinear mechanisms in the pulse propagation allows supercontinuum generation, which is used to enhance the axial resolution of the optical coherence tomography (OCT) systems. First mechanism demonstrated is the soliton self-compression, we came up to realize pulse compression of 28.4 fs around 1300 nm by the generation of solitons of different orders to obtain ultrashort pulses of about 4 fs pulses in a PCF length of 66 cm, then, we improved the pulse compression until 1.2 fs in a PCF length of 26 cm. The exploitation of the interplay between many nonlinear effects as self-phase modulation, intrapulse Raman scattering and self-steepening as second mechanism allows a generation of supercontinuum with a spectral bandwidth of SBW=260 nm. The obtained spectral bandwidth could contribute to enhance the OCT imaging axial resolution which can be evaluated to 2.8 μm in air, working at 1.3 μm center wavelength which is widely used in several fields.

1 introduction

Optical coherence tomography (OCT) is a new technology for noninvasive cross-sectional imaging of tissue structure in biological system. Since OCT is based on low-coherence interferometry, the longitudinal image resolution, Δz , is inversely proportional to the bandwidth, $\Delta\lambda$, and proportional to the square of the center wavelength λ_0 [1] :

$$\Delta z = \frac{2 \ln(2)}{\pi} \left(\frac{\lambda_0^2}{\Delta\lambda} \right) \quad (1)$$

The spectral region from 1.2 to 1.8 μm is of particular interest for OCT since it provides a high penetration depth in biological tissue. High resolution in this spectral region requires extremely broad bandwidths because of the $\lambda^2/\Delta\lambda$ dependence of the longitudinal resolution. Standard OCT use longitudinal resolution of 10-15 μm . An axial resolution of less than 5 μm at 1.3 μm can be achieved by using a broad bandwidth light source. High nonlinearity air-silica microstructure fibers can generate an extremely broad supercontinuum by the use of femtosecond laser sources.

The supercontinuum (SC) light using photonic crystal fibers (PCF) can be generated by different methods as pulse compression using solitons effects [2], the self phase modulation along with other nonlinear effects such as stimulated Raman scattering and four wave mixing when occurring simultaneously inside optical fibers [3].

In this work, a new design of high nonlinear photonic crystal fiber (HN-PCF) based on square-lattice geometry has been presented for supercontinuum generation, we demonstrate the supercontinuum generation using several mechanisms in

anomalous dispersion regime. First, a pulse compression using soliton effects around 1300 nm is achieved [4], and 1.2 fs pulses are generated in only 26 cm of fiber, a supercontinuum of spectral bandwidth SBW $\approx$ 100 nm is generated. The interplay between several effects such as self phase modulation, self-steepening and intrapulse Raman scattering is used as a second mechanism for supercontinuum generation, it allowed a spectral bandwidth SBW=260 nm in only 1.89 mm length of PCF.

2 design and optimization procedures of hn-pcf

The proposed geometry shown in Fig. 1 is composed of six rings of air holes with silica as background of the core. d_i is the air hole diameter of the ring i (1-6) of the PCF and $d_{1-6}=637 \mu\text{m}$, pitch ($\Lambda=0.65 \mu\text{m}$) is the distance between two successive air holes. Full-vector Finite-Element Method (FEM) with a Perfectly Matched Layer (PML) as bounding conditions has been used to investigate the optical characteristics of the proposed PCF.

Fig. 1. The proposed PCF

The PML technique allows to strongly absorb outgoing waves from the interior of a computational region without reflecting them back into the interior [6]. The distribution of field and the effective index of the fundamental mode HE_{11} are calculated, then, the optical parameters such as the dispersion D and the group velocity dispersion (GVD) can be calculated by [3]:

$$D = -\frac{\lambda}{c} \frac{d^2 \text{Re}[n_{eff}]}{d\lambda^2} = \frac{2\pi c}{\lambda^2} \beta_2 \quad (2)$$

$\text{Re}[n_{eff}]$ is the real part of the effective index, c is the light speed and β_2 is the GVD. The blue curve of the Fig. 2 illustrates the dispersion values of the regular PCF. By reducing the hole diameter of the first ring to $d_1=0.34 \mu\text{m}$ and keeping the holes diameters of the other rings equal to $0.637 \mu\text{m}$, we minimize the dispersion value to $4.67 [\text{ps}/\text{nm.km}]$ (red curve).

Fig. 2. Dispersion curves of regular PCF (bleu curve), and optimized air hole diameter of the first ring -PCF (red curve).

In order to acquire ultra-broadband SC in the proposed PCF, the dispersion curve and the geometry of the fiber are optimized through several steps. The first step illustrated the influence of the variation of the air hole diameters in the first ring. In the second step, we kept the optimized air holes diameters of the first ring and we optimized the distance between the air holes of the different rings (pitch).

Fig. 3. Influence of the air hole diameter of the first ring on the chromatic dispersion.

In the last step, we modified the air holes diameters of the other rings by keeping the optimized d_1 and pitch. Fig. 3 illustrates the effect of varying the air hole diameter of the first ring, the dispersion value is minimizing by decreasing the value of (d_1). For $d_1=0.26 \mu\text{m}$, $d_{(2-6)}=0.637 \mu\text{m}$ and $\Lambda=0.65 \mu\text{m}$ the dispersion value is decreasing to be $2.34 [\text{ps}/\text{nm.km}]$.

Figure 4 shows the variation of the dispersion with the pitch value by maintaining the optimized value of d_1 and by keeping the other holes diameters at $d_{(2-6)}=0.637 \mu\text{m}$, the variation indicates that by decreasing the value of the pitch, the Zero Dispersion Wavelength (ZDW) is shifted to the blue side of the wavelength and the dispersion around $\text{ZDW}=1300 \text{ nm}$ in our case is minimized.

Fig. 4. Influence of the distance between two successive air holes on the chromatic dispersion

The last rings are used to locate the dispersion to a desirable position and there are kept at a higher air-filling fraction d/Λ from 0.4 to 0.98 to confine light better within the core and to reduce confinement loss as much as possible.

With the optimized parameters $\Lambda=0.65 \mu\text{m}$, $d_1/\Lambda=0.4$, $d_2/\Lambda=0.9$, $d_3/\Lambda=0.89$, $d_4/\Lambda=d_5/\Lambda=d_6/\Lambda=0.98$, we performed the anomalous dispersion and the GVD to be $1.0677 [\text{ps}/\text{nm.km}]$ and $-0.9572 [\text{ps}^2/\text{km}]$ respectively (Fig. 5).

Fig. 5. Chromatic dispersion and group velocity dispersion of the optimized HNL-PCF.

The nonlinearity coefficient is primarily governed by two parameters: the nonlinear index of the material (n_2) and the effective area (A_{eff}). The nonlinearity coefficient is calculated using the relation [3] :

$$\gamma = \left(\frac{2\pi}{\lambda}\right) \left(\frac{n_2}{A_{eff}}\right) \quad (3)$$

where n_2 is the nonlinear refractive index of material, λ is the pump wavelength and A_{eff} is the effective area of the fundamental mode, and it's calculated using the following equation:

$$A_{eff} = \frac{(\iint_{-\infty}^{\infty} |E(x,y)|^2 dx dy)^2}{\iint_{-\infty}^{\infty} |E(x,y)|^4 dx dy} \quad (4)$$

The numerical value of the nonlinear refractive index n_2 of pure silica is reported to be $2.2 \times 10^{-20} \text{ m}^2/\text{W}$. The proposed design of HNL-PCF permits us to reduce the effective area; therefore, the nonlinear coefficient γ increases significantly to reach $55.45 [\text{W}^{-1} \cdot \text{km}^{-1}]$ as mentioned in Fig. 6.

Fig. 6. Effective area and nonlinear coefficient of the optimized HNL-PCF

Figure 6 shows that effective area increases and the nonlinear coefficient decreases with wavelength, this can be explained by the dependence of the mode field diameter (MFD) on wavelength i.e. the more MFD is important the more mode profile is extended outside the core and the nonlinear effects are less important.

3 Supercontinuum generation and mechanisms

The numerical simulation of SC spectrum has been performed by solving the generalized nonlinear Schrodinger equation (GNLSE) using split-step Fourier method (SSFM) [3]. The first mechanism used for generating SC is based on soliton

compression where the GNLSE takes into account the contributions of the linear effects (i.e. attenuation, chromatic dispersion and high order dispersions), and the nonlinear effects as kerr effect while in the second mechanism of SC generation, self-phase modulation (SPM), self-steepening and intrapulse Raman scattering are used. The GNLSE is given in following relation [3]:

$$\frac{\partial A}{\partial z} + \frac{\alpha}{2} A - \left(\sum_{n \geq 2} \beta_n \frac{i^{n+1}}{n!} \frac{\partial^n A}{\partial T^n} \right) = i\gamma \left(1 + \frac{1}{w_0} \frac{\partial}{\partial T} \right) \cdot [A(z, T) \int_{-\infty}^{\infty} R(T') |A(z, T - T')|^2 dT'] \quad (5)$$

where T is the time, $A(z,t)$ is the complex amplitude of the optical field, α is the attenuation coefficient of the fiber, $\beta_n (n=2 \text{ to } 4)$ is the n -th order of propagation constant, γ is the nonlinear coefficient.

The nonlinear response function, $R(T)$, which includes instantaneous electronic as well as delayed Raman contributions, is given by :

$$R(T) = (1 - f_r) \delta(T) + f_r h_r(T) \quad (6)$$

where $f_r = 0.18$, and the Raman response function is given by [3]:

$$h_r(t) = (\tau_1^{-2} + \tau_2^{-2}) \tau_1 \exp(-t/\tau_2) \sin\left(\frac{t}{\tau_1}\right) \quad (7)$$

In our study, we consider the injected pulses having secant hyperbolic field profile emerging from a femtosecond laser:

$$U(0, T) = \sqrt{P_0} \operatorname{sech}\left(\frac{T}{T_0}\right) \quad (8)$$

where P_0 is the peak power, T_0 the temporal width of the pulse and $T_0 = T_{FWHM}/1.763$.

3.1 Soliton self-compression

In the anomalous dispersion region, the balance between the group velocity dispersion (GVD) and the nonlinear effect Self Phase Modulation (SPM) is responsible for the formation of solitons, whose order N increases with the pulse intensity.

$$N = \left(\sqrt{\frac{L_D}{L_{NL}}} \right) \quad (9)$$

$$\text{with } L_D = \frac{T_0^2}{\beta_2} \text{ and } L_{NL} = \frac{1}{\gamma P_0}.$$

In this work, a pulse with a full width at half maximum (FWHM) of 28.4 fs is compressed around 1300 nm, by generation of solitons of different orders ($N=2$, $N=3$, $N=4$) and varying the input power (table I).

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

$$F_c = \frac{T_0}{T_{comp}} \quad (10)$$

where $T_{comp} = T_0 - T_{diff}$ is the width of the compressed pulse and T_{diff} is the difference between the width of the initial pulse T_0 and that of the compressed pulse.

The quality of compression is evaluated by the quality factor Q_c that is given by the following relationship:

$$Q_c = \frac{P_{comp}}{F_c} \quad (11)$$

P_{comp} is the peak power of the compressed pulse normalized to the input pulse.

Table 1. parameters of compression of N order-soliton

$P_0(W)$	N	L=18cm	L=26cm	L=66cm
86	2	$T_{comp}=26fs$ $F_c=1.09$ $Q_c=0.87$ $T_{diff}=2.4 fs$	$T_{comp}=17fs$ $F_c=1.67$ $Q_c=0.55$ $T_{diff}=11.4fs$	$T_{comp}=4fs$ $F_c=7.1$ $Q_c=0.29$ $T_{diff}=24.4fs$
193	3	$T_{comp}=9.1fs$ $F_c=3.12$ $Q_c=0.34$ $T_{diff}=19.3fs$	$T_{comp}=1.2fs$ $F_c=23.6$ $Q_c=0.19$ $T_{diff}=2.4 fs$	Soliton fission region
342	4	$T_{comp}=6.2fs$ $F_c=4.58$ $Q_c=0.3$ $T_{diff}=22.2fs$	Soliton fission region	Soliton fission region

First, we generated the second order-soliton in the proposed HN-PCF to obtain 4 fs pulses from a compression of 28.4 fs in a PCF length of 66 cm Fig. 7.

Fig. 7. Soliton self compression in 66 cm of HN-PCF: Input pulse of 28.4 fs (blue), and a compressed pulse of 4 fs (red).

We improved the pulse compression, by the generation of the third order soliton until 1.2 fs in a PCF length of 26 cm (Fig. 8).

Fig. 8. Soliton self compression: input pulse of 28.4fs (blue), and 1.2 fs pulse compressed (red).

Figure 9 depicts the spectral evolution and approximately 50 nm supercontinuum is generated in 66 cm of PCF at 1300 nm pump wavelength.

Fig. 9. Spectral evolution of the input pulse in 66 cm of PCF at 1300 nm.

3.2 Self-phase modulation, self-steepening and intrapulse Raman scattering

We consider the propagation of optical pulses as short as ≈ 50 fs. Figure 10 illustrates the effect of varying the input pulse power on the output spectra in 1.89 mm of HNL-PCF; we can see that output spectra are broadened as the incident pulse power increases. In fact, by increasing the input pulse power, nonlinear effects dominate the dispersion effects. This leads to spectral broadening of the propagated pulse; induced by the interplay between many nonlinear effects such as self phase modulation, self-steepening and intrapulse Raman scattering [3]. Besides of spectral broadening due to Self-Phase Modulation (SPM), Self-Steepening leads to an asymmetry in the SPM-broadened spectra of ultrashort pulses, it creates an optical shock on the trailing edge of the pulse. As a result, the trailing edge becomes steeper along the distance of propagation (Fig. 11).

Fig. 10. Supercontinuum generation in 1.89 mm of HNL-PCF for different input pulse power.

This phenomenon is due to the intensity dependence of the group velocity that results in the peak of the pulse moving slower than the wings. A steeper trailing edge of the pulse implies larger spectral broadening on the blue sides as SPM generates blue components near the trailing edge (Fig. 11).

Fig. 11. Temporal evolution of the input pulse propagation inside the optimized HNL-PCF.

By pumping with pulses of $T_{FWHM} = 50$ fs, the Raman-gain amplify the low frequency components of the pulse, as a result, the pulse spectrum shifts toward the low frequency side (Near Infrared) as the pulse propagates inside the fiber. The introduction of this different effects in our work allows to generate a SC of Spectral Bandwidth $SBW=260$ nm at -20dB from the peak point at 1,3 μ m wavelength using only 1.89 mm length of PCF and by pumping with 770 W (Fig. 12).

The obtained spectral bandwidth could contribute to enhance the OCT imaging axial resolution which can be evaluated to 2.8 μ m in air, working at 1.3 μ m center wavelength which is widely used in several fields.

Fig. 12. The supercontinuum generation at 1.3 μ m using 1.89 mm of HNL-PCF.

4 Conclusion

A highly nonlinear photonic crystal fiber with optimized dispersion around the pump wavelength is designed. It is demonstrated that the desired curve of dispersion can be performed by adjusting the air hole filling ratio of the composed fiber rings. Using two kinds of nonlinear mechanisms, we have generated two supercontinua, first, using the soliton self-compression which allows a compression of the input pulses, a second solution is the use of the interplay between many nonlinear effects such as self-phase modulation, intrapulse Raman scattering and self-steepening to generate a second supercontinuum of $SBW=260$ nm, that can enhance the axial resolution of an optical coherence tomography system.

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