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Design of high duty ratio nonlinear photonic crystal fiber with near-zero flattened dispersion after 1.205 μm

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ABSTRACT

The paper presents a high nonlinear photonic crystal fiber (HN-PCF) with highly duty ratio for time-stretch analog-to-digital conversion (TSADC). The simulation results show that a nonlinear of 42.26 W^{-1} km^{-1} and the flattened dispersion of less than 1.0 ps/(nm km) are obtained in more than 495 nm waveband (1205–1700 nm). Owing to its high nonlinear coefficient and flattened dispersion, the high nonlinear PCF is expected to be suitable for supercontinuum (SC) generation. The numerical simulation results demonstrate that the proposed high duty ratio HN-PCF can generate wideband SC.

1. Introduction

Time stretch analog-to-digital conversion (TSADC) is a well-known optical signal processing method. TSADC consists of an optical time stretch preprocessor followed by an electronic digitizer. The time stretch preprocessor reduces the bandwidth of the high-speed electrical signal by a stretch factor M, effectively increasing both the sampling rate and the input bandwidth of the digitizer by M [1]. TSADC needs optical pluses with narrow and flat spectrum as time stretch optical carrier. The pulse generation based on spectral slicing of the supercontinuum (SC) spectrum generated in optical fibers is another technique. Using picosecond laser as light source, SC light can be generated by photonic crystal fiber (PCF) replacing femtosecond laser [2]. PCF with high nonlinearity and flat dispersion properties is very suitable for generation SC optical source. Since the first observation of SC spectrum generation in PCF by Ranka [3], several experiments and numerical simulations have been performed to investigate the SC generation in normal and anomalous regimes [4–6]. Yuan and Sang generated broad and ultra-flattened SC spectrum in visible wavelengths using PCF with central holes [7].

SC spectrum generation in PCF is a complicated nonlinear optical phenomenon characterized by a dramatic white-light spectrum [8]. Self-phase modulation (SPM), cross-phase modulation (XPM), four-wave mixing (FWM), soliton effects and Raman shift and coupling with dispersive waves, are the main effects leading to the generation of a broad spectrum in high nonlinear PCF (HN-PCF). Generation and application of wide-band SC spectrum in different wave bands by launching short pulses in a PCF with tens of centimeters length have been realized. However, dispersion will broaden optical pulse and compress optical spectrum with opposite effect of nonlinearity. Therefore, it is very important to keep the dispersion coefficient near-zero in application of SC spectrum generation.

In the paper, one simple HN-PCF with high duty ratio is proposed that have near-zero flattened dispersion after wavelength 1205 nm. Simulation results show that the proposed HN-PCF is suitable as optical source of TSADC.

2. Proposed HN-PCF structure

Fig. 1 shows the proposed HN-PCF structure with six rings. For convenient stimulation, the deformation of cladding holes and core birefringence are neglected and only one central hole is considered. The structure parameters are as follows: the average cladding hole radius $d_{clad} = 8\ \mu m$, hole to hole pitch $\Lambda = 9.8\ \mu m$, duty ratio $d/\Lambda = 81\%$.

As confinement loss is a measure of the light confinement ability within the core region of the PCF. When the number of air holes in the cladding is infinite, confinement loss does not occur. The high duty ratio HN-PCF has larger air holes than conventional hexagonal PCF. Since high duty ratio HN-PCF with larger air holes can produce

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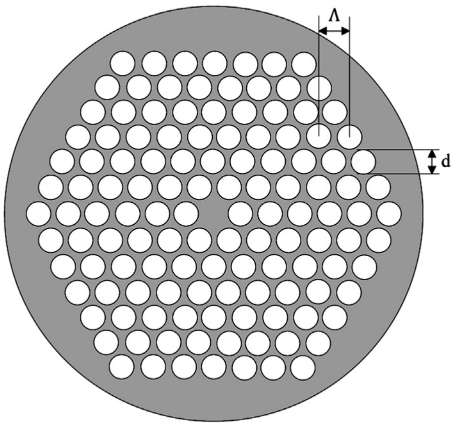

Fig. 1. Cross section of proposed HN-PCF.

a lower refractive index around a core than conventional hexagonal PCF, it has lower confinement loss.

3. PCF properties and simulation results

PCF is homogeneous with the air holes surrounded by silica. Full vector effective index method is used to analyze the dispersion properties of PCF. For the PCF made of silica, the boundary conditions are described as [9],

$$E_z(\rho = R) = H_z(\rho = R) = 0 \tag{1}$$

where R is the radius of the field. Moreover, and fields can be represented as,

$$\begin{aligned} E_z\left(\rho, \theta, z\right) &= E_l(\rho)e^{il\theta}e^{-yz} \\ H_z\left(\rho, \theta, z\right) &= H_l(\rho)e^{il\theta}e^{-yz} \end{aligned}. \tag{2}$$

From boundary conditions in Eq. (1) and the separation of variables method, dispersion relation can be derived for the fundamental modes. Among all the solutions of the characteristic equations, the effective refractive index of EH11 mode exhibits the highest one, corresponding to the cladding space-filling mode, with its characteristic equation written as,

$$\begin{aligned} \frac{I_2(w,r)}{I_1(w,r)} &= -\frac{1}{w\times r} - \frac{w\times r}{2}\left(1+\frac{n_{si}^2(\lambda)}{n_{air}^2}\right)g(u) - w\times r\left[\frac{1}{4}\left(1-\frac{n_{si}^2(\lambda)}{n_{air}^2}\right)^2 g^2(u) + \frac{f(w,u)}{n_{air}^2}\right]^{1/2} \\ g(u) &= \frac{1}{\omega r}\frac{J_0(ur)Y_1(uR) - Y_o(ur)J_1(uR)}{J_1(ur)Y_1(uR) - Y_1(ur)J_1(uR)} - \frac{1}{u^2r^2} \\ f(w,u) &= \frac{1}{r^4}\left(\frac{1}{u^2}+\frac{1}{w^2}\right)\left(\frac{n_{si}^2}{u^2}+\frac{n_{air}^2}{w^2}\right) \\ w^2 &= \omega^2\left(n_{eff}^2 - n_{air}^2\right)/c^2 \\ u^2 &= \omega^2\left(n_{si}^2 - n_{eff}^2\right)/c^2 \end{aligned} \tag{3}$$

where I_m is the m-order modified Bessel function of the first kind, n_{air} is the refractive index of the air, is the wavelength-depended refractive index of silica, c is velocity of light, J_m and Y_m are the first and second kind of m-order Bessel functions, respectively. n_{eff} is the effective index of the space filling mode. We can solve numerically to obtain effective index using Eq. (3). The dispersion parameter D and the propagation constants are defined as,

$$D = \frac{\lambda}{c}\frac{d^2 n_{eff}}{d\lambda^2} \quad \& \quad \beta_2 = -\frac{\lambda^2}{2\pi c}D \quad \& \quad \beta_3 = \frac{d\beta_2}{d\omega} \tag{4}$$

The effective area and nonlinear coefficient can be represented as,

$$A_{eff} = \frac{\left(\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\left|E\right|^2 dxdy\right)^2}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\left|E\right|^4 dxdy} \& \gamma = \left(\frac{2\pi}{\lambda}\right)\left(\frac{n_2}{A_{eff}}\right) \tag{5}$$

where E is electric field, n_2 is the nonlinear refractive index.

Based on the structure in Fig. 1 and above theory, we simulate characteristics of the high duty ratio HN-PCF, especially we concentrate 1310 nm communication window. Fig. 2 shows the wavelength versus chromatic dispersion, second-order and third-order propagation constants, effective area and nonlinear phenomena of HN-PCF in the wavelength range of 1.2 – 1.4 μm. Fig. 2(a) demonstrates the chromatic dispersion of HN-PCF is very small, the flatter dispersion of less than 1.0 ps/nm km is obtained more than 495 nm waveband (1205–1700 nm). 1310 nm window is sliced to analyze other properties. Fig. 2(b) and (c) shows the second-order and third-order propagation constants β_2, β_3 of HN-PCF. Fig. 2(d) and (e) displays the effective area A_{eff} and nonlinear coefficient γ of HN-PCF, 43.5 W^{-1} km^{-1} is obtained at 1310 nm wavelength. From all the results above, it can be seen that HN-PCF has flatter dispersion and higher nonlinear coefficient than conventional hexagonal PCF, this is because the higher duty ratio. Because of all properties, it is chosen for SC generation.

4. SC generation in HN-PCF

The generation of a SC spectrum by the proposed high duty ratio HN-PCF is numerically evaluated, the nonlinear Schrodinger equation (NLSE) is used to analyze it [10]. The NLSE is solved using split-step Fourier method. A sech^2 input optical pulse with a full width at half maximum (FWHM) of 2.5 ps through HN-PCF. The fiber parameters used in the calculation are $\beta_2 = -0.58\ ps^2/km$, $\beta_3 = 0.9155 \times 10^{-3}\ ps^2/km$, $\gamma = 42.2\ W^{-1}\ km^{-1}$, and $T_R = 3$ fs at center wavelength $\lambda_c = 1.31$ μm.

Fig. 3(a) and (b) shows the temporal and spectral evolution of a 2.5 ps FWHM sech^2 pulse launched into a 60 m HN-PCF with 10 W peak power. Optical pulse undergoes an initial compression stage that is common feature of any high-order soliton, caused by self-phase modulation (SPM). When optical pulse transfers about 60 m, soliton has distortion even fission after 60 m caused by high-order dispersion and nonlinearity, as shown in Fig. 3(a). Spectrum is stretched at 60 m transmission length with more than 200 nm bandwidth, as shown in Fig. 3(b). The spectrum has extremely broadened at 60 m due to pulse shape sudden changes. Optical pulse shape exhibits a narrow spike that has wanted to separate from the main pulse. Trend of separation is due to a change in the group velocity of the shortest fundamental soliton. As the optical pulse fission, its group velocity is reduced and the soliton spectrum shifts toward shorter and longer wavelengths.