Proposal for dispersion compensating square-lattice photonic crystal fiber

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A dispersion-compensating square-lattice photonic crystal fiber for broadband compensation which covers the S, C and L communication bands, i.e. wavelength ranging from 1 460 nm to 1 625 nm is proposed in this paper. Theoretically, it is shown a negative dispersion coefficient of about −595 ps/(nm·km) to −1 288 ps/(nm·km) over S to L bands and −975 ps/(nm·km) at the operating wavelength 1 550 nm. The relative dispersion slope is perfectly matched to that of conventional single-mode fiber of about 0.003 6 nm^{-1}. Besides the proposed photonic crystal fiber shows the large non-linear coefficient of 61.88 W/km at the operating wavelength of 1 550 nm. Moreover, the variation of structural parameters is also studied and discussed here.

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Photonic crystal fiber (PCF) is a pure silica optical fiber having small air holes arranged in the host silica matrix and the air hole arrangement goes along its propagation axis. PCFs have gained remarkable attention from the optoelectronics society in recent years. The most appealing characteristic of PCFs is that they possess tunable chromatic dispersion properties which are very different from those of the conventional optical fibers. An attractive property of PCF is that the variable design parameters of air hole diameters and hole pitches give greater flexibility and independence for the better figure of merits to get the required application in various optical sectors[1-4]. The chromatic dispersion in the conventional optical fiber because of pulse signal spreading should be compensated to get errorless optical data communication. The spreading of pulse signals can be compensated by using the dispersion compensating fiber (DCF) having a large negative dispersion coefficient[5]. The DCF should be kept as short as possible in length to reduce the insertion loss and the cost. Again, the value of the negative dispersion coefficient should be as large as possible. The negative dispersion coefficient of DCF should cover a wideband spectrum to successfully and efficiently compensate for the dispersion phenomena at all the frequencies of dense wavelength division multiplexing (DWDM). Besides, with the large negative dispersion coefficient, the relative dispersion slope (*RDS*) should be matched with conventional single mode fiber (SMF) at the same time[6]. Moreover, PCF with a high-non-linear coefficient is needed in high-bit-rate transmission and non-linear optics applications[7]. Therefore, it is important to keep special attention to chromatic dispersion, *RDS*, bandwidth, non-linearity, and mode property when designing DCF. Generally, the tiny air holes are embedded on the vertex of an equilateral triangle with six air holes in the first ring surrounding the core, this type of PCF is called the hexagonal-lattice PCF (H-PCF) or conventional PCF. Besides the hexagonal structures, other design structures such as octagonal-lattice (O-PCF), decagonal-lattice (D-PCF) PCF have been investigated vastly. The complex design method and many variable parameters have made these PCFs impractical to implement. Thus, the demand for a simple dispersion compensating PCF structure still exists for realizing all the figures of merits discussed above. Previous designs that are proposed are based on triangular-lattice (H-PCF, O-PCF, D-PCF) PCF, although proposals for simple square-lattice PCF (S-PCF) with dispersion compensating ability and other figure of merits are very few.

In this paper, we have proposed an S-PCF with six rings of air holes for dispersion compensation over S to L wavelength bands. The attractive property of our proposed S-PCF is the design simplicity with a high negative dispersion coefficient and large non-linearity as well as

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perfect *RDS*. According to the simulation work, it is shown that the designed perfectly *RDS* matched S-PCF shows high negative dispersion of −975 ps/(nm·km) and high nonlinearity of 61.88 W/km at the operating wavelength of 1 550 nm.

The proposed PCF is made of fused silica and has a square array of air holes running along its length. This is an index guiding PCF. The transverse cross-section of the PCF is shown in Fig.1, where Λ is the pitch of the lattice, d_1 is the air hole diameter of the first ring, d_2 is the air hole diameter of the second ring, d_3 is the air hole diameter of the third ring, and d_4 is the air hole diameter of other rings. The air hole diameter of the first ring is relatively large because it is known that an increase in the air hole diameter of the first ring results in the large negative dispersion coefficient. The air hole diameters of the second and the third ring are relatively smaller because these rings of reduced diameter provide a change in the *RDS* which helps in matching the *RDS* with conventional single-mode fiber (SMF). The total number of air hole rings is chosen to be six to simplify as much as possible the structural combination of the PCF. The last two rings of holes are required to maintain moderate confinement loss.

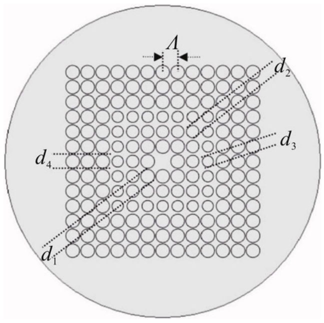

Fig.1 The transverse cross-section of the square-lattice PCF

The PCF is simulated by a finite element method (FEM) with a perfectly matched layer (PML). The FEM directly solves the Maxwell equations to best approximate the value of the effective refractive index. If the modal effective refractive index, $n_{\rm eff}$ is obtained by solving an eigenvalue problem came from Maxwell equations using the COMSOL Multiphysics, chromatic dispersion, dispersion slope, *RDS*, residual dispersion, effective area, non-linear coefficient, and confinement loss of the PCF can be easily calculated.

Chromatic dispersion D can be obtained using the following relation

$$D(\lambda)=\frac{\lambda}{-c}\times\frac{{\rm d}^2\,{\rm Re}[n_{\rm eff}]}{{\rm d}\lambda^2}\ ,\qquad(1)$$

where Re[$n_{\rm eff}$] is the real part of effective refractive index $n_{\rm eff}$, λ is the wavelength, and c is the velocity of light in vacuum. The material dispersion given by the Sellmeier formula[8] is directly included in the calculation. Therefore, D in Eq.(1) corresponds to the chromatic dispersion of the PCF.

The confinement loss $L_{\rm c}$ is obtained from the imaginary part of $n_{\rm eff}$ as

$$L_{\rm c}=8.686\times k_0\times{\rm Im}[n_{\rm eff}],\qquad(2)$$

where Im[$n_{\rm eff}$] is the imaginary part of the refractive index, and $k_0=2\pi/\lambda$ is the wavenumber in the free space.

The effective area $A_{\rm eff}$ is calculated as

$$A_{\rm eff}=\frac{(\iint_{-\infty}^{\infty}|E|^2\,{\rm d}x{\rm d}y)^2}{\iint_{-\infty}^{\infty}|E|^4\,{\rm d}x{\rm d}y}\ ,\qquad(3)$$

where E is the electric field derived from the Maxwell equations.

The nonlinear co-efficient γ is calculated as follows

$$\gamma=\frac{2\pi}{\lambda}\frac{n_2}{A_{\rm eff}}\times10^3\ ,\qquad(4)$$

where n_2 in Eq.(4) is the non-linear index coefficient in the non-linear part of the refractive index and $A_{\rm eff}$ is the effective area.

The *RDS* is calculated as follows

$$RDS=\frac{S_{\rm SMF}(\lambda)}{D_{\rm SMF}(\lambda)}=\frac{S_{\rm DCF}(\lambda)}{D_{\rm DCF}(\lambda)}\ ,\qquad(5)$$

where $S_{\rm SMF}(\lambda)$ and $S_{\rm DCF}(\lambda)$ are the dispersion slope of the SMF and DCF respectively. The *RDS* of SMF is 0.003 6 nm^{-1}.

The effective index curve for both x and y-polarized (optimum) modes of the PCF is shown in Fig.2. The effective index shows a linear relation with a variety of wavelengths.

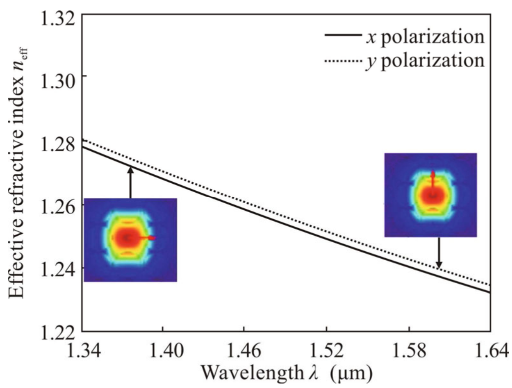

Fig.2 Effective refractive index curve of the PCF as a function of wavelength for Λ=0.81 μm, d_1/Λ=0.91, d_2/Λ=0.83, d_3/Λ=0.75, d_4/Λ=0.91

The dispersion characteristics of the proposed PCF for its optimum value is shown in Fig.3. According to a simulation result, the proposed PCF shows a negative dispersion coefficient of about −595 ps/(nm·km) to −1 288 ps/(nm·km) over S and L-bands for y-polarization. The dispersion value of the proposed PCF at 1 550 nm is about −975 ps/(nm·km) which far exceeds the dispersion values of conventional dispersion-compensating SMF [typically −100 ps/(nm·km)]. The dispersion characteristics of the proposed PCF for optimum parameters, a variation of pitch, a variation of first ring radius, a variation of second ring radius and the third ring radius are shown in Figs.3—7 respectively for y-polarization while remaining parameters are kept constant. The chromatic dispersion variation with a variety of different parameters is needed during the fabrication process. These results indicate that how much the chromatic dispersion changes with up to 5% different parameter variation. The optimum condition is obtained with Λ=0.81 μm, d_1/Λ=0.91, d_2/Λ=0.83, d_3/Λ=0.75, d_4/Λ=0.91. With a variation of these parameters some good results can be obtained, but with the deviation from *RDS* value of 0.003 6 nm^{-1} of SMF.

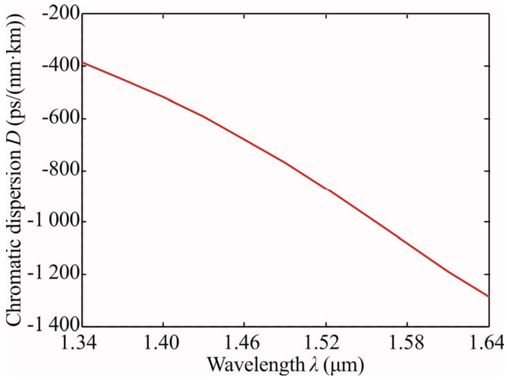

Fig.3 Chromatic dispersion curve of the PCF as a function of wavelength for *y*-polarization and optimum condition Λ=0.81 μm, d_1/Λ=0.91, d_2/Λ=0.83, d_3/Λ=0.75, d_4/Λ=0.91

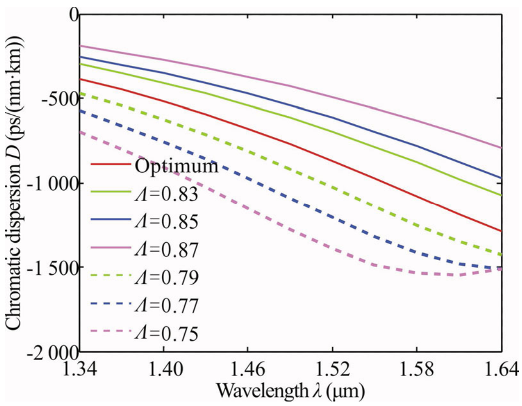

Fig.4 Chromatic dispersion curve of the PCF as a function of wavelength for pitch variation

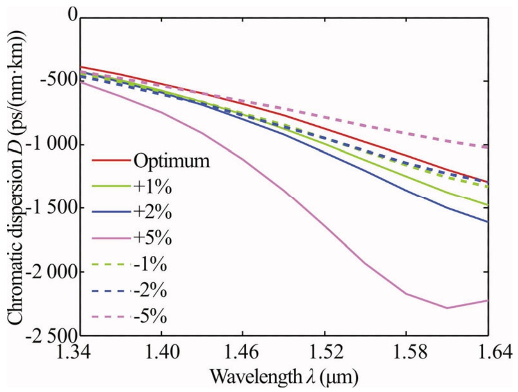

Fig.5 Chromatic dispersion curve of the PCF as a function of wavelength for the first ring the variation

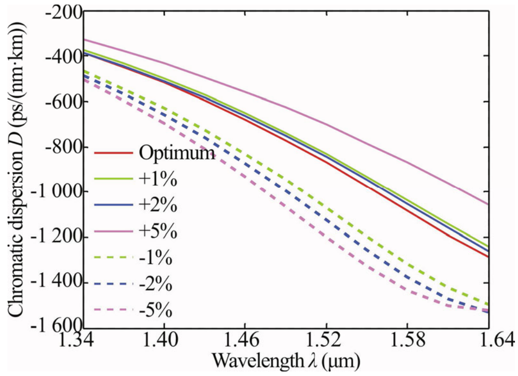

Fig.6 Chromatic dispersion curve of the PCF as a function of wavelength for the second ring variation

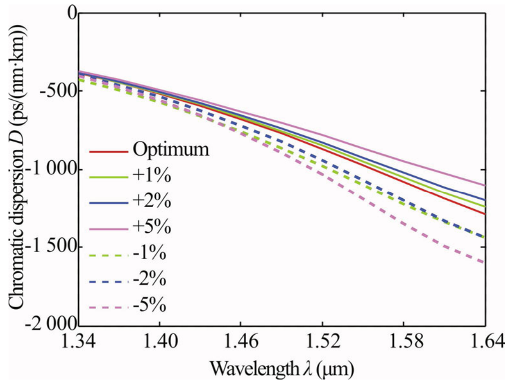

Fig.7 Chromatic dispersion curve of the PCF as a function of wavelength for the third ring variation

The dispersion slope, *RDS*, residual dispersion of the PCF for an optimum condition is shown in Figs.8—10, respectively. From Fig.8, it is shown that the proposed PCF has a better dispersion slope of −2.55 to −3.26 for S to L wavelength bands. From Fig.9, it is shown that the proposed PCF has perfectly matched *RDS* of 0.003 599 nm^{-1} which is also the *RDS* of conventional SMF at the operating wavelength of 1 550 nm. Fig.10 shows the calculated residual dispersion obtained after the dispersion compensation by a 0.71 km long optimized PCF for the dispersion considered in one span (40 km long) of the transmission of SMF. It is found that the residual dispersion value which ranges from −39.42 ps/nm to −26.78 ps/nm in the wavelength range of 1 430 nm to 1 640 nm enables the proposed PCF to be a better candidate for high-bit-rate transmission systems for S, C and L band.

Fig.11 represents the effective area as a function of wavelength and Fig.12 represents the wavelength dependence of non-linear coefficient γ as a function of wavelength for optimum design parameters. From these figures, it is found that the proposed PCF is highly non-linear and the non-linear coefficient is found 61.88 W/km for *y*-polarization at operating wavelength 1 550 nm, which is suitable for optical parametric amplification, supercontinuum generation, and soliton pulse generation. Confinement loss of the proposed PCF for *y*-polarization is shown in Fig.13 which shows moderate confinement loss at the operating wavelength of 1 550 nm.

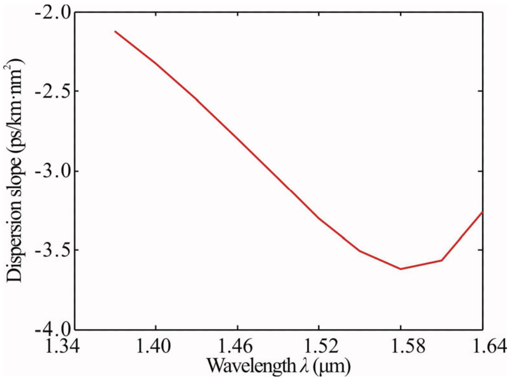

Fig.8 Dispersion slope curve as a function of wavelength for *y*-polarization and optimum condition Λ=0.81μm, d_1/Λ=0.91, d_2/Λ=0.83, d_3/Λ=0.75, d_4/Λ=0.9

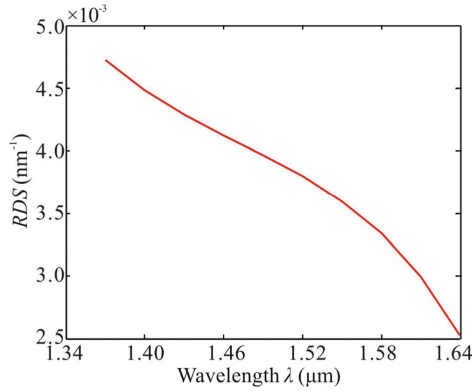

Fig.9 *RDS* curve as a function of wavelength for *y*-polarization and optimum condition Λ=0.81 μm, d_1/Λ=0.91, d_2/Λ=0.83, d_3/Λ=0.75, d_4/Λ=0.91 which shows perfectly matched *RDS* of with SMF at wavelength 1 550 nm

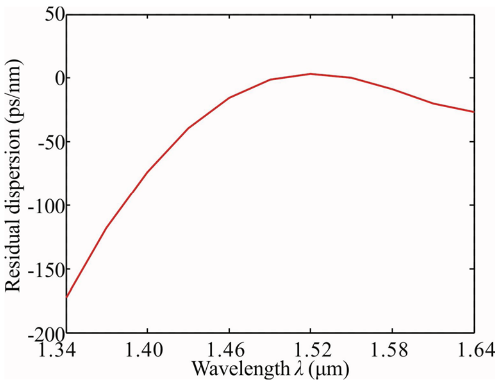

Fig.10 Residual dispersion curve as a function of wavelength for *y*-polarization and optimum condition Λ=0.81 μm, d_1/Λ=0.91, d_2/Λ=0.83, d_3/Λ=0.75, d_4/Λ=0.91

At last, we have compared our proposed S-PCF with other S-PCF concerning the different figures of merits in Tab.1. Some of the S-PCF have a high negative dispersion coefficient of greater than 1 500 ps/(nm·km) and a high non-linear coefficient of greater than 100 W/km. Although they did not discuss *RDS* which is an essential figure of merit for dispersion compensating fiber. Thus, we believe that our proposed PCF is a perfect candidate for dispersion compensating applications.

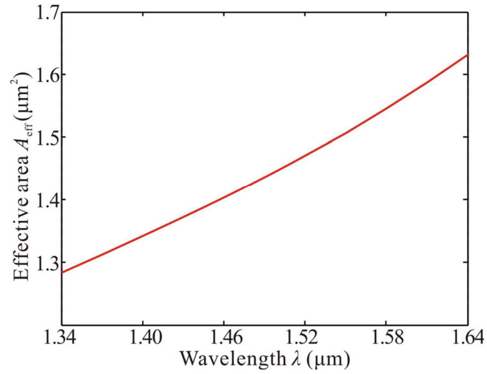

Fig.11 Effective area curve as a function of wavelength for *y*-polarization and optimum condition Λ=0.81 μm, d_1/Λ=0.91, d_2/Λ=0.83, d_3/Λ=0.75, d_4/Λ=0.91

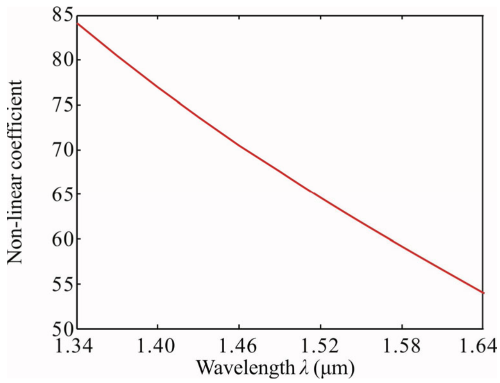

Fig.12 Non-linear coefficient curve as a function of wavelength for *y*-polarization and optimum condition Λ=0.81 μm, d_1/Λ=0.91, d_2/Λ=0.83, d_3/Λ=0.75, d_4/Λ=0.91

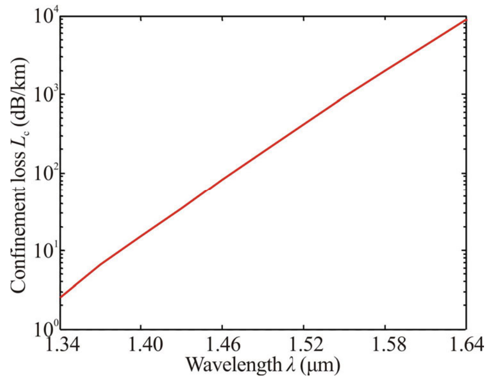

Fig.13 Confinement loss curve as a function of wavelength for *y*-polarization and optimum condition Λ=0.81 μm, d_1/Λ=0.91, d_2/Λ=0.83, d_3/Λ=0.75, d_4/Λ=0.91

Here we have proposed an S-PCF that has a high negative dispersion coefficient with perfectly matched dispersion slope with conventional SMF and high non-linear coefficient. This proposed PCF offers a high negative dispersion coefficient of about −595 ps/(nm·km) to −1 288 ps/(nm·km) over S to L-bands and −975 ps/(nm·km) at the operating wavelength 1 550 nm and it offers a high non-linear coefficient of 61.88 $W^{-1}\cdot km^{-1}$ at the operating wavelength 1 550 nm also. Another special advantage is that, compared with previously presented S-PCF, the design procedure and geometrical structure is very simple because relatively fewer geometrical parameters are used. So, it can hope that our proposed S-PCF will be useful and successful in dispersion compensation for broadband transmission application and non-linear optics application.

Tab.1 Comparison between properties of the proposed S-PCF and recently published S-PCFs at 1 550 nm

References	*D* (ps/(nm·km))	*RDS* (nm^{-1})	γ (W/km)
[9]	−1 672	-	117.3
[10]	−1 212	-	117.4
[11]	-	-	91.25
[12]	−1 083	-	110
Our S-PCF	−975	0.003 6	61.88

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