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S+C+L 波段色散斜率补偿光子准晶体光纤

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摘　要:针对光纤通信中的色散补偿,尤其是密集波分复用系统的多信道同时补偿的需求,提出了一种用于宽带色散斜率补偿的光子准晶体光纤.该光纤结构包层空气孔为准晶体排列,并且在纤芯引入了中心缺陷.通过对光纤特性的数值分析表明,在 1 460～1 625 nm 的光通信波段,该结构光纤的相对色散斜率为 0.004 4～0.002 9 nm^{-1},相对色散斜率与标准单模光纤近似相等,且负色散值达−2 476 ps・nm^{-1}・km^{-1}.对标准单模光纤进行色散补偿后,在 S+C+L 波段色散值为(−0.5～0)ps・nm^{-1}・km^{-1}.该光纤可用于对当前光纤通信系统进行宽带色散补偿,实现多信道同时补偿,简化结构,并降低补偿成本.

关键词:光子准晶体光纤;色散斜率;补偿;相对色散斜率
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Dispersion Slope Compensating Photonic Quasi-crystal Fiber over S+C+L Band

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Abstract: For multi-channel dispersion compensation in dense wavelength division multiplexing (DWDM) systems optical communication networks, a broadband dispersion slope compensating photonic quasi-crystal fiber (PQF) is proposed. The PQF has a six-fold symmetric quasi-periodic array of air holes in cladding and a high index rob in the concentric core. The simulating results of the dispersion slope and dispersion of PQF reveal that the relative dispersion slope (RDS) can reach a low value 0.004 4 nm^{-1} to 0.002 9 nm^{-1} that is equal to the standard single mode fiber (SMF) over S+C+L band approximately; the PQF can achieve dispersion slope compensation effectively, while obtain a larger negative dispersion coefficient of −2 476 ps・nm^{-1}・km^{-1} over optical communication band 1 460 nm to 1 625 nm. The value of dispersion compensation result is (−0.5～0)ps・nm^{-1}・km^{-1} to the SMF in the S+C+L band. The designed PQF can achieve multi-channel dispersion compensation, simplify the structure and reduce compensation costs, and then it can be used for wide-band dispersion slope compensation.

Key words: Photonic quasi-crystal fiber (PQF); Dispersion slope; Compensation; Relative dispersion slope (RDS)

0 Introduction

The transmission impairment caused by dispersion and dispersion slope in a single mode fiber (SMF) is severe for long distance high-bit-rate transmissions that made dispersion and dispersion slope compensation techniques essential. In the ultra-long haul DWDM systems, the continuous compensation bandwidth of chirped fiber Bragg grating (FBG) is narrow in the wide

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communication band, meanwhile it will bring transport costs to the ultra-long haul DWDM system, when the devices are cascaded, for the reason that the chirped FBG exists group delay jitter[1]. The cost of dispersion compensating fiber (DCF) will be lower than the FBG after achieving mass production, therefore, the preferred method is DCF technology. Photonic crystal fibers (PCFs)[2-4] have been paid great attention because of its great advantage in the flexible design of dispersion profile[5-6]. Wu et al.[7] have presented a broadband DCF by introducing the air hole in the center of pure silica index-guiding PCF, and they theoretically and experimentally demonstrate that broadband DCF based on index guiding PCF with defected core. The chromatic dispersion coefficient varies from -440 to -480 ps·nm^{-1}·km^{-1} in the range of 1 500 to 1 625 nm. This fiber can be used for broadband dispersion compensation in wavelength-division multiplexing optical communication systems. Yang et al.[8] have reported a modified dual-core photonic crystal fibers (DC-PCFs), based on pure silica, with special grapefruit holes in the inner cladding. The fiber has broadband, large negative dispersion, and the negative dispersion coefficient around -380 to -420 ps·nm^{-1}·km^{-1} in the C band. This fiber can realize dispersion and dispersion slope compensation, while its compensation band and value of dispersion is too low. Begum et al.[9] have proposed a dual-concentric-core pure silica dispersion compensating photonic crystal fibers. Their DC-PCFs shows dispersion value varies linearly from -190 to -405 ps·nm^{-1}·km^{-1} in the wavelength range 1 460 to 1 630 nm. This fiber can realize dispersion compensating, however, the value of RDS which is 0.004 3 nm^{-1} is larger than the RDS of SMFs whose value is 0.003 5 nm^{-1} at 1 550 nm.

A photonic quasi-crystal fiber is a novel microstructure fiber with a quasi-periodic structure[10], which has a long-range order but no periodicity. It has been found that PQFs can give rise to unusual phenomena and some unique dispersion properties that were not found in PCFs[10-11].

In this paper, we demonstrate a broadband dispersion slope compensating photonic quasi-crystal fiber, which is a promising component for dispersion and dispersion slope compensation in the range of 1 460～1 625 nm.

1 Geometries of the proposed PQF

The geometry of elementary units of the quasi-crystal, which is formed of adjacent equilateral triangles and squares, is shown in Fig. 1(a). The distances between the centers of neighboring air-holes are the same where we refer to Λ as the distance of neighboring air-holes. The schematic cross section of the proposed fiber is shown in Fig. 1(b), which is composed of a high index (ABH160 glass) concentric core and cladding which consists of air holes. d_1 is the diameter of the concentric core, the diameter of the cladding air holes is d_2. The presented PQF is a single core compensating fiber with high refractive index for broadband dispersion slope compensation, and it is reported for the first time. The refractive index of ABH160 is obtained from the equation[12]

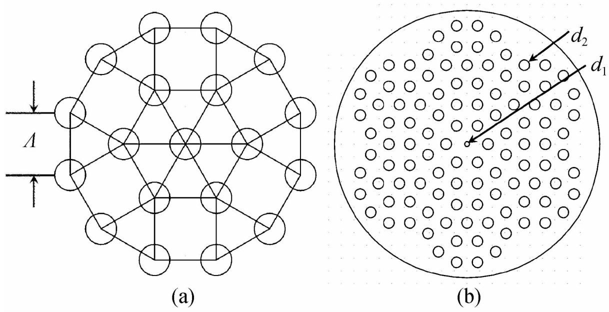


Fig. 1 (a) Geometry of elementary units of the quasi-crystal and (b) cross section of the PQF

$$n^2(\lambda)=1+\frac{A_1}{1/a_1^2-1/\lambda^2}-A_2\lambda^2 \tag{1}$$

where n is the refractive index of ABH160; λ is the wavelength in the vacuum; A_1, A_2, a_1 are the coefficients for the ABH160 glasses, respectively. The values of coefficients A_1, A_2, a_1 are adopted from [12]. The refractive index of SiO_2 is obtained from Sellmeier equation[13]

$$n^2-1=\sum_{i=1}^{3}\frac{A_i\lambda^2}{\lambda^2-l_i} \tag{2}$$

where n is the refractive index of SiO_2; λ is the wavelength in the vacuum; A_i, l_i are the coefficients for the SiO_2, respectively.

The dispersion of the PQF can be considered as the sum of material dispersion and waveguide dispersion approximately. The chromatic dispersion D is obtained from the real part of n_{eff} in the unit of ps/km/nm as below[14]

$$D=-\frac{\lambda}{c}\frac{\mathrm{d}^2\mathrm{Re}(n_{\mathrm{eff}})}{\mathrm{d}\lambda^2} \tag{3}$$

where Re(n_{eff}) stands for the real part of the fundamental mode refractive index n_{eff}, and c is the velocity of light in vacuum.

2 Dispersion compensation

For multichannel high-speed WDM systems, dispersion compensation over a broad wavelength range is necessary. This means that it is necessary to compensate for the dispersion (D) and the dispersion slope (DS). The conditions of broadband dispersion compensation are[15]

$$\begin{aligned} D_1 L_1 + D_2 L_2 = 0 \\ DS_1 L_1 + DS_2 L_2 = 0 \end{aligned} \tag{4}$$

where D_1, DS_1, L_1 are the dispersion, dispersion slope, length of the SMFs and D_2, DS_2, L_2 are the dispersion, dispersion slope, length of the compensating fiber (CF), respectively.

We use the relative dispersion slope (RDS) to simply judge the possibility for dispersion and dispersion slope compensation over a wide range of wavelengths. The RDS is defined as the ratio of the dispersion slope and the dispersion coefficient of the fiber [9]

$$\mathrm{RDS} = \frac{DS}{D} \tag{5}$$

From Eq. (4) and Eq. (5), we can see that the condition for dispersion and dispersion slope compensation is that the RDS of the CF shall be equal to the relative dispersion slope of the standard SMF

$$\mathrm{RDS}_{\mathrm{CF}} = \mathrm{RDS}_{\mathrm{SMF}} \tag{6}$$

3 Numerical results and discussion

For the dual-core photonic crystal fibers, it will generate large negative dispersion around the phase-matching wavelength when the mode field redistribute between the inner core and the outer core. However, this kind of fibers has only narrowband negative dispersion coefficient, it can't achieve dispersion compensation of all the wavelengths. In order to efficiently compensate the dispersion of all the wavelengths from 1 460 to 1 625 nm, the negative dispersion of PQF should span to wide spectrum. It is necessary to achieve the dispersion and dispersion slope compensation at the same time. In order to broaden the bandwidth of the negative dispersion, here a kind of high index (ABH160 glass) rob is introduced in the center area. The diameter of concentric core is 0.640 μm, which is at the level of the wavelength dimension. Therefore, the mode field cannot be trapped tightly in the concentric core, and part of the mode field leaks out to the surrounding quartz area in a wide wavelength range. It can be considered that part of the fundamental mode field exists in the concentric core and part in the surrounding quartz area. This redistribution of the mode field makes the bandwidth of the negative dispersion broaden.

In our study, a finite element method is used for numerical analysis. We calculated the chromatic dispersion, dispersion slope and RDS in the wavelength range from 1 460 to 1 625 nm for $\Lambda = 3.0$ μm, $d_2/\Lambda = 0.5$ and $d_1 = 0.640$ μm. The chromatic dispersion curve is shown in Fig. 2, the peak dispersion is 2 476 ps · nm^{-1} · km^{-1} at 2 110 nm, and the full width at half maximum of dispersion is 1.06 μm. In order to get a better dispersion slope compensation effect, we adjust the structure parameters to achieve full compensation for the dispersion slope in the range of 1 460～1 625 nm, while obtain large negative dispersion coefficient. The calculated value of RDS is from 0.004 4 to 0.002 9 nm^{-1} over S+C+L band in the optical communication windows, and that is equal to the RDS of SMF. Thus the PQF that we designed can realize dispersion slope compensation. The properties of the PQF at 1 460 nm, 1 550 nm, 1 625 nm are in the Table 1 for $\Lambda = 3.0$ μm, $d_2/\Lambda = 0.5$ and $d_1 = 0.640$ μm.

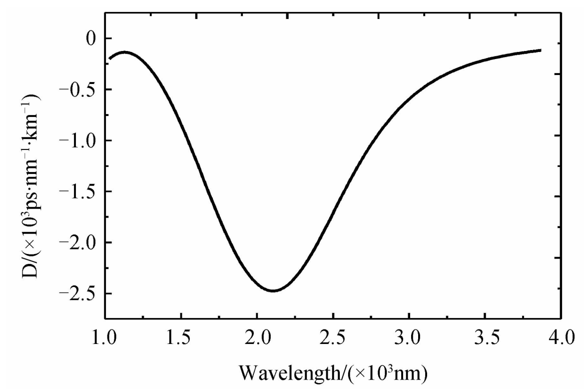


Fig. 2 The dispersion profile of PQF

Table 1 The properties of PQF

Wavelength/nm	1 460	1 550	1 625
D/(ps · nm^{-1} · km^{-1})	−710.8	−1 015.9	−1 293.1
DS/(ps · nm^{-2} · km^{-1})	−3.11	−3.56	−3.76
RDS/nm^{-1}	0.004 4	0.003 5	0.002 9

It is noticed that dispersion, dispersion slope and RDS value of standard SMFs are about 17 ps · nm^{-1} · km^{-1}, 0.06 ps · nm^{-2} · km^{-1} and 0.003 5 nm^{-1} at 1 550 nm. We study the change of RDS in the range of 1 460 nm to 1 625 nm for the first time. The RDS of PQF is 0.003 5 nm^{-1} that is equal to the RDS of standard SMFs at 1 550 nm, and the RDS of PQF is equal to the RDS of standard SMF approximately over S+C+L band, thus the dispersion slope and dispersion of SMF can be compensated completely in the range of 1 460 nm to 1 625 nm, while the PQF has a larger dispersion coefficient.

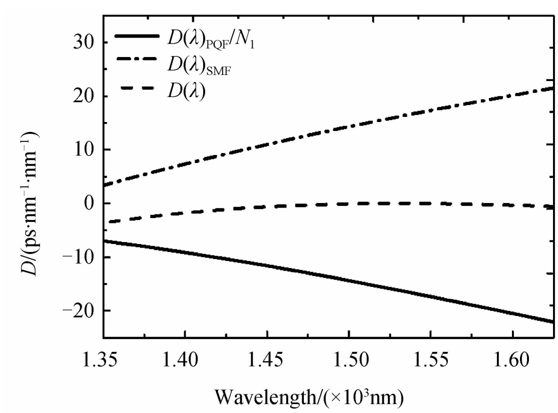
To achieve dispersion and dispersion slope compensation over S+C+L band, $D_{\mathrm{PQF}}(\lambda)/N_1$ should completely compensate for $D_{\mathrm{SMF}}(\lambda)$ in the range of 1 460 nm to 1 625 nm. We can define the compensation results $D(\lambda)$ and $DS(\lambda)$ as

$$D(\lambda)=\frac{D_{\mathrm{PQF}}(\lambda)}{N_1}+D_{\mathrm{SMF}}(\lambda) \tag{7}$$

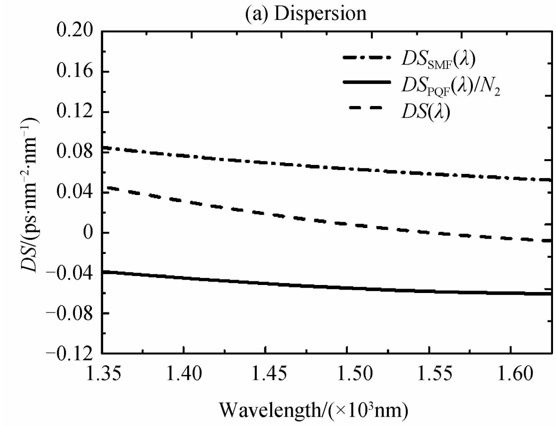
$$DS(\lambda)=\frac{DS_{\mathrm{PQF}}(\lambda)}{N_2}+DS_{\mathrm{SMF}}(\lambda) \tag{8}$$

where $D(\lambda)$ and $DS(\lambda)$ are compensation result of dispersion and dispersion slope; $D_{\mathrm{PQF}}(\lambda)$ and $DS_{\mathrm{PQF}}(\lambda)$ are dispersion and dispersion slope of PQF; $D_{\mathrm{SMF}}(\lambda)$ and $DS_{\mathrm{SMF}}(\lambda)$ are dispersion and dispersion slope of SMF; N_1 and N_2 are compensation times of dispersion and dispersion slope at 1 550 nm, respectively.

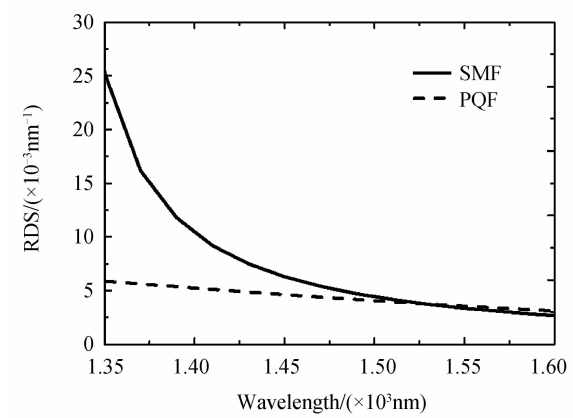
In the Fig. 3 (a), the dash line shows the compensation result of dispersion, the value of $D(\lambda)$ is $-0.5\sim0$ ps·nm^{-1}·km^{-1} in the S+C+L band, thus the PQF achieves dispersion compensation completely. The dash line in the Fig. 3 (b) shows the compensation result of dispersion slope, the value of $DS(\lambda)$ is 0.016$\sim$0.008 ps·nm^{-2}·km^{-1} that approaches to zero over S + C + L band , it indicates that the broadband dispersion slope compensation can be achieved. In Fig. 3 (c), the RDS line (dash line) of PQF almost overlaps the RDS line (solid line) of SMF in the range of 1 460～1 625 nm. From Fig. 3 and above discussion, we can see that the PQF that we designed can achieve broadband dispersion slope and dispersion compensation over S+C+L band.



(a) Dispersion



(b) Dispersion slope



(c) RDS

Fig. 3 Compensation results

In the fiber fabrication procedure, the conventional stack and draw method which cannot easily generate complex structures is not suitable for the PQF. Instead, it is feasible for a sol-gel casting method to fabricate the PQFs. Because of the small size of the air-holes in the PQFs, one important issue to be considered during the manufacturing process is the dispersion slope and RDS tolerance to the imperfect manufacture. It is known that the parameters can only be guaranteed with limited precision. Thus, it is necessary to analyze the effects of air-hole diameters′ and other diameters′ fluctuations on dispersion slope and RDS properties.

Fig. 4 (a), (b) show the influence of the concentric core on dispersion slope profile and RDS, where $\Lambda=3.0$ μm, $d_2/\Lambda=0.5$, d_1 is 0.630, 0.640, 0.650 μm, respectively. The dash lines of Fig. 4 (a), (b) represent optimized dispersion slope and RDS of PQFs for d_1 = 0.640 μm, respectively. We can see that with a 0.01 μm enlargement (reduction) of d_1, the curves of dispersion slope and RDS shift up (down). Table 2 shows main data of these three PQFs at 1 550 nm.

Table 2 The DS and RDS of PQFs with different diameters of concentric core at 1 550 nm

d_1/μm	0.630	0.640	0.650
DS/(ps·nm^{-2}·km^{-1})	−3.75	−3.56	−3.36
RDS/nm^{-1}	0.003 3	0.003 5	0.003 7

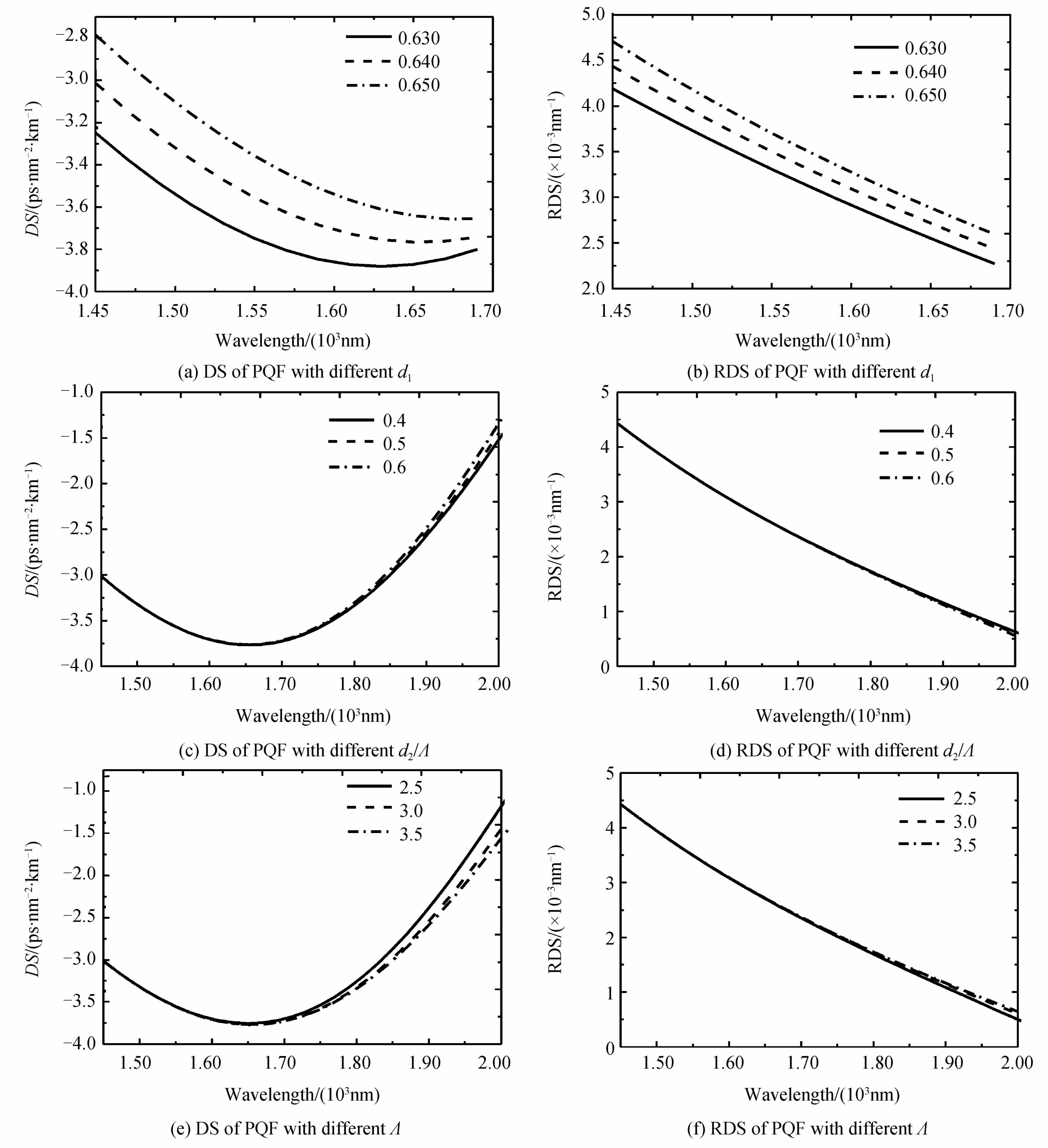


Fig. 4　The effects of diameters' fluctuations

From Table 2, we can see that with enlargement (reduction) of d_1, the absolute dispersion slope decreases 5.6% (increases 5.3%), and the RDS increases 5.7% (decreases 5.7%). The change of RDS is slightly. Therefore, we still can realize dispersion slope compensating effectively, even d_1 enlarge or diminish for 1.6%. The value of d_2/Λ has little impact on dispersion slope and RDS as shown in Fig. 4(c) and (d). We can see that the curve of RDS overlap even when the diameters of cladding air holes change by 0.3 μm at the range of 1 460 nm to 1 800 nm. In Fig. 4(c), the dispersion slope is not affected by the change of d_2/Λ at the range of 1 450 nm to 1 650 nm. Fig. 4(e) and (f) show the change of dispersion slope and RDS with different Λ (2.5 μm, 3.0 μm, 3.5 μm) which is the distance of air hole to hole. It is clear that there is little change for dispersion slope and RDS over the S+C+L band. Especially, the curve of RDS overlaps over the S+C+L band.

According to the above simulation results, we can see that a variation of parameters which include d_2/Λ and Λ serves to have little impact on dispersion slope and RDS, therefore, we can only control d_1 to obtain high negative dispersion and suitable value of RDS which approximates to 0.003 5 nm^{-1} at 1 550 nm. In reality, not all the parameters are distorted from their optimum value in the same way and some averaging effects are likely to occur, however, our designed PQF still can realize dispersion and dispersion slope compensation. The dispersion slope compensation PQF that we proposed is good for the practical application, because it is robust to small fabrication imperfections. The traditional arc-fusion method can be used to splice the photonic crystal fiber and standard single mode fibers, the splice loss can drop to a low value by optimizing the discharge parameters, and then satisfy the application request[16].

The nonlinear coefficient increases because of introducing the high refractive index rob in the concentric core. However, the PQF has a larger compensation times to the SMF, it will need shorter PQFs to compensate the SMFs, then it can reduce the accumulation of nonlinear effects.

4 Conclusion

In conclusion, we have theoretically investigated the proposed broadband dispersion slope compensating fiber using the index-guiding PQF with defected core with high index (ABH160) based on SiO_2. Our designed PQF can achieve dispersion slope compensation effectively, while has broadband large negative dispersion, in the calculated wavelength range of 1 460 nm to 1 625 nm. We study the change of RDS for the first time, and the RDS varies from 0.004 4 to 0.002 9 nm^{-1}. The value of RDS is 0.003 5 nm^{-1} that is equal to the RDS of the standard SMF, and the confinement loss is less than 10^{-5} dB/km at 1550 nm. The compensating property can easily be controlled by the defected core with high index, and the PQF has a low requirement on the manufacture. This kind of PQF can effectively compensate dispersion and dispersion slope accumulated by transmission fibers currently deployed in DWDM optical communication systems.

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