

Broadband Dual-Core Microstructured Optical Fiber for Dispersion Compensation in Long-Reach Data Center Interconnects

Zhenfan Zhou

Nanjing University of Posts and Telecommunications

Wanting Shao

Nanjing University of Posts and Telecommunications

Peili Li

Nanjing University of Posts and Telecommunications

Weihua Shi

`njupt_shiwh@126.com`

Nanjing University of Posts and Telecommunications

Fuxiao Ma

Nanjing University of Posts and Telecommunications

Research Article

Keywords: fiber optics, photonic crystal fiber, broadband dispersion compensation, dispersion compensation factor, low loss

Posted Date: September 23rd, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11004278/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Broadband Dual-Core Microstructured Optical Fiber for Dispersion Compensation in Long-Reach Data Center Interconnects

Zhenfan Zhou¹ • Wanting Shao¹ • Peili Li¹ • Weihua Shi¹ • Fuxiao Ma^{1,2}

¹College of Electronic and Optical Engineering, College of Flexible Electronics (Future Technology), Nanjing University of Posts and Telecommunications, Nanjing 210023, Jiangsu, China

²School of Integrated Circuits, Wuxi University of Technology, Wuxi 214000, Jiangsu, China

Zhenfan Zhou and Wanting Shao contributed equally to this work.

Corresponding authors: Weihua Shi(njupt_shiwh@126.com); Fuxiao Ma(mafx34@163.com)

Abstract

Chromatic dispersion accumulation in standard single-mode fiber (SSMF) can limit the transmission performance of long-reach data-center interconnects, particularly in dense wavelength division multiplexing (DWDM) systems. To address this issue, a broadband dispersion-compensating microstructured optical fiber with a weakly coupled dual-core structure is proposed. The cladding region of the broadband dispersion-compensating photonic crystal fiber (B-DCPCF) is composed of periodically arranged air holes with a triangular lattice structure. By enlarging the diameter of the first-ring air holes and reducing the diameter of the second-ring air holes, a weakly coupled dual-core structure is achieved, which enables broadband negative dispersion characteristics. Numerical simulations are performed to optimize the structural parameters of the proposed B-DCPCF. The optimized fiber exhibits a broadband negative dispersion range of -1150 to -2613 ps/(nm·km) across the S-, C-, and L-bands. In the C-band, the dispersion compensation multiple (DCM) reaches 135.17, while the confinement loss remains below 0.1 dB/km throughout the entire band. At 1550 nm, the dispersion slope and relative dispersion slope of the B-DCPCF are calculated to be approximately

$-8.47 \text{ ps}/(\text{nm}^2 \cdot \text{km})$ and 0.0035 nm^{-1} , respectively. Its relative dispersion slope closely matches that of SSMF. This agreement enables the simultaneous compensation of chromatic dispersion and dispersion slope. The high DCM also reduces the required compensation-fiber length and facilitates compact dispersion management. These characteristics indicate that the proposed B-DCPCF has potential for broadband dispersion compensation in long-reach dense wavelength division multiplexing data-center interconnects.

Keywords fiber optics • photonic crystal fiber • broadband dispersion compensation • dispersion compensation factor • low loss

1 Introduction

With the rapid growth of digital data traffic, fiber-optic communication systems are continuously evolving toward higher transmission rates, increased capacity, and extended transmission distances (Winzer et al. 2018). Long-reach data-center interconnects require high-capacity optical communication over extended fiber links. DWDM is widely employed to increase the capacity of such links. However, in SSMF-based DWDM links, chromatic dispersion accumulates with transmission distance, which causes pulse broadening and intersymbol interference at high data rates and narrow channel spacing. These effects degrade signal quality and limit system performance. Therefore, broadband dispersion compensation and dispersion-slope matching are important for long-reach DWDM transmission (Pan et al. 2002). Dispersion-compensating fibers (DCFs) are commonly used to compensate for the accumulated dispersion. However, conventional DCFs generally have a relatively low dispersion compensation multiple and therefore require a longer compensation length. Among various microstructured optical fibers, photonic crystal fibers (PCFs) are particularly attractive for dispersion engineering because of their flexible air-hole structures. Their dispersion characteristics can be effectively tailored through the geometric parameters of the air-hole cladding. Therefore, PCFs have considerable potential for broadband dispersion compensation (Wang et al. 2025).

DCFs are classified as either narrowband or broadband. Although narrowband dispersion-compensating photonic crystal fibers (DCPCFs) can achieve extremely large negative dispersion, with magnitudes on the order of 10^3 – $10^5 \text{ ps}/(\text{nm} \cdot \text{km})$, at specific wavelengths (Bala et al. 2017; Singh et al. 2022), their limited compensation bandwidth prevents complete dispersion compensation across

the entire operating wavelength range of DWDM systems. To achieve broadband dispersion compensation in DWDM systems, researchers commonly design weakly coupled dual-core DCPCFs (Zhao et al. 2008; Liang and Shi 2022), which can simultaneously compensate for chromatic dispersion and dispersion slope and thus provide a high dispersion compensation factor over a broad wavelength range.

For broadband dispersion compensation in DWDM systems, a DCPCF based on the weakly coupled dual-core mechanism should exhibit large negative dispersion and a dispersion slope matched to that of the transmission fiber. A high DCM and good dispersion flatness are also required. Based on these performance requirements, broadband dispersion-compensating photonic crystal fiber designs reported in the literature can be classified into two main categories: geometry-tailored pure-silica designs (Allam et al. 2024; Mondal 2026; Halder and Anower 2024; Mondal 2024) and doped or all-solid designs (Wang et al. 2019; Xu et al. 2021; Ma et al. 2025). Pure-silica DCPCFs control mode coupling primarily through changes in the air-hole diameter, lattice pitch, number of air-hole rings, and core-defect structure. Allam et al. (Allam et al. 2024) developed a hexagonal DCPCF that covers the wavelength range from 1260 to 1675 nm. The fiber achieves a dispersion compensation factor of 100 and an effective dispersion from -0.15 to $+0.15$ ps/(nm·km) in the C-band. Mondal et al. (Mondal 2026) reported a DCPCF with circumferentially arranged air holes. Over the wavelength range from 1450 to 1620 nm, the design provides a dispersion compensation factor of 62.5 and an effective dispersion from -0.1 to $+0.1$ ps/(nm·km). Halder et al. (Halder and Anower 2024) designed a modified hexagonal–decagonal PCF through adjustments to the core air holes and lattice parameters. At 1550 nm, the fiber has a negative dispersion of -7755 ps/(nm·km) and a birefringence of 1.905×10^{-2} . Mondal (Mondal 2024) introduced a broadband PCF with a circular lattice. Its dispersion ranges from -452 to -1408 ps/(nm·km) over 1400–1700 nm. At 1550 nm, its dispersion and relative dispersion slope are -932 ps/(nm·km) and 0.0036 nm^{-1} , respectively. Doped or all-solid-state DCPCFs primarily achieve broadband dispersion compensation by adjusting the Ge doping concentration, the size of the doped region, the diameter of the solid glass rod, and the refractive index difference between the inner and outer cores. The all-solid-state double-concentric-core fiber proposed by Wang et al. (Wang et al. 2019) has an average compensation factor of 18.45 in the 1385–1575 nm range, with residual dispersion controlled within ± 0.72 ps/(nm·km); The Ge-doped annular outer-core photonic crystal fiber proposed by Xu et al. (Xu et al. 2021) maintains effective dispersion

within ± 1.38 ps/(nm·km) in the 1460–1637 nm range. Ma et al. (Ma et al. 2025) achieved temperature-controlled tunable dispersion compensation in the 1360–1625 nm range by selectively filling a dual-core PCF with temperature-sensitive materials; the dispersion for the X and Y polarization modes was -309 to -1140 ps/(nm·km) and -68 to -222 ps/(nm·km), respectively, with compensation factors of 57.90 and 9.52, respectively, at 1550 nm. Pure quartz DCPCFs can flexibly adjust mode coupling and dispersion characteristics by optimizing the air gaps and core structures; however, within a certain operating wavelength range, it is difficult to achieve both a high dispersion compensation factor and dispersion flatness. Doped or all-solid DCPCFs can improve the match between modes through coordinated control of material and structural parameters. These fibers offer advantages in bandwidth expansion and residual-dispersion suppression. However, their dispersion compensation factors are relatively low, and they require high fabrication precision, which may lead to additional loss and refractive-index nonuniformity.

To overcome the trade-off between a high dispersion compensation factor and broadband dispersion flatness in conventional DCPCFs, a B-DCPCF is proposed. By setting different air hole parameters in the core and near-core cladding regions, a dual-core waveguide structure with distinct refractive index distributions is constructed, and the confinement of the guided mode by the inner core is appropriately reduced. As the wavelength increases, part of the optical field energy gradually transfers from the inner core to the outer core, thereby enhancing the wavelength coupling between the inner and outer core modes. Owing to this coupling effect, the B-DCPCF achieves large negative chromatic dispersion over a broad communication band, while its dispersion slope closely matches that of the transmission fiber. As a result, the proposed fiber offers a high dispersion compensation factor and a flat dispersion profile.

2 Structural Design of the B-DCPCF

To achieve large negative chromatic dispersion over a broad wavelength range and enable broadband dispersion compensation, this work proposes a solid-core B-DCPCF with a concentric dual-core configuration. The design concept is based on wavelength-dependent coupling between the modes supported by the inner and outer cores. Different effective refractive-index distributions and modal confinement conditions are established in the two core regions through control of the near-core air-hole diameters. As the wavelength increases, the confinement of the inner-core mode decreases, and

optical power is gradually transferred from the inner core to the outer core. Therefore, the inter-core modal coupling exhibits strong wavelength dependence. To implement this design concept, the cladding of the B-DCPCF comprises seven rings of air holes arranged in a periodic triangular lattice. The central air hole is omitted to form a solid inner core. The air holes in the first ring have a larger diameter, whereas those in the second ring have a smaller diameter. This radial variation in air-hole diameter modifies the effective refractive-index distribution in the near-core region. As a result, an annular outer-core region is formed around the inner core, and a concentric dual-core structure is established. The two-dimensional cross-sectional structure of the B-DCPCF is shown in Fig. 1(a). Here, Λ denotes the pitch, which is defined as the center-to-center distance between two adjacent air holes. The parameters d_1 and d_2 denote the air-hole diameters in the first and second rings, respectively. To reduce fabrication complexity, all air holes from the third to the seventh ring have the same diameter d_3 . The three air-hole diameters satisfy $d_2 < d_3 < d_1$.

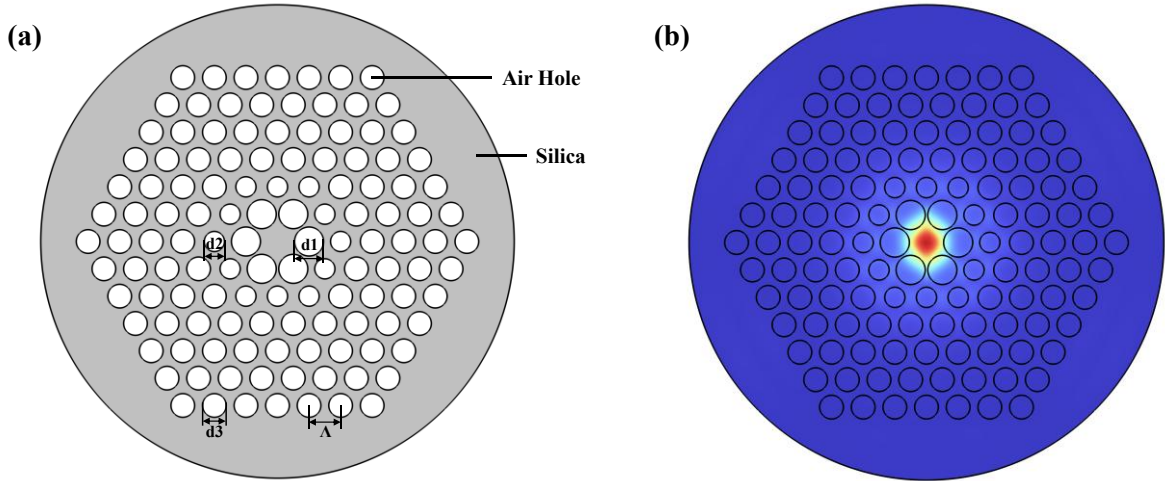


Fig. 1 (a) Two-dimensional cross-sectional view of the B-DCPCF; (b) Fundamental mode field map

The B-DCPCF uses silica as its host material. The refractive index of silica is calculated from the Sellmeier equation (Icenogle et al. 1976),

$$n_{\text{SiO}_2}^2(\lambda) = 1 + \sum_{i=1}^3 \frac{A_i \lambda^2}{\lambda^2 - B_i^2} \quad (1)$$

where λ is the wavelength, and A_i and B_i are the Sellmeier coefficients, with A_i equal to 0.69675, 0.408128, 0.890815, and B_i equal to 0.0047701, 0.0133777, and 98.02107.

Fig 1(b) shows the fundamental-mode field distribution of the proposed B-DCPCF. The optical field is almost entirely confined to the core, which indicates that the B-DCPCF provides strong confinement for the fundamental mode. Based on established PCF fabrication techniques, the

proposed B-DCPCF is, in principle, compatible with the conventional stack-and-draw method (Cho et al. 2008). Silica capillaries and solid silica rods can be assembled to form the air-hole cladding and the two solid cores, respectively, followed by jacketing and fiber drawing.

3 Principle of Dispersion Compensation

Dispersion refers to signal distortion that occurs when different frequency components or modal components of an optical signal propagate at different velocities. The dispersion D of the fiber can be calculated from the second derivative of the effective refractive index of the guided mode with respect to wavelength (Hsu et al. 2015).

The dispersion slope $D_s(\lambda)$ is obtained from the wavelength derivative of the chromatic dispersion $D(\lambda)$ (Allam et al. 2024). Since $D(\lambda)$ and $D_s(\lambda)$ exhibit different wavelength dependences, practical dispersion compensation must account for both quantities, which makes broadband dispersion compensation challenging. To account for the compensation of both D and D_s , the relative dispersion slope (RDS) is introduced and expressed as:

$$RDS(\lambda) = \frac{D_s(\lambda)}{D(\lambda)} \quad (2)$$

If the RDS of the DCF matches that of the transmission fiber, the DCF can simultaneously compensate for dispersion and dispersion slope. At 1550 nm, the RDS of SSMF is approximately 0.0035 nm^{-1} .

To achieve complete dispersion compensation, the sum of the accumulated dispersions of the SSMF and the B-DCPCF at wavelength λ should be zero (Begum et al. 2009). In other words, the accumulated dispersions of the SSMF and B-DCPCF must sum to zero. After compensation of the SSMF by a certain length of DCF, the uncompensated dispersion remaining in the system is defined as the residual dispersion $RD(\lambda)$, which can be expressed as

$$RD(\lambda) = D_{SSMF}(\lambda)L_{SSMF} + D_{DCF}(\lambda)L_{DCF} \quad (3)$$

When $RD(\lambda) = 0 \text{ ps/nm}$, complete compensation of the system can be achieved.

Effective dispersion (ED) refers to the dispersion remaining within 1 kilometer after the system has undergone dispersion compensation, and can be expressed as

$$ED(\lambda) = \frac{RD(\lambda)}{L_{SSMF} + L_{DCF}} \quad (4)$$

Similarly, an ED value closer to zero corresponds to reduced residual dispersion, greater compensation efficiency.

The DCM is the ratio of DDCPCF to DSMF and can be calculated using the following formula:

$$\text{DCM} = -\frac{D_{\text{DCPCF}}(\lambda)}{D_{\text{SMF}}(\lambda)} \quad (5)$$

As shown in Equation (5), the larger the negative dispersion value of the DCPCF, the larger the DCM. Based on the dispersion compensation conditions, the required length of the DCPCF is shorter, thereby reducing compensation costs and facilitating the miniaturization of dispersion-compensating devices.

The confinement loss L_c is used to evaluate the optical-field confinement capability of a PCF. Its calculation depends on the imaginary part of the effective refractive index of the fundamental mode, and the detailed expression is given in Reference (Ma et al. 2023). A lower L_c indicates stronger optical-field confinement.

4 Numerical Simulation and Discussion

The structural parameters of an optical fiber significantly affect its dispersion characteristics. The initial structural and material parameters of the B-DCPCF are $N = 3$, $\Lambda = 1.00 \text{ } \mu\text{m}$, $d_1 = 0.92 \text{ } \mu\text{m}$, $d_2 = 0.64 \text{ } \mu\text{m}$, and $d_3 = 0.75 \text{ } \mu\text{m}$. Unless otherwise specified, these parameters are kept unchanged. In this section, the B-DCPCF is numerically analyzed by COMSOL Multiphysics based on the finite element method (FEM) and perfectly matched layer (PML) boundary conditions. MATLAB-based curve fitting is subsequently employed to investigate the effects of variations in these parameters on the dispersion characteristics of the B-DCPCF.

4.1 Effect of Structural Parameters on the Dispersion Characteristics of the B-DCPCF

4.1.1 Influence of the Number of Air-Filled Layers on Dispersion Characteristics

Fig. 2 shows the dispersion curves for different numbers of air-hole layers (N), with $\Lambda = 1.00 \text{ } \mu\text{m}$, $d_1 = 0.92 \text{ } \mu\text{m}$, $d_2 = 0.64 \text{ } \mu\text{m}$, and $d_3 = 0.75 \text{ } \mu\text{m}$. Each curve exhibits a pronounced negative-dispersion peak at a specific wavelength. The negative-dispersion peak occurs because its corresponding wavelength coincides with the phase-matching wavelength λ_p , at which mode coupling between the inner and outer cores causes a rapid change in the effective refractive index. As N increases from 4 to 8, the negative dispersion of the B-DCPCF in the S-, C-, and L-bands (1460–1625 nm) also increases. However, when N increases from 6 to 8, the dispersion curves nearly overlap, which indicates a significantly smaller increase. As N increases, the air-filling fraction of

the B-DCPCF and the refractive-index contrast between the core and cladding increase, which leads to a larger magnitude of negative dispersion. For $N \geq 6$, the outer cladding boundary is sufficiently far from the core region and has a negligible effect on the effective index of the fundamental mode. Therefore, the negative dispersion gradually stabilizes. Considering the need to achieve a high negative dispersion and a broad dispersion-compensation bandwidth while reducing the practical manufacturing cost and complexity, $N = 6$ is selected.

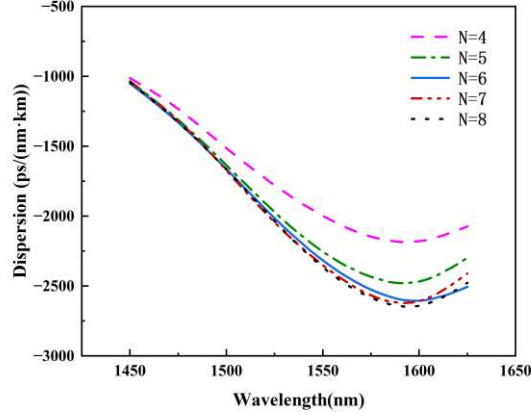


Fig. 2 Curves showing the variation of dispersion with wavelength as N changes

4.1.2 Effect of Air Hole Spacing on Dispersion Characteristics

When $N = 6$, $d_1 = 0.92 \text{ } \mu\text{m}$, $d_2 = 0.64 \text{ } \mu\text{m}$, and $d_3 = 0.75 \text{ } \mu\text{m}$, the pitch Λ is varied from 0.95 to 1.05 μm . The corresponding effective refractive index and dispersion curves are shown in Fig. 3(a) and 3(b), respectively. As shown in Fig. 3(a), the effective refractive index of the fundamental mode of the B-DCPCF decreases with increasing wavelength, whereas it increases with increasing Λ . As shown in Fig. 3(b), when Λ is 0.95 or 1.00 μm , the magnitude of the negative dispersion first increases and then decreases across the S-, C-, and L-bands, and it reaches a peak at the phase-matching wavelength λ_p . This peak arises from the abrupt change in the effective refractive index induced by coupling between the inner- and outer-core modes. As Λ increases, the air-filling fraction decreases, and the mode coupling becomes weaker. Consequently, λ_p shifts toward longer wavelengths, while the negative-dispersion peak decreases in magnitude and undergoes a redshift. When $\Lambda = 1.05 \text{ } \mu\text{m}$, λ_p shifts to an even longer wavelength; therefore, within the wavelength range considered, the negative dispersion only increases and no distinct peak is observed.

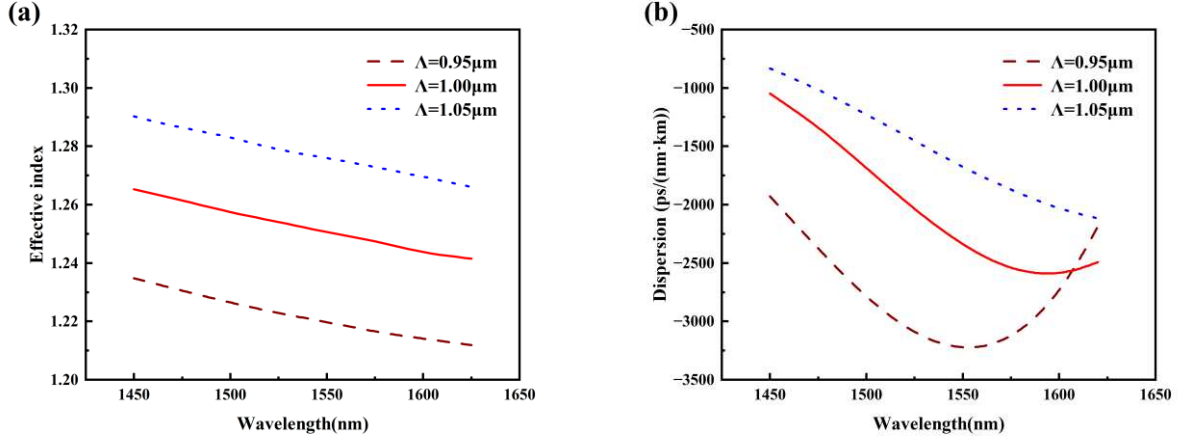


Fig. 3 As Λ varies, (a) the curve of effective refractive index versus wavelength; (b) the curve of dispersion versus wavelength

Since the B-DCPCF designed in this paper needs to compensate for both the dispersion and the dispersion slope of the SSMF, the RDS of the B-DCPCF matches that of the SSMF when $\Lambda = 1.00 \mu\text{m}$; therefore, Λ is set to $1.00 \mu\text{m}$.

4.1.3 Effect of Air-Filled Hole Diameter on Dispersion Characteristics

The designed B-DCPCF features three different air hole diameters. Next, we will use the combined control variable method to perform optimization analyses on d_1, d_2 , and d_3 , respectively.

The influence of the air-hole diameter d_1 on the dispersion characteristics of the B-DCPCF is investigated. Fig. 4 presents the simulated effective refractive index and dispersion curves of the fundamental mode. As shown in Fig. 4(a), the effective refractive index of the fundamental mode gradually decreases as the wavelength and d_1 increase. Fig. 4(b) shows that, over the S-, C-, and L-bands, the magnitude of the negative dispersion first increases and then decreases as the wavelength increases, and a dispersion peak therefore occurs. As d_1 increases from 0.90 to $0.94 \mu\text{m}$, the negative-dispersion peak shifts toward shorter wavelengths, and its magnitude gradually increases. On the short-wavelength side of the dispersion peak, the negative-dispersion slope also gradually increases. This phenomenon occurs because a larger d_1 increases the air-filling fraction of the inner cladding and thus strengthens the interaction between the modes. When $d_1 = 0.92 \mu\text{m}$, the RDS of the B-DCPCF matches that of the SSMF at $1.55 \mu\text{m}$. Therefore, d_1 is set to $0.92 \mu\text{m}$.

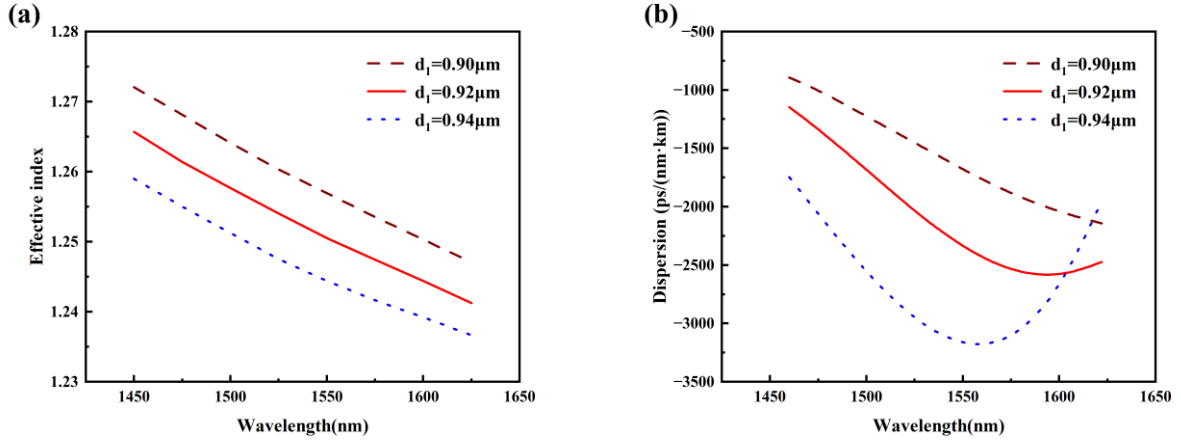


Fig. 4 As d_1 varies, (a) the curve of effective refractive index versus wavelength; (b) the curve of dispersion versus wavelength

The effect of the air hole diameter d_2 on the dispersion characteristics of the B-DCPCF was investigated. The simulation results for the fundamental mode effective refractive index curve and dispersion curve are shown in Fig. 5. As can be seen from Fig. 5(a), the fundamental mode effective refractive index of the B-DCPCF gradually decreases with increasing wavelength and d_2 , with little change at short wavelengths and a sudden change at long wavelengths. As shown in Fig. 5(b), for $d_2 = 0.62$ and $0.64 \mu\text{m}$, the magnitude of the negative dispersion of the B-DCPCF first increases and then decreases across the S-, C-, and L-bands and reaches a peak. As d_2 increases to $0.66 \mu\text{m}$, the dispersion peak shifts toward longer wavelengths, the magnitude of the negative dispersion decreases, and the slope on the short-wavelength side of the peak declines. This occurs because a larger d_2 reduces the air-filling fraction of the outer core and weakens the mode coupling. When $d_2 = 0.64 \mu\text{m}$, the *RDS* at 1550 nm is consistent with that of an SSMF; therefore, d_2 is set to $0.64 \mu\text{m}$.

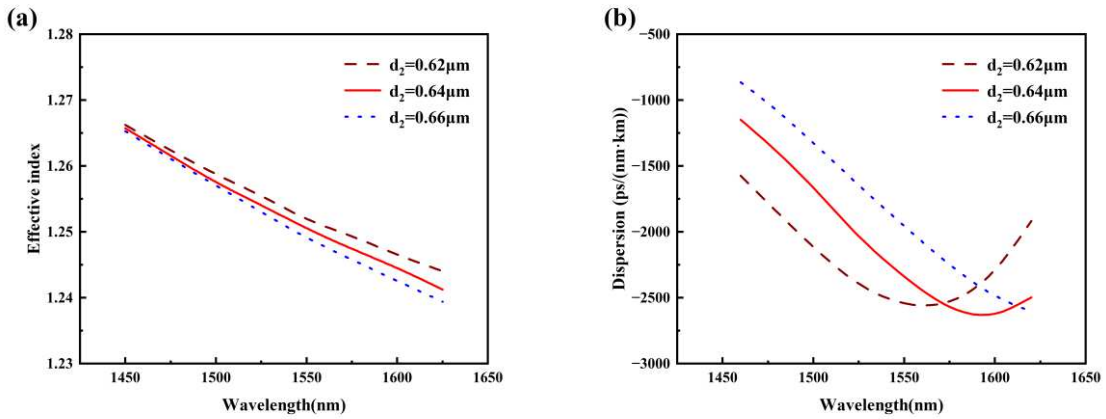


Fig. 5 As d_2 varies, (a) the curve of effective refractive index versus wavelength; (b) the curve of dispersion versus wavelength

The influence of the air-hole diameter d_3 on the dispersion characteristics of the B-DCPCF was investigated. Fig. 6 presents the simulated effective refractive index and dispersion curves of the fundamental mode. As shown in Fig. 6(a), the effective refractive index decreases as the wavelength and d_3 increase. The variation remains relatively small in the short-wavelength region, whereas an abrupt change occurs in the long-wavelength region. Fig. 6(b) shows that, over the S-, C-, and L-bands, the negative dispersion of the B-DCPCF first increases and then decreases as the wavelength increases; thus, a dispersion peak exists. As d_3 increases from 0.73 to 0.77 μm , the negative-dispersion peak shifts toward longer wavelengths, while its magnitude gradually decreases. On the short-wavelength side of the dispersion peak, the negative-dispersion slope also gradually decreases. This behavior occurs because a larger d_3 raises the air-filling fraction of the outer cladding and thus enhances the mode-coupling strength. When $d_3 = 0.75 \mu\text{m}$, the *RDS* of the B-DCPCF matches that of SSMF at 1.55 μm . Therefore, d_3 was set to 0.75 μm .

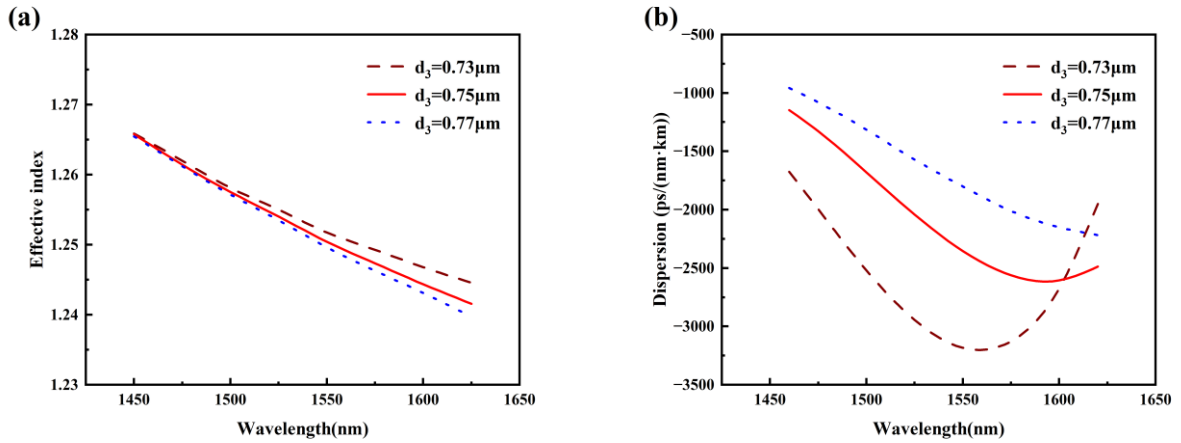


Fig. 6 As d_3 varies, (a) the curve of effective refractive index versus wavelength; (b) the curve of dispersion versus wavelength

In summary, the structural parameters of the B-DCPCF were optimized to fully exploit its broadband dispersion compensation performance and satisfy the requirements for simultaneous compensation of dispersion and dispersion slope in SSMF at 1.55 μm . A controlled-variable analysis determined the optimized structural parameter set as follows: $N = 6$, $\Lambda = 1.00 \mu\text{m}$, $d_1 = 0.92 \mu\text{m}$, $d_2 = 0.64 \mu\text{m}$, and $d_3 = 0.75 \mu\text{m}$.

4.2 Performance Analysis

With the optimized parameter set, the dispersion and confinement loss of the B-DCPCF were evaluated over a broad wavelength range, as shown in Fig. 7. In Fig. 7(a), the magnitude of the

negative dispersion initially increases with wavelength, reaches a maximum near 1590 nm, and then decreases slightly at longer wavelengths. The dispersion ranges from approximately -1150 to -2613 ps/(nm·km) across the S-, C-, and L-bands. At 1550 nm, the dispersion slope D_s and RDS are approximately -8.47 ps/(nm²·km) and 0.0035 nm⁻¹, respectively. The RDS closely matches that of SSMF, which supports simultaneous compensation of chromatic dispersion and dispersion slope at this wavelength. In addition to the dispersion characteristics, confinement loss is an important factor because excessive modal leakage can increase transmission attenuation and restrict the practical compensation length. Therefore, the confinement loss L_c of the optimized B-DCPCF was also evaluated, as shown in Fig. 7(b). The confinement loss remains nearly zero from 1450 to 1550 nm and then increases with wavelength. These results indicate that the proposed B-DCPCF maintains low confinement loss over most of the investigated wavelength range.

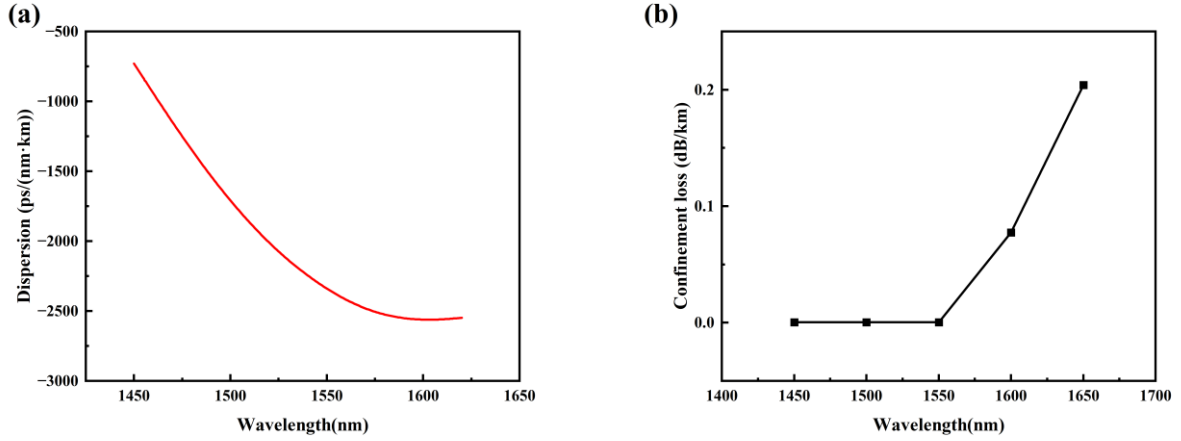


Fig. 7 (a) the curve of dispersion versus wavelength;(b) the curve of confinement loss versus wavelength

Since commercial DCFs are mainly applied for C-band dispersion compensation, the dispersion characteristics and compensation capability of the B-DCPCF in this wavelength band are further optimized and analyzed. The calculated results show that the dispersion value of the B-DCPCF in the C-band ranges from -2086 to -2461 ps/(nm·km), with a compensation ratio range of 131.05–135.17, an average compensation ratio of 134.12, and a compensation ratio of 135.07 at 1550 nm. The confinement loss remains below 0.1 dB/km. The length of the B-DCPCF is set to 1 km, and the RD and ED are calculated based on the maximum, minimum, 1550 nm, and average compensation ratios, respectively. Fig. 8(a) and (b) present the RD and ED characteristics of the B-DCPCF in the C-band, respectively. The calculation results indicate that the minimum RD and ED values are obtained when the compensation ratio is set to the average value of 134.12. The RD variation range

is -19 to 49 ps/nm, while the ED variation range is -0.14 to 0.36 ps/(nm·km).

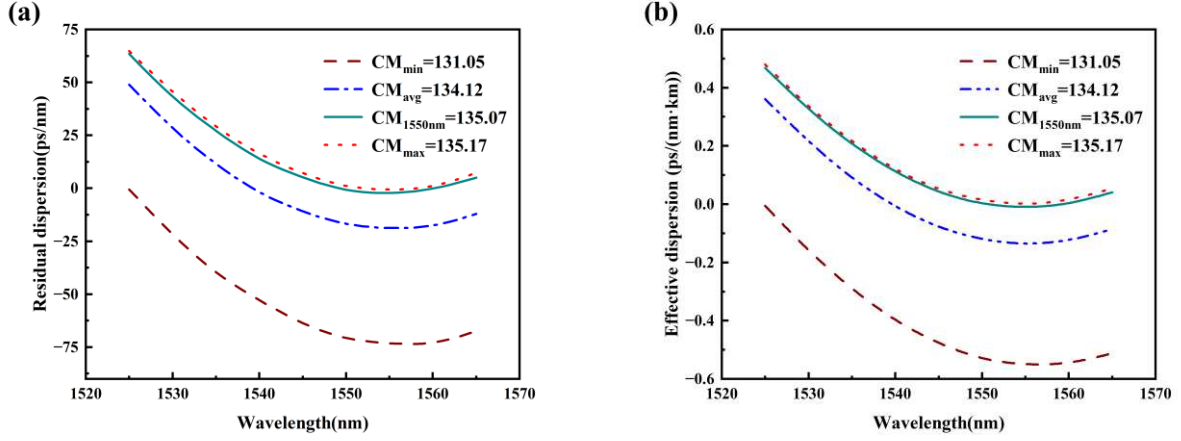


Fig. 8 (a) RD ; (b) ED of B-DCPCF at different compensation factors

To ensure a fair comparison, Tables I and II separately summarize the broadband performance over the C-band and the performance at 1550 nm. As shown in Table I, the proposed B-DCPCF provides a large negative dispersion of -2086 to -2461 ps/(nm·km) from 1525 to 1565 nm, with a dispersion compensation factor of 131.05–135.17. Its negative-dispersion magnitude and compensation factor are substantially larger than those of the commercial DCF and the reported TB-DC-PCF. At 1550 nm, the relative dispersion slope is approximately 0.0035 nm $^{-1}$, which closely matches that of SSME. The confinement loss also remains below 0.1 dB/km. These results indicate that the proposed fiber combines high compensation efficiency with effective mode confinement. Table II shows that some reported structures achieve larger negative-dispersion peaks or higher compensation factors at 1550 nm. However, these peak values are often reported only at 1550 nm or for a specific polarization. In contrast, the proposed B-DCPCF achieves a favorable balance among negative-dispersion magnitude, compensation bandwidth, dispersion-slope match, and confinement loss. These characteristics make the proposed B-DCPCF a promising candidate for compact broadband dispersion compensation in long-reach DWDM data-center interconnects.

Table I Comparison of broadband dispersion-compensation characteristics of the proposed B-DCPCF with commercial and reported DCFs over the C-band (1525–1565 nm)

Parameters Fibers	D (ps/(nm·km))	RDS (nm ⁻¹)	CM	RD (ps/nm)	ED (ps/(nm·km))	L_c (dB/km)
Commercial DCF	-100 ~ -170	0.0028~0.0043	≈8	-	-	≤0.55
Kaijage et al. (2009)	-295~-342	0.00388	≈19.3	-13.7~+13.7	-	<10 ⁻⁴
Monfared & Mojtahedinia (2014)	-1650 ~ -2305	-	124	-	-	-
Proposed B-DCPCF, this work	-2086 ~ -2461	0.0026~0.0060	≈134	-19 ~ 49	-0.14 ~ 0.36	<0.10

Table II Single-wavelength dispersion-compensation characteristics of the proposed B-DCPCF and reported PCF-based DCFs at 1550 nm

Parameters Fibers	D (at 1550 nm) (ps/(nm·km))	RDS (nm ⁻¹)	CM	RD (ps/nm)	ED (ps/(nm·km))	L_c (dB/km)
Allam et al. (2024)	-1716	0.0036	≈101	-	-	-
Allam et al. (2024)Design A	≈-1070	≈0.0036	≈63	-	-	1.1
Mondal (2024)	-4542	-	≈267	-	-	-
Mondal (2026)	≈-1030	0.0035	62.5	-10 ~ +10	-0.1 ~ +0.1	-
This work	≈-2350	0.0026~0.0060	≈134	-19 ~ 49	-0.14 ~ 0.36	<0.10

5 Conclusion

In conclusion, the proposed B-DCPCF achieves large negative dispersion over the S-, C-, and L-bands through weak coupling between the central core mode and the adjacent defect-core mode. The numerical results show that the air-hole diameters in the inner cladding rings strongly affect the coupling strength and the wavelength dependence of the effective refractive index. Therefore, these geometrical parameters provide an effective means to control the magnitude and bandwidth of the negative dispersion. For the optimized structure with $N = 6$, $\Lambda = 1.00 \text{ } \mu\text{m}$, $d_1 = 0.92 \text{ } \mu\text{m}$, $d_2 = 0.64 \text{ } \mu\text{m}$, and $d_3 = 0.75 \text{ } \mu\text{m}$, the dispersion varies from approximately -1150 to -2613 ps/(nm·km) over 1460–1625 nm. In the C-band, the DCM reaches 135.17, which substantially reduces the

required compensation-fiber length. The confinement loss remains below 0.1 dB/km, which indicates effective mode confinement. At 1550 nm, the dispersion slope and RDS are approximately -8.47 ps/(nm²·km) and 0.0035 nm⁻¹, respectively. The close RDS match between the B-DCPCF and SSMF supports simultaneous compensation of chromatic dispersion and dispersion slope and reduces residual dispersion across wavelength channels. Compared with previously reported dispersion-compensating fibers, the proposed structure provides a favorable balance among negative-dispersion magnitude, compensation bandwidth, RDS match, and confinement loss. The combination of high DCM, broadband negative dispersion, matched RDS , and low confinement loss suggests that the proposed B-DCPCF has potential for compact broadband dispersion compensation in long-reach DWDM data-center interconnects.

References

- Allam, M.A., Ali, T.A., Rafat, N.H.: Broadband dispersion compensation and high birefringence photonic crystal fiber for CWDM/DWDM networks. *Opt. Quantum Electron.* **56**, 1023 (2024). <https://doi.org/10.1007/s11082-024-06884-9>
- Bala, A., Chowdhury, K.R., Mia, M.B., Faisal, M.: Highly birefringent, highly negative dispersion compensating photonic crystal fiber. *Appl. Opt.* **56**, 7256–7261 (2017). <https://doi.org/10.1364/AO.56.007256>
- Begum, F., Namihira, Y., Razzak, S.M.A., Kaijage, S.F., Hai, N.H., Kinjo, T., Miyagi, K., Zou, N.: Novel broadband dispersion compensating photonic crystal fibers: applications in high-speed transmission systems. *Opt. Laser Technol.* **41**, 679–686 (2009). <https://doi.org/10.1016/j.optlastec.2009.02.001>
- Cho, T.Y., Kim, G.H., Lee, K.I., Lee, S.B., Jeong, J.M.: Study on the fabrication process of polarization maintaining photonic crystal fibers and their optical properties. *J. Opt. Soc. Korea* **12**, 19–24 (2008). <https://doi.org/10.3807/JOSK.2008.12.1.019>
- Halder, A., Anower, M.S.: Design and numerical analysis of a modified core hexa-deca photonic crystal fiber for highly negative dispersion and birefringence control in optical communication bands. *Sci. Rep.* **14**, 29075 (2024). <https://doi.org/10.1038/s41598-024-80539-3>
- Hsu, J.M., Zheng, W.H., Lee, C.L., Horng, J.S.: Theoretical investigation of a dispersion compensating photonic crystal fiber with ultra-high dispersion coefficient and extremely low confinement loss. *Photonics Nanostruct. Fundam. Appl.* **16**, 1–8 (2015). <https://doi.org/10.1016/j.photonics.2015.06.001>
- Icenogle, H.W., Platt, B.C., Wolfe, W.L.: Refractive indexes and temperature coefficients of germanium and silicon.

- Appl. Opt. **15**, 2348–2351 (1976). <https://doi.org/10.1364/AO.15.002348>
- Kaijage, S.F., Namihira, Y., Hai, N.H., Begum, F., Razzak, S.M.A., Kinjo, T., Miyagi, K., Zou, N.: Dispersion compensating square photonic crystal fiber for optical communication systems. *IEEE J. Trans. Electron. Inf. Syst.* **129**, 601–607 (2009). <https://doi.org/10.1541/ieejieiss.129.601>
- Liang, H., Shi, W.: Numerical studying of broadband tunable dispersion compensation based on photonic crystal fiber. *Opt. Eng.* **61**, 076109 (2022). <https://doi.org/10.1117/1.OE.61.7.076109>
- Ma, F., Li, P., Shi, W.: Residual dispersion compensation photonic crystal fiber based on simulated annealing algorithm and Livelink data interaction. *Opt. Fiber Technol.* **81**, 103462 (2023). <https://doi.org/10.1016/j.yofte.2023.103462>
- Ma, F., Shao, W., Shi, W., Li, P.: Temperature-controlled tunable broadband dispersion compensation photonic crystal fiber with high birefringence for DWDM transmission system. *Microw. Opt. Technol. Lett.* **67**, e70413 (2025). <https://doi.org/10.1002/mop.70413>
- Mondal, K.: Design of simple circular photonic crystal fiber having ultra-large negative dispersion and high birefringence for dispersion compensation. *Opt. Quantum Electron.* **56**, 1726 (2024). <https://doi.org/10.1007/s11082-024-07616-9>
- Mondal, K.: Design of broadband dispersion compensating photonic crystal fiber with circularly distributed holes for optical communication applications. *J. Opt.* (2026). <https://doi.org/10.1007/s12596-026-03080-8>
- Monfared, Y.E., Mojtahedinia, S.A.: Highly birefringent photonic crystal fiber with high negative dispersion for broadband dispersion compensation. *Optik* **125**, 5969–5972 (2014). <https://doi.org/10.1016/j.ijleo.2014.07.038>
- Pan, Z., Song, Y.W., Yu, C., Wang, Y., Yu, Q., Popelek, J., Li, H., Li, Y., Willner, A.E.: Tunable chromatic dispersion compensation in 40-Gb/s systems using nonlinearly chirped fiber Bragg gratings. *J. Lightwave Technol.* **20**, 2239–2246 (2002). <https://doi.org/10.1109/JLT.2002.806773>
- Singh, S., Upadhyay, A., Sharma, D., Taya, S.A.: A comprehensive study of large negative dispersion and highly nonlinear perforated core PCF: theoretical insight. *Phys. Scr.* **97**, 065504 (2022). <https://doi.org/10.1088/1402-4896/ac6d1a>
- Wang, C., Zhang, Y., Wu, Z., Zhang, G., Zhang, Y., Jiang, L.: Design of all-solid dual-concentric-core microstructure fiber for ultra-broadband dispersion compensation. *Appl. Sci.* **9**, 3366 (2019). <https://doi.org/10.3390/app9163366>
- Wang, H., Zhang, X., Yi, X., Qi, J., Yan, S., Bing, P.: Photonic crystal fibre optic sensor based on a U-shaped detection channel with large air-hole cladding. *J. Mod. Opt.* **72**, 28–37 (2025). <https://doi.org/10.1080/09500340.2025.2459337>

- Winzer, P.J., Neilson, D.T., Chraplyvy, A.R.: Fiber-optic transmission and networking: the previous 20 and the next 20 years [Invited]. *Opt. Express* **26**, 24190–24239 (2018). <https://doi.org/10.1364/OE.26.024190>
- Xu, H., Kong, Q., Zhou, C.: Crossings in photonic crystal fiber with hybrid core and design of broadband dispersion compensating photonic crystal fiber. *Opt. Fiber Technol.* **63**, 102485 (2021). <https://doi.org/10.1016/j.yofte.2021.102485>
- Zhao, X., Zhou, G., Li, S., Liu, Z., Wei, D., Hou, Z., Hou, L.: Photonic crystal fiber for dispersion compensation. *Appl. Opt.* **47**, 5190–5196 (2008). <https://doi.org/10.1364/AO.47.005190>

Statements and Declarations

Author contributions Zhenfan Zhou performed the data processing and analysis, prepared and optimized the figures, and wrote the original draft of the manuscript. Wanting Shao developed the theoretical framework and numerical model underlying this study and performed the numerical simulations using COMSOL Multiphysics. Fuxiao Ma participated in the discussion and interpretation of the results and contributed to the critical review and language editing of the manuscript. Peili Li and Weihua Shi supervised and guided the research and contributed to the critical review and revision of the manuscript. All authors read and approved the final manuscript.

Funding This work was supported by the National Natural Science Foundation of China (Grant No. 61571237).

Data availability The datasets generated or analyzed during the current study are available from the corresponding author on reasonable request.

Conflict of interest The authors declare no Conflict of interest.