Design of a broadband dispersion compensated ultra-high nonlinear photonic crystal fiber

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Abstract

A photonic crystal fiber (PCF) with four circular rings of air holes expanded toward the cladding region is proposed. Four circular tiny air hole rings have been used between the air holes in a regular circular PCF to achieve low dispersion and confinement loss. Additionally, the core region is perforated with a rectangular-shaped hole filled with an extremely nonlinear material, gallium phosphide, to achieve the desired level of nonlinearity. We achieved extremely high nonlinearity and birefringence values of 4.6104 W\(^{-1}\) km\(^{-1}\) and 0.078 at the 1.55 µm telecommunication window by doing so. Further, we observed the structure with varying pitch (Λ) values and found a significant reduction in dispersion and confinement loss, as well as a decrease in effective material loss. Thus, at 1.55 µm, an ultra-high negative dispersion of \(-8000\) ps/nm km is achieved, particularly with Λ = 1.8 µm, along with extremely low confinement and material losses of 10\(^{-9}\) dB/km and 0.017 cm\(^{-1}\), respectively. Similarly, other critical parameters such as the power fraction, numerical aperture, and effective area have been examined. Hence, owing to these enhanced optical properties, the proposed PCF is capable of effectively compensating for dispersion, generating supercontinuum, and maintaining polarization.

Keywords Birefringence · Confinement loss · Dispersion · Effective area · Nonlinearity · Photonic crystal fiber
1 Introduction

Photonic crystal fiber (PCF) is a rapidly growing research area in the optical field due to its advantages over simple optical fiber like higher birefringence values, large nonlinearity, and low loss (Yang et al. 2015; Luke et al. 2016; Zhao et al. 2017; Singh and Prajapati 2022). PCF has numerous applications, including polarization-maintaining fiber, supercontinuum triggering, and biomedical fields (Wu et al. 2016; Dudley et al. 2006; Sultana et al. 2018a). PCF finds its extraordinary virtues due to the presence of micro-structured circular air holes inside the cladding section that are spread along the whole fiber length (Bjarklev et al. 2003). In PCF, there are mainly two guiding mechanisms are existing. Among these two mechanisms, the first, total internal reflection (TIR), is responsible for guiding the light rays travelling inside the core by maintaining the higher value of core RI as compared to cladding (Upadhyay et al. 2020). Second, light is guided in a photonic bandgap (PBG) fiber by a band gap effect in a core with a lower RI than its cladding (Upadhyay et al. 2020). In both types of propagation characteristics of PCF, the core and cladding refractive index differences must be maintained with the design of recurring micro structured holes. Contrary to conventional fiber, the optical characteristics of a PCF like birefringence, nonlinearity, dispersion, and losses are easily controlled with the design versatility of micro-structured holes (Rahaman et al. 2020). PCF properties can also be controlled with air hole diameter, pitch size, lattice design pattern, perforated core, doping of the core, and the used background material (De et al. 2017). Among all the optical properties, dispersion, birefringence, and nonlinearity are the major properties of a PCF that are required for different applications. Dispersion compensation can be achieved using PCF with large negative dispersion compensation (Amin and Faisal 2016). High birefringence is required for fiber polarization maintenance, temperature sensing, and optical communication (Amin and Faisal 2016; Liu et al. 2013; Al-Qaisi and Akkin 2010). Birefringence of order $10^{-2}$ can be achieved by designing the asymmetrical core with non-circular air holes and by using variable air holes (Yang et al. 2015; Hansen et al. 2001; Habib and Khandker 2015). However, the birefringence is limited to this value due to the minimum RI difference inside the core and cladding, which both have silica as background material. Furthermore, high nonlinearity is required for the generation of supercontinuums and the contraction of nonlinear pulses (Pandey et al. 2021a; Sultana et al. 2018b). In order to achieve this, one has to design the fiber in such a manner that the effective area of core mode light is confiscated in a small core area. The nonlinearity of the fiber having silica as background material is very low (maximum of up to $100 \ W^{-1} \ km^{-1}$). It is mainly due to its low nonlinear coefficient value (i.e., $2.1 \times 10^{-20} \ m^2/W$) (Anas et al. 2018). Hence, either silica should be doped with foreign elements or a high nonlinear RI material can be used in order to increase the nonlinear coefficient (Anas et al. 2018; Hasan et al. 2014).

Researchers showed that high nonlinearity as well as birefringence can be obtained with the use of nanoscale tiny holes doped with high nonlinear RI material in the core. In this connection, nowadays, materials such as gallium phosphide (GaP), arsenic trisulfide (As$_2$S$_3$), silicon nitride (Si$_7$N$_3$), and carbon disulfide (CS$_2$), which have high nonlinear RIs have been doped with silica in order to achieve a high nonlinear coefficient value of a PCF. Among these materials, GaP is mostly preferred due to its high nonlinear RI ($6.6 \times 10^{-18} \ W^{-1} \ m^{-1}$). In addition, it is a material with an indirect bandgap that allows more light energy to pass through above a wavelength of 0.6 µm (Harris 1998). This means that it allows more light energy to pass through than SiO$_2$ above this wavelength. It also has low absorption and extinction coefficients below the photon bandgap energy of less than
1 eV, which means that it has less loss in the near infrared spectrum (Akinlami and Olatunji 2016). Therefore, GaP maintains exceptional optical transmission properties. Amin and Faisal (2016) proposed GaP filled nanoscale slots in the core of spirally structured air hole cladding PCF and achieved nonlinearity of 104 W⁻¹ km⁻¹. Likewise, As₂S₃ core doped PCF with dual cladding was coined by Zhang et al. and they obtained high birefringence and nonlinearity of 0.25 and 3.8 × 10⁴ W⁻¹ km⁻¹, respectively (Akinlami and Olatunji 2016; Zhang et al. 2018). Paul et al. (2018a) showed that a numerical aperture (NA) of 0.852 and nonlinearity of 4.72 × 10⁻⁴ W⁻¹ km⁻¹ can be obtained with an elliptical core quasi-PCF. Again, Paul and Ahmed (2019) proposed a hexagonal cladding PCF with an elliptical core filled with highly nonlinear RI material (Si₇N₃) and achieved nonlinearity of 4.8 × 10⁴ W⁻¹ km⁻¹ and NA of 0.85 at 1.0 μm. However, they have not discussed the dispersion profile of the proposed structure, as it is one of the most dominant performance parameters of the PCF.

In this manuscript, a highly doped four-layer structured circular PCF is presented in which the cladding region is densely filled with circular tiny and large air holes of diameter d/4 and d, respectively. A rectangular-shaped slot of width 2.2 μm and a height 0.66 μm has been deliberately perforated in the Centre of the fiber core. In order to achieve higher nonlinearity and improve birefringence, this section is loaded with a very high nonlinear material GaP. Therefore, the maximum obtained nonlinearity and birefringence at 1.55 μm are 4.6 × 10⁴ W⁻¹ km⁻¹ and 0.078, respectively. Apart from this, when the proposed model is analyzed with three different pitch (λ) values that are λ = 1.8 μm, 2.0 μm, and 2.2 μm, extreme reductions in propagation loss, effective material loss (EML), and dispersion have been observed. Even so, the dispersion becomes negative in the broad wavelength range of 1.3–2.2 μm (including the telecommunication window). Further, an in-depth discussion regarding other concerning optical parameters of the propounded model has been included in the manuscript.

2 Structure geometry and design analysis

PCF’s optical properties can be determined with the help of its various design parameters, like hole diameter, pitch value, and air hole’s angular position with respect to the core nucleus. The geometrical orientation of the propounded PCF is given in Fig. 1. Here the fiber center is symmetrically arranged with four circular layers of ring around it. Each layer

![Fig. 1 The 2D view of the proposed PCF with zoomed centre core section](image-url)
consists of air holes of diameter \(d\). And these holes are inserted in such a way that they form a circular lattice. The radius of each circular ring can be approximated by \(R_m = 3 \times \Lambda\). Here, \(m\) denotes the number of rings (i.e., 1, 2, 3 and 4) and \(\Lambda\) denotes distance between the consecutive circular holes, and its value is taken as 2.1 \(\mu\text{m}\).

Further, the cladding section is highly doped with circular tiny air holes (diameter \(d/4\)) in order to confirm the low dispersion and propagation loss. These air holes are also arranged into four circular rings, the radius of each ring being calculated using \(S_m = (m + 1/2) \times \Lambda\). The middle region of the core is perforated with a rectangular slot of 2.2 \(\mu\text{m}\) and a height of 0.66 \(\mu\text{m}\), respectively. And, this rectangular bar is filled with an extremely high nonlinear material, gallium phosphide (GaP). In addition, an artificial layer called PML has been set all around the outer boundary of the PCF. This layer helps to absorb the redundant light energy scattered outside of the core region. Therefore, it improves the computational reliability of the proposed model.

With the rapid advancement in technology, many fabrication techniques have been developed for fiber designing. Therefore, the propounded structure can be fabricated with the preforms technique, die-cast process, 3-D printing, stack and draw, extrusion, and sol–gel method (Pandey et al. 2020, 2021b; Faruk et al. 2020; Sang et al. 2005; Naghizade and Mohammadi 2019; Cook et al. 2015; Yakasai et al. 2019).

Table 1 depicts the sizes of structural entities like pitch value, diameter of the air hole and outer circle, height and width of the rectangular slot, taken for the analysis of the proposed PCF. Deliberately, the operating wavelength has been taken as 1.55 \(\mu\text{m}\). It is because our entire analysis is mainly focused on this telecommunication wavelength.

### 3 Numerical procedure and inspection

The COMSOL Multiphysics, utilised for numerical investigation for proper portraiture of the proposed structure. The Maxwell equation is solved with the help of FEM in order to get the modal field distribution and effective mode indices calculation of the structure. PML is applied as an outer layer to the structure to absorb the scattering and reflection losses (Sultana et al. 2018b). A complex solution of Maxwell’s equation is used to perform modal scanning over the entire cross-sectional area of the propounded PCF. Furthermore, the whole cross section area is subdivided into triangular subspaces. Finally, using FEM, the Maxwell’s equations (Upadhyay et al. 2020) are solved for these subspaces with a solution as given in Eq. 1.

| Table 1 | Design parameter description of the proposed model |
|---------|-----------------------------------------------------|
| Design parameter | Abbreviation | Value |
| Pitch | \(p\) | 1.8–2.2 [\(\mu\text{m}\)] |
| Diameter of air hole | \(d\) | 0.69–0.77 [\(\mu\text{m}\)] |
| Diameter of outer circle | \(D\) | 20 [\(\mu\text{m}\)] |
| Width of rectangle | \(W\) | 2.2 [\(\mu\text{m}\)] |
| Height of rectangle | \(H\) | 0.66 [\(\mu\text{m}\)] |
| Wavelength | \(w\) | 1.55 [\(\mu\text{m}\)] |
| Frequency | \(f\) | 193.54 THz |
\[(M - N \times n_{\text{eff}})(E) = 0\]  
\[(1)\]

where \(M\) and \(N\) denote the conventional matrices for absorbing and inverse PML, \(n_{\text{eff}}\) represents the effective RI, \(E\) depicts the electric field of the structure.

The waveguide dispersion (Rahaman et al. 2020) can be assessed with the help of \(n_{\text{eff}}\) using Eq. 2, which is given below.

\[D(\text{ps/nm km}) = -\frac{\lambda}{C} \frac{d^2 g(n_{\text{eff}})}{d\lambda^2}\]  
\[(2)\]

where \(\lambda\) displays the wavelength under consideration, \(c\) shows the speed of light in vacuum, and \(\Re(n_{\text{eff}})\) represents real part effective RI.

Generally, the value of \(n_{\text{eff}}\) is different for the \(x\) and \(y\) components of the electric field. The larger the asymmetric fiber core, the greater the birefringence can be obtained. The birefringence (De et al. 2017) of the structure can be calculated as follows:

\[B = \left|\left(n_{\text{eff}}^x - n_{\text{eff}}^y\right)\right|\]  
\[(3)\]

Confinement loss (Amin and Faisal 2016) is a measure of modal light diversion from the core to the cladding and can be evaluated as mentioned in Eq. 4.

\[\text{CL(dB/m)} = 8.686 \times \frac{2\pi}{\lambda} \times \Im(n_{\text{eff}})\]  
\[(4)\]

where \(\Im(n_{\text{eff}})\) symbolises the imaginary part of effective refractive index (ERI).

The occupancy area of core mode light is actually the effective area. The effective area of a fiber should be required very small as possible for a focused output. From the numerical investigation, one can predict the effective area (Yang et al. 2015) of mode light for the proposed structure using the underneath formula.

\[A_{\text{eff}}(\mu m^2) = \frac{\int_{-\infty}^{+\infty} |E|^2 dxdy}{\int_{-\infty}^{+\infty} |E|^4 dxdy}\]  
\[(5)\]

Here, \(E\) is field distribution of \(x\)-and \(y\)-polarized mode.

The nonlinear properties of the fiber such as solitons generation, four wave mixing, and supercontinuum generation, are feasible for high nonlinear coefficient PCF. It has an inverse relationship with \(A_{\text{eff}}\). The numeric value of the nonlinear coefficient (Dudley et al. 2006) can be evaluated with Eq. 6.

\[\gamma (W^{-1}\text{Km}^{-1}) = \left(\frac{2\pi}{\lambda}\right) \left(\frac{n_{\text{RI}}}{A_{\text{eff}}}\right)\]  
\[(6)\]

Here \(n_{\text{RI}}\) is the nonlinear refractive index of GaP (i.e., \(6.6 \times 10^{-18} \text{ W}^{-1} \text{ m}^{-1}\)).

The PCF experiences loss from the absorbance of used background material. Normally, the used dielectric materials are not transparent in the wavelength range (0.8–2.8 \(\mu\)m). Such a type of light absorption loss normally represents effective material loss (EML). And the proposed structure’s goal is to reduce this type of loss as well (Sultana et al. 2018b). Therefore, it can be estimated with the formula given in Eq. 7.
\[ \alpha_{\text{EML}} \left( \text{cm}^{-1} \right) = \left( \frac{\varepsilon_0}{\mu_0} \right) \left( \frac{\int_{\text{mt}} n \alpha_{\text{mt}} |E_z^2| \, dA}{\int_{\text{St}} S_Z \, dA} \right) \]  

(7)

where \( n \) denotes RI of background material, \( \alpha_{\text{mt}} \) shows bulk absorption loss, \( \varepsilon_0 \) and \( \mu_0 \) represent free space permittivity and permeability, \( S_Z \) depicts the pointing vector along \( z \)-direction, which is also the direction of wave propagation, and it can be evaluated as \( S_Z = \frac{1}{2} (E_z \times H^*_z) \) in which \( E_z \) describes the electric field and \( H^*_z \) is complex conjugate of the magnetic field along the \( z \)-direction.

Normally, the fiber is used for optical power transmission. The transmitted power (Paul and Ahmed 2019), which is similar to the power carried in the core of the proposed PCF structure, can be calculated using Eq. 8.

\[ \text{PF} \left( \% \right) = \frac{\int_{\text{R}} S_Z \, dA}{\int_{\text{St}} S_Z \, dA} \times 100 \]  

(8)

Here, PF denotes the power fraction, the \( \int_{\text{R}} \) is integration for the region of interest that is core, claddings, and background material, and \( \int_{\text{St}} \) is integration over the defined structural area of the propounded PCF.

How much power a PCF can congregate in its core is denoted by the numerical aperture (NA) (Paul and Ahmed 2019) of this proposed structure, and this is associated with the effective area of core light. This unit less optical parameter can be evaluated using Eq. 9.

\[ \text{NA} = \frac{1}{\left[ 1 + \frac{\pi \text{A}_{\text{eff}}}{\lambda^2} \right]^{1/2}} \]  

(9)

### 4 Results and discussions

Here, different properties of the suggested PCF are birefringence, nonlinearity, numerical aperture (NA), and, power fraction are analysed against different values of wavelength under consideration with vibrational core pitch values (\( \Lambda \)).

Figure 2 represents the electrical field distribution inside the core of a propounded PCF at a communication wavelength (i.e., 1.55 \( \mu \)m). Parallel polarization (x-pol) and perpendicular (y-pol) polarization the electric field distribution in the core mode is

![Fig. 2](image_url)  

Fig. 2 a and b represents the field distributions of x and y polarized mode at 1.55 \( \mu \)m wavelength
given in Fig. 2a and b. It is also worth mentioning that the core mode light is perfectly trapped within the GaP doped rectangular core.

The fiber’s background material has positive dispersion, which can cause a pulse broadening effect. Hence, material dispersion should be compensated for with the help of negative waveguide dispersion in order to get a zero dispersion wavelength (ZDW). From Fig. 3, we can conclude that the waveguide dispersion curve is negative for the communication wavelengths (1.33–1.55 µm). However, ZDW is observed at a 1.2 µm wavelength (there should be two ZDW as per Fig. 3) which is useful for supercontinuum generation at E + S + C bands (Amin and Faisal 2016). It is also seen in Fig. 3 that with the variation in core pitch values of the rectangular slot, the dispersion profile of the proposed structure also changes. And, the maximum negative dispersion of $-8000$ ps/nm/km is achieved at 1.55 µm for a core pitch value of 1.8 µm. Hence, with the achieved optimum results, we can easily say that the proposed design can also be worked as a dispersion compensating fiber.

For sensing applications of the PCF, it is required that it have higher birefringence, and it can be enhanced by introducing an asymmetric structure in the core region. Figure 4 shows the plot of birefringence versus operating wavelength for numerous core pitch values. It can be observed from Fig. 4 that birefringence reduces with increasing core pitch values as increasing core pitch deforms the symmetry of the core. Therefore,
the maximum calculated value of the birefringence is 0.078, obtained at 1.55 µm for Λ = 1.8 µm.

Figure 5 illustrates the confinement loss with respect to the wavelength under consideration. The deviation of the light from the core of the fiber to the cladding is termed as loss which arises in the structure due to a possible small RI difference between the core and the cladding. From Fig. 5, it is seen that propagation loss increases with wavelength monotonously. With the increase in core pitch, the RI difference decreases between the core and cladding, which effectively shoots the loss high. The proposed PCF shows a very minimal loss of 10^{-9} dB/km at 1.55 µm for Λ = 1.8 µm. Such a small loss value makes the PCF viable for waveguide transmission.

Figure 6 illustrates the graph between effective area and wavelength. The effective area, in general, describes the confinement area of the core mode propagating light. Core mode generally shows a lower incurred loss. According to Fig. 7, A_{eff} increases linearly with operating wavelength and has a linear relationship with core pitch value. However, the minimum observed value of A_{eff} is equal to 0.58 µm² at 1.55 µm for Λ = 1.8 µm.

Fig. 5  The confinement loss for proposed PCF structure with respect to wavelength

Fig. 6  The effective area (A_{eff}) for proposed PCF structure with respect to wavelength
Fig. 7 The nonlinearity for proposed PCF structure with respect to wavelength

The nonlinearity of the recommended structure is inversely proportional to the effective area of the core mode light. We can see in Fig. 7 that as the wavelength value decreases, nonlinearity increases. A similar nonlinear response can be observed with core pitch, indicating that nonlinearity decreases as core pitch values increase. Therefore, the maximum value of the nonlinear coefficient calculated at 1.55 µm is $4.6 \times 10^4$ W$^{-1}$ km$^{-1}$ for $\Lambda = 1.8$ µm. This ensures that the propounded structure can be used in four wave mixing, supercontinuum generation, and also in temperature sensing.

Figure 8 shows a plot of EML with a change in wavelength. Generally, the nature of EML is opposite to that of the core power fraction curve of the suggested design, as shown in Fig. 8. The EML increases with an increase in core pitch values because the RI difference between the core and cladding decreases with an increase in $\Lambda$. Therefore, an increase in $\Lambda$ increases loss of the proposed structure. However, we achieved a minimum EML 0.017 cm$^{-1}$ for $\Lambda = 1.8$ µm at 1.55 µm.

Figure 9 displays the change in the nature of the core power fraction curve against the change in operating wavelength. The power fraction curve shows a downward curvature with wavelength. It is also found that the core power fraction is decreasing with an increase in core pitch values. The maximum achieved core power fraction is 38.5%
in between the communication wavelengths (1.33–1.55 µm). Such a high value of power fraction ensures low loss in the core mode of light propagation. Hence, the proposed PCF could be a potential candidate for long-distance low loss propagation of light.

Figure 10 describes the variation in numerical aperture (NA) with operating wavelength for different core pitch values. From Fig. 10, it can be seen that the NA decreases with an increase in core pitch value (Λ). The NA response increases up to the wavelength of 1.8 µm and then decreases afterwards. From Fig. 10, the numeric value of NA observed at 1.55 µm is 0.88 for Λ = 1.8 µm. Because of the high NA, the proposed structure is being used in biomedical imaging applications (Hassan et al. 2020).

Table 2 displays a comparative study between the performance parameters of the suggested GaP filled PCF with those of other PCFs for the telecommunication wavelength of 1.55 µm. All the optical parameters (especially dispersion) of our proposed PCF are much improved when compared to the other recently reported articles cited in the above table. Moreover, the analysis of an additional parameter such as EML has also been done in our work, which is not demonstrated in the other published works mentioned in Table 2.
Table 2  Comparison between the performance parameter of proposed PCF with other PCFs at 1.55 µm

| Refs                        | Material used | Dispersion ps/ (nm km) | $L_v$ (dB/km) | $\gamma$ (W$^{-1}$ km$^{-1}$) | NA | B | EML (cm$^{-1}$) |
|-----------------------------|---------------|------------------------|---------------|-------------------------------|----|---|----------------|
| Paul et al. (2018a)         | Chalcogenide  | –                      | $2.08 \times 10^{-5}$ | $4.58 \times 10^{4}$     | 0.846 | – | –               |
| Paul and Ahmed (2019)       | Si$_3$N$_7$   | –                      | 0.25          | $4.48 \times 10^{4}$     | 0.834 | – | –               |
| Monfared and Ponomarenko (2019) | CS$_2$    | 0.00007                 | 0.3           | $7.9 \times 10^{3}$     | –   | – | –               |
| Anas et al. (2018)          | GaP           | –                      | $10^{-8}$     | $9 \times 10^{4}$     | 0.83 | 0.25 | –               |
| Paul et al. (2018b)         | GaP           | –                      | –             | $3.57 \times 10^{4}$     | 0.68 | – | –               |
| Chen et al. (2020)          | As$_2$S$_3$   | –                      | –             | –                            | –   | $10^{-4}$ | –               |
| Sharafali and Nithyanandan (2020) | CCl$_4$ | 70                      | –             | 0.0937                      | –   | – | –               |
| Pandey et al. (2021c)       | GaP           | $-6586$                 | –             | 39.612                      | 0.875 | – | –               |
| Proposed                    | GaP           | $-8000$                 | $10^{-9}$     | $4.6 \times 10^{4}$     | 0.88 | 0.078 | 0.017           |
5 Conclusion

In this manuscript, we have studied the behavioral change in optical parameters with the change in wavelength for various core pitch values. The optimized values of all optical parameters are obtained for the core pitch (Λ) value of 1.8 µm. From the analysis, we conclude that the proposed structure is highly commendable to be used in polarization sustaining devices and in four wave mixing because it shows high birefringence of 0.078 and high nonlinearity of $4.6 \times 10^4$ W$^{-1}$ km$^{-1}$ at 1.55 µm. The recommended PCF also has a very low confinement loss of order 10–9 dB/m, a low EML of 0.017 cm$^{-1}$, and a very large NA of 0.88, making it suitable for use in bio-medical applications. Apart from this, the structure also demonstrated high negative dispersion for the whole communication wavelength range (1.33–1.55 µm) and surges as high as −8000 ps/nm km at 1.55 µm. Thus, it can be said that the propounded PCF is beneficial to be used in dispersion shifted fiber, broad band dispersion compensated fiber, fiber waveguide sensors, and fluidic applications of fiber.

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Declaration

Conflict of interest The authors declare no conflict of interest.

References

Akinlami, J.O., Olatunji, O.A.: Optical properties of gallium phosphide (GaP). J. Nat. Sci. Eng. Technol. 13, 18–27 (2016)
Al-Qaisi, M.K., Akkin, T.: Swept-source polarization-sensitive optical coherence tomography based on polarization-maintaining fiber. Opt. Express 18(4), 3392–3403 (2010)
Amin, M.N., Faisal, M.: Highly nonlinear polarization-maintaining photonic crystal fiber with nanoscale GaP strips. Appl. Opt. 55(35), 10030–10037 (2016)
Anas, M.T., Asaduzzaman, S., Ahmed, K., Bhuiyan, T.: Investigation of highly birefringent and highly nonlinear Hexa Sectored PCF with low confinement loss. Results Phys. 11, 1039–1043 (2018)
Bjarklev, A., Broeng, J., Bjarklev, A.S.: Photonic Crystal Fibers. Kulawer Academic Press, Boston (2003)
Chen, N., Zhang, X., Lu, X., Zhang, Z., Mu, Z., Chang, M.: Numerical investigation of a short polarization beam splitter based on dual-core photonic crystal fiber with As2S3 layer. Micromachines 11(7), 706–720 (2020)
Cook, K., Canning, J., Leon-Saval, S., Reid, Z., Hossain, M.A., Comatti, J.-E., Luo, Y., Peng, G.-D.: Air-structured optical fiber drawn from a 3D-printed preform. Opt. Lett. 40(17), 3966–3969 (2015)
De, M., Gangwar, R.K., Singh, V.K.: Designing of highly birefringence, dispersion shifted decagonal photonic crystal fiber with low confinement loss. Photon. Nanostruct. Fundam. Appl. 26, 15–23 (2017)
Dudley, J.M., Genty, G., Coen, S.: Supercontinuum generation in photonic crystal fiber. Rev. Mod. Phys. 78(4), 1135–1184 (2006)
Faruk, M., Khan, N.T., Biswas, S.K.: Highly nonlinear bored core hexagonal photonic crystal fiber (BC-HPCF) with ultra-high negative dispersion for fiber optic transmission system. Front. Optoelectron. 13(4), 433–440 (2020)
Habib, M.S., Khandker, E.: Highly birefringent photonic crystal fiber with ultra-flattened negative dispersion over S+ C+ L+ U bands. Appl. Opt. 54(10), 2786–2789 (2015)
Hansen, T.P., Broeng, J., Libori, S.E.B., Knudsen, E., Bjarklev, A., Jensen, J.R., Simonsen, H.: Highly birefringent index-guiding photonic crystal fibers. IEEE Photon. Technol. Lett. 13(6), 588–590 (2001)
Harris, D.C.: Durable 3–5 µm transmitting infrared window materials. Infrared Phys. Technol. 39, 185–201 (1998)
Hasan, M.I., Habib, M.S., Habib, M.S., Razzak, S.M.A.: Highly nonlinear and highly birefringent dispersion compensating photonic crystal fiber. Opt. Fiber Technol. 20(1), 32–38 (2014)
Hassan, M.M., Kabir, M.A., Hassain, M.N., Nguyen, T.K., Paul, B.K., Ahmed, K., Dhasarathan, V.: Numerical analysis of circular core shaped photonic crystal fiber for orbital angular momentum with efficient transmission. Appl. Phys. B 126(9), 1–8 (2020)
Liu, Z., Wu, C., Tse, M.-L.V., Lu, C., Tam, H.-Y.: Ultrahigh birefringence index-guiding photonic crystal fiber and its application for pressure and temperature discrimination. Opt. Lett. 38(9), 1385–1387 (2013)
Luke, S., Sudheer, S.K., Pillai, V.P.M.: Tellurite based circular photonic crystal fiber with high nonlinearity and low confinement loss. Opt. Mater. 88, 406–411 (2019)
Naghizade, S., Mohammadi, S.: Design and engineering of dispersion and loss in photonic crystal fiber 1×4 power splitter (PCFPS) based on hole size alteration and optofluidic infiltration. Opt. Quantum Electron. 51(1), 1–14 (2019)
Pandey, S.K., Prajapati, Y.K., Maurya, J.B.: Design of simple circular photonic crystal fiber having high negative dispersion and ultra-low confinement loss. Results Opt. 1, 100024–100029 (2020)
Pandey, S.K., Singh, S., Prajapati, Y.K.: A novel design with an ultra-flattened dispersion and low confinement loss by varying tiny air-hole concentration at core and cladding. Opt. Rev. 28, 304–313 (2021a)
Pandey, S.K., Maurya, J.B., Verma, R.N., Prajapati, Y.K.: Multimode hexagonal photonic crystal fiber for extremely negative chromatic dispersion and low confinement loss. Opt. Quantum Electron. 53(2), 1–12 (2021b)
Pandey, S.K., Maurya, J.B., Prajapati, Y.K.: Photonic crystal fiber with high nonlinearity and extremely negative dispersion. Opt. Quantum Electron. 53(12), 1–13 (2021c)
Paul, B.K., Ahmed, K.: Si₃N₄ material filled novel heptagonal photonic crystal fiber for laser applications. Ceram. Int. 45(1), 1215–1218 (2019)
Paul, B.K., Khalek, M.A., Chakma, S., Ahmed, K.: Chalcogenide embedded quasi photonic crystal fiber for nonlinear optical applications. Ceram. Int. 44(15), 18955–18959 (2018a)
Paul, B.K., Moctader, M.G., Ahmed, K., Khalek, M.A.: Nanoscale GaP strips based photonic crystal fiber with high nonlinearity and high numerical aperture for laser applications. Results Phys. 10, 374–378 (2018b)
Rahaman, M.E., Hassain, M.M., Mondal, H.S., Saha, R., Muntaseer, A.S.: Theoretical analysis of large negative dispersion photonic crystal fiber with small confinement loss. Appl. Opt. 59(28), 8925–8931 (2020)
Sang, X., Chu, P.L., Yu, C.: Applications of nonlinear effects in highly nonlinear photonic crystal fiber to optical communications. Opt. Quantum Electron. 37(10), 965–994 (2005)
Sharafali, A., Nithyanandan, K.: A theoretical study on the supercontinuum generation in a novel suspended liquid core photonic crystal fiber. Appl. Phys. B 126(4), 1–12 (2020)
Singh, S., Prajapati, Y.K.: Antimonene-gold based twin-core SPR sensor with a side-polished semi-arc groove dual sensing channel: an investigation with 2D material. Opt. Quantum Electron. 54(114), 1–14 (2022)
Sultana, J., Islam, M.S., Islam, M.R., Abbott, D.: High numerical aperture, highly birefringent novel photonic crystal fibre for medical imaging applications. Electron. Lett. 54(2), 61–62 (2018a)
Sultana, J., Islam, M.S., Faisal, M., Islam, M.R., Ng, B.W.-H., Ebendorff-Heidepriem, H., Abbott, D.: Highly birefringent elliptical core photonic crystal fiber for terahertz application. Opt. Commun. 407, 92–96 (2018b)
Upadhyay, A., Singh, S., Prajapati, Y.K., Tripathi, R.: Numerical analysis of large negative dispersion and highly birefringent photonic crystal fiber. Optik 218, 164997–165008 (2020)
Wu, Z., Shi, Z., Xia, H., Zhou, X., Deng, Q., Huang, J., Jiang, X., Wu, W.: Design of highly birefringent and low-loss oligoporous-core THz photonic crystal fiber with single circular air-hole unit. IEEE Photon. J. 8(6), 1–11 (2016)
Yakasai, I.K., Abas, P.E., Ali, S., Begum, F.: Modelling and simulation of a porous core photonic crystal fibre for terahertz wave propagation. Opt. Quantum Electron. 51(4), 1–16 (2019)
Yang, T., Wang, E., Jiang, H., Hu, Z., Xie, K.: High birefringence photonic crystal fiber with high nonlinearity and low confinement loss. Opt. Express 23(7), 8329–8337 (2015)
Zhang, X., He, M., Chang, M., Chen, H., Chen, N., Qi, N., Yuan, M., Qin, X.: Dual-cladding high-birefringence and high-nonlinearity photonic crystal fiber with As₂S₃ core. Opt. Commun. 410, 396–402 (2018)
Zhao, T., Lian, Z., Benson, T., Wang, X., Zhang, W., Lou, S.: Highly-nonlinear polarization-maintaining As$_2$Se$_3$-based photonic quasi-crystal fiber for supercontinuum generation. Opt. Mater. 73, 343–349 (2017)

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