PCF Design With Extremely High Nonlinearity And Extremely Negative Dispersion

Sanat Kumar Pandey

Government Polytechnic

J.B. Maurya

NIT Patna: National Institute of Technology Patna

Yogendra Kumar Prajapati (✉ yogendrapra@gmail.com)

MNNIT, Allahabad <https://orcid.org/0000-0002-6752-5667>

Short Report

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PCF design with extremely high nonlinearity and extremely negative dispersion

SANAT KUMAR PANDEY¹, J.B. MAURYA², YOGENDRA KUMAR PRAJAPATI³

¹ Department of Electronics Engineering, Government Polytechnic, Lucknow, UP 226016, India

²Department of Electronics and Communication Engineering, National Institute of Technology, Patna, Bihar, 800005, India

³Department of Electronics and Communication Engineering, Motilal Nehru National Institute of Technology, Allahabad, UP 211004, India

* yogendrapra@gmail.com, yogendrapra@mnnit.ac.in

Abstract: In this manuscript we designed a circular photonic crystal fiber (PCF) having three rectangular holes filled with GaP in the core region, three air hole rings and one annular air ring in cladding region. We found highest negative dispersion for the 1.8 μm pitch alongwith very low confinement loss at wavelength 1.55 μm . This designed PCF offers high nonlinearity (39612 $\text{W}^{-1}\text{km}^{-1}$) and high negative dispersion (-6586 $\text{ps nm}^{-1}\text{km}^{-1}$) alongwith zero confinement loss at 1.55 μm wavelength. We also compared the proposed PCF with the previously published PCF structure and found that the nonlinearity and negative dispersion of the designed PCF are very high in comparison to circular air hole based PCF. Another performance parameters viz. birefringence, numerical aperture, effective area and effective material loss are also analyzed.

Keywords: Communication, confinement loss, dispersion, nonlinearity, photonic crystal fiber

1. Introduction

Optical fiber communication channel provides more flexibility and reliability than the free space communication medium and play a role of main pillar of the modern telecommunication. As compare to photonic crystal fibers conventional fibers have less structural flexibility. Due to this, conventional optical fiber have limitation in its versatile uses as in high power mechanism[10], nonlinear fiber optics[11], spectroscopy [12], metrology, sensing applications[13], super-continuum generation[14], optical coherence tomography[15], quantum dots[16], etc. In contrast, photonic crystal fiber (PCF) has compact nature, robustness, less environmental effects, light-weight, and minimum cost makes PCF based devices more popular which easily can work in enormous environmental conditions [17]. PCF is an advance fiber technology to guide the light wave effectively through it. Generally, the light, an electromagnetic wave, can propagate through PCF by obeying two principles: first through low refractive index medium surrounded by high refractive index medium, and second through high refractive index medium surrounded by low refractive medium [9]. In PCFs a high refractive index material (silica) is used as background material which is doped in periodic manner with the low refractive index material (air holes) [8]. The optical characteristics of PCF can be changed by altering its geometry like shape, size, filling material, and pitch of holes. PCF has many advantages over the traditional fiber e.g., high nonlinearity and negative dispersion with very low confinement loss [1-3], high confinement field, tunable birefringence [4], high effective area [5], polarization-maintaining capability [6-7], high birefringence, and high effective area.

PCF can be used in telecommunication, sensing and laser technology due to its high nonlinearity. To achieving high nonlinearity in photonic crystal fibers it is needed to maintain the small effective mode area. The nonlinearity parameter can be improved by using higher refractive index value material at core region [19]. Photonic crystal fibers (PCF) fabrication is possible by periodically inserting array of microscopic air-holes in symmetrical manner across complete length of fiber inside the low-loss periodic dielectric material. Here, light is guided not only by refractive index differences it also guided with structural modifications [20].

To meliorate operational parameters, to improve handling compatibility and reduce the optical losses and manufacturing cost, many optical fiber crystals structures are being designed and fabricated [21]. In this sequence, a

simple hybrid structure called photonic crystal fiber was fabricated in 1999 by J. Broeng et al. [22]. A PCF having low dispersion and low confinement loss with both negative and positive dispersion property in visible spectrum can be designed by varying the dimension, structure, and arrangement of microscopic air-holes in silica dielectric [23]. Dispersion compensation is essential in long distance fiber communication. Significant effort has been carried out by the researcher around the world since last few years to reduce the dispersion and flattened the curve for dispersion compensation. Razzak et al. suggested a nonlinear photonic crystal fiber (HNL-PCF) for the telecommunication window [24]. They obtained high nonlinearity coefficient of $27 \text{ W}^{-1}\text{km}^{-1}$ at $1.55\mu\text{m}$ wavelength and flattened dispersion of $0 \pm 0.5 \text{ ps}/(\text{nm.km})$ in a range of $1.46\mu\text{m}$ to $1.66\mu\text{m}$ wavelength with low confinement loss 0.06db/km in the overall band of interest. In 2014 and 2016, Hasan et al. presented PCFs structures which have octagonal structure with elliptical core and equiangular spiral structure and obtained high negative dispersion as $-544.7 \text{ ps}/(\text{nm.km})$ and $-526.99 \text{ ps}/(\text{nm.km})$ [25]. In 2016 Hasan et al. proposed another octagonal PCF with single mode which has high birefringence and ultra-flattened high negative dispersion $-608.93 \text{ ps}/(\text{nm.km})$ with dispersion variation of $-12.7 \text{ ps}/(\text{nm.km})$ in the range of $1.46\text{--}1.625\mu\text{m}$ wavelength and high birefringence 1.81×10^{-2} at optimal design parameter and $1.55\mu\text{m}$ wavelength [26]. In 2018, Y.K. Prajapati et al. proposed a hexagonal PCF structure doped with germanium for wideband supercontinuum generation, which has nonlinearity coefficient value $0.0166 \text{ W}^{-1}\text{m}^{-1}$ and the flattened dispersion smaller than the $-11.8 \text{ ps}/(\text{nm.km})$ at $1.55\mu\text{m}$ [27]. It is seen from the literature review that not all the performance parameters can be improved at once. Different authors have designed different PCF to improve few performance parameters as per the application.

In the presented article, a PCF structure is designed to obtain extremely high nonlinearity and extremely negative dispersion alongwith zero confinement loss by including three rectangular GaP holes in the core region. The proposed PCF is comprised of three air hole rings, one annular air hole ring in cladding region and three rectangular GaP filled holes in the core region.

2. Design and modal realization of the proposed HN-PCF

2.1 Design and geometry

The optical characteristics of PCF can be altered by the geometrical parameters such as distance between two consecutive air-holes (pitch, Λ), diameter of circular air-holes, angular position of circular air-holes and air filling fraction for fabrication. The proposed high nonlinear photonic crystal fiber (HN-PCF) is designed by selecting a circular silica glass material ring of radius $D/2$ (where $D = 10 \times \Lambda$) as shown in Fig. 1. Then, inserting a circular annular air ring of inner radius d and outer radius $1.5 \times d$, where d is diameter of air hole. Cladding region is made with circular rings of air-holes (diameter d), where each ring have radius $R_n = n\Lambda$, where $n=2, 3$, and 4 is ring number and pitch value ($\Lambda=1.8 \mu\text{m}$, $\Lambda=2.0 \mu\text{m}$, and $\Lambda=2.2 \mu\text{m}$). The rotation angle of air-holes on each ring is $Q_n=60^\circ/n$ and the total count of air-hole on each ring is $6n$. We introduce three rectangular shape GaP filled holes in the core region to improve the nonlinearity of the proposed structure. The numerical analysis of designed HN-PCF is performed by using finite element method with the help of COMSOL Multiphysics (5.1).

Fig.1: 2D schematic of the proposed PCF with its enlarged core view.

The proposed PCF has two degrees of freedom, i.e., Λ and wavelength. By selecting proper values of these parameters we can achieve the required dispersion and nonlinearity coefficient with low confinement loss. To measure the above performance parameters for communication application of NH-PCF, we have accomplished modal analysis in the following sections.

2.2 Modal realization and performance parameters

During the simulation, finite element method was employed in the x - y plane and wave was propagating in the z -direction. A perfectly matched layer (PML) was used to minimize the simulation window. Maxwell's equation for structures having PML can be represented as [28];

$$\nabla \times \{[s]^{-1} \nabla \times E - k_0^2 n^2 [s] E\} = 0 \quad (1)$$

Here, s and $[s]^{-1}$ represent the PML matrix and its inverse, respectively. E is electric field, n is refractive index of background material, and $k_0 = 2\pi/\lambda$ is wave number in free space, where λ is operating wavelength. Form (1) we can find modal effective refractive index (n_{eff}) with the help of which we have optimized the various performance parameters of HN-PCF viz. dispersion, confinement loss, birefringence, effective area, numerical aperture, nonlinearity coefficient, effective material loss etc. with respect to operating wavelength.

2.2.1. Dispersion

As we know that an optical source does not only transmit a particular fixed frequency but also transmits a range of frequencies. There is a propagation delay between each frequency component of the transmitted light signal. This results in broadening of transmitting pulses corresponding to different modes. This phenomenon is termed as intermodal dispersion and can be analysed as [29];

$$D(\lambda) = -\frac{\lambda}{c} \frac{d^2 R_{re}(n_{eff})}{d\lambda^2} \quad \frac{ps}{nm.km} \quad (2)$$

Here, $D(\lambda)$ represent total dispersion of HN-PCF which is an algebraic sum off material and waveguide dispersion [30].

$$D(\lambda) = D_m(\lambda) + D_w(\lambda) \quad (3)$$

The $D_m(\lambda)$ of silica glass waveguide is analysed with the Sellmeier equation whereas $D_w(\lambda)$ with the geometrical model index of HN-PCF [31]. Zero net dispersion, i.e. $D(\lambda)=0$ or $D_w(\lambda) = -D_m(\lambda)$ can be achieved by optimizing the structural parameters.

2.2.2. Confinement loss

Generally, light traveling through the PCF should be confined to core region only but it leaks in the radial direction away from the core, i.e., towards the cladding region. This leaked energy is known as confinement loss and can be given as [29];

$$L_c = 8.686 \times k_0 \times \text{Im}(n_{eff}) \text{ dB/m} \quad (4)$$

2.2.3. Birefringence

The mod value of difference between the x -polarised and y -polarised effective refractive indices (ERI) at a particular wavelength is known as birefringence and can be formulated as [32];

$$B = \left| \text{Re} \{ n_{eff}^x - n_{eff}^y \} \right| \quad (5)$$

Here, n_{eff}^x and n_{eff}^y represent the ERI in the x and y direction polarization modes, respectively.

2.2.4. Effective Area

The distribution area of electric field is known as effective area (A_{eff}) of PCF. This signifies the light carrying capacity of PCF without introducing nonlinear effects. It is different for different PCF and depends on structural parameters and operating wavelength. It helps to find out nonlinear phase shift and can be expressed as [34];

$$A_{eff} = \frac{(\iint_{-\infty}^{+\infty} |E|^2 dx dy)^2}{\iint_{-\infty}^{+\infty} |E|^4 dx dy} (\mu m)^2 \quad (6)$$

2.2.5. Numerical aperture (NA)

Numerical aperture (NA) is an optical characteristic of PCF it shows the gathering capability of light into the core region. NA is unit less parameter and it depends on effective area (A_{eff}) of PCF [33];

$$NA = \left[1 + \frac{\pi A_{eff}}{\lambda^2} \right]^{-1/2} \quad (7)$$

2.2.6. Nonlinear coefficient

Highly non-linear PCF is preferred because it reduces effective mode area for better communication. For any PCF, the nonlinearity coefficient (γ) is always inversely proportional to effective area and given as [33];

$$\gamma = \left(\frac{2\pi}{\lambda} \right) \left(\frac{n_2}{A_{eff}} \right) \quad (8)$$

Where, n_2 is the nonlinear refractive index of GaP ($6.5 \times 10^{-18} \text{ m}^2/\text{w}$) filled in the rectangular shape holes bored in core region.

2.2.7. Effective Material Loss

Effective material loss (EML) is an important parameter to analyze the power fraction pattern in core region of PCF. It is inversely proportional to power fraction and can be formulated as [35];

$$\alpha_{EML} = \frac{1}{2} \left(\frac{\epsilon_0}{\mu_0} \right) \left(\frac{\int_{A_m} n \alpha_m |E|^2 dA}{\int_{All} S_z dA} \right) \quad (9)$$

Here, α_{EML} is effective material loss, α_m is material absorption loss, A_m is intended area of the material, E is electric field component associated with that area, n is the material refractive index, ϵ_0 and μ_0 denote the free space permittivity and permeability, respectively. The denominator of (9) i.e., $\int_{All} S_z dA$ represents the entire domain area.

2.3 Fabrication possibility of Proposed HN-PCF

PCF can be fabricated by different fabrication techniques, e.g., sol-gel casting, stack and draw technique, extrusion, ultrasonic drilling, etc. [36-39]. The sol-gel casting technique provides high design flexibility and is generally used in the fabrication of dispersion compensating PCFs [38]. Stack and draw is a cost-effective technique which offers easy control over the shape [36, 37]. However, any of the above techniques can be used to fabricate the proposed HN-PCF due to its simple design structure as compare to previous published PCFs structures [40-41].

3. Results and discussions

The electric field distribution of *x*- polarized and *y*- polarized modes of the proposed HN-PCF with GaP filled rectangular holes in the core region at 1.55 μm , the commercial operating wavelength for optical communication, is shown in Fig. 2a and Fig. 2b, respectively. It can be clearly observed that the field is confined in the core region for both of the polarized modes. The field leakage in the case of *x*-polarized is almost zero whereas a little amount of field is leaking in the case of *y*-polarized mode. This shows that field confinement is better in the case of *x*-polarized mode. This highly confined field inside core region of proposed HN-PCF motivated us to go for further analysis of different parameter which is accomplished further in the manuscript.

Dispersion coefficient of the proposed HN-PCF is investigated for three different pitches, i.e., $\Lambda=1.8\mu\text{m}$, $\Lambda=2.0\mu\text{m}$ and $\Lambda=2.2\mu\text{m}$ and optimized with respect to operating wavelength in Fig. 3. It is found that operating wavelength as well as pitch has impact on the dispersion coefficient. The wavelengths corresponding to zero dispersion coefficient are 2.01 μm , 1.91 μm , and 1.89 μm at pitch 1.8 μm , 2.0 μm , and 2.2 μm , respectively. It is found that the dispersion decreases by increasing the pitch for wavelength less than $\sim 1.3 \mu\text{m}$ and greater than $\sim 2.3 \mu\text{m}$ whereas it increases by increasing the pitch for wavelength between $\sim 1.3 \mu\text{m}$ and $\sim 2.3 \mu\text{m}$. It can clearly be seen that dispersion is highest negative, -6586 ps/(nm.km), for $\Lambda=1.8\mu\text{m}$ at 1.55 μm operating wavelength. This signifies that the proposed HN-PCF for $\Lambda=1.8\mu\text{m}$ can be used as an excellent dispersion compensator at 1.55 μm commercially utilized wavelength.

Confinement loss of the proposed HN-PCF is investigated for three different pitches, i.e., $\Lambda=1.8\mu\text{m}$, $\Lambda=2.0\mu\text{m}$ and $\Lambda=2.2\mu\text{m}$ and optimized with respect to operating wavelength in Fig. 4. It is found that confinement loss decreases by increasing the pitch for wavelength less than 1 μm and greater than 2.2 μm whereas it is zero for all the considered pitch for wavelength between 1 μm and 2.2 μm . Therefore, proposed HN-PCF has zero confinement loss at 1.55 μm commercially utilized wavelength.

Birefringence of the proposed HN-PCF is investigated for three different pitches, i.e., $\Lambda=1.8\mu\text{m}$, $\Lambda=2.0\mu\text{m}$ and $\Lambda=2.2\mu\text{m}$ and optimized with respect to operating wavelength in Fig. 5. It is found that birefringence increases monotonically with the wavelength. It can also be seen that birefringence increases with the pitch at any particular wavelength. The proposed HN-PCF has birefringence of 0.094 for 1.8 μm pitch at 1.55 μm commercially utilized wavelength.

Effective area of the proposed HN-PCF is investigated for three different pitches, i.e., $\Lambda=1.8\mu\text{m}$, $\Lambda=2.0\mu\text{m}$ and $\Lambda=2.2\mu\text{m}$ and optimized with respect to operating wavelength in Fig. 6. It is found that effective area increases monotonically with the wavelength. It can also be seen that effective area increases with the pitch at any particular wavelength. The proposed HN-PCF has effective area of 0.69 (μm)² for 1.8 μm pitch at 1.55 μm commercially utilized wavelength.

Numerical aperture of the proposed HN-PCF is investigated for three different pitches, i.e., $\Lambda=1.8\mu\text{m}$, $\Lambda=2.0\mu\text{m}$ and $\Lambda=2.2\mu\text{m}$ and optimized with respect to operating wavelength in Fig. 7. It is found that numerical aperture increases monotonically with the wavelength upto 2 μm beyond which it becomes almost constant. Further, numerical aperture has negligible variation with respect to pitch at any particular wavelength. The proposed HN-PCF has numerical aperture of 0.875 for 1.8 μm pitch at 1.55 μm commercially utilized wavelength. It is worth noting here that high value of numerical aperture is desirable for better coupling of incident light to the PCF.

Nonlinearity coefficient of the proposed HN-PCF is investigated for three different pitches, i.e., $\Lambda=1.8\mu\text{m}$, $\Lambda=2.0\mu\text{m}$ and $\Lambda=2.2\mu\text{m}$ and optimized with respect to operating wavelength in Fig. 8. It is found that nonlinearity coefficient decreases with the increasing wavelength. This decrement is very sharp upto 1 μm wavelength, then decreases slowly upto 2 μm wavelength, and becomes almost constant beyond 2 μm wavelength. Further, nonlinearity coefficient increases with the pitch at any particular wavelength. This increment is high upto 1.2 μm wavelength, then slowly becomes low till 2 μm wavelength, and finally almost constant beyond 2.2 μm wavelength. The proposed HN-PCF has nonlinearity coefficient of 39612 $\text{W}^{-1}\text{km}^{-1}$ for 1.8 μm pitch at 1.55 μm commercially utilized wavelength.

Effective material loss of the proposed HN-PCF is investigated for three different pitches, i.e., $\Lambda=1.8\mu\text{m}$, $\Lambda=2.0\mu\text{m}$ and $\Lambda=2.2\mu\text{m}$ and optimized with respect to operating wavelength in Fig. 9. It is found that effective material loss is constant by increasing the wavelength upto 1.8 μm and beyond which it increases at a rapid rate. Further, effective material loss is constant for all the considered pitch at any particular wavelength upto 1.8 μm and beyond which it increases by increasing the pitch. The proposed HN-PCF has effective material loss of $1.8 \times 10^{-7} \text{ (cm}^{-1}\text{)}$ for 1.8 μm

pitch at $1.55 \mu\text{m}$ commercially utilized wavelength. It is worth noting here that low value of effective material loss is desirable for better performance of a PCF.

Now, the different performance parameters of proposed HN-PCF is compared with the previously proposed different PCFs which are already published in peer reviewed reputed journals as given in Table I. It can easily be seen that the proposed HN-PCF has extremely high negative dispersion coefficient, i.e., $-6586 \text{ ps}/(\text{nm.km})$, alongwith zero confinement loss and extremely high nonlinearity coefficient of $39612 \text{ W}^{-1}\text{km}^{-1}$ at $1.55 \mu\text{m}$ commercially utilized wavelength. In addition, the proposed HN-PCF has highest birefringence of 0.094 and zero effective material loss at $1.55 \mu\text{m}$ wavelength.

Fig.2: Electric field distributions in the proposed HN-PCF for $1.8 \mu\text{m}$ pitch at $1.55 \mu\text{m}$ operating wavelength; a) x polarized mode shown with horizontal arrow, and b) y - polarized mode shown with vertical arrow.

Fig. 3: Wavelength response of dispersion coefficient (D) of proposed HN-PCF for three different pitches, i.e. $\Lambda = 1.8 \mu\text{m}$, $\Lambda = 2.0 \mu\text{m}$, and $\Lambda = 2.2 \mu\text{m}$.

Fig.4: Wavelength response of confinement loss (L_c) of proposed HN-PCF for three different pitches, i.e. $\Lambda = 1.8 \mu\text{m}$, $\Lambda = 2.0 \mu\text{m}$, and $\Lambda = 2.2 \mu\text{m}$.

Fig.5: Wavelength response of birefringence (B) of proposed HN-PCF for three different pitches, i.e. $\Lambda = 1.8 \mu\text{m}$, $\Lambda = 2.0 \mu\text{m}$, and $\Lambda = 2.2 \mu\text{m}$.

Fig.6: Wavelength response of effective area (A_{eff}) of proposed HN-PCF for three different pitches, i.e. $\Lambda = 1.8 \mu\text{m}$, $\Lambda = 2.0 \mu\text{m}$, and $\Lambda = 2.2 \mu\text{m}$.

Fig.7: Wavelength response of numerical aperture of proposed HN-PCF for three different pitches, i.e. $\Lambda = 1.8 \mu\text{m}$, $\Lambda = 2.0 \mu\text{m}$, and $\Lambda = 2.2 \mu\text{m}$.

Fig.8: Wavelength response of nonlinearity coefficient (γ) of proposed HN-PCF for three different pitches, i.e. $\Lambda = 1.8 \mu\text{m}$, $\Lambda = 2.0 \mu\text{m}$, and $\Lambda = 2.2 \mu\text{m}$.

Fig.9: Wavelength response of effective material loss (α_{EML}) of proposed HN-PCF for three different pitches, i.e. $\Lambda = 1.8 \mu\text{m}$, $\Lambda = 2.0 \mu\text{m}$, and $\Lambda = 2.2 \mu\text{m}$.

Table I. Comparison of different performance parameters of proposed HN-PCF for pitch $\Lambda=1.8 \mu\text{m}$ with previously published PCF at $1.55 \mu\text{m}$ wavelength

PCFs	Year	D [ps/(nm.km)]	L_c (dB/km)	γ ($\text{W}^{-1}\text{Km}^{-1}$)	B
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Ref. [42]	2010	-212	-	-	-
Ref. [43]	2012	-227	0.1	-	0.0175
Ref. [44]	2012	-393	4	-	0.0065
		-115	2	-	0.0278
Ref. [45]	2013	-457.4	0.09	11.26	10^{-7}
Ref. [46]	2013	-588	< 1	31.85	0.0181
Ref. [47]	2014	-562.52	0.091	130.20	0.021
Ref. [48]	2014	-723.1	0.135	-	0.0379
Ref. [49]	2016	-608	0.04	-	0.0181
Ref. [50]	2018	-118	-	0.0166	-
Ref. [51]	2019	-722.48	0.117	21.23	0.245
Proposed	2020	-6586	0.0	39612	0.094

4. Conclusion

Different performance parameters of the proposed HN-PCF is analyzed and compared with previously published PCF. At 1.55 μm commercially utilized wavelength, the proposed HN-PCF for pitch 1.8 μm has extremely high negative dispersion coefficient, i.e., -6586 ps/(nm.km), alongwith zero confinement loss, extremely high nonlinearity coefficient of 39612 $\text{W}^{-1}\text{km}^{-1}$, high birefringence of 0.094, and zero effective material loss. Therefore, the proposed HN-PCF can be used as dispersion compensator in high speed optical communication.

Competing interest: The authors declare no conflict of interest.

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