ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

A REVIEW ON HIGHLY BIREF RINGENT DISPERSION COMPENSATION PHOTONIC CRYSTAL FIBER

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ABSTRACT

This paper discusses several optimum designs for high birefringence and dispersion compensation in Photonic Crystal Fiber (PCF) for broadband compensation covering the E, S, C, L bands wavelength ranging from (1360 to 1640 nm). The finite element method (FEM) with perfectly matched layer (PML) is generally used to investigate the guiding property. Large negative dispersion over wideband range is obtained in many modified structures with varying dispersion coefficient and with relative dispersion slope (RDS) matched to that of single mode fiber (SMF) of about 0.0036 nm^{-1} at 1550nm. High birefringence of order 10^{-2} is observed in most cases with asymmetric structures. In addition to this other properties of PCF like effective area, non-linearity, residual dispersion, and confinement loss are also reported and discussed.

Keywords: birefringence, dispersion, effective mode area, nonlinearity, confinement loss.

1. INTRODUCTION

Photonic crystal fibers (PCFs) are destined to create a great impact in the modern optical fiber optics which has been evolving right from the 1970's and they are regarded as one of the most active fields of current optics research. PCFs are optical fibers that employ a micro structured arrangement of air holes running along the length of the fiber in a background material of different refractive index [1]. In contrast to conventional fibers the greatest advantage of PCFs are the design flexibility which is helpful in attaining a variety of peculiar optical properties, and thereby making them fascinating for a wide range of applications. PCFs provide a variable index contrast between core and cladding with more degrees of design freedom effectively used for tailoring various guiding properties such as chromatic dispersion, birefringence, nonlinearity, and effective mode area [2-3]. The design parameters such as air-hole diameter d, air-hole rings, hole-to-hole spacing, and pitch Λ. PCFs have been revolutionizing the optical communication systems because of their special optical properties such as single mode operation, freedom in design, low loss and flattened dispersion characteristics [4-5]. The PCF has many applications in implementation of digital circuitry such as multiplier and de-multiplier, logic gates and polarization splitter (couplers), optical sensors and medical detection etc[6]. PCFs are indeed a promising technology which can overcome several limitations of the classical optical fibers.

2. PCF PARAMETERS

PCF has many advantages over conventional fiber such as, high birefringence, short coupling length, flattened dispersion, endless single mode polarization with high nonlinearity, low confinement loss.

A. Birefringence (B)

Birefringence is a most important property of PCFs. Birefringent PCFs can simply realized compared with conventional fibers. The refractive index contrast between the core and the cladding is higher than that of conventional fibers. Conventional circularly symmetric optical fibers do not maintain the polarization state of the guided mode along their length. In high birefringent PCF the polarization state is preserved along the propagation to achieve high precision measurements of physical quantities, so enhancement of birefringence of fibers has become very important in recent years [7-9]. To describe the birefringence of PCF, the modal birefringence of the PCF is considered. The modal birefringence (B) is defined as the difference of the absolute value of the effective refractive index of the x polarization mode and y polarization mode. n_x and n_y are the effective refractive index for the fundamental x polarization mode and y polarization mode. There are different ways of designing birefringent fibers, such as the use of anisotropic materials or applying stresses in the cladding region. For nominally isotropic silica fibers, the usual method is to create a spatial asymmetry in the index or shape profile by applying a stress to the fiber [10-12]. To increase the effective index difference between the two orthogonal polarization modes and obtain birefringent PCFs, the structural asymmetry can be altered with the air hole size near the core area and also by introducing the elliptical air holes [11-12]. Among the reported polarization maintaining PCFs [13-25] till date, different approach are followed to create birefringence. In PCFs [13-15] modulated air-holes are used. PCF [14] has a microstructure core, PCFs [16-7] scale down air-holes dimension along one of the axes, and uses a squeezed hexagonal lattice with elliptical air holes [18]. PCFs [19-20] have air-holes defect in the core, and they use rectangular -lattice structures [21-22]. PCFs [23-24] use respectively a stress applying part and two scaled-up air-holes near the core, and PCF [25] has a squeezed hexagonal lattice. These PCFs attain birefringence of the order 10^{-4} to $10^{-2}$with various pitches. The PCF [25] with a squeezed hexagonal lattice and elliptical air-holes can provide birefringence of the order 10^{-2}, the highest birefringence reported to date. Yue *et al* [11] and Sun *et al* [12] have demonstrated that it is possible to design PCFs with relatively large birefringence of the order of 10^{-3}and10^{-2}.The drawback of proposed design is fabrication becomes challenging by the use of several rings of elliptical air holes in the cladding region and controlling the elliptical air holes during the fabrication process might be difficult [10].

Ademgil *et al* [26] has been demonstrated that it is possibleto design a bending-insensitive nonlinear PCF with a birefringence9×10^{-3}at a 1.55 μm wavelength. It is seen that the birefringence is sensitive to the varying wavelength. It can be anticipated that, as hole-to-hole spacing decreases, the birefringence increases. It can be noted that birefringence for Λ=1.7 μm and Λ =2 μm at 1.55μm operating wavelength is 9×10^{-3} and 7.3×10^{-3}respectively.In the PCF structure of Selim *et al* [27] a very high birefringence of the order $1.81 \times 10^{-2}$is obtained at 1.55 μm wavelength .

Xuyou *et al* [28] has proposed a new type of lozenge cladding photonic crystal fiber (L-PCF) which is composed of elliptical holes based on rectangle lattice. The properties of a hexagonal cladding (H-PCF) with the same structure parameters are investigated and it is found that the mode field is effectively limited in the core of the proposed L-PCF, and it can achieve a higher birefringence than H-PCF with the same air holes size, shape, pitch and layer number. The modal birefringence of the L-PCF is higher than that of the H-PCF for the wavelength range 1.70μm. At the wavelength of 1.55μm, the value of the birefringence for the proposed L-PCF is about 0.013, while the value of birefringence for the H-PCF is about 0.0083. Imran Hasan *et al* [29] has proposed an octagonal photonic crystal fiber (OPCF) with an elliptical array of circular air holes in the fiber core region. In this structure the air-holes of the first ring are placed in such a way that leads to obtain a birefringence of the order 2.1×10^{-2}at the wavelength of 1.55μm. Here birefringence of 0.97×10^{-2} and 1.04×10^{-2} are obtained for zero-dispersion wavelengths (ZDW)ie at 0.88 μm and 0.908 μm respectively on slow axis and fast axis respectively.

Lee *et al* [30] and Yamamoto *et al* [31] have experimentally demonstrated that it is possible to design highly nonlinear PCFs with a relatively large birefringence of the order 10^{-3} of at 1.55μm telecommunication wavelengths. Lee *et al* [30] have demonstrated a birefringent PCF for the use of optical code-division multiple-access (OCDMA) applications. Similarly, Yamamoto *et al* [31] have demonstrated highly birefringent PCF with a Ge-doped core. The birefringence value of the birefringent photonic crystal fiber is not sensitive to the change of temperature, while the refractive index of ethanol will be changed with the varied temperature. So if the air-holes of PCF are filled with ethanol, the birefringence value will change along with the varied temperature, which can be used as a sensing principle to measure temperature [32]. The paper discusses, a method called End Face Reflection of the optical fiber which is used to measure the refractive index against the change of temperature. The experimental results indicate that, on the condition of the incident wavelength of 1.55 μm, the refractive index of ethanol changed from 1.3691 to 1.3602 within the temperature ranging from $24.5^{oc}$to 44.5^{oC}. The birefringence value of the filled PCF changed from 1.9×10^{-4}to2.2×10^{-4}. Birefringent properties in a fiber can be used to eliminate the effect of polarization mode dispersion in transmission systems. It can also used for optical frequency synthesis, ultrafast femtosecond laser sources, fiber based gyroscopes. Highly birefringent fibers are extensively used in fiber loop mirrors as a major component for optical fiber sensing applications; the additional property of high negative dispersion would provide better performance for the fiber sensor design and also in long distance data transmission system [8].

B. Dispersion (D)

In optical communication system, pulse broadening due to dispersion is the key issue that reduces transmission data rates and overall bandwidth of the system. For this we use dispersion compensating fibers (DCFs). A standard single mode optical fiber has positive dispersion of 10 to 20 ps/(nm km). For effective compensation of such positive dispersion with minimum length and then cost, the DCF should have large negative dispersion [33]. The chromatic dispersion profile can be easily controlled by varying the hole diameter and the hole-to-hole spacing. Controllability of chromatic dispersion in PCFs is a very important problem for practical applications to optical communication systems, dispersion compensation, and nonlinear optics. The sum of the material and waveguide dispersion constitutes the total dispersion or chromatic dispersion.

Different PCFs structures have been designed and reported for dispersion compensation applications by many research groups. Birks *et al* [34] first proposed the idea of using PCFs for dispersion compensation application, however effective area of the design is relatively small that would result a large coupling loss with SMFs. A similar approach is used by Shen *et al* [35], in his proposal the designed PCF is optimized for broadband dispersion compensation with a negative dispersion coefficient of approximately -475 ps/(nm km). A dual core PCF is proposed in [33] for dispersion compensation which achieves a large dispersion peak of about -59,000 ps/(nm km). Habib *et al* [36] proposed a dispersion compensating PCF based on spiral structure which successfully achieves negative dispersion coefficient of −327 ps/(nm km) at 1.55μm wavelength. Square lattice PCF is proposed in [37] that shows negative dispersion of −204.4 ps/(nm km) requiring relatively longer fiber for compensation. Octagonal PCF is proposed in [27] that provides a negative dispersion of −588 ps/(nm km) at 1.55μm wavelength.

Samiul *et al* [38] has presented a photonic crystal fiber based on hexagonal structure for improved negative dispersion. The proposed structure demonstrated that it is possible to obtain negative dispersion coefficient of -712 ps/(nm km) and relative dispersion slope (RDS) perfectly match to that of single mode fiber (SMF) of about 0.0036 nm^{-1} at the operating wavelength 1.55μm. The proposed PCF structure by Mejbaul *et al* [39] is a single mode hybrid cladding circular photonic crystal fiber (HyC-CPCF). The paper illustrates that the designed HyC-CPCF operates as a single mode fiber over E + S + C + L bands and provides a high negative dispersion of -650 ps/(nm km) with RDS of 0.0036 nm^{-1}at 1.55μm wavelength. The proposed HyC-CPCF possesses -62 ps/(nm km) higher negative dispersion coefficient than [16]. The PCF proposed in [16] can only compensate dispersion over S + C + L wavelength band whereas the proposed HyC-CPCF is enough capable to compensate dispersion over E + S + C+ L wavelength band and thus provides more compensation bandwidth. Hasan *et al* [40] presents an optimum design of a hybrid photonic crystal fiber (HyPCF) based on a modified structure for broadband compensation covering the S, C and L communication bands. With optimized parameters Λ = 0.85 μm, d1 = 0.833 μm, d2 = 0.8075 μm, d3 = 0.9215μm, d4 = 0.697 μm and d5 = 0.935μm it can be seen that the designed PCF has negative dispersion coefficient of -153.41 ps/(nm km) and-555.93 ps/(nm km) for x-polarized mode and y-polarized mode respectively at 1.55μm. Mejbaul *et al* [41] present a single mode circular photonic crystal fiber (C-PCF) for broadband dispersion compensation covering 1400 to 1610 nm wavelength band. The proposed C-PCF contains only circular air holes and a total of five air-hole rings. The material of the proposed structure is considered as silica. Numerical study reveals that a negative dispersion coefficient of about -386.57 to -971.44 ps/(nm km) is possible to obtain over the wavelength ranging from 1400 to 1610 nm with a relative dispersion slope (RDS) of about 0.0036 nm^{-1} at 1550 nm wavelength. Selim *et al* [27] propose and demonstrate a modified octagonal structure for broadband dispersion compensation covering the S, C, and L communication bands i.e. wavelength ranging from 1460 to 1625 nm. It is shown theoretically that it is possible to obtain negative dispersion coefficient of about 400 to 725 ps/(nm km) over S and L-bands and a relative dispersion slope (RDS) close to that of single mode fiber (SMF) of about 0.0036 nm^{-1}

i) Flattened dispersion

Flattened dispersion in PCF is always associated with high non linearity. Such fibers are important for data transmission with wavelength division multiplexing and for adiabatic soliton compression. The air-hole pitch, Λ is varied to achieve Flattened chromatic dispersion in wide band wavelength range [42]. Flattened dispersion curve will be in the range of 0 ± 5 ps/nm/km is obtained in a 1.33 to 1.71 μm wavelength range. The dispersion level is about -5.36, -2 and +1.58 ps/nm/km, respectively in a broad range of wavelength from 1.35 to 1.65 μm, for $d2/\Lambda$ = 0.30, 0.32 and 0.34[14].

Nguyen *et al* [43] it reports a novel design in PCFs with nearly zero ultra-flattened dispersion characteristics. Setting the hole to hole spacing Λ and the air-hole diameter *d* as Λ =2.6 m and *d*/ Λ =0.24 respectively, it is possible to realize a nearly zero ultra-flattened dispersion PCF in telecommunication window. It is shown that nearly zero dispersion values between 0 ± 0.22 ps/(nm km) can be achievedover S+C+L wavelength bands with confinement losses of lessthan 10^{-8}dB/km.A highly nonlinear photonic crystal fiber (HNL-PCF)based on an octagonal structure with isosceles triangular-latticedcladding is proposed for the telecommunication window by AbdulRazzak *et al* [44]. It isdemonstrated that the proposed PCF has ultra flattened dispersion of 0.5 ps/(nm km) obtained in a1.46μm to 1.66μm wavelength with low confinement losses less than0.06 dB/km in the entire band of interest.

ii) Residual dispersion

A residual dispersion compensating octagonal photonic crystal fiber (OPCF), with an elliptical array of circular air holes in the fiber core region, is proposed by Imran *et al* [29] The OPCF structure is proposed to have large average negative dispersion, ultra-high birefringence and wide compensation bandwidth simultaneously. It is demonstrated that it is possible to obtain large average negative dispersion of -562.52 ps/(nm· km) over240 nm and -369.10 ps/(nm· km) over 630 nm wavelength bandsfor the fast and the slow axis, respectively. This novel OPCF design is proposed to obtain very large average negative dispersion for both the fast and the slow axis with a zero-dispersion wavelength (ZDW) for compensating the residual dispersion of SMFs. Imran Hasan *et al* [45] has presented a residual dispersion compensating photonic crystalfiber (PCF) is proposed having elliptical-shaped core and octagonal structure with isosceles triangular-latticed cladding. It is demonstrated that it ispossible to obtain average dispersion of -544.7 ps/(nm km) in a wavelength range of 1.46–1.70 μm with ultrahigh birefringence

C. Effective mode area

Effective mode area is another important parameter of PCF. It is the quantitative measure of area that a fiber mode covers in transverse dimension. Effective mode area is the effective measure of area in which fundamental mode is confined during propagation of light in fiber. For optical nonlinearities in PCF effective mode area is the major parameter that is to be considered. Undesirable nonlinear impairments can be suppress by large mode area in PCF. Optical nonlinearities always depend on the power density inside the device. Therefore for a fixed power, the higher the effective area, the lower will be the effect of nonlinearities. One of the ongoing challenge in PCF structure designing is the design of structures having small mode areas that lead to a high nonlinear coefficient. Designers use various approaches to obtain desired effective mode area like varying the size of the air holes in the cladding region, varying hole-to-hole spacing. [46-47].For a fixed pitch it is possible to increase the effective area significantly by narrowing the air-holes or by enlarging the pitch for a fixe d/Λ value. The effective area can also be related to the spot-size, with

Gaussian approximation $A_{eff} = \pi\omega^2$[48] and this will make A_{eff} important in the calculation of confinement losses, bending losses, splicing losses, and numerical aperture.

In the photonic crystal fiber structure by Ademgil *et al* [26] it is clear that effective mode area increases steadily with the increases in wavelength. It can be also noted that with increasing hole to hole spacing effective mode area is increasing. This would contribute to increase the nonlinearities produced by refractive index power dependence in the proposed structure. Effective area of the DC-HyPCF [49] for optimum design parameters at 1.55μm is 2.63 μm^2. It changes about ±0.028 μm^2 for ±1% change in parameters, ±0.05 μm^2 for ±2% change in parameters, ±0.13 μm^2 for ±5% change in parameters. This structure having small effective area will result in a very high nonlinear coefficient.

D. Non-linearity

Both linear and nonlinear response would obtain from medium when the intense pulse like laser propagates through photonic crystal fiber. The major nonlinear effects are four wave mixing (FWM), Stimulated Raman Scattering (SRS), self and cross phase modulation (SPM and XPM), Soliton affects, Self-Steepening (SS) etc [46].

The nonlinear effects in optical fibers mainly originate from nonlinear refraction, which is a phenomenon that refers to the intensity dependence of the refractive index resulting from the contribution of third order susceptibility[17]. In section C we have already discussed about the inverse proportionality of nonlinear coefficient γ to the effective mode area. As per equation of both effective mode area and nonlinearity, the core diameter decreases which definitely reduces the effective area leads to high nonlinearity. Thus nonlinearity decreases with wavelength while effective mode area increases with wavelength. Poli *et al* [50] and Saitoh *et al* [51] have demonstrated theoretically that PCF structure designs with nonlinear coefficients of about 30 and 44 $W^{-1}km^{-1}$ respectively at 1.55μm telecommunication wavelength are possible.In the equation for calculating nonlinear coefficient n_2 (Kerr constant) is an important value which is the ratio between the nonlinear refractive-index coefficient, and the effective area over a given wavelength of the optical field. Ahighly nonlinear polarization maintaining single mode hybrid cladding circular photonic crystal fiber (HyC-CPCF) is proposed by Mejbaul *et al* [39]. The nonlinear coefficient of this structure decreases with wavelength and at 1.55 μm wavelength it is $45.5W^{-1}km^{-1}$.

Ademgil *et al* [26] propose an index guiding highly nonlinear birefringent photonic crystal fiber (PCF).In this paper they demonstrate that it is possible to design a simple PCF structure configuration with a birefringence in the order of 10^{-2} and a nonlinear coefficient of $49W^{-1}km^{-1}$ at the wavelength of 1.55 μm. Recently this types PCFs with high birefringence and high nonlinear coefficient have received growing attention in telecommunication [52-53]. Yamamoto *et al.* [53] and Lee *et al* [52] have experimentally demonstrated the highly nonlinear PCFs with a relatively high birefringence at 1.55μm wavelength. In Lee *et al* [52] structure, they demonstrated a birefringent PCF having nonlinear coefficient, of $31W^{-1}km^{-1}$ for the use in optical code-division multiple access (OCDMA) applications and Yamamoto *et al.* [53] have demonstrated highly birefringent PCF with a Ge-doped core having a nonlinear coefficient of 19 $W^{-1}km^{-1}$.Nonlinear threshold device based on PCF is proposed in [54] for optical code division multiple access application that has a nonlinear coefficient of $31W^{-1}km^{-1}$.The high Non-linearity property of PCF is used in wide range of application such as pulse-forming, in self-phase modulation for switching, spectroscopy and wavelength conversion applications[55-56].

E. Confinement loss

When an electromagnetic wave propagates through a photonic crystal fiber, a small portions of energy will definitely escapes. In the PCF structure as the number of air holes is finite, the power leakage is inevitable. There are many other factors in designing the PCF that can affect the confinement loss [57]. The resulting loss can be large in the solid-core PCF for small values of d/Λ. By selecting the air hole diameter and pitch properly the loss could be minimized to a greater extent. The number of layers also plays an important role where selection of small pitch is impossible. The confinement loss is given by$k_0$times $Im[n_{eff}]$ multiplied by 8.686.It is expressed in dB/m. Here $Im[n_{eff}]$is the imaginary part of complex effective refractive index and $k_0$is the free space wave number given by $k_0=\frac{2\pi}{\lambda}$.

Hasan *et al* [40] illustrated an optimum design of a hybrid photonic crystal fiber (HyPCF) based on a modified structure covering the S, C, and L communication bands. For this structure the Confinement loss at 1.55μm is 0.134 dB/nm. In the five air-hole rings structure demonstrated this value is less than 0.007dB/m and 0.135 dB/m for x-polarized mode and y-polarized mode respectively. PCF supports second-order mode in shorter wavelengths. But in this structure calculated confinement loss of the second order mode is 34.4dB/m which is 10-20 times higher than the fundamental modes. This indicates that only fundamental mode will guided in the core. Thus it is evident that the fiber will effectively operate only as a single mode fiber. In the PCF structure [58] with an index guiding core surrounded by a triangular array of air holes, it has been demonstrated that it is possible to design a PCF that exhibits low confinement losses and small effective mode area across a wide wavelength range. In the structure, to reduce the confinement losses, five rings of air holes are taken. The purpose is to keep birefringence at the optimum level and reduce confinement losses. The confinement losses can be reduced by increasing the air hole size in inner cladding area. In that case according to simulations the birefringence reduces. Thus there should be a trade-off between high birefringence and low confinement losses. In this paper only the fundamental modes $HE_{11}^{x}$and$HE_{11}^{y}$are considered. From the simulation result it is clear that losses for the HE_{11}^{y}mode are greater than for the HE_{11}^{x} polarization mode.The confinement losses increase rapidly when the wavelength increases.

Design and analysis of a nonlinear Photonic crystal fiber having low confinement loss is proposed by Anand *et al* [59]. The design suffers from only a small confinement loss due to the circular air holes in the cladding region with a much larger pitch measurement. Most of the optical fibers operating in UV regions suffer from high losses. In this proposed structure, a surprisingly low confinement loss of 2.778×10^{-12}dB/km is obtained at a wavelength of 25 nm which is way below the wavelength range of 500 nm to 1700 nm.Thus its conclude that the proposed PCF design can act as a lossless waveguide in UV regions. Abdul Razzak *et al.* [60] a novel technique for the control of chromatic dispersion and confinement loss in hexagonal photonic crystal fibers (H-PCFs) is demonstrated. The paper illustrate that it is possible to obtain very low confinement loss of less than 0.0001 dB/km from a six ring modified H-PCF (MH-PCF). From the discussed stimulation results it is clear that core diameter has no role in the confinement loss but it depends mainly on air filling ratio.

3. CONCLUSIONS

The different PCF structures which we have discussed exhibits high performance in properties such as birefringence, dispersion compensation, nonlinear coefficient, and low confinement loss. In this study, a full vectorial FEM is used to investigate the optical properties of PCF. It is extremely challenging to satisfy all of the performance criteria simultaneously. It is confirmed that PCF with low effective area gives high non linearity. High birefringence with large nonlinearity has been reported. Fabrication of the proposed PCFs believed to be possible with a high feasibility and is not beyond the realm of today's existing PCF technology. These reported results can be widely used for the four wave mixing, fiber loop mirror, polarization control in fiber-optic sensors and telecommunication applications, broadband dispersion compensation in high-bit-rate transmission networks.

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