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Dispersion Flattened Large Negative Hybrid Photonic Crystal Fiber with Low Confinement Loss

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ABSTRACT: *A hybrid photonic crystal fiber consisting of hexagonal and octagonal rings is presented for the compensation of residual dispersion in the range of 1260-2000 nm. Hybrid design is used to control dispersion and confinement loss characteristics simultaneously. Hexagonal structure is used to control the dispersion characteristics and octagonal structure is used to control the confinement loss characteristics.*
The designed PCF shows ultra-flattened average negative dispersion of –110.21 (ps/nm/km) with an absolute dispersion variation of 1.49 (ps/nm/km) in the entire previously mentioned wavelength range. Negligible confinement loss and moderate effective area are also obtained using this design. The dispersion characteristics are investigated using an efficient finite element method with perfectly matched layers.

Index Terms: *PCF, Photonic Crystal Fiber, Ultra flattened Dispersion, Large Negative Dispersion, Hybrid PCF, Confinement Loss, Effective Area.*

I. INTRODUCTION

Photonic crystal fibers (PCFs) or microstructure optical fiber (MOF) or holey fibers (HFs) is a artificial photonic crystal structure. It is a single material optical fiber consisting of a silica air microstructure. It contains microscopic air-holes in a silica background running down length of the fiber that form the silica-air microstructure as well as the lower refractive index cladding [1]. Air-holes can be arranged in the cladding in a periodic (hexagonal arrangement being the common) or an aperiodic fashion. The core may either be a solid (made of silica) or a hollow (made of air). The former core type PCF guides light based on the modified TIR mechanism likewise conventional fibers. The later guides light based on a new mechanism which is known as the photonic band gap (PBG). Hence, for PCFs, it is not necessary that the core must be made of a higher refractive index material than the cladding. Similarly, it is also not necessary that only the TIR mechanism confines light into the core of all optical fibers. The properties like dispersion, birefringence, confinement loss, nonlinearity etc. of PCFs can be controlled by tailoring the geometrical structure of cladding & core. Among the properties of PCF, chromatic dispersion is the most important one for fiber optic communication application. Long-haul transmission systems require single mode optical fibers (SMFs) with nonzero chromatic dispersion to avoid nonlinear interactions like crosstalk and information loss [2]. The SMFs have anomalous dispersion from 10 to 20 ps/nm/km. So, this anomalous dispersion is needed to be suppressed and can be done by including a dispersion-compensating fiber (DCF) of short length with a large negative dispersion in the optical link [3]-[5]. This dispersion compensating technique has been studied by many research groups and several papers have been published on this topic. A flat negative dispersion coefficient of about −98.3 ps/nm/km with absolute dispersion variation (ΔD) of 1.1 ps/nm/km was proposed over $S + C + L$ wavelength band in [6]. A PCF which exhibits ultraflattened negative dispersion over $S + C + L + U$ wavelength bands and average dispersion of about −179 ps/nm/km with an absolute dispersion variation of 2.1 ps/nm/km was proposed in [3]. The design shown in [4] describes flat negative dispersion of –212 ps/nm/km with a flat variation of 11 ps/nm/km over $E + S + C + L + U$ wavelength bands in which the core is Ge-doped. Recently, a Negative dispersion coefficient of –227 ps/nm/km with absolute dispersion variation of about 8.6 ps/nm/km has been obtained over $E + S + C + L + U$ bands using equiangular spiral photonic crystal fiber styles are shown in [5]. The improvement of this work was described in [7] with negative dispersion of –393 ps/nm/km with a variation of 10.4 ps/nm/km. More recently, a photonic crystal fiber in photonic crystal fiber has been proposed which ensure highest average negative dispersion to date having average dispersion of –457.4 ps/nm/km over $E + S + C + L + U$ wavelength bands

[8]. All the designs mentioned above have obtained dispersion profile within the wavelength range from 1360 nm to 1690 nm. Again, the minimum variation of dispersion of the reported designs is about 2.1 ps/nm/km. The designs of [4,5,7,8] have complex structures and are very difficult to fabricate using conventional stake-and-draw method.

In this Paper the designed hybrid PCF shows ultra-flattened average negative dispersion of –110.21 (ps/nm/km) with an absolute dispersion variation of 1.49 (ps/nm/km) in the entire previously mentioned wavelength range. Negligible confinement loss and moderate effective area are also obtained using this design. The dispersion characteristics are investigated using an efficient finite element method with perfectly matched layers.

II. HYBRID PCF DESIGN

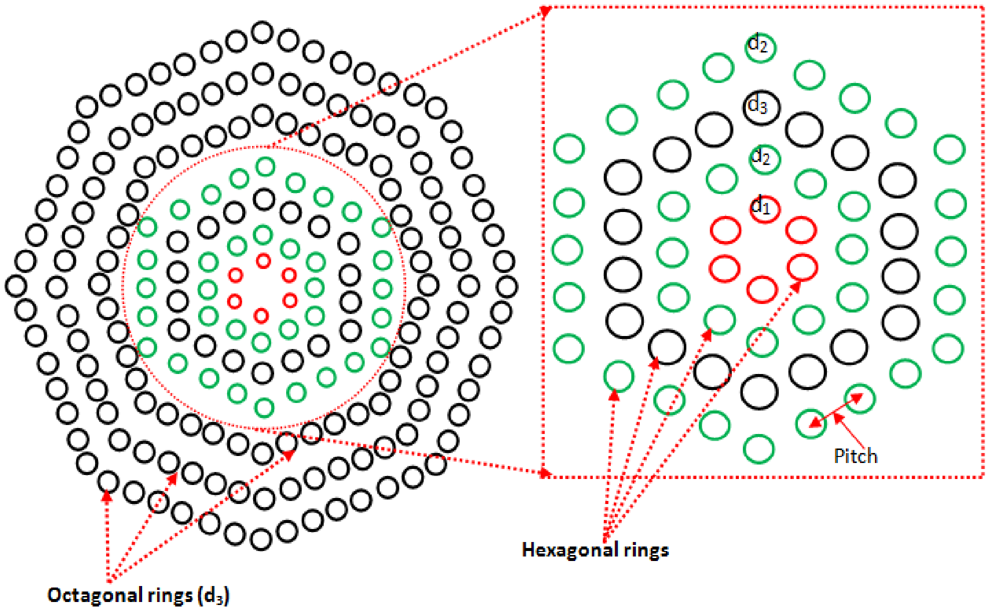

Fig.1 Cross section of geometrical model of proposed hybrid DCF

Fig.1 shows the geometry of the design which has 7 air hole rings with air hole diameters of d_1, d_2, d_3, and the pitch Λ (distance between centers of consecutive air holes). All the air hole rings are taken circular. The inner four rings have hexagonal structure of triangular lattices and outer three rings have octagonal structure. As the octagonal structure has isosceles triangular lattices, it has more air hole rings in the cladding region than the conventional fibers. This results in a higher air-fling ratio (AFR) and a lower refractive index around the core, thereby providing strong confinement ability and low confinement losses. The hexagonal structure is best for dispersion controlling and octagonal structure is well known for confinement loss controlling [6]. The air hole diameters of third, fifth, sixth and eight rings are same (d_3) and are different for other rings (d_1, d_2) but pitch is same for all the rings. The numbers of air-holes in the first to seventh rings are respectively 6, 12, 18, 24, 40, 48, and 56. First ring and second ring diameters have been tailored very carefully so that we can have dispersion with a very small variation in the entire range. The air hole diameter of first ring is kept low to keep the dispersion variation to a very low level. The air hole ring diameter of fifth to eighth ring is kept high to keep the confinement loss to relatively low value. The proposed design is similar to [7] but modified cladding leads to a very distinct dispersion characteristics. For optimum numerical analysis pitch (Λ) was taken 0.90 µm and first ring air filling fraction (d_1/λ) was taken 0.38.

III. NUMERICAL METHODS & EQUATIONS

The simulation tool used for this study is COMSOL software of version 4.2 and an efficient finite element method (FEM) with circular perfectly matched layers has been used to characterize the performance of the H-PCF. The PCF cross sections, with a fixed number of air-holes are divided into homogeneous subspaces where Maxwell's equations are solved by accounting for the adjacent subspaces. These subspaces are triangles that permit a good approximation of the PCF structures.

Chromatic Dispersion:
The chromatic dispersion D of a MOF is calculated from the n_{eff} value vs. the wavelength using the following [1]

$$D(\lambda) = -\frac{\lambda}{c}\frac{d^2 Re[neff]}{d\lambda^2}$$

in (ps/(nm.km)), where $Re\ (n_{eff})$ is the real part of the effective refractive index, λ is the operating wavelength, and c is the velocity of light in a vacuum. The material dispersion can be obtained from the three-term sellmeier formula and is directly included in the calculation. In MOFs, the chromatic dispersion D is related to the additional design parameters like geometry of the air holes, pitch, and hole diameters. By optimizing these parameters, suitable guiding properties can be obtained.

Confinement Loss:
Confinement loss L_c is the light confinement ability within the core region. The increase of air hole rings help the confinement of light in the core region, which results in smaller losses than those with less air hole rings. Also, increasing the air holes diameter results in the increasing of the air filling fraction and consequently decreasing the loss. The confinement loss L_c then obtained from the imaginary part of refractive index n_{eff} as follows [1]

$$L_c = \frac{20\times10^6}{\ln(10)}\ k_0\ Im\ (n_{eff})$$

with the unit dB/km, where $Im\ (n_{eff})$ is the imaginary part of the effective refractive index, in the $k_0=\frac{2\pi}{\lambda}$ is the wave number in the free space.

Mode Field Diameter and Effective Area:
A beam of light guided through the fiber does not have strict cross-sectional boundaries. The beam is most intense in the center, with its intensity declining gradually from the center outward. The most popular model used in single mode fibers for the beam intensity is a Gaussian distribution, given by

$$I(r) = I(0)\exp(-2r^2/\ w_r^2)$$

where, $I(r)$ is the current value of the beam's intensity at the radius r, $I(0)$ is the maximum beam intensity at r = 0, and w_r is the mode field radius. Fig. 2.7 shows the intensity distribution of a light beam inside a fiber. The effective area is the area where the beam intensity drops to 13.5% of the maximum value and the diameter of which is called the mode field diameter (MFD) and can be calculated directly from the electric field distribution by using the Petermann-II definition [10].
The MFD of PCFs can be written as

$$MFD=2\sqrt{\left(\int_0^\infty E(r)^2\ rdr\right)/\left(\int_0^\infty [dE(r)/dr]^2 rdr\right)}$$

Effective area corresponding to the MFD can be given in rectangular co-ordinates

$$A_{eff}=\left(\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}|E|^2\ dxdy\right)^2/\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}|E|^4\ dxdy$$

where, E is the electric field distribution drawn by solving Maxwell's equations using the FEM and A_{eff} is the effective area.

IV. OBTAINING OPTIMUM PARAMETERS OF THE DESIGNED HYBRID PHOTONIC CRYSTAL FIBER

The guiding properties like chromatic dispersion, confinement loss, effective area, nonlinearity, and birefringence of PCF are different and better than conventional PCF [8]. These properties need to be controlled to obtain the desired result. The guiding properties can be controlled by tailoring parameters like air-hole diameters, number of air-holes, pitch, core diameter etc .Optimization of the parameters is necessary to obtain the desired guiding characteristics of photonic crystal fiber. Trial and error method is used to obtain the desired properties of PCF. In order to optimize the parameters while changing one parameter other parameters were kept constant.

In this section optimizing procedure of ultra-flattened large negative chromatic dispersion and properties like confinement loss, effective area etc. are discussed related to the scope of this design.

4.1 Ultra-Flattened Large Negative Chromatic Dispersion

The wavelength dependence of chromatic dispersion properties of proposed structure is shown in Fig.2 This design exhibits an average dispersion of –110.21 (ps/nm/km) with an absolute variation of 1.49 (ps/nm/km) in the wavelength range of 1250-2000 nm. This covers very high range of 750-nm bandwidth. This result was obtained for the optimum values of d_1/Λ= 0.38,d_2/Λ= 0.52, d_3/Λ= 0.60, and pitch, Λ = 0.90 μm. It is evident from the figure that there is abrupt change in dispersion.

Another important parameter for negativity and flatness is pitch. From Fig. 4 it is observed that with the decreasing of pitch the flatness of negative dispersion increases and the magnitude of dispersion decreases. But after crossing one specific point the magnitude of dispersion as well as flatness decreases. So using trial and error method that specific point was found out and this is our optimum value of pitch. It is seen from the figure that there is abrupt change in the dispersion curve. For this design the optimum value of pitch was taken as 0.38 µm. The pitch was set to this value and other parameters were changed to obtain optimum point.

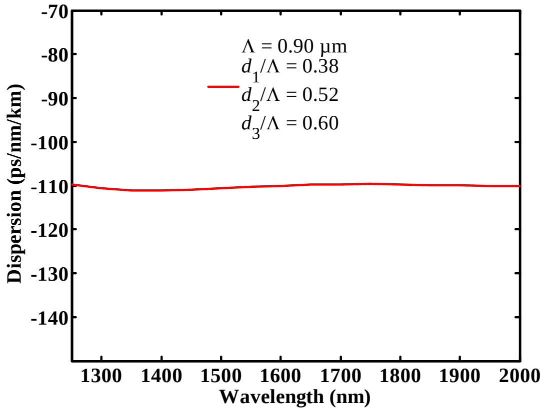

Fig.2 Flattened negative dispersion over 750-nm bandwidth wavelength bands at optimum design parameters

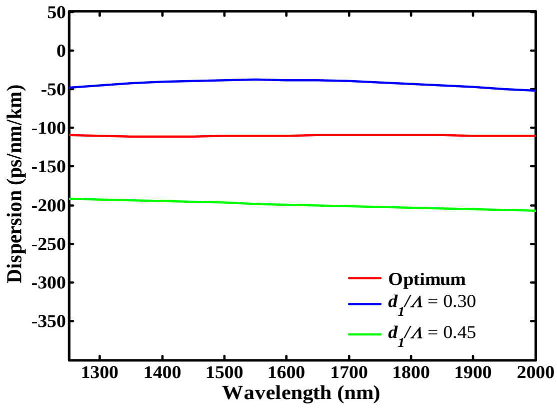

Fig. 3 Changing first air-hole ring diameter to obtain optimum flattened negative dispersion

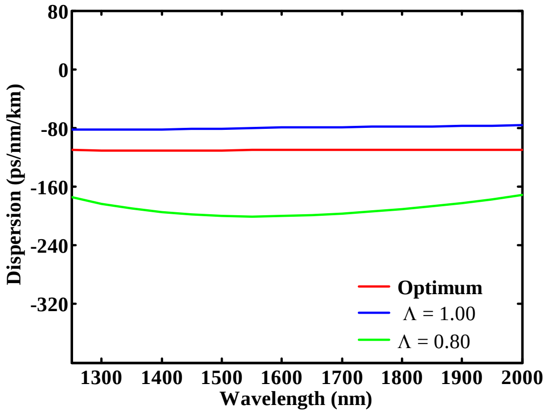

Fig.4 Changing pitch to obtain optimum flattened negative dispersion

So after the optimization the values of the optimized parameters is taken as d_1/Λ=0.38, d_2/Λ=0.52, d/Λ= 0.60 and pitch (Λ)=0.90 µm. Using these parameters as optimum the value of confinement loss, effective area are determined.

4.2 Effective Area

The cure of effective area for the optimum design parameters is shown in Fig. 5 The value of average effective area of this fiber is found to be around 4.5μm^2. The effective area is relatively small and can be used for some nonlinear applications. It is evident from the figure that effective area of the fiber increases with the wavelength and there is no evidence of abrupt change in effective area. The effective area of the fiber at 1550 nm is 4.2 μm^2.

4.3 Confinement Loss

Wavelength dependence of confinement loss of the HyPCF for optimum design parameters is shown in Fig. 6 The confinement loss is found to be high and this value is 0.01dB/m at 1550 nm. Confinement loss in HyPCF is much lower than normal hexagonal structured PCF due to more air-holes in the cladding region for same ring. The techniques about reducing confinement loss are discussed in the next chapter. It is evident from the figure that confinement loss of the fiber increases with the wavelength and there is no evidence of abrupt change.

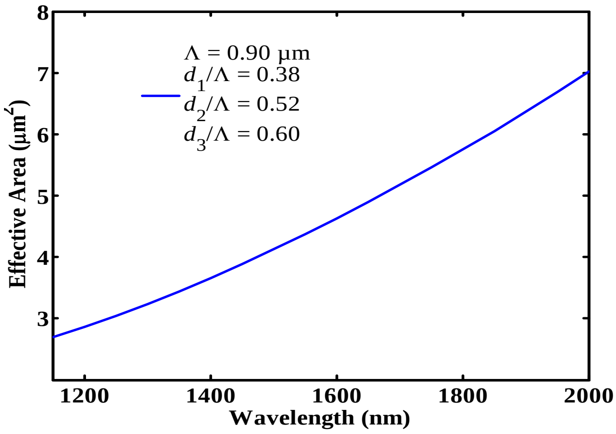

Fig. 5 Effective area for the optimum parameters

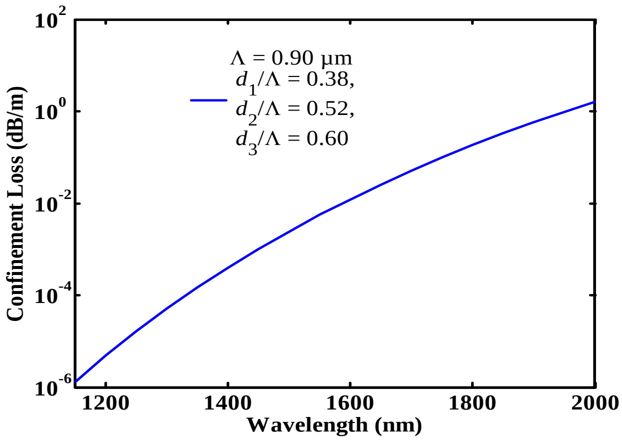

Fig. 6 Confinement loss for the optimum parameters

V. CONCLUSION

In this paper, a hybrid PCF has been proposed for residual dispersion compensation. It has been demonstrated that our structure shows ultra flattened large negative dispersion of –110.2 ps/nm/km with an absolute dispersion variation of 1.49 ps/nm/km in a broad wavelength ranging from 1250 nm to 2000 nm. The dispersion variation (ΔD) and the wavelength range of the obtained dispersion profile are updated and the confinement loss is negligible. This structure is much easier to fabricate and can be applied in the communication link for broadband dispersion compensation.

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