

Design of Highly Birefringent Bending Insensitive Single Mode Photonic Crystal Fiber

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Abstract

Objectives: Bending insensitive Photonic Crystal Fiber will possess low loss and the research aims for high birefringence and large nonlinearity. Bending insensitive Photonic Crystal Fiber (PCF) along with high birefringence and high nonlinearity is being presented in this paper. **Methodology:** The fiber is bent by applying some bending radius along with the angle in the direction of the bending and the effects due to these angles are being extensively studied by using Finite Element Method (FEM). **Findings:** The birefringence in the range of 10^{-2} can be achieved and nonlinear coefficient in the range of 70-110 $W^{-1}Km^{-1}$ can be obtained. The PCF possesses very low effective mode field area (MFA) which would be leading to positive effect on the bending losses. The number of air hole rings used in the designed structure is very less so the designed fiber is easy to fabricate. **Applications:** This fiber can be used in the medical applications for detecting the tumors, for Optical Code Division Multiple Access (OCDMA) applications, high power laser applications.

Keywords: Bending Insensitive Fiber, Effective Mode Field Area (MFA), Finite Element Method (FEM), Nonlinear Coefficient, Photonic Crystal Fiber (PCF).

1. Introduction

Photonic Crystal Fiber's (PCF's) are also called as micro-structured fiber's or holey fiber's, is a form of all silica fiber. The core region of the fiber is mostly made up of silica and number of air holes are present in the cladding region¹. Since the PCF's were fabricated first time in the year 1986 the PCF's had been a topic of research Photonic Crystal Fiber's possessing of the defect region in the center part within a regularly placed lattice of the air holes are having most amount of demand in the research department. These type of fiber's gives much freedom for manipulation of the optical properties if needed PCF's are being characterized into two types with respect to the guiding mechanism used namely photonic band-gap fiber's and index guided fiber's. In case of the photonic

band-gap fiber's the band-gap is created between the core and the cladding region due to the refractive index difference within the core and the cladding region and the light is guided. In index guiding mechanism the light is guided into the fiber by Total Internal Reflection (TIR)^{2,3}. Because of the availability of the air holes the effective refractive index of the cladding region reduces and this helps for the light to get penetrated into the core region due to TIR

PCF's possesses many unique properties than that of the conventional optical fibers for example endlessly single mode operation, ultra-flattened dispersion for high wavelength range, polarization, high birefringence, controllable nonlinearity property⁴⁻⁶. These unique properties of the PCF's are dependent on the design details of the fiber like less sensitivity for the bending losses even though for higher effective mode areas, where small or high effective

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mode areas are responsible for strong or weak nonlinearity. The index guiding type of the PCF's possesses the nonlinearity 10-100 times that of the conventional optical fibers^{7,8}. In case of the PCF's the refractive index contrast between the core and the cladding region is greater than the conventional fibers so the highly birefringent PCF's can simply be formed⁹. Nonlinearity as well as the birefringence properties are having great demand in the PCF's. The high birefringence can be obtained by making use of the different anisotropic materials. For achieving high birefringence in the silica fiber the symmetry of the fiber structure is needed to be broken by applying some stress to the fiber^{10,11}.

Highly birefringent fibers are mostly used in many sensing applications such as temperature and pressure sensing^{12,13}. The PCF's provides much higher birefringence than that of the conventional optical fibers. For producing high birefringence in the fiber the symmetry of the fiber structure should be broken and the air holes situated in the core region should be consisting of different diameters¹⁴. By using different diameter air holes present in the core region (elliptical air holes) high amount of birefringence can be obtained. It could be difficult to fabricate the fiber which consists of more number of air hole rings in the cladding region. But the use of more number of rings or elliptical air holes cannot be controlled when fabricating the fiber¹⁵.

To construct PCF's possessing lower effective mode areas which will have a higher nonlinear coefficient is challenging task. By designing the diameter of the air holes present in the cladding region or by adjusting the pitch (center to center distance between two adjacent air holes) the effective mode area which is required can be obtained. Earlier^{16,17} it has already been proved that PCF's possessing nonlinear coefficient around 30 and 44 $W^{-1}Km^{-1}$, respectively at 1.55 μm operating wavelength can be constructed. Here the pitch is kept very small around 0.9 μm which could be difficult for fabrication.

Normalized frequency which can also be known as V parameter is another very important property in the design of the PCF¹⁶. The mode with which the fiber is designed fiber should be known. Generally the PCF are operated in the single mode. For the PCF to work in single mode the value of normalized frequency should be less than 2.405 compared to¹⁷. Normalized frequency depends on the hole to hole spacing of the fiber so by keeping the hole to hole spacing less the normalized frequency can be

obtained as per requirement¹⁸. Single mode fibers possess very low bending losses.

In today's world PCF's providing very high birefringence as well as high nonlinear properties are being sought out in the telecommunication applications^{18,19}. Earlier it has been proved that it is possible to design the PCF's which provides high birefringence in the range of 10^{-3} at 1.55 μm of operating wavelength. These type of PCF's which possess high birefringence as well as high nonlinear coefficient are used for the Optical Code Division Multiple Access (OCDMA) applications. PCF's with tapered structures are also reported recently²⁰.

Many applications require the PCF's to have very high birefringence, low bending losses as well as very high nonlinear coefficient simultaneously. Bending losses are considered very crucial in the telecommunication applications²¹. Bending the fiber has always been crucial for the development of the PCF's. As the fiber is bent the electric field profile of the PCF's would be moving towards the direction of the bending and therefore bending losses occur into the PCF. As there are number of air hole rings present around the core region of the fiber it would be simple to produce better refractive index profile than the conventional optical fiber by keeping the diameter of these air holes as per our convenience^{22,23}. As far as the bending is considered, the bending losses can well be reduced to such an extent by adjusting the hole to hole spacing and by adjusting the diameter of the air holes present in the core region. Since the number of air holes present are finite it is impossible to avoid the leakage of the mode field from the central core region to the outer cladding region. By using more number of air holes in the cladding region the bending losses can be reduced to certain extent²⁴.

Effective Mode Field Area (MFA) is considered another very important property of the PCF. The smaller the effective mode field area the smaller would be the bending losses of the PCF. Smaller effective mode field areas provides positive effect on the bending losses. Effective mode field area is the area which a fiber is covering in the transverse dimensions. Smaller effective mode field area would give high nonlinearity in the PCF. Highly nonlinear PCF's are in much demand nowadays. Lower effective mode field area would be giving high power density which is important for highly nonlinear properties to be significant. With the help of the PCF's having very high nonlinearities the supercontinuum can be produced that too with very low pumping power. Smaller effective mode

field areas are very much important since it would make the PCF more insensitive towards the bending. Small effective mode field areas has been of great importance because it will be having positive effect on the bending losses.

A fiber designed by²⁵ would be showing less loss till the fiber is bent to 5 mm of bending radius but if the fiber is bent beyond 5 mm then the losses would become sufficiently high.

This paper proposes a new structure of PCF which can easily be bent to the bending radius as small as 3 mm. The core region of the fiber is obtained by removing two air holes from the center and different air hole diameters are used for the core region air holes as well as for cladding region air holes so that to reduce the bending losses of the fiber. It is designed to provide very low loss in the range of 0.075 to 0.085dB/m when the fiber is bent as small as 3 mm. Hence the designed PCF is advantageous over existing conventional single mode fibers since it shows low losses.

2. Theoretical Analysis

The proposed fiber is designed for being insensitive to the bending. Figure.1 is showing the topological structure of the designed PCF. In the designed structure the first row in the design is moved towards right by $\frac{a}{2}$ and also different diameters have been used for the core region air holes as well as for cladding air holes. Additionally the hole to hole spacing is adjusted such that to achieve high birefringence and low bending losses. In the design shown in this paper less number of air hole rings are used so that it would be suitable for fabricating the fiber. The fiber is designed in such a way that it should possess high birefringence, low bending losses, low effective mode field area and high nonlinear coefficient. This paper would be depicting the innovative design of highly birefringent bending insensitive nonlinear PCF. High birefringence can be obtained by breaking the symmetry of the fiber such as by using elliptical air holes in the core region. So for making the structure asymmetric the central row in the design is moved to the right by $\frac{a}{2}$. Adding to that the diameter size along the core region of the designed fiber differs from one another. Each and every air hole in the cladding region is having similar diameter but again the extremely last row of air holes in the cladding region are having

higher diameter than the others so that to decrease the losses. The proposed PCF can be designed by conventional stack and draw method but generally the stack and draw method has some drawbacks like it could only be used for designing the structures possessing triangular or honey-comb like core region. So sol-gel based fabrication method is more suitable as it is having wide range of applications and it would be possible to design structures which would possess the core region apart from triangular or honey-comb shape. It is also proved that it is very much possible to design bending insensitive fiber which would be showing very low bending losses for as much less bending radius as possible.

Finite Element Method (FEM) is used for obtaining the real component of the effective refractive index where the light is confining at the particular wavelength. The FEM method is widely used because of its simplicity and user friendly nature²⁶⁻²⁹. By Perfectly Matching (PML) all the layers the properties could be investigated as per requirement³⁰. The PML is another additional layer used to match all the other layers, it acts as the boundary region for the designed fiber. These PML layers are useful for obtaining the imaginary part of refractive index profile which is required for calculating the bending loss of the fiber. The silica refractive index is taken as 1.45 while that of the air holes is 1.

Practical use of designed fiber would require the fiber to be bent. While bending the fiber the effective index profile of the fiber would be moving towards the direction of the bend that leads to the bending losses. While calculating the bending losses the PML is needed to be used for obtaining the imaginary part. The following equation shows how to apply the bending to the fiber

$$n_{eff}(x, y) = n(x, y) \left(1 + \frac{x}{R_{bend}} \right) \quad (1)$$

where $n(x, y)$ is the original refractive index profile of the PCF, R_{bend} is bending radius, and x is the distance from the center of the PCF. Because of the bending, there is difference between the refractive index of the outside cladding and the inside cladding.

The effective mode field area is related to the size of the core region of the fiber. The effective mode field area is obtained by the following equation as shown

$$A_{eff} = \frac{\left(\iint_S |E_t|^2 dx dy\right)^2}{\iint_S |E_t|^4 dx dy} \mu m^2 \tag{2}$$

where E_t denotes the electric field vectors and S is the whole cross section of the PCF. The effective mode field area should be less so that to get lower bending losses. The formula for calculating the bending loss L_b is as given as

$$L_b = \frac{2 \times \pi \times 8.686 \times I_m(n_{eff})}{\lambda} dB / m \tag{3}$$

where n_{eff} is the wavelength dependent effective index, $I_m(n_{eff})$ is coefficient of the imaginary part of n_{eff} , and λ is the operating wavelength respectively.

The nonlinearity can be obtained by the equation

$$\gamma(\lambda) = \frac{2\pi \times n_2}{\lambda \times A_{eff}(\lambda)} \tag{4}$$

Where the A_{eff} effective mode field area, n_2 is the non-linear refractive index coefficient and its value is $n_2 = 2.76 \times 10^{-20} m^2 / W$

To determine the normalized frequency also called as the V parameter, the refractive index difference between the core and cladding along with the hole to hole spacing and wavelength are considered. The normalized frequency of the fiber can be calculated from the equation given as

$$V_{eff} = \frac{2\pi \Lambda}{\lambda} \sqrt{n_{core} - n_{eff}} \tag{5}$$

where Λ is the hole to hole spacing, n_{core} is the refractive index of the core region, n_{eff} is the refractive index profile at the particular wavelength.

3. Proposed Structure

Figure.1 shows the schematic cross section of the proposed PCF with a rectangular core, different diameters of the air holes are used along the axis of the core region as well as for the cladding region.

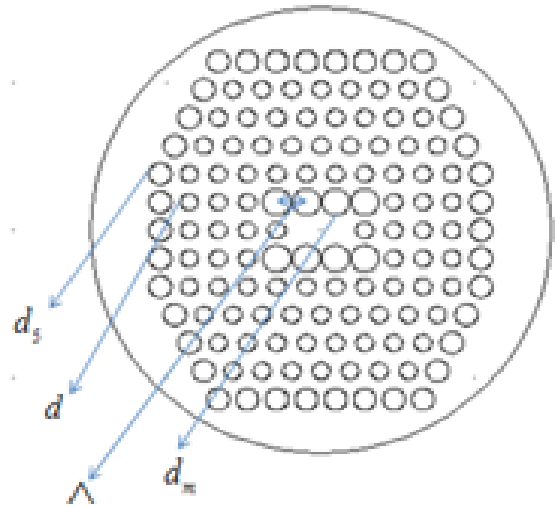


Figure 1. Cross-section of the proposed PCF, $d_m/\Lambda = 0.941$, $d/\Lambda = 0.588$, $d_s/\Lambda = 0.764$.

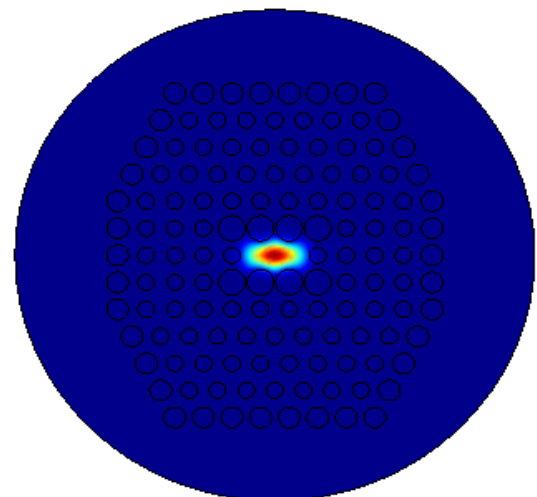


Figure 2. The Electric field distribution of the PCF at 1550 nm wavelength.

4. Results

Figure.3 shows the dependence of bending loss with respect to the bending radius for different pitches. It is observed from the Figure.3 that by decreasing the pitch the bending loss is decreasing. When the pitch is less, then the refractive index contrast between the core and the cladding is less and so the losses are less. It can also be said from Figure.3 that even though we bend the fiber to bending radius as low as 3mm then also the bending losses of the fiber are very less.

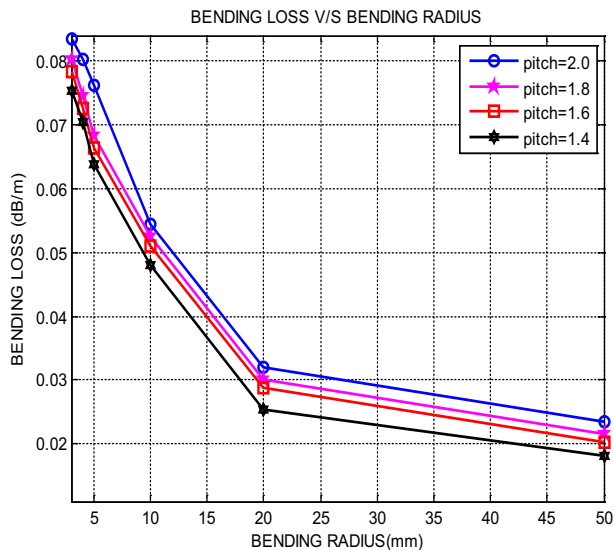


Figure 3. Bending loss dependence with bending radius for different pitch values.

Figure.4 shows the relationship of the bending loss with respect to the bending radius for different angular orientations of the core region. It is observed from the Figure.4 that by increasing the angle the bending loss in the fiber is increasing but still the loss is very less. The angular orientation of the fiber are along the direction of the bending plane where the pitch is 1.9 μm and the operating wavelength is 1550 nm. The angular orientations of the fiber are having very crucial effect on the losses of the fiber when the fiber is bent. By increasing the bending radius the effect of angular orientation is increasing. The effect of angular orientation depends on the size of the core region. When the pitch is high or the size of the core region is more, then the effect of angular orientation becomes almost same for all bending radius.

Compared with the reference paper²⁴ the proposed structure in this paper possesses very less bending losses in the range of 0.075-0.085 dB/m at the bending radius of 3 mm. The PCF in reference paper²⁴ was bent till 5 mm the losses were low but by bending the fiber below 5 mm there would be increase in the losses. This property has been overcome in this paper. Along with low losses this PCF in this paper produces high birefringence, low effective mode field area, high non-linearity and single mode operation. Also in this paper effects of angular orientation along the direction of bent is observed.

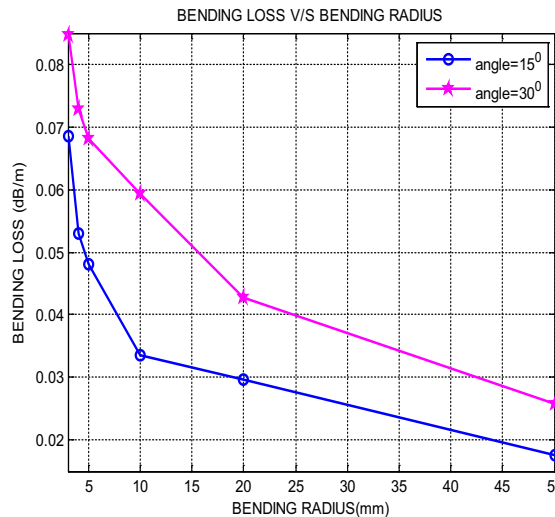


Figure 4. Bending loss dependence with bending radius for different angular orientation.

Figure.5 depicts the relationship of the birefringence with respect to the wavelength for different pitches. It can be observed from the Figure.5 that when the pitch is increasing the birefringence is decreasing, but still the birefringence is as high as in the range of 10^{-3} . It can also be said that the birefringence is very much dependent on the wavelength. As the wavelength is increasing the birefringence is increasing. The fibers having high birefringence can be used in super-continuum generation applications. For achieving the high birefringence the hole to hole spacing should be less.

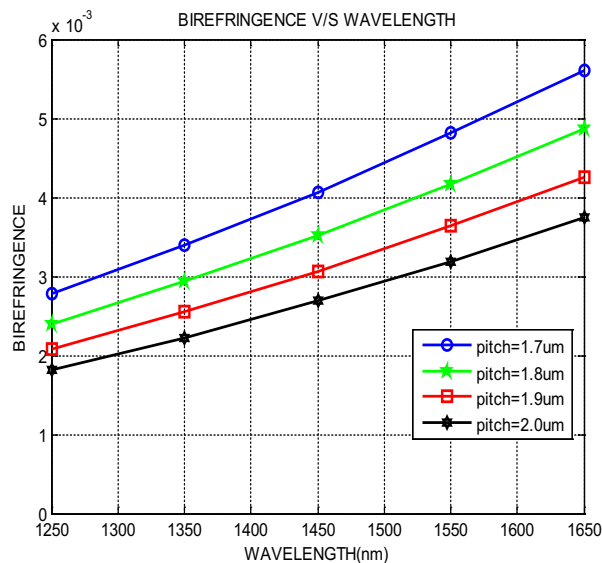


Figure 5. Birefringence variation with respect to the wavelength.

Figure.5 shows that by further decreasing the hole to hole spacing higher birefringence can be obtained than the Figure.6 . Here the birefringence as high as in the order of 10^{-2} can be achieved. When the hole to spacing is 1.1 μm and the operating wavelength is 1550 nm the birefringence as high as 0.013177 can be achieved. The birefringence increases by increasing the wavelength. These highly birefringent PCF's can be used for supercontinuum generation applications. The power required for generating different supercontinuum would be very less than the non-birefringent PCF's. Asymmetrical PCF structures induces high birefringence in the order of 10^{-2} at 1550 nm.

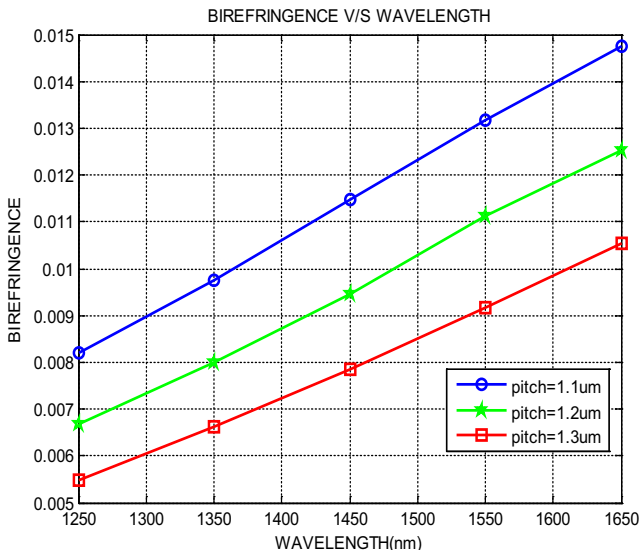


Figure 6. Birefringence variation with respect to the wavelength.

Figure.7 shows the relationship of the effective mode area with respect to the wavelength for different hole to hole spacing. It is observed from the Figure.7 that by increasing the hole to hole spacing the effective mode area of the fiber is increasing and also by increasing the wavelength, the effective mode area of the fiber is increasing. The effective mode areas of the PCF's at the wavelength of 1550 nm are much less than that of the conventional fiber. When the effective mode area is less it helps in increasing the nonlinearity of the fiber.

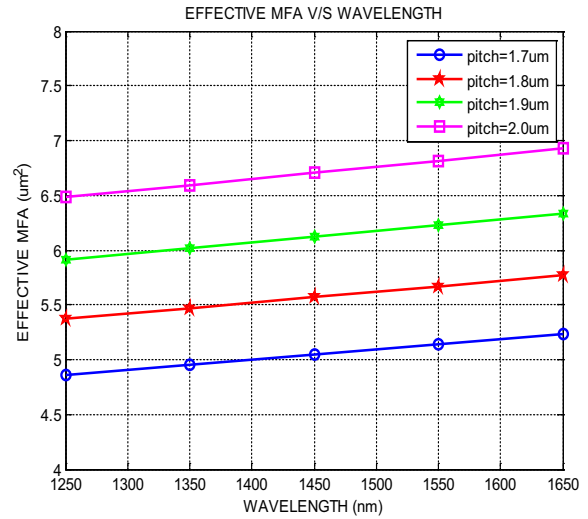


Figure 7. Variation of effective mode area of the fundamental mode with respect to wavelength.

Figure.8 shows that by further decreasing the hole to hole spacing the effective mode areas as less as possible can be achieved. It is observed from the Figure.8 that by increasing the wavelength the effective mode area increases steadily. Further by increasing the hole to hole spacing the effective mode area can be increased but still the effective mode area is very less.

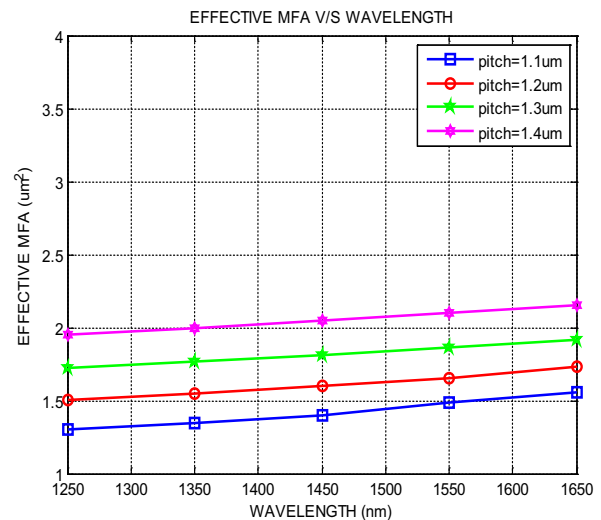


Figure 8. Variation of effective mode area of the fundamental mode with respect to wavelength

Figure.9 is showing the relationship of the nonlinearity γ with respect to the wavelength for different hole to hole spacing.

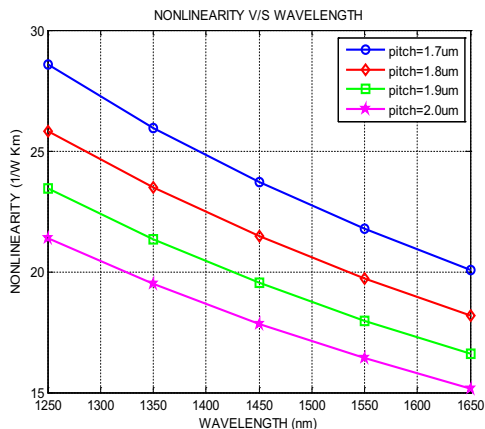


Figure 9. Variation of nonlinearity of the fundamental mode with respect to wavelength.

It is observed from the Figure.9 that by increasing the hole to hole spacing the nonlinearity is decreasing.

The nonlinearity and the effective mode area are inversely proportional to each other. Similarly by increasing the wavelength the nonlinearity is decreasing. It can be observed from Figure.9 that the nonlinearity is $21.76 W^{-1} Km^{-1}$, when the pitch is $1.7 \mu m$ and the operating wavelength is 1550 nm . As the designed PCF is having very less effective mode area it can be said that it is insensitive to bending. Small effective mode area possesses positive effect on the bending loss of the fiber⁹.

Figure.10 shows that by further decreasing the hole to hole spacing the higher nonlinearity can be achieved. It can be said from the Figure.10 that when the hole to hole spacing is $1.1 \mu m$ and the operating wavelength is 1550 nm then the nonlinearity as high as $75.2 W^{-1} Km^{-1}$ is achieved. Such highly nonlinear fibers can be used for soliton pulse transmission applications^{7,9}. By increasing the hole to hole spacing and the wavelength the nonlinearity decreases steadily.

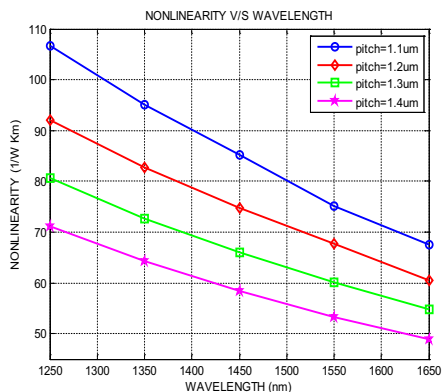


Figure 10. Variation of nonlinearity of the fundamental mode with respect to wavelength.

Figure.11 shows the relationship of the normalized frequency or V parameter with the operating wavelength for different hole to hole spacing. From the Figure.11 it is observed that by decreasing the hole to hole spacing and by increasing the wavelength, the normalized frequency value is decreasing. For the PCF to be operating in the single mode the value of normalized frequency should be less than 2.405. Figure.11 suggests that for all hole to hole spacing the normalized frequency value is less than 2.405 and so the PCF designed in this paper is endlessly single mode fiber.

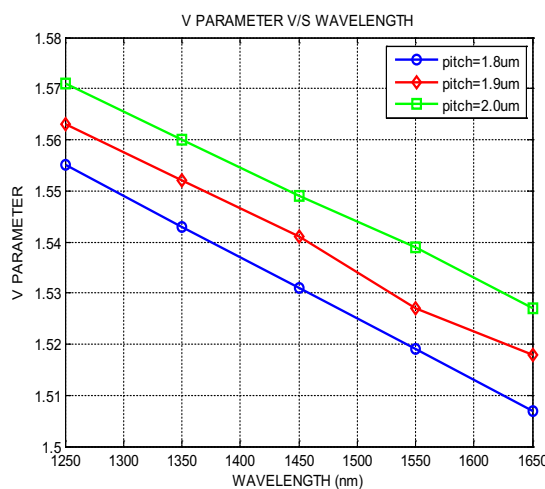


Figure 11. Variation of V parameter of the fundamental mode with respect to wavelength.

5. Conclusion

The bending insensitive PCF has been designed precisely in this paper. The PCF shows very low losses even for bending of 3 mm. Angular orientation effects along the direction of bending is also thoroughly observed. Even though the fiber is bent having some angle along the direction of bending the PCF shows very low losses. The designed PCF also provides very high birefringence, low effective mode field area, high nonlinearity and extensively single mode operation. The low effective mode field area leads to less bending losses. The proposed PCF in this paper is insensitive towards bending. Due to the presence of less number of air holes in the cladding region it is easy to fabricate the PCF designed in this paper.

6. References

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