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A novel design of photonic crystal fiber containing square holes in a square lattice with high dispersion tolerance, flattened dispersion and low effective mode area

S. TIWARI[a], B. K. SINGH[a], G. G. SONI[b], P. C. PANDEY[a,*]
[a]*Department of Physics, Indian Institute of Technology (Banaras Hindu University), Varanasi-221005, Uttar Pradesh, India*
[b]*Department of Applied Physics, SGS Institute of Technology & Science, Indore – 452003, Madhya Pradesh, India*

A unique photonic crystal fiber (PCF) which consists of circular core surrounded by square lattice cladding is presented. The square lattice cladding further consists of square-shaped air holes. Flattened chromatic dispersion (D) is obtained for this structure in the C and L communication bands at different values of the ratio of square hole width to the pitch (d/Λ) of the PCF. The main advantage of this structure is its high dispersion tolerance capability for change in the distance between core and square holes cladding (d^1). There is observed only about 2.4 ps/nm-km variation in D for -5 to +5% change in d^1. Effective mode area has been obtained for this PCF structure which comes out to be small enough to make this fiber suitable to be used in non-linearity related applications.

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1. Introduction

Photonic crystal fibers have proved to be advantageous in many respects than the conventional optical fibers. PCF structure contains an array of air holes as part of its cladding which distinguishes it from the conventional optical fibers [1,2] which have only a core and cladding or a combined core and cladding in case of multi-mode graded index fiber. There are two types of PCF based on light guidance inside the core, one works on effective index method and the other on photonic band-gap (PBG) effect. The PCF with effective index guiding phenomena consists of solid core while the other type of PCF based on PBG consists of hollow core. In the effective index based guidance of light the mechanism is similar as compared to the guidance of light in conventional single-mode optical fibers. In this case, there is a modified total internal reflection (M-TIR) in the PCF since the refractive index of cladding keeps changing with the wavelength applied. The core region has a higher refractive index as compared to the composite refractive index of cladding in this type of PCF. Usually pure silica with refractive index 1.45 is used to make the core of these PCF’s but other glasses or materials of higher refractive index could also be used to make the core for proper light guidance. These kind of PCF’s show unique properties such as atypical dispersion exhibition over visible and near infra-red range [3,4], transportation of ultra-short pulses and with-standing a wide range of wavelengths. Considering the other type of PCF which is based on PBG guidance mechanism, the core has a lower refractive index as compared to the effective refractive index of surrounding cladding [5]. There is a PBG effect in the two dimensional photonic crystal cladding which does not allow light in certain wavelength range to propagate through it. This PBG effect can also be seen in nature, for example the beautiful color combination visible on peacock feathers and butterfly wings is a result of the same. If light is guided into the air core of PBG guidance based PCF, the PCF can provide many favorable applications such as low loss guidance and high-power beam delivery [6] without any damages to the fiber. These types of PCF are almost insensitive to bending even for very sharp bends subjected to the fiber. Filling the hollow air core with liquids or gases can make these fibers to be used as sensors [7-9].

PCF’s made of pure silica show very low losses and can handle high temperatures also. The core of the PCF containing pure glass or air has an advantage over the doped or impure material used for core fabrication. PCF’s have been a center of interest for a variety of applications which include sensing, data communications and signal processing [10]. The cladding of PCF may consist of hexagonal, triangular or square lattice arrangement of air-holes. Further, the shape of the air-holes in the cladding could be modified from the conventional circular shape to elliptical, square or rectangular.

In this paper, we have proposed a PCF consisting of square holes arranged in a square lattice configuration, known as cladding with a large circular core at the center as shown in Fig. 1. The dispersion properties of PCF with circular holes arranged in a square lattice cladding were first studied by Bouk et. al [11]. They obtained the values of dispersion parameter (D) as negative at pitch, $\Lambda=1\mu m$

and positive at Λ=2 and 3 µm respectively. The first PCF structure to use square holes in a square lattice structure was studied by H.D. Inci et. al [12]. They compared two structures with circular and square shaped holes arranged in a square lattice cladding. They obtained lowest value of D equal to -80 ps/nm-km at approximately 0.8 µm wavelength and got positive values of D for the communication wavelength 1.55 µm in both circular and square hole structures. They used different d/Λ values ranging from 0.1 to 0.9 for the calculation of the values of D. In our case, we have got negative values of D at different values of d/Λ ranging from 0.33 to 0.47, with lowest value of D equal to -157 ps/nm-km at 1.6 µm wavelength. Also, we obtained negative values of dispersion at and around 1.55 µm wavelength. The major difference in our structure as compared to [12] is, we have incorporated a solid circular core of pure flint glass having refractive index equal to 1.6177. The core can be easily fabricated while making the PCF by stacking a solid flint glass rod at the centre of other hollow silica rods in the preform. We have achieved a flattened dispersion for the C band (1530-1565 nm) as well as L band (1570-1610 nm) combined together. The flattening in dispersion is best achieved for the ratio of d/Λ =0.47. The most important advantage of this structure which we have shown in this paper is its high dispersion tolerance capability. As we change the distance between the core to the first air-hole ring (d^1) by ±1%, ±2% and ±5%, there is very little change observed in the dispersion parameter values. If we consider dispersion tolerances in [13-15], we have achieved more robust and insensitive structure considering fabrication aspect of PCF. Lastly we have calculated the values of effective area (A_{eff}) for different ratios of d/Λ at wavelengths ranging from 1.4 µm to 1.8 µm.

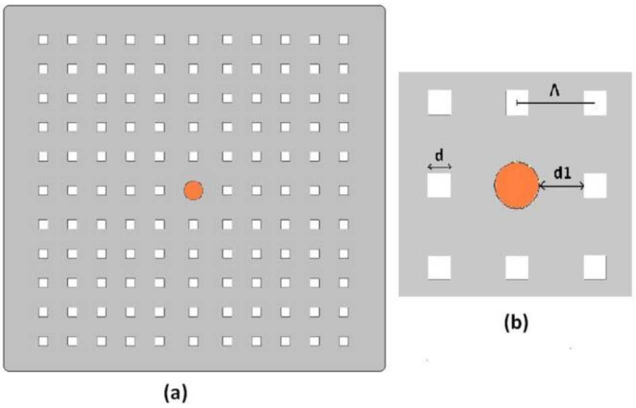

Fig. 1. Transverse cross-section of the (a) Designed PCF with 5 air-hole rings around a solid circular core. (b) Inner core with first air hole ring showing pitch Λ, square hole width d and distance between first ring and core as d^1.

2. Fiber design

The PCF structures which were proposed initially and which are most commonly studied are based on hexagonal and triangular lattice arrangement of holes in the cladding. A lot of research has been done on the optimization of the structure of PCF for improved applications [16-18]. High negative dispersion has been achieved in PCF by modifying the structural parameters [19-20]. Mainly we can control two parameters of PCF which are air-hole size in the cladding region and the distance between those air-holes called pitch. Besides hexagonal and triangular lattice, a PCF structure can also be fabricated based on square or rectangular lattice configuration in the cladding. Talking about the holes in the cladding, they can be fabricated with different types of shapes which include circular, elliptical, square or rectangular. A lot of work has been done on hybrid structure PCF's which contain a combination of the above mentioned lattice and hole types [21,22]. We have used square shaped-holes in our structure embedded in a square lattice configuration. As per our knowledge this type of structure is only studied once by [12]. They studied the properties of 4 ring air-hole PCF structure which was created obtained by omitting the first ring of air-holes close to the centre. In our structure, we have taken 5 rings of air-holes with one central solid core of pure glass (flint) with higher refractive index. The refractive index of this glass, found in nature varies from 1.6-1.62 and for our work we have carefully chosen the refractive index as 1.6177 as at this value there is better guidance of the fundamental mode in the core region. The core diameter is taken as 2.4 µm and the side of the square-shaped air holes is taken to be 1.2 µm. The distance between the centre of air holes (Λ) is made equal to 3.6 µm.

3. Chromatic dispersion

Chromatic dispersion is a major factor which causes pulse broadening in optical fibers. It is composed of material and waveguide dispersion. The chromatic dispersion (D) of PCF is given by the equation:

$$D = D_m + D_w$$

Here, D_m stands for material dispersion and D_w is the waveguide dispersion. Interaction of different wavelengths with ions, molecules or electrons in a material generates material dispersion. While waveguide dispersion depends on the structure of the PCF specifically the size, arrangement of air-holes in the cladding and the refractive index contrast between that of core and cladding. The equation for material dispersion (D_m) is given by –

$$D_m = -\frac{\lambda}{c}\,\frac{\partial^2 (n_m)}{\partial \lambda^2} \tag{1}$$

And that for waveguide dispersion (D_w) is given by –

$$D_w = -\frac{\lambda}{c}\,\frac{\partial^2 [\mathrm{Re}(n_{eff})]}{\partial \lambda^2} \tag{2}$$

In the equations (1) and (2), λ is the wavelength of light used, n_m is the refractive index of material, Re (n_{eff}) is the real part of n_{eff} where n_{eff} is the effective refractive index and c is the velocity of light. The material dispersion can be calculated by using the Sellmeir equation [23]. In this paper material dispersion is not taken into account since we are emphasizing on the geometrical structure. The value of Re (n_{eff}) for the calculation of chromatic dispersion is obtained by using a fully vectorial finite element method [24]. A latest version 4.4 of commercial software Comsol has been used for this purpose.

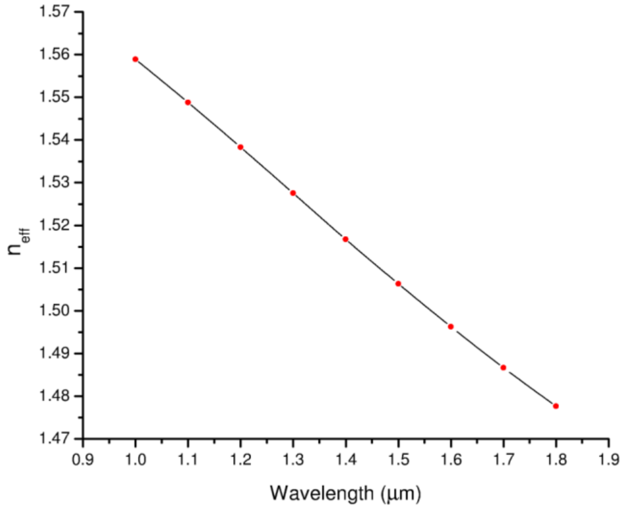

Fig. 2. Effective refractive index of the PCF with Λ=3.6 μm plotted against wavelength.

A graph of n_{eff} vs λ has been plotted in Fig. 2 which shows a line with linearly decreasing slope. Using the values of $n_{eff,}$ dispersion parameter values have been calculated which are plotted against wavelength in Fig. 3. The graph shows a negative dispersion slope between 1.0 to 1.6 μm wavelengths. At 1.6 μm the value of D is lowest which is equal to -157.17 ps/nm-km. Now the pitch of the structure is changed to get different d/Λ values keeping the width of air-hole constant, equal to 1.2 μm. D is calculated for these d/Λ values and graphs are plotted between D and λ in Fig. 4 keeping the wavelength scale on X-axis from 1.3 to 1.8 μm for better image resolution in the flattened dispersion regime. Decrease in negative dispersion is visible with increase in the d/Λ ratio of the structure from 0.33 to 0.47. Dispersion flattening is observed as the d/Λ ratio increases and variation in D is only about 5 ps/nm-km for d/Λ = 0.47 in the C and L communication bands combined.

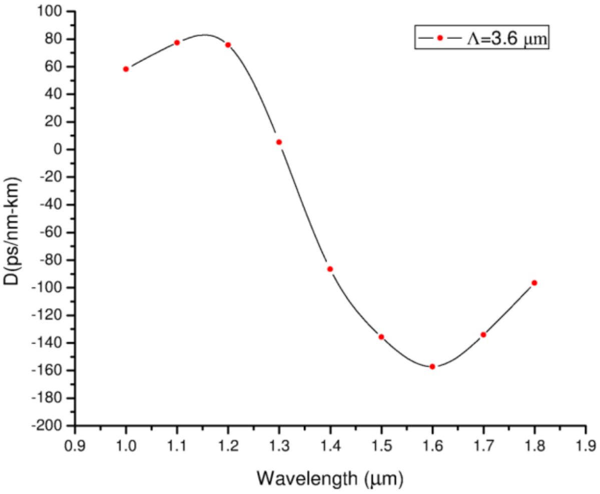

Fig. 3. Dispersion properties of the PCF with Λ=3.6 μm.

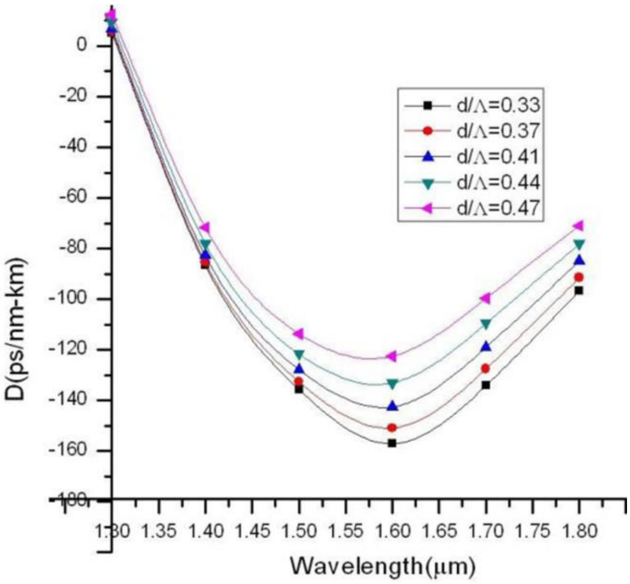

Fig. 4. Dispersion properties of the PCF with different values of d/Λ keeping square-hole width d=1.2 μm as constant.

4. Dispersion tolerance

At the time of fabrication of PCF's, there is a preform used which is composed of silica rods stacked together [10]. A chance of ±1% to ±2% variation in the distance between cladding holes from the center of the fiber may occur at the time of drawing of the fiber. In our structure since the central core is fixed, distance d^1 is taken from the core circumference to the starting point of the cladding air-holes (first air-hole ring). This distance is varied by ±1%, ±2% and ±5% through adjusting the location of air-hole cladding with respect to the core. The distance between the center of two adjacent air-holes known as pitch (Λ) is kept fixed at 3.6 μm when changing of the distance d^1 is done. Now since dispersion is dependent on the relative distance of cladding with respect to the core, there is a possibility of change in the dispersion parameter values with change in d^1. Fig. 5 shows graphs plotted between dispersion and wavelength by varying d^1 from ±1 to ±5%. It is deduced from the above mentioned figure that for -1 to +1% variation in d^1 there is 0.5 ps/nm-km change in dispersion for the wavelength range 1.4 to 1.6 µm. For -2 to +2%, -5 to +5 % change in d^1 there is observed about 0.8 and 2.4 ps/nm-km change in dispersion value respectively in the same wavelength range. Our structure is better in terms of fabrication tolerance than most of the other structures including [13,14] in which dispersion tolerance graphs are plotted by varying the global diameter (diameter of air-hole rings) of mixed structure PCF's. In our work we have varied d^1 which is equivalent to the variation of global radius as our core size is fixed.

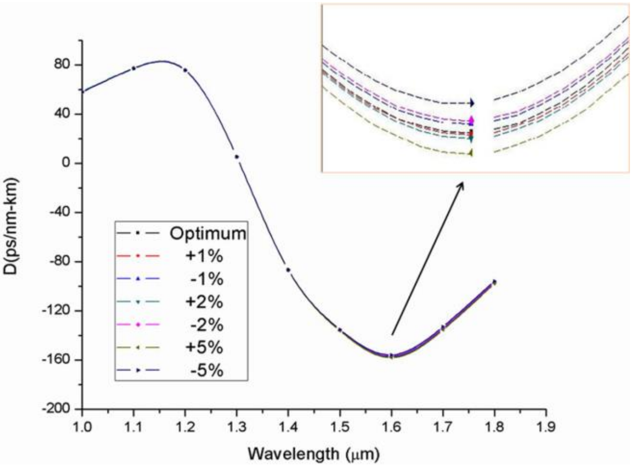

Fig. 5. Dispersion properties of PCF: Values of D calculated at d^1, ±1 - 5% variation in d^1 and plotted against wavelength. Insat shows zoom image of the specific graph portion situated at the starting point of arrow.

5. Effective area

The effective area for a PCF structure can be evaluated by using the equation

$$A_{eff} = \frac{(\int\int |E|^2 \, dxdy)^2}{\int\int |E|^4 \, dxdy} \qquad (3)$$

In the above equation E is the electric field applied to the structure at the core and dx, dy are the transverse components of surface area of the input end of PCF. Effective area is a measure of the area covered by the fundamental mode propagating in the fiber and it keeps increasing with the increase in the operating wavelength. Fig. 6 shows graphs plotted between A_{eff} and λ for different values of d/Λ. At d/Λ =0.33 the value of A_{eff} is 4.83 µm^2 which keeps decreasing with the increase in the ratio of d/Λ and A_{eff} is obtained to be 4.75 µm^2 for d/Λ=0.47. This effective area is small enough to provide high values of non-linear coefficient (γ) as γ is inversely proportional to $A_{eff.}$ The high values of γ make this fiber suitable to be used in non-linear optics, super continuum generation and soliton pulse propagation [27]. Also the fiber becomes more insensitive to bending.

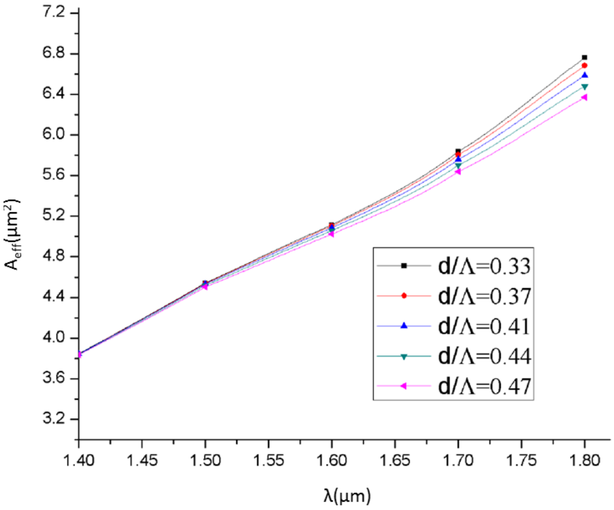

Fig. 6. Variation of effective mode area with wavelength for different values of d/Λ.

6. Conclusions

A novel structure of PCF has been proposed in this paper based on square holes in a square lattice cladding with a solid circular core. Simulation results show that negative dispersion has been achieved for wavelengths in the range of 1.3 to 1.8 µm and beyond for this structure. A flattened dispersion with maximum variation of 5 ps/nm-km is obtained for C and L band combined together i.e. from 1530-1610 nm for d/Λ ratio=0.47. The distinctively significant feature of this structure is it's high dispersion tolerance capability at the communication wavelength of 1.55 µm. There is only 2.4 ps/nm-km change in dispersion observed by variation in d^1 from -5 to +5%.

References

[1] J. C. Knight, Nature **424**, 847 (2003).
[2] Philip Russell, Science **299**, 358 (2003).
[3] J. C. Knight, J. Arriaga, T. A. Birks, A. Ortigosa-Blanch, W. J. Wadsworth, P. St. J. Russell, IEEE Photon. Technol. Lett. **12**, 807 (2000).
[4] A. Ferrando, E. Silvestre, P. Andres, J. J. Miret, M. V. Andres, Opt. Express **9**, 687 (2001).
[5] J. C. Knight, J. Broeng, T. A. Birks, P. St. J. Russell, Science **282**, 1476 (1998).
[6] G. Humbert, J. Knight, G. Bouwmans, P. Russell, D. Williams, P. Roberts, B. Mangan, Opt. Express **12**, 1477 (2004).
[7] John M Fini, Meas. Sci. Technol. **15**, 1120 (2004).
[8] Yi Zhang, Chao Shi, Claire Gu, Leo Seballos, Jin Z. Zhang, Applied Physics Letters **90**, 1935041 (2007).
[9] W. Jin, H. F. Xuan, H. L. Ho, Meas. Sci. Technol. **21**, 094014 (2010).

[10] F. Poli, A. Cucinotta, S. Selleri, Springer Series in Materials Science, 102 (2007).
[11] H. Bouk, A. Cucinotta, F. Poli, S. Selleri, Optics Express **12**, 941 (2004).
[12] Halime Demir Inci, Sedat Ozsoy, Optical Materials **35**, 205 (2012).
[13] M. I. Hasan, M. Selim Habib, M. Samiul Habib, S. M. Abdur Razzak, Optical Fiber Technology **20**, 32 (2014).
[14] Md. Imran Hasan, M. Samiul Habib, M. Selim Habib, S. M. Abdur Razzak, Photonics and Nanostructures – Fundamentals and Applications **12**, 205 (2014).
[15] Md. Selim Habib, Md. Samiul Habib, S. M. Abdur Razzak, Md. Anwar Hossain, Optical Fiber Technology **19**, 461 (2013).
[16] K. P. Hansen, Optics Express **11**, 1503 (2003).
[17] L. P. Shen, W. P. Huang, G. X. Chen, S. S. Jian, IEEE Photon Technol Lett **15**, 540 (2003).
[18] Yejin Zhang, Sigang Yang, Shizhong Xie, Wanghua Zheng, Chen Lianghui, Microwave and Optical Technol Lett, **50**, 1073 (2008).
[19] R. K. Sinha, Shailendra K. Varshney, Microwave and Optical Technol Lett, **37**, 129 (2003).
[20] Ming Chen, Qing Yang, Tiansong Li, Mingsong Chen, Ning He, Optik **121**, 867 (2010).
[21] Lin Zhao, Zhonghua Su, Yong Hao, Optik **124**, 6574 (2013).
[22] Soan Kim, Chul-SikKee, Chung Ghiu Lee, Optics Express **17**, 7952 (2009).
[23] A. Ghatak, K. Thyagarajan, Introduction to Fiber Optics, Cambridge University Press (1998).
[24] Yan-feng Li, Ching-yue Wang, Ming-lie Hu, Optics Communications **238**, 29 (2004).
[25] G. P. Agarwal, Non-Linear Fiber Optics, Academic Press (2001).

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[*] Corresponding author: pcpandey.app@iitbhu.ac.in