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DUAL CORE PHOTONIC CRYSTAL FIBER WITH HIGH NEGATIVE DISPERSION AND LOW COUPLING LENGTH

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ABSTRACT

In this paper we presented a dual core Octagonal shape Photonic Crystal Fiber to achieve a high negative dispersion coefficient of -1650 ps/ns/km at a communication wavelength 1550nm. The effect of structural parameters on birefringence, dispersion and the coupling length of designed fiber is analyzed using coupling mode theory and the full-vector finite element method (FEM). In the cladding region, the air hole diameter is reduced to achieve a high negative dispersion coefficient. This design support single- endless transmission over a wide wavelength range of 1350-1750nm including S, C, L bands of communication system. This dual core PCF design achieved a short coupling length in the range of (32-36) µm and a birefringence value in the order of 10^{-3} is also observed.

Keywords: birefringence, coupling length, dispersion, dispersion compensating fiber, normalized power.

INTRODUCTION

Optical fibers are used as communication channel to transmit light waves over a long distance with possibly attaining a minimum loss. It is because the signal gets degraded during the transmission [1]. To solve this problem a new class of optical fiber with highly structured glass and a periodic distribution of air holes along its length is developed called Photonic Crystal Fiber (PCF). A defect region is formed in the center of the fiber through which light can propagate by total internal reflection principle [2-4]. PCF controls the optical properties of the optical fiber such as air hole diameter (d) and hole-hole spacing (Λ) control the dispersion properties, transmission as well as non linear properties. PCF have numerous advantages over conventional fiber some of them are guidance through hollow core (air hole), high birefringence [5], low attenuation, more power transmission, dispersion management and confinement property. But in the design process of PCF some parameter are considered, dispersion is one of the important property which leads to the broadening of individual pulses during propagation causing the overlapping of neighboring pulses. At receiver light pulses get indistinguishable. One way to solve this problem is to use dispersion compensating fiber. It ismost widely used for compensating the dispersion over a transmission link. This improves the transmission length of system without the need of using electronic regeneration of signals [6]. The reason behind having a very large negative dispersion in this dispersion compensating fiber is the coupling between two asymmetric concentric core i.e. inner mode and outer mode. These two modes can be matched by proper design at desired wavelength. There are various dispersion compensation techniques developed[14-17] some are dispersion compensation filters, higher mode order, Fiber Bragg grating, dispersion compensating fiber.In this paper, we designed a dual core octagonal lattice PCF to compensate negative dispersion over a wide wavelength range of 1.35-1.75µm. Such dual core OPCF widely used in dispersion compensation, polarization maintaining optical devices and splitter. It is also used in digitally circuitry such as pulse delay, logic gates, Mux-Demuxetc [7]. The Finite Element Method (FEM) in COMSOL Multi-physics is used as a simulation tool.

PCF DESIGN

Geometrical structure

The cross-sectional geometry of proposed DC-OPCF is shown in Figure-1, in which periodic air holes are arranged in order to form a octagonal lattice. Dual core is formed by removing two air hole neighbors to central air hole. The core is surrounded by big size air holes of diameter (d_1) and a ring of air holes of diameter (d_2) in the cladding region. Our proposed structure combines both asymmetrical core and cladding.

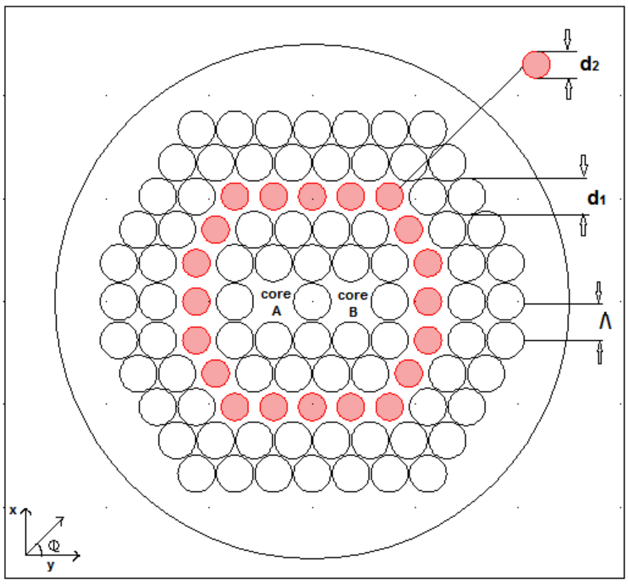

Figure-1. Cross-section of designed DC-PCF.

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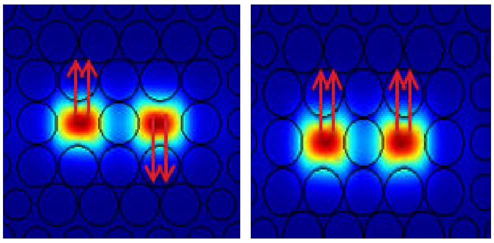
DC-OPCF is analyzed by lattice length (∧), the circular air hole's d_1 and d_2 respectively which control the dispersion, transmission as well as nonlinear properties of PCF. The refractive index of cladding of silica cladding and air is 1.4446 and 1 at 1.5µm respectively. We use Full –Vector Method (FEM) with an anisotropic perfectly matched layer (PML) to evaluate different characteristics of DC-PCF (Dispersion, Bending loss, confinement loss etc). In Figure-2 shows Electric Field distribution of designed structure for x and y mode respectively. The even mode and odd mode of designed DC-OPCF is evaluated and their corresponding x and y polarized electric field distribution is shown in Figure-2 a) and b) respectively, at design parameter of lattice length/pitch (Λ) =0.75µm, d_1=0.72µm, d_2=0.54µm.



a) b)

Figure-2(a-b). Electric Field distribution of x-even and y-odd mode and vectors direction respectively at 1550 nm.

Design process of DC-OPCF consists of the following steps shown in the in Fig. 3. In the first step geometric parameters like size and shape of air holes, no of air hole rings, hole-hole distance and background material are chosen. Then the next step is setting simulation parameter (operating wavelength and field). Mesh analysis is done to by setting boundary condition. Mode analysis refers to evaluation of the DC-PCF guided modes and selecting a well confined mode is performed in the next step. If the simulated result satisfied then carry out further analysis, if not then change the geometrical parameter like air hole diameter, hole-hole distance to obtain desired results.

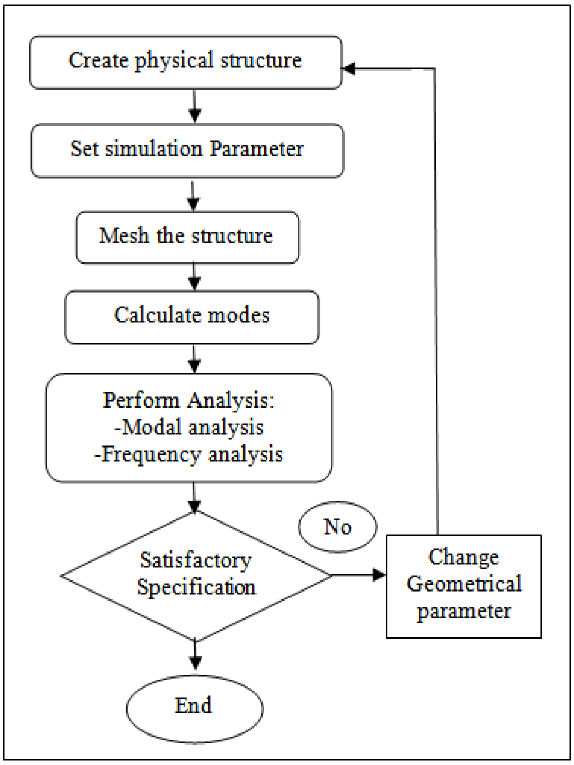


Figure-3. Flowchart of design process of DC-PCF.

Characteristics analysis of DC-OPCF

In case of broadband compensating fiber one of the modes dominates the other in confinement of light such as y-polarized mode has the highest refractive index than x polarized fundamental mode [10]. The birefringence is given by:

$$B = |n_{\text{eff}}^{x} - n_{\text{eff}}^{y}| \quad (1)$$

Where n_{eff}^{x} and n_{eff}^{y} are effective refractive indices of x and y direction.The air hole diameter and lattice length (/\) value affect the modal birefringence. Figure-4(a-b) shows the variation in the modal birefringence for the different values of air hole diameter (d_1) and lattice length (/\) as a function of wavelength.

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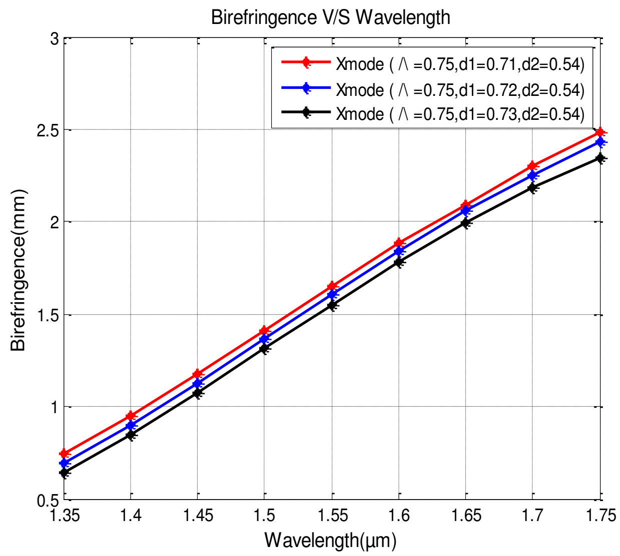

Figure-4(a). The relation between birefringence and wavelength for different values of d_1=0.71, 0.72, 0.73μm.

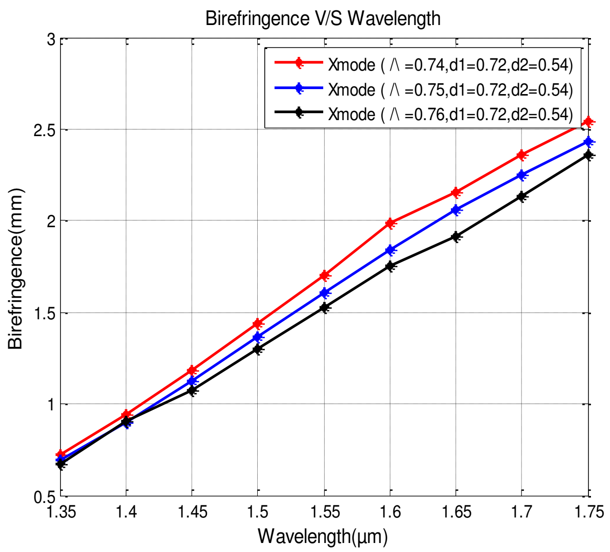

Figure-4(b). The relation between birefringence and wavelength for different values of /\=0.74, 0.75, 0.76μm.

From Figure-4(a-b) it is seen that the birefringence increases with the wavelength.

Dispersion is the vital parameter in the design of the optical transmission system. It is caused due to the propagation delay difference between the different spectral components of transmitted signal causes the broadening of each transmitted mode. Existence of the dispersion in the long distance optical data transmission system broadens the transmitted pulse thereby degrading the signal. It makes the system less reliable. The chromatic dispersion caused by finite spectral line width of the optical source. It is given as:

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

Whereλ is operating wavelength, c is speed of light in vacuum, Re [Neff] is real part of effective mode index. Dispersion in optical fiber can't be removed completely but it can be reduced to a very small value. The idea of using PCF for dispersion compensation (DC) was first proposed by T.A. Birks [8]. Single mode fiber has a positive dispersion, so the fundamental requirement of a DCF for wavelength division multiplexing operation are a large negative dispersion and over a wide wavelengths [9]. There are various dispersion compensating fibers designed having negative dispersion coefficient [15-17]. A high negative dispersion coefficient of magnitude -1650 ps/nm/km is achieved at 1.55μm and -1870ps/nm/km at 1.65μm, by optimizing the parameter at lattice length/pitch (/\) =0.75μm, d_1=0.73μm, d_2=0.54μm shown in Figure-5.

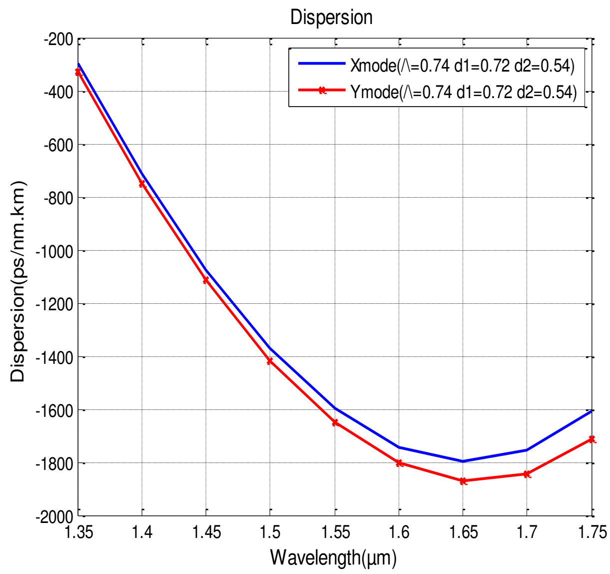

Figure-5. The chromatic dispersion for pitch(/\)=0.75μm, d_1=0.72μm, d_2=0.54μm.

If a fiber link consist of SMF of length LSFM with dispersion DSFM and a DCF of length LDCF and dispersion DDCF then the dispersion compensation condition is given as:

$$D_T = D_{SFM} \times L_{SFM} + D_{DCF} \times L_{DCF} \qquad (3)$$

From equation it is seen that the dispersion compensating fiber have negative dispersion in order to nullify or reduce the dispersion caused by the transmission fiber, The length and the dispersion of the dispersion compensating should be chosen in such a way that $D_T$becomes zero. So to reduce length and cost, fiber is designed to have a high negative dispersion value for Odd mode operation. For dispersion compensation we consideredpitch (/\)=0.75μm, d_2=0.54μm and for different values of d_1. Dispersion value of PCF as a function of wavelength is shown in Figure-6(a) In the spectral range

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of wavelength 1.35μm to 1.65μm dispersion value varies from -200 to -2000 ps/nm/km. Dispersion coefficient decreases as the hole diameter d_1 increases.

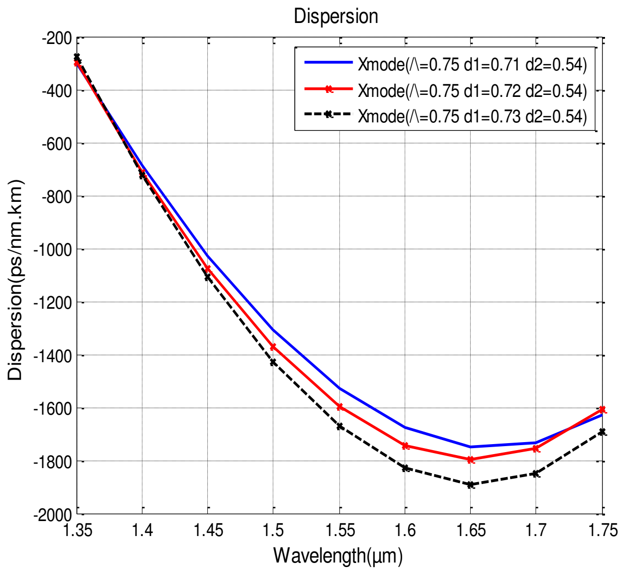

Figure-6(a). The chromatic dispersion as a function of wavelength for pitch(/\)=0.75μm, d_2=0.54μm, d_1=0.71,0.72,0.73μm.

As the diameter of outer ring hole is reduced in order to achieve a high negative dispersion. Figure-6(b) shows the variation of dispersion for different values of d_2 with pitch (/\)=0.75μm, d_1=0.72μm. It is seen that the dispersionnature of graph is similar to that of Figure-6(a) with dispersion value varies between -200 to -2000 ps/nm/km. As $d_2$increase the dispersion value increases.

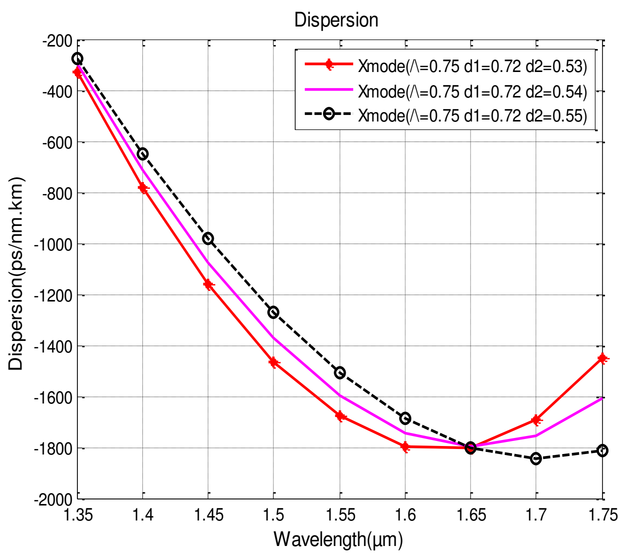

Figure-6(b). The chromatic dispersion as a function of wavelength for pitch(/\)=0.75μm, d_1=0.72μm, d_2=0.53, 0.54, 0.55μm.

Lattice length (pitch) also affects the dispersion coefficient. Figure-6(c) shows the dispersion coefficient as a function of wavelength for different values of lattice length (pitch)/\=0.74, 0.75, 0.76μm. Dispersion decreases as pitch value increases. The dispersion values vary from -200 to 2000ps/nm/km in the range 1.35 to 1.75μm wavelength range. Nature of graph for dispersion versus wavelength for different characteristics is same. By choosing one of parameter dispersion compensation carried out over communication wavelength.

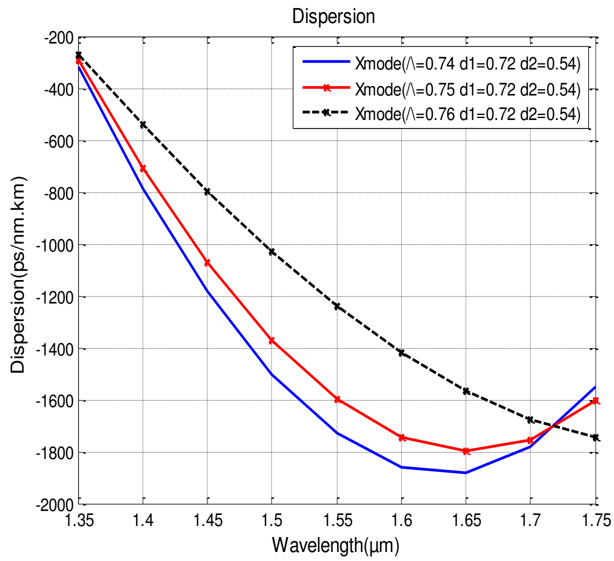

Figure-6(c). The chromatic dispersion as a function of wavelength for pitch(/\)=0.74,0.75,0.76μm, d_1=0.72μm, d_2=0.54μm.

The Nonlinear property of PCFs are playing important role in the field of nonlinear optics. Fibers with high values of effective nonlinearity can reduce device length and the optical power requirement for fiber based on nonlinear optical device. Nonlinearity coefficient γ(λ) is given by

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

wheren_2= $2.8\text{x}10^{-20} m^2 w^{-1}$ is the non linear refractive index of silica material and A_{eff} is the effective mode area which is calculated by

$$A_{eff} = \frac{(\iint |E|^2 dx\, dy)^2}{\iint |E|^4 dxdy} \tag{5}$$

Figure-7(a, b) shows the effective mode area and nonlinearity as a function of wavelength for (/\)=0.75μm, d_2=0.54μm, d_1=0.72μm. The designed fiber has high effective area and low nonlinearity.

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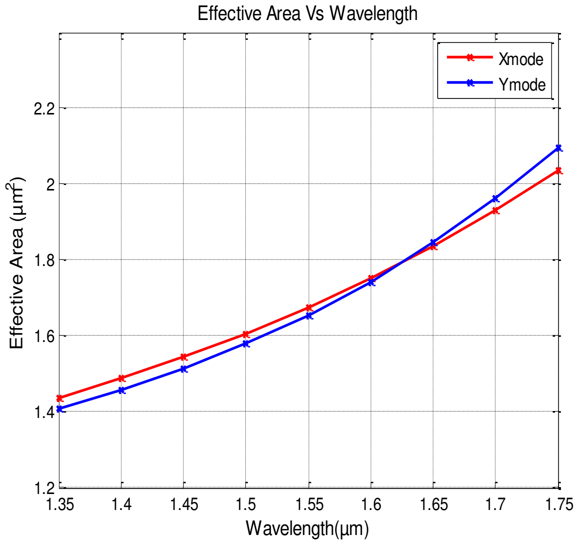

Figure-7(a). The effective area as a function of wavelength for pitch (/\)=0.75μm, d_2=0.54μm, d_1= 0.72μm.

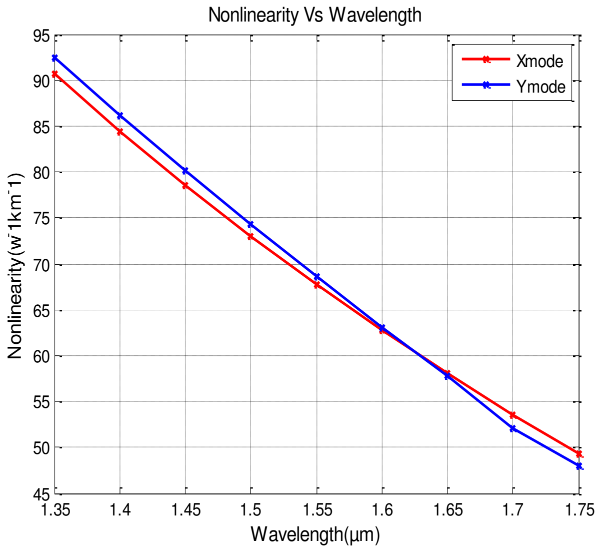

Figure-7(b). The nonlinearity as a function of wavelength for pitch (/\)=0.75μm, d_2=0.54μm, d_1= 0.72μm.

In the dual core PCF coupling length is also an important characteristic. It is also called as Beat Length which is defined as,

$$L_{ci} = \frac{\pi}{\beta^{i}_{\text{even}} - \beta^{i}_{\text{odd}}} = \frac{\lambda}{2\left(n^{i}_{\text{even}} - n^{i}_{\text{odd}}\right)} \quad (6)$$

Where, i=*x* and *y* polarization modes. When x polarization (or y) beam incident on one of core, both even and odd modes are formed. Two modes are superimposed and the mode field enhanced in that core and counteracted entirely in other core. In the symmetric dual-core PCF, all the energy will transfer from one core into the other and back again as it propagates along the fiber. This result in a power switching between two cores takes place [11]. Figure-8(a) shows the coupling length(x-mode, y-mode) as a function of wavelength for different values of d_2 with pitch (/\)=0.75μm, d_1=0.72μm.

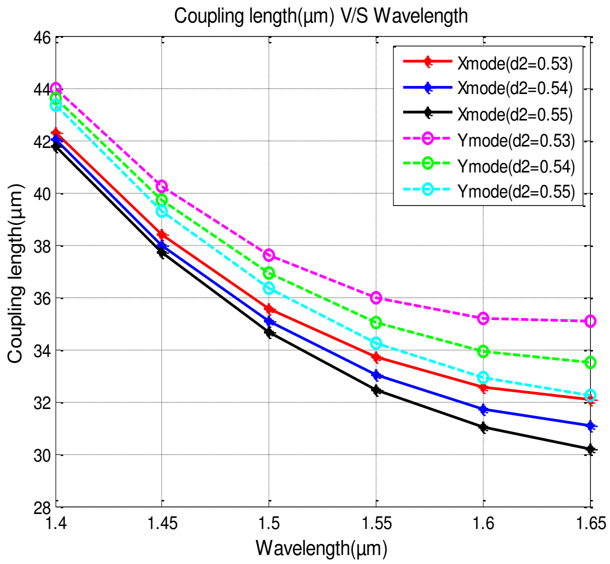

Figure-8(a). The coupling length as a function of wavelength for pitch (/\)=00.75μm, d_1=0.72μm, d_2=0.53, 0.54, 0.55μm.

The coupling length decrease as the increase in wavelength because the mode field is slightly extends in cladding and coupling between two cores is difficult to achieve and also as lattice length is squeezed [13-14]. As the air hole diameter d_2 increases the coupling length decreases. Figure-8(b) show the coupling length(x-mode, y-mode) as a function of wavelength for different values of $d_1$with pitch (/\)=0.75μm, d_2=0.54μm.

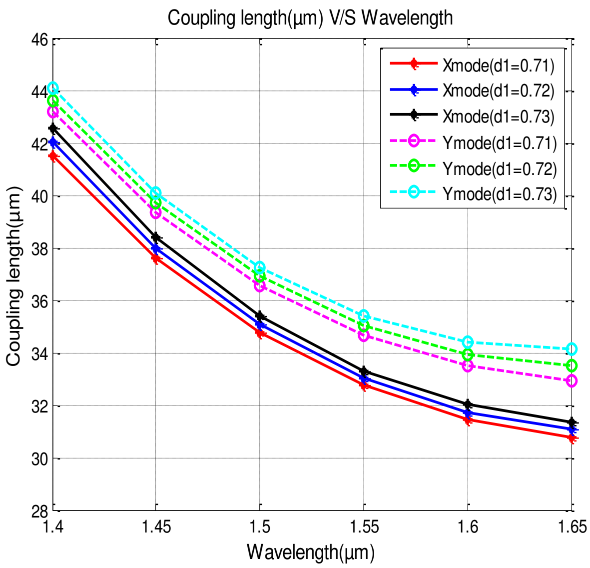

Figure-8(b). The coupling length as a function of wavelength for pitch (/\)=0.75μm, d_2=0.54μm, d_1=0.71, 0.72, 0.73μm.

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Similarly for different pitch (/\) the coupling length is shown in Figure-8(c).

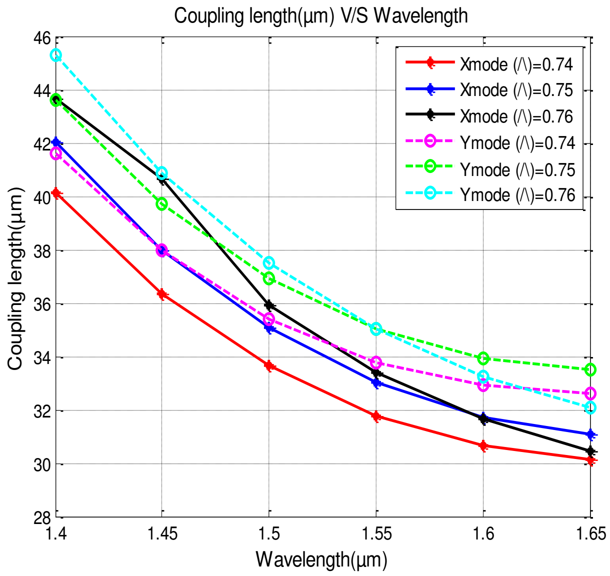

Figure-8(c). The coupling length as a function of wavelength for pitch (/\) =0.74, 0.75, 0.76μm, d_2=0.54μm, d_1=0.72μm.

Now we find output power in x and y polarization modes. Let, P_{in} is the input power in. The output power of of x polarized and y polarized in core is [18-19],

$$P_{i-out} = P_{in}\cos^2\left(\frac{\pi L}{2L_i}\right) \tag{7}$$

$L_i$can be calculated from eq.(1) and Normalized power (NP_i) can be defined as,

$$NP_i = \frac{P_{i-out}}{P_{in}} = \cos^2\left(\frac{\pi L}{2L_i}\right) \tag{8}$$

where i=x, y. As shown in Figure-9 the peak amplitude of P_x and P_y lies between 1 and 0 respectevely.

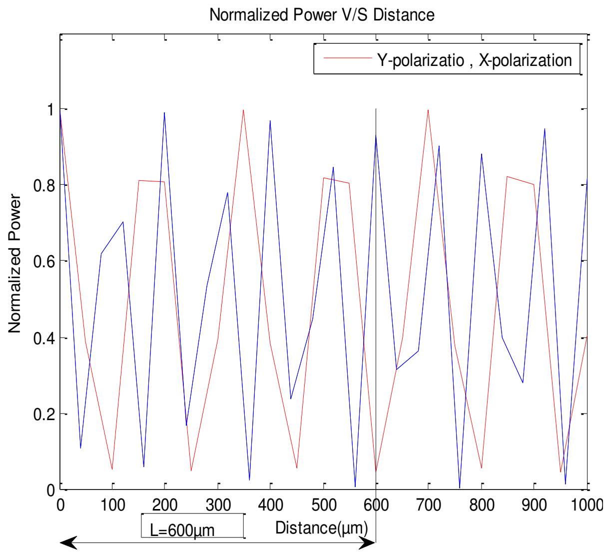

Figure-9. Variation of Normalized Power (NPi) with distance propagation for /\=0.75,d1=0.72,d2=0.54 μm.

It is seen from Figure-8, that the power exchanges periodically with the wavelength 1.5 μm. At fiber length of L= 600 μm the power in x and y mode completely seperated out for pitch(/\)=0.85μm and d==0.72 μm.

CONCLUSIONS

In our proposed DC-OPCF structure, we designed a high negative dispersion compensating fiber which achieved a negative dispersion coefficient -1650ps/nm/km at 1.55 μm. Using this, design dispersion compensation can achieved over a wide wavelength range including S, C, L and U communication band. Proposed design has low effective area and high nonlinearity. A short coupling length of 32 μm is achieved at 1.55 μm.Two polarized (x and y) modes separated completely (180^0 phase shift) at length of 600μm at pitch= 0.85μm and d=0.72 μm, so this design can also be used as polarization splitter and Multiplier and Demultiplier applications.

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