Photonic Crystal Fiber and Photonic Crystal Waveguide based 1x4 Power Splitters for Optical Network

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ABSTRACT
In this paper 1x4 fixed and flexible power splitters using multicore photonic crystal fiber(PCF)and photonic crystal waveguide array(PCWA) is proposed.Multicore PCF power splitter comprises of four identical cores surrounding the central core (Fixed power splitter).The central core is surrounded by non identical cores(Flexible power splitter).The optical power launched into the central core is equally divided into four neighbouring cores with 25% coupling ratio(Fixed power splitter).An unequal distribution of power is observed when the diameters of the cores surrounding the central core are varied. The PCWA power splitter comprises of a rectangular array of dielectric rods in air. This array is integrated with multimode interference coupler (MMI).Fixed and flexible power splitting ratio is obtained by varying the diameter of the rods. The PCWA power splitters are compact(14μm) as compared to the PCF power splitters (57μm).These novel structures are investigated using Finite Difference Time Domain Method(FDTD).Coupled mode analysis is also carried out to understand the super mode patterns and coupling characteristics. The device size reduction compared with the conventional MMI power splitter is attributed to the large dispersion of the PCW and PCF.

General Terms
Performance, Design, Theory and Algorithm.

Keywords
Power Splitter, Multicore, PCF, PCW and FDTD

1. INTRODUCTION
Power splitting is the basic function of the integrated optics. Such devices play vital role in passive optical distribution network, complex photonic integrated circuits as well as advanced active components such as interferometer, switches [1],[2] and nonlinear all optical devices[3].In the last few decades various solutions have proposed to split and combine optical signal.MMI coupler based power splitters are popular due their compact structure, polarization insensitivity and tolerance to fabrication parameter[4].By using conventional rectangular geometry of MMI coupler only discrete power splitting ratio can be obtained even when the overlapping of the self images are introduced[5]. When "tap" function is required a small portion of the power is required. For several applications in optical network free choice of power splitting is required depending on the situation [6]. Ring lasers with 2x2 MMI couplers at its o/p were proposed to obtain a flexible power splitting ratio [7].The device is complex. In [8] a new class of MMI coupler with interference section in between to have a free choice of power splitting ratio is proposed.

Later a new concept of tapering in MMI coupler is investigated. In [9] MMI coupler with tunable power splitting ratio is realized. Such devices have wide tuning range, compact structure and find applications in optical switches. These devices offer around 20% tunability. Later a novel design of integrating MMI coupler with PCWA for flexible splitting ratio is proposed in [10]

In 1991, the idea that the well known "stop bands" in periodic structure is extended to prevent propagation in all the directions was leading to attempts worldwide, to fabricate three-dimensional PBG materials. Hence photonic crystal fibers (PCF), which guides the light by PBG effect, are fabricated [11], [12], [13].Since then several PCF based devices such as lasers, filters, switches and multiplexers and demultiplexers are realized. The concept of multicore PCF lead to the realization of 1x4,1x8 power splitters with fixed power splitting ratio [13].This concept of multicore in PCF is extended to design the 1x4 PCF with flexible splitting ratio by modifying the core diameters [14].With the development of PCWs, several PCW based devices such as interoferometers,lasers,multiplexers,demultiplexers and power splitters are developed[15][16].Current research is to integrate MMI coupler with PCW,which allows the realization of true time delay line(TTD)[17] and other photonic devices.

PCF used in this work is multicored.The Photonic crystal fibers (PCFs), consisting of a core surrounded by a cladding were first proposed in 1996.Light in the PCF is well confined in the longitudinal direction in the core region. According to their light guiding mechanism, PCF can be divided into two different types. 1) PCF, which guides light by total internal reflection (TIR) 2) PCF, where guidance is provided by the photonic band gap (PBG) effect. PCFs have perfectly periodic structure of air holes in the cladding region. By having different air hole diameters along the two orthogonal axis, the no characteristics of PCFs, such as birefringence and dispersion can be controlled [18].PCFs, which guides the light by total internal reflection has the solid core and the PCFs, which guides the light by PBG has hollow core as shown in the "Figure 1".

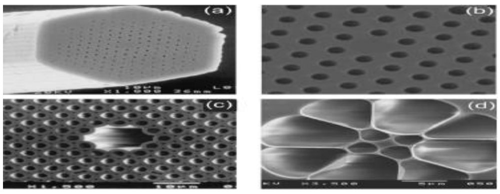

Fig 1: a&b Solid core PCF and c&d Hollow core PCF [13]

This paper is divided into five major sections.Section 2 describes theory of PCF based 1x4 power splitter. Section 3describes the PCW based 1x4 power splitter .In section 4 we present the results which will enable the user to have a free choice of power splitters for particular applications. Finally section five provides some conclusions.

2. PCF BASED 1x4 POWER SPLITTER

2.1 Modeling of PCF power splitter

The simplified model of the multicore PCF based Power Splitter and its index profile is shown in "Figure 2".The Multicore PCF has a large central core surrounded by four cores. Incase of fixed power splitter all the four outer cores have same diameter. When flexible power splitting is required, the diameters of the outer cores are varied proportionately. The power is launched into the central core. Gaussian pulse with1550nm wavelength is chosen.FDTD method is adopted for the analysis [19].The power is coupled from the central core to the adjacent cores. To understand this phenomenon coupled mode theory is used [20].This type of PCF based power splitters are fabricated using stack and draw method. The background index of silica is 1.45. The inner and outer cores are made of Ge, and As doped silica rods with a refractive index of 2%, -0.7% respectively. Due to limits set by manufacturability, the period, "Λ" is chosen to be 1.0 µm. The inner core diameter, d_5/Λ, is chosen to be 0.8, followed and then by an outer core with $d_n/\Lambda = 0.2$.Where "n"=1, 2, 3, 4 The outer cladding is made up of air hole rings with diameter d_6/Λ=0.2.

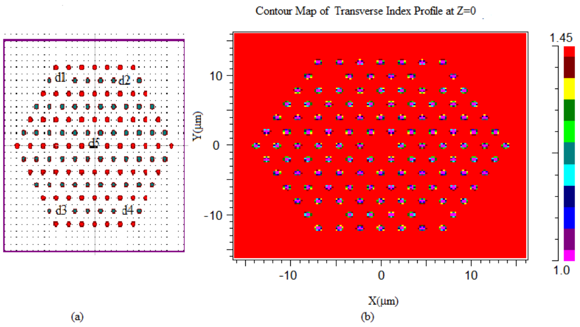

Fig 2: a) Schematic view of Multicore PCF based 1x4 Power Splitter b) Index profile.

"Figure 3" shows the variation of n_{eff} versus wavelength. It can be seen that, at the phase matched wavelength 1.55 µm, the effective index changes rapidly with wavelength. This is the reason for high dispersion of the structure at 1.55µm, as depicted in "Figure 4" The PCF used in this design has very high negative dispersion coefficient of about -4400 ps/nm/km, with a half width full maxima (HWFM) of 40 nm.These types of PCFs are also used extensively in the design of True Time Delay line for antenna beam steering, Mux/Demux, Resonators and Micro fluidics and Sensors.

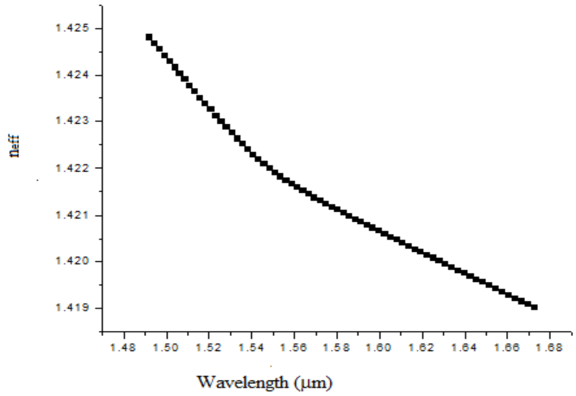

Fig 3: Variation of n_{eff} with Wavelength

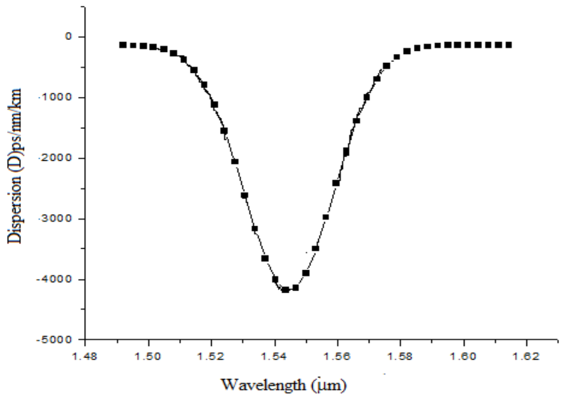

Fig 4: Relationship between dispersion value D and Wavelength

The cladding of the photonic crystal fiber has number of air holes. By controlling the size of the air holes the optical properties such as effective index, the number of modes and the dispersion can be controlled. The optical fiber which guides the light by PBG effect has a photonic band gap for TE and TM polarization as shown in the "Figure 5"

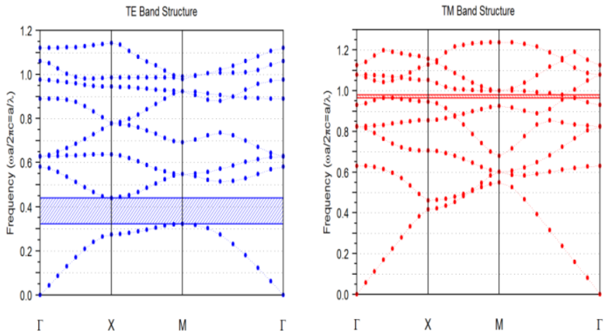

Fig 5: TE and TM band gap for the chosen PCF

2.2 Analysis of PCF based power splitter

Coupled mode theory is used for evaluating the field at the four cores. The central core and the outer cores behave like two parallel waveguides and the high dispersion is due to the coupling between the two waveguides. "Figure 6".shows the coupling effect between the central core and the outer small cores. In this case the power launched into the central core is equally divided into other neighbouring cores with 25% coupling ratio .The resent research has shown that compact design of 6-8 core PCFs are possible. These type of PCFs find great applications as power splitters. Hybrid polarization is used for simulation.

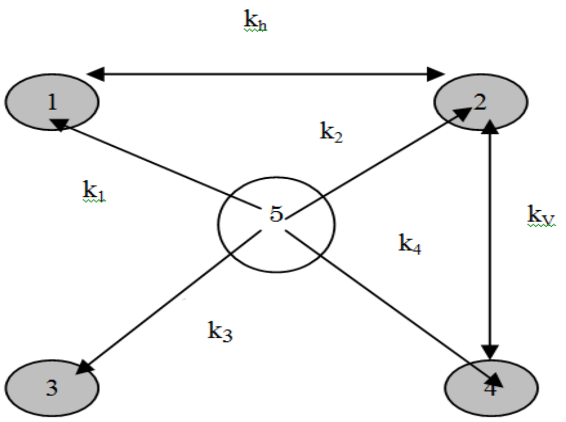

Fig 6: Coupling between the central core and outer cores

k_i represents the coupling between the central core & outer core.k_h&k_v is the horizontal and vertical coupling between the outer cores. The mode coupling between the cores can be described by the set of equations given below.

$$\frac{da_1}{dz} + j\beta_1 a_1 = -ja_1(k_1 + k_h + k_v) \quad (1)$$

$$\frac{da_2}{dz} + j\beta_2 a_2 = -ja_2(k_2 + k_h + k_v) \quad (2)$$

$$\frac{da_3}{dz} + j\beta_3 a_3 = -ja_3\ (k_3 + k_h + k_v) \quad (3)$$

$$\frac{da_4}{dz} + j\beta_4 a_4 = -ja_4\ (k_4 + k_h + k_v) \quad (4)$$

Where a_k (k=1, 2, 3, 4, &5) are the amplitude of the fundamental mode in core. "k"and "β" is the propagation constant. These outer cores behave like parallel waveguides and the high dispersion is due to the coupling between the central waveguide and the outer waveguides. By expanding the propagation constant "β" of the modes using Taylors series , we get,

$$\beta_i(\omega) \approx \beta(\omega_p) + (\omega-\omega_p)\frac{d\beta_i}{d\omega}\bigg|_{\omega=\omega_p} + \frac{(\omega-\omega_p)^2}{2}\frac{d^2\beta_i}{d\omega^2}\bigg|_{\omega=\omega_p} \quad (5)$$

where i = 1...5 represents the inner and the outer waveguides respectively and ω_p represents the phase matched frequency.In this arrangement the dispersion reaches the maximum value for phase matched wavelength $\lambda = \lambda_p$, given by

$$D_{Max} = \mp\sum_{i=1}^{4}\frac{\pi}{2c\kappa_i}\left(\frac{dn_1}{d\lambda} - \frac{dn_2}{d\lambda}\right)^2 \quad (6)$$

For unequal power distribution, the diameter of each core is varied by 0.01 μm

The modes in the cores are calculated by solving the four modal equations. Each Eigen vector corresponds to a mode. Plus sign indicates the phase of the mode, "1" represents the amplitude. Minus sign indicates out of phase. The operation of this power splitter is understood by the concept of five super modes. This is shown in "Figure 7".

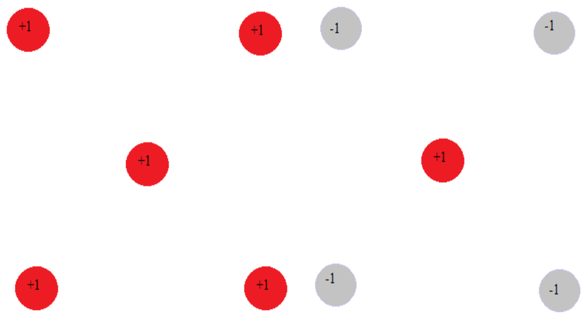

Fig 7:Relative amplitude and phase of the super modes in 1x4 PCF Power Splitter.

2.3 Losses in PCF based power splitters

Bending losses: As compared to conventional single mode fiber, the bending losses are less. Unless the fiber breaks substantial amount of bending losses are not observed. This is because of the small value of Δβ between the edges of Photonic Band Gap(PBG).Other losses are

- Absorption and Rayleigh scattering losses.
- Confinement losses.
- Coupling losses

3. PCW BASED 1x4 POWER SPLITTER

3.1 Modeling of PCW power splitter

The proposed 1x4 power splitter is schematically depicted in "Figure 8".The width of the i/p waveguide "b"=1μm which is a single mode waveguide.MMI coupler is a slab waveguide with refractive index n=3.45.The dimension of the MMI coupler is 5μm x10μm.MMI coupler is integrated with PCW array.PCW array is rectangular lattice of dielectric rods in air. The radius, and the refractive index of the rods are taken r=0.2a, (a=period)and n=3.45.The four Photonic Crystal waveguides are created by eliminating four rows rods. (creating line defect in PC) and the diameter of the rods adjacent to the waveguides are varied as a/λ,a/2λ and a/3λ where λ is the operating wavelength(creating point defect in PC).When fixed power splitting is required, all the o/p waveguides are of equal width. Here creating a point defect is not desirable. The thickness of the guiding layer is 150nm.Substrate thickness is 500nm.These o/p PC waveguides are replacing the conventional waveguides.

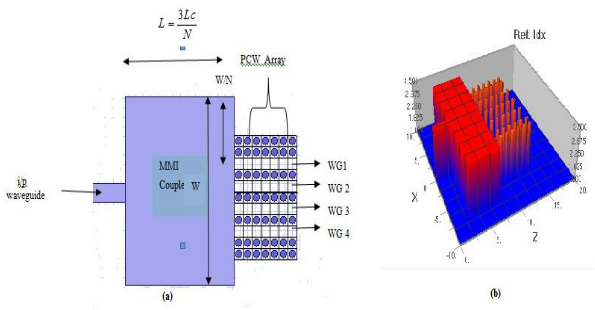

Fig 8: a) Schematic view of PCW based 1x4 Power Splitter b) Index profile

The PCW array in the proposed power splitter has two PBG for TM polarization as shown in “Figure 9”.Plane wave expansion method is used to evaluate these band gaps. Full vectorial method is adapted to compute the fundamental mode. The fundamental mode and the modal index is shown in “Figure 10”.

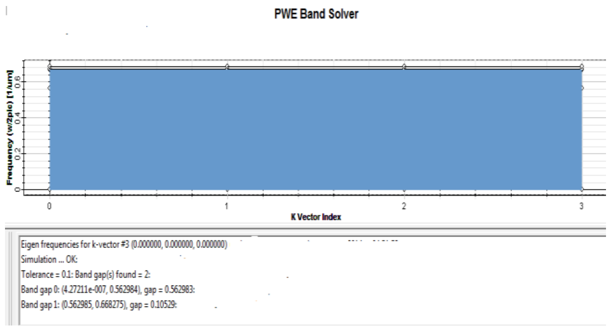

Fig 9:Photonic Band gap(PBG) for the PCW array

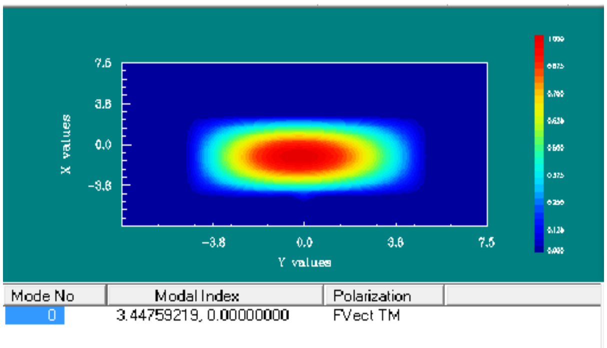

Fig 10: Fundamental mode with modal index

In order to make the device compact, it is essential that the PCW array used in this novel device has to be dispersive. This is tested by observing the variation of the effective index with wavelength, followed by computing dispersion at different wavelengths. This is shown in “Figure 11”and “Figure 12”. The PCW used in our design has very high negative dispersion coefficient of about -4500 ps/nm/km.

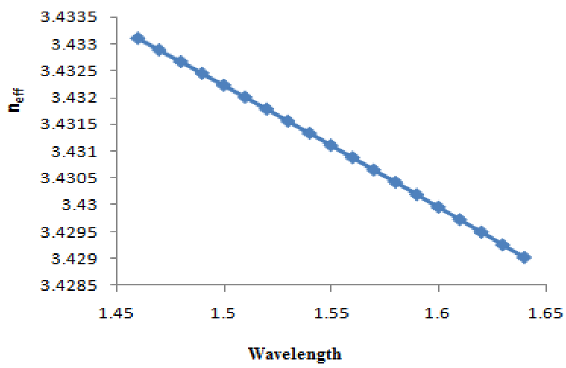

Fig 11: Variation of n_{eff} with Wavelength

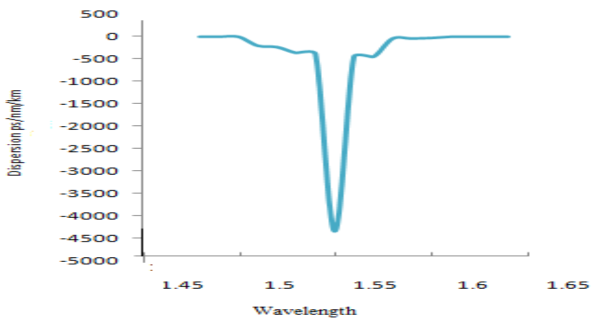

Fig 12: Relationship between dispersion value D and Wavelength

3.2 Analysis of PCW based power splitter

The i/p MMI coupler used in this novel power splitter has one i/p waveguide which is planar and the o/p waveguides are PCW array comprising of four waveguides created by the removing four rows of rods to accomplish equal distribution. Whereas the flexible Power Splitter comprises of four rows of rods with unequal diameter.

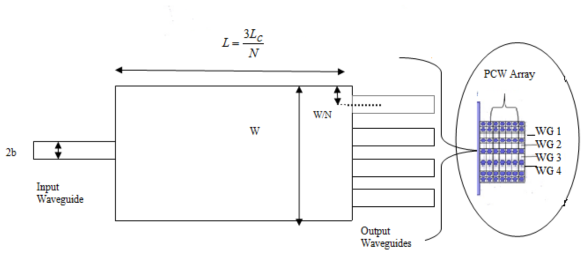

Fig 13: MMI coupler where the o/p waveguides are replaced by PCW array

The geometry of the 1x4 flexible power splitter with one input and three o/p is depicted in “Figure 13”.Allowed i/p and o/p locations are at the integer multiples of W/N of the total MMI width. Where “W” is the equivalent MMI width, which is the geometric width of the MMI coupler including the penetration into the neighbour material of the waveguide. The length of such a MMI coupler is given by the relation

$$L_N^M = \frac{M}{N} . L_C . \quad : \quad (7)$$

with

$$L_C = \frac{4 n_{eff} W^2}{3\lambda} \quad (8)$$

Where “M” is the possible MMI lengths of overlap for MMI with (N-1) possible i/p and o/p waveguides,n_{eff} is the effective refractive index,λ is the operating wavelength and L_c is the coupling length of the MMI coupler.The splitting ratio P_c/P_b depends on the width of the PCW waveguide and the effective index of the individual waveguide.Wherin P_c and P_b are the coupled power and the i/p power.To obtain a flexible power splitting ratio,the normalized width of the o/p waveguides “dΩ” is varied by varying the size of the rods incase of PCW based power splitter and the diameter of the cores are varied incase of PCF-based power splitter.This results in the variation of n_{eff} of each path.Hence L_c is varied resulting in flexible coupled power.The coupled power is given by

$$P_C \approx Cos^2(0.5\pi dr) \qquad (9)$$

The propagation constant β in the array section of the Power splitter depends on "dΩ".The propagation of light in the array section is computed using coupled mode theory. The "dΩ" of the array waveguide is chosen such that, the equal and unequal distribution of power is ascertained.

$$d\Omega = \frac{m.\lambda_C}{n_{eff}} \qquad (10)$$

Where m is the order of the array,λ_c is the central wavelength and n_{eff} is the effective index. For this Wavelength the fields in the individual waveguide will arrive at the o/p aperture with equal phase but their strength is reduced to quarter. When the diameter of the rods are varied for flexible power splitting, there is some phase change at the o/p of the individual waveguide. This is due to the change in the propagation constant β.

There are no bending losses and coupling losses as in the case of Photonic crystal "Y" splitter and Power splitter based on Direction coupler principle. However there may be some losses while fabricating the device. This is due to the integration of the MMI coupler with Photonic crystal array. Furthermore, propagation losses can be ignored as the length of the array section is very short.

4. RESULTS AND DISCUSSION

To verify the equal power distribution in the multicore PCF power splitter, FDTD analyzer is used. Power is launched into the central core, For "Z"=0 the power is confined to the central core. "Z" is the distance. This is shown in "Figure 14". When all the outer cores are of equal diameter, power is efficiently coupled from the central core to the outer core as depicted in "Figure 15".This is achieved after travelling a distance "Z"=53μm which is better than 5.8mm distance of the earlier multicore PCF power splitter. Thus validating the operation of 1x4 power splitter. 25% coupling ratio is achieved in this case.

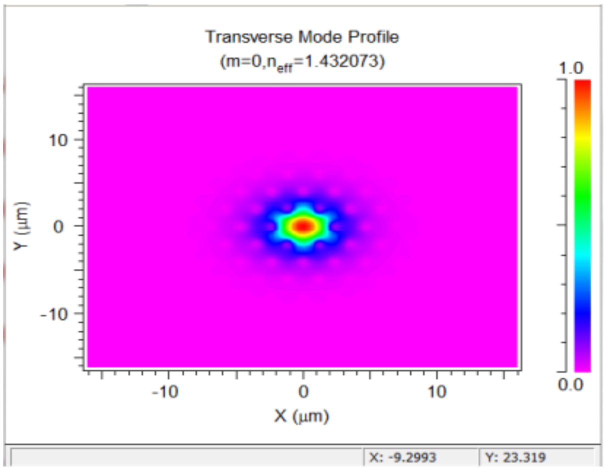

Fig 14: Modal Field distribution at z=0μm at 1550nm.

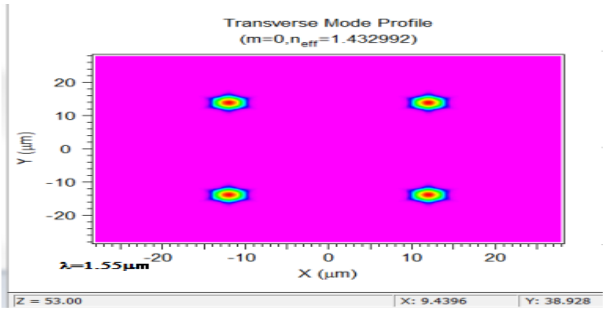

Fig 15: Modal Field distribution in 1x4 multicore PCF for Z=53μm

When outer core diameters are varied unequal power splitting ratio is observed. This is the basis for the design of Flexible power splitter, True Time Delay (TTD) line,Mux/Demux and Optical Cross Connect. The unequal distribution of power is shown in "Figure 16".This is achieved for "Z"=57μm.

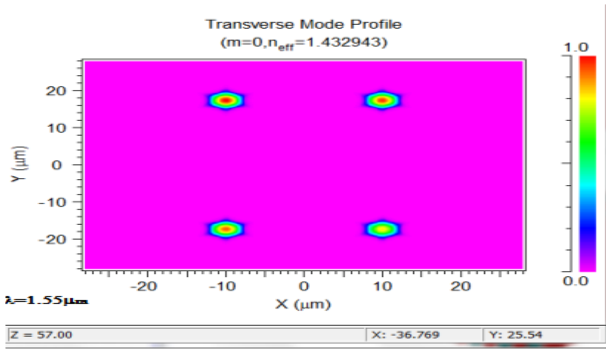

Fig 16: Modal Field distribution in 1x4 multicore PCF for Z=57μm.

PCF based 1x4 Power Splitter is analyzed in terms of material, device length and coupling efficiency.FDTD analysis is performed on PCW based 1x4 Power Splitter. In this case the material used is GaAS instead of SiO_2. Here MMI coupler is integrated with PCW array and observed the light propagation from a planar device to Photonic crystal array . When continuous wave is launched through single mode i/p waveguide, it diverges in the MMI section, and enters the four o/p photonic crystal waveguides. This is shown in "Figure 17".

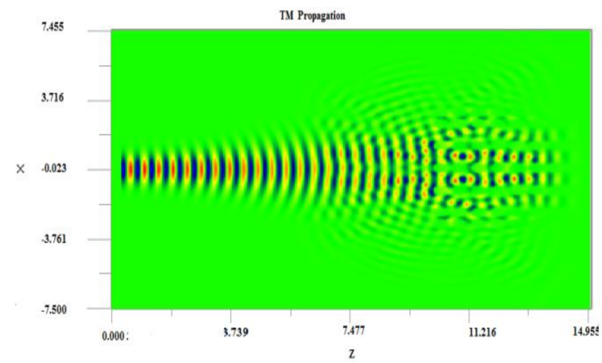

Fig 17: Light propagation in 1x4 PCW Power Splitter at Z=14μm.

In case of fixed Power Splitter, Field associated with each o/p waveguide is equal.Wherin the field associated with o/p waveguides varies in case of flexible power splitter. The propagation of light in the four o/p waveguides in fixed and flexible Power Splitters are depicted in “Figure 18”.

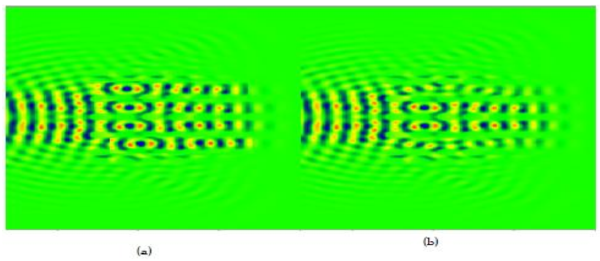

Fig 18: Light propagation in a) Fixed Power Splitter b) Flexible Power Splitter.

In “Figure 18” we observe that,o/p beams are parallel incase of fixed 1x4 power splitters,wherin the beams are bent incase of flexible power splitter. This is due to the variation in propagation constant “β” along each optical path, due to variation of the diameter of the dielectric rods. Although there is some phase change, it does not effect the performance of power splitter. However this property can be exploited for designing the Mux/Demux as explained in earlier publication[21].

Numerical simulation results are compared with theoretical analysis. This is ascertained by observing the poynting vector in both the cases as shown in “Figure 19”,thus validating the function as 1x4 power splitter.

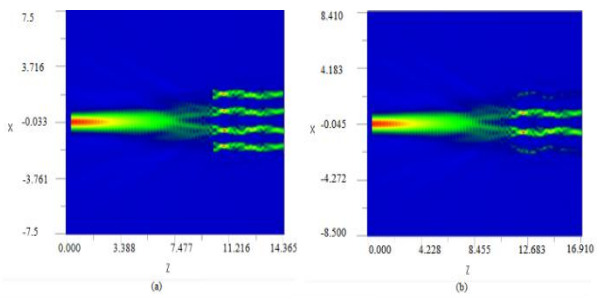

Fig 19: Poynting vector showing power in a) 1x4 fixed power splitter b) 1x4 flexible power splitter

The unequal power distribution along the four o/p arms/outer cores is due to the variation in field strength associated with each arm(PCW) and each core(PCF).

“Table 1” shows the comparison between PCF and PCW 1x4 Power Splitters

Table 1. Performance of PCF &PCW 1x4 Power Splitters

Type	**Dispersion** ps/nm/Km	**Device length (µm)**	**Material**	**Coupling Ratio**
PCF (Fixed)	-4400	53	SiO_2	25% to each core
PCF (Flexible	-4400	57	SiO_2	Variable
PCW (Fixed)	-4500	13.5	GaAs	21% to each port
PCW (Flexible)	-4500	14	GaAs	Variable

5. CONCLUSSION

PCF and PCW based fixed and flexible power splitters are investigated in this paper for hybrid and TM mode propagation with FDTD method. The performance of each structure is characterized and compared with each other for maximum power transmission. By engineering the various parameters of PCF, Photonic Crystal and MMI coupler 1x3,1x2 and 1x8 power splitters can be designed for optical network. Here rectangular lattice structure is considered for investigation. This work can be extended for other lattice structures such as hexagonal,BCC and FCC. It’s being proved that when a planar waveguide is integrated with PCF and PCW, more complex and versatile designs can be incorporated in Photonics.

6. ACKNOWLEDGMENTS

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