Photonic Crystal Fiber and Photonic Crystal Waveguide based Demultiplexers for Optical Network

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ABSTRACT
Novel designs of demultiplexers based on photonic crystal fibers (PCF) s and photonic crystal waveguides (PCW) s are presented here. We have considered two types of PCFs and PCWs, namely Dual concentric core PCF, Multicore PCF, PCW with dielectric rods in air and PCW with air holes in dielectric background. Finite difference time domain method (FDTD) is employed to analyze all these devices at 1550nm.The performance of these devices are investigated in terms of optical efficiency, dispersion, device length and cross talk.

Categories and Subject Descriptors
B.4.3. **[Interconnections]**: Fiber optics.

General Terms
Performance, Design, Theory and Algorithm.

Keywords
Dual concentric core, Multicore, PCF, PCW and FDTD

1. INTRODUCTION
A powerful aspect of the optical communication link is that, multiple wavelengths can be sent along a single fiber simultaneously in the 1300 to 1600nm spectral band. The technology of combining multiple wavelengths on to single fiber is known as “Wavelength division multiplexing” or WDM. The literature often uses the term dense WDM (DWDM).This term is commonly used in the present day fiber-optic networks. [1]. The implementation of the WDM networks requires a variety of passive and active devices to combine, distribute isolate and amplify optical power at different wavelengths.The key component is Mux/Demux. In 1988, M.K.Smit proposed the angularly dispersive devices based on phased array known as Arrayed waveguide grating (AWG) [2].The arrayed waveguide grating is an imaging device. This device images the field of an input wave-guide on to an array of output wave-guides in a dispersive way.Hence serves as a Mux/Demux.In [3] a new concept of variable width arrayed waveguide was proposed wherein the width of the waveguides in the array section was varied linearly to make the device dispersive inorder to separate the wavelengths.However the short “s-bend” structure at the input and the output sections of the array sections were discarded in the Demux proposed in [4].In the last few decades Photonic crystal(PC) and Photonic crystal Fibers(PCFs) have inspired great interest recently because of their potential ability to control light wave propagation.[5]. Since the first working model was demonstrated in the year 1996, PCFs[6], fibers with an array of periodic air-holes running down the length of the fiber, have gained an increasing popularity due to their unique properties such as endlessly single-mode operation[7], high non-linearity, ultralow loss [8], and so on. PCF structures can be designed to have higher negative dispersion values compared to conventional DCFs.Since then no of PCF based devices such as lasers, sensors and true time delay line are fabricated [8].Recent research has shown that compact, multifunctional PC based devices can be fabricated in micro-nanoscale.Further the bending losses for PCwaveguides are less, the proposed device shows excellent performance[9]. The strong light confinement in PC structures allows the design of waveguide components that can perform complex interconnections within a small area. Hence no of PC based devices such as Directional coupler, Power splitters, Lasers Filters and Mux/Demux are proposed[10]-[14].In 2010 an attempt was made to integrate PCF and PC to Multimode interference coupler to design highly dispersive Mux/Demux and True time delay lines(TTD).[15]-[17].

In this study, we are analyzing the performance of PCF and PC based Demultiplexers on the basis of optical efficiency,dispersion,device length and cross talk. The detailed analysis of all these devices is presented in our earlier publications. [15]- [16].These devices are multifunctional as they can be used as Optical cross connects, TTD, Swtches, Filters and Routers apart from being used as Mux/Demux.

This paper is divided into six major sections.Section 2 describes the theoretical analysis on a simplified model of Demux.Section 3describes the PCF based Demux.Section 4 describes the PCW based Demux.In section 5 we present the results which will enable the user to have a free choice of Demux for particular applications.Finally section six provides some conclusions.

2. THEORY
The simplified model of the proposed structure is shown in (Figure 1).This device behaves like an arrayed waveguide grating(AWG).Adispersive device without any bends,compact yet allowing the separation of wavelengths suitable for “C”band.In the novel devices discussed here array

waveguides[2] in AWG is replaced by PCFs and PCWs. A brief analysis is presented here.The analysis is carried out in three parts.Part1Input,Multimode Interference(MMI) coupler,Part 2, Array section for PCF and PCW and Part 3,the o/p MMI coupler.The central wavelength is 1550nm.The light enters the MMI section and diverges,a phase shift is introduced here.The light enters the PCFs and PCWs with different propagation constant β.The variation in β is due to change in effective index n_{eff}.In the novel device $n_{eff}$is varied by varying the diameters of the cores in PCF based Demux.Br varying d/a ratios of the dielectric rods in case of PCW based Demux.Where “d” is the diameter of the rod and “a” is the period of the lattice.Opticalpath length for different wavelengths aredifferent.Hence constructive interference takes place at o/p MMI coupler.Thelocation of the focusing spot shifts for different wavelength,thus enabling the separation of wavelengths.This is shown in (Figure 2).

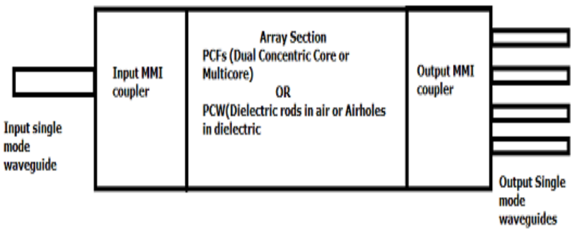

Fig 1: A schematic diagram showing how PCFs and PCare incorporated into array sections of AWG

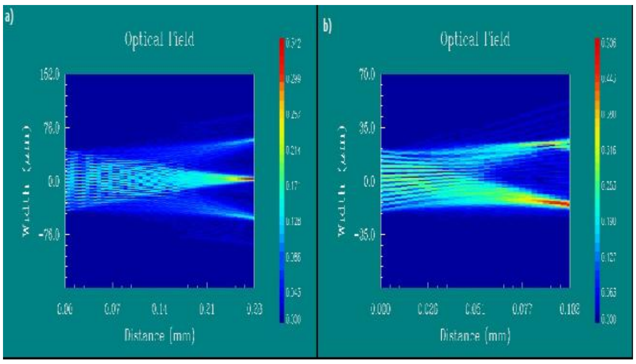

Fig 2: a) Focusing spot for central wavelength λ_0b) Shifted focusing spot for $\lambda<\lambda_0$.

2.1 Geometry of the MMI coupler.

The i/p MMI coupler used in this novel Demux has one i/p waveguide which is planar and the o/p waveguides are PCW array or PCFs and vice versa incase of o/p MMI coupler.This is presented in (Figure 3).

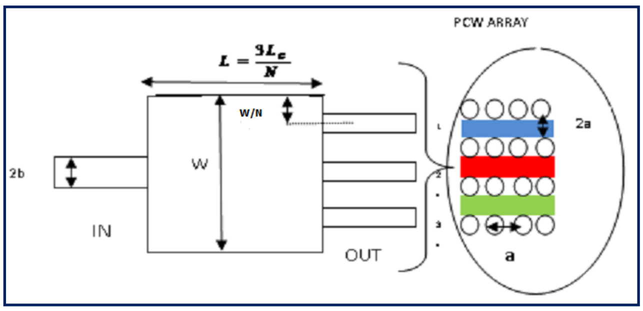

Fig 3: MMI coupler where the o/p waveguides are replaced by PCW array.

The geometry of the 1x3 flexible power splitter withone input and three o/p is depicted in (Figure 3).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 [18]

$$L_N^M = \frac{M}{N}.L_C......................(1)$$

$$with$$

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

Where “M” is the possible MMI lengths of overlap MMI with (N-1) possible i/p and o/p waveguides.neff is the effective refractive index,λ is the operating wavelength and Lc is the coupling length of the MMI coupler.

The splitting ratio Pc/Pb depends on the width of the PCW waveguide and the effective index of the individual waveguides.Wherin Pc and Pb 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/airholes incase of PCW-Demux and the diameter of the cores are varied incase of PCF-Demux.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;

$$P_C \approx Cos^2(0.5.\pi.d\Omega)..................(3)$$

The propagation constant β in the array section(Figure 1) of the Demux depends on “dΩ”.The propagation of light in the array section is computed using coupled mode theory[14].The dipsersion offered by the array section contributes for phase shift in the array sections. The phaseshift varies with λ.

The “dΩ” of the array waveguide is chosen such that the optical path length difference between the adjacent waveguides equals an integer multiple of the central wavelength of the demultiplexer.

$$d\Omega = \frac{m.\lambda_C}{n_{eff}}.............................(4)$$

$$m = order\ of\ the\ array$$

$$\lambda_C = Central\ wavelength$$

$$n_{eff} = Effective\ index$$

For this Wavelength the fields in the individual waveguide will arrive at the o/p aperture with equal phase (apart from an integer multiple of λ) and the field distribution at the i/p aperture will beproduced at the output aperture. The divergent beam at the i/p aperture is thus transformed into a convergent one with equal amplitude and phase distribution and an image of the i/p field at the object plane will be formed at the center of the image plane (o/p MMI coupler).For other wavelengths the focusing spot moves along the image plane.Very important parameters of the Demux are cross talk, insertion loss and dispersion.

The cross talk specification, which puts a lower limit on the receiver spacing d_{ry}(spacing between the o/p waveguides). Cross talk levels lower than –30 to –35dB are difficult to realize. In our design crosstalk levels of the order of –35 to –50dB is considered, and the crosstalk level between the adjacent channels is considered to be ≅ -100dB.

The crosstalk level in dB is related to the power overlap integral P_{lover}:

$$CT(dB) = 10\log(P_{over})............(5)$$

Where P_{lover} is the overlap integral, whose value is computed using overlapping integral tool?

The positioning of the o/p waveguides depends on the dispersion offered by the Demux.In conventional MMI coupler it is "W/N".In the proposed device the position of the o/p waveguides relies on the focusing spot.

The dispersion 'D' of the array is the lateral displacement (dS) of the focal spot along the image plane per unit frequency change.

$$D = \frac{ds}{df} = \frac{1}{f_c}.\frac{n_{eff}(array)}{n_{eff}(MMI)}.\frac{d\Omega}{\Delta\alpha}..........(6)$$

$fc = Central\ \ frequency$

$d\Omega = effective\ width\ of\ \ the\ array\ waveguides$

$n_{eff}(array) = effective\ index\ of\ \ the\ array\ waveguides$

$n_{eff}(MMI) = effective\ index\ of\ \ the\ MMI\ coupler.$

$\Delta\alpha = Divergence\ angle\ in\ the\ MMI\ coupler$

Total loss in the PCF and PCW Demux is:

$$L_{(total)} = L_{(0)} + L_p.............(7)$$

$L_{(0)} = Insertion\ loss$

$L(p) = \Pr opagation\ loss$

$$L(total) \approx -17^{e-4\pi^2 we^2 / d\Omega} + Lp.....(8)$$

$We = Width\ of\ \ the\ Gaussian\ \mathrm{mod}\, al\ \ field$
$inside\ the\ array$

Non-uniformity value (Lu) is minimum since the number of waveguides in the array sections isfew. The non-uniformity Lu is defined asintensity ratio (in dB) between the outer and the central channel. Hence it can be ignored in this study.

3.PCF BASED DEMUX

Photonic crystal fibers (PCFs) consisting of a core surrounded by a cladding were first proposed in 1996[1].Light in the PCF is well confined longitudinal direction in the core region. According to their light guiding mechanism, PCF can be divided into two different types.

1) PCF that guides light by total internal reflection TIR 2) guidance is provided by the photonic band gap (PBG) effect. Exhibited by a perfectly periodic structure in the cladding region.By having different air hole diameters along the two orthogonal axis, the no characteristics of PCF,'s such as birefringence and dispersion can be controlled [2].PCF's which guides the light by total internal reflection has the solid core and the PCF's which guides the light by PBG has hollow core as shown in the (Figure 4).

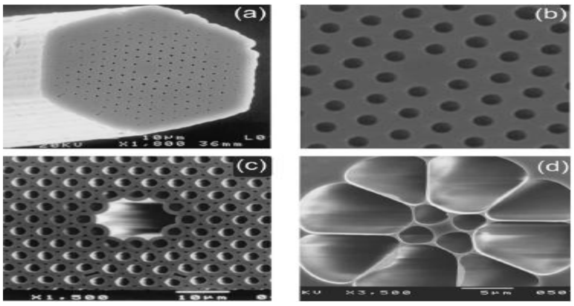

Fig 4: a&b Solid core PCF and c&d Hollow core PCF[19]

The PCFs used in the array section of our proposed Demux are 1) Dual Concentric core PCF 2) Multicore PCF with a large central core surrounded by four cores with different diameter depicted in (Figure 5).

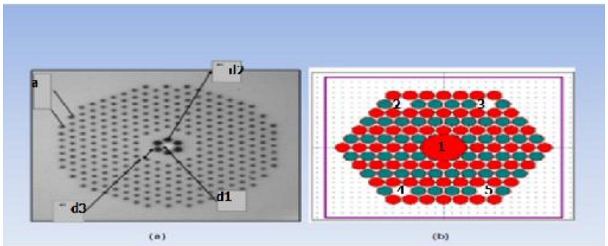

Fig 5:a)Dual concentic core PCF b) MulticorePCF

3.1 Dual Concntric corePCF

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, "a"was chosen to be 2.0 µm. The inner core diameter, d_1/a, was chosen to be 1.2, followed by an inner cladding made up of air holes with d_2/a = 0.75, and then by an outer core with d_3/a = 0.41. The outer cladding is made up of air hole rings with diameter d_4/a = 0.41. BandSolve software was used to simulate the structure. (Figure 6a) shows the variation of n_{eff} versus wavelength. It can be seen that, at the phase match wavelength around 1.55 µm, the effective index changes rapidly.(Figure 6b) shows the dispersion curve.

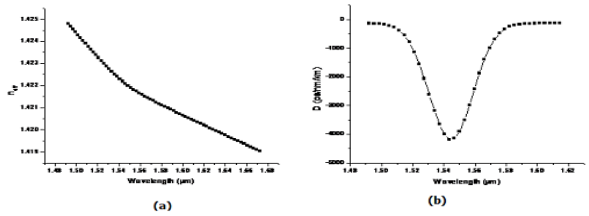

Fig 6: (a) variation of n_{eff} with λ(b) Dispersion curve

3.2 MulticorePCF

The multicore fiber design is shown in (Figure 5b).The fiber design comprises of four identical cores, d_2-d_5 surrounding the central core d_1. The multicore PCF consists of hexagonal ring of rods in air. The free space wavelength is 1550nm.The width of the core is 2*sqrt(fill*cell volume/pi). There is a large central core whose diameter is four times as that of the neighbouring cores. The period is a=4 µm.The background material chosen for numerical simulation is Silica(n=1.45). Green (Ge doped Silica) and red (As doped silica)There are 4 cores surrounding the central core.Outer cores are hollow created by the removal of rods.Central core is created by the removal of the rod and by the down dropped rod(red) with a large core diameter. This core is a hardcore. In this case the power launched into the central core is divided into other neighbouring cores with variable coupling ratio.This is due to the variation in the outer core diameters. They differ by 0.1µm.(Figure 7a) shows the variation of n_{eff} versus wavelength. It can be seen that, at the phase match wavelength around 1.55 µm, the effective index changes rapidly. (Figure 7b) shows the dispersion curve.

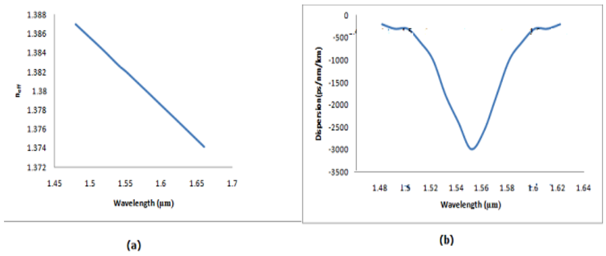

Fig 7: (a) variation of n_{eff} with λ(b) Dispersion curve

3.3 Applications of PCFs

Dual concentric core PCF and Multicore PCF have wide applications in the Photonic Networks.They are1)Mux/Demux 2)Wavelength Converters 3) Lasers 4) True time delay lines for antenna beam steering 5) Switches 6) Power splitters with equal and flexible splitting ratios.

4.PCW BASED DEMUX

Photonic crystals (PCs) are periodically patterned materials with strong dielectric contrast[5]There are high dielectric and low dielectric regions in the PCs as shown (Figure.8).The periodic structures forbid the wave propagation within the frequency range, which is known as photonic band gap(PBG).There are ID,2D and 3D Photonic crystals.

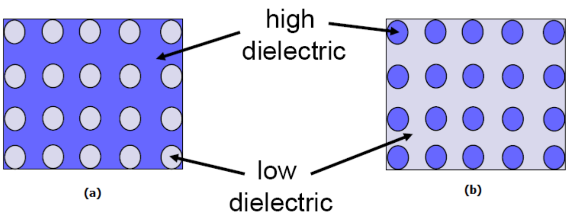

Fig 8: (a)PCs with periodic airholes in dielectric background (b)Dieleciric cylinders in air.

We have used 2D Photonic crystal in our study.shown in (Figure 9a).The waveguides in PC is generally obtained by removing one or more rows of dielectric rods in horizontal or vertical direction or by missing airholes.This is consideredas a linedefect ,Point defect can also be introduced by varying the size of rods or by varing the size of the airholes depicted in (Figure 9b). When defect is introduced, the PC guides the light.

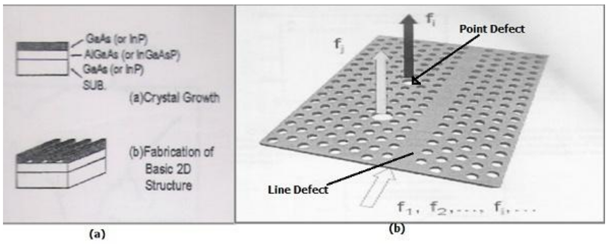

Fig 9: (a)2D Photonic crystal(PC) (b)PC with line & point defect[5]

4.1 PCW with Dielectric Rods in air

The PC discussed here, is composed of rectangular lattice of dielectric cylinders in the air (n=3.45) with radius "r"=0.3a in air, where "a" represents the periodicity of the latticea=500nm, Substrate thickness is 690nm and the thickness of the guiding layer is 150nm. Perfectly matched layer (PML) boundary condition is applied to absorb outgoing waves efficiently.This PC is used in the array section of (Figure 1).Three waveguides are created by missing rods. The diameter of the rods on either side of the waveguides are 1) d, 2) d/λ,3) d/3λ 4) d/4λ.Depicted in (Figure10).This arrangement changes the propagation constant β and the effective index n_{eff} along each waveguide resulting in large dispersion.(Figure 11).

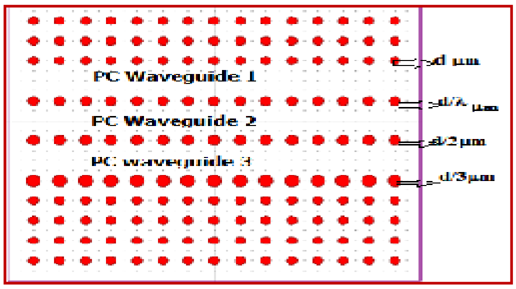

Fig 10:Schematic diagram of PCW array

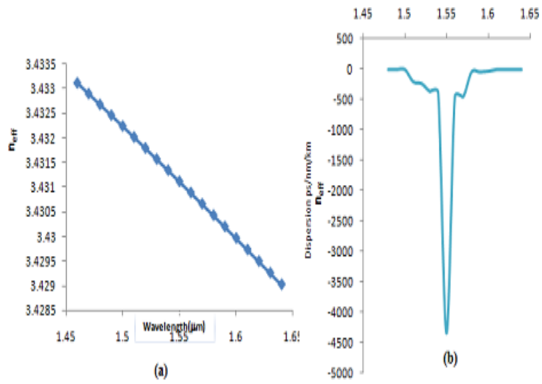

Fig 11: (a) variation of n_{eff} with λ(b) Dispersion curve

4.2 PCW with Air holes in Dielectric background

The PC discussed here, is composed of rectangular lattice of air holes in dielectric background (n=3.45) with radius "r" of air holes 0.49a in air, where "a" represents he periodicity of the lattice a=600nm, Substrate thickness is 690nm and the thickness of the guiding layer is 150nm. Perfectly matched layer (PML) boundary condition is applied to absorb outgoing waves efficiently. This PC is used in the array section of (Figure 1).Three waveguides are created by missing airholes.The diameter of the air holes on either side of the waveguides are 1)2r, 2) r/λ, 3) r/3λ 4) r/4λ 5) r/5λDepicted in (Figure12).This arrangement changes the propagation constant β and the effective index n_{eff} along each waveguide resulting in large dispersion. (Figure 13).

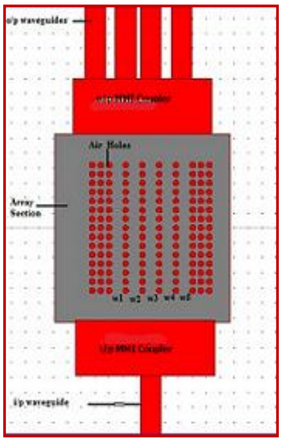

Fig 12: Schematic view of PCW- Air hole Demux

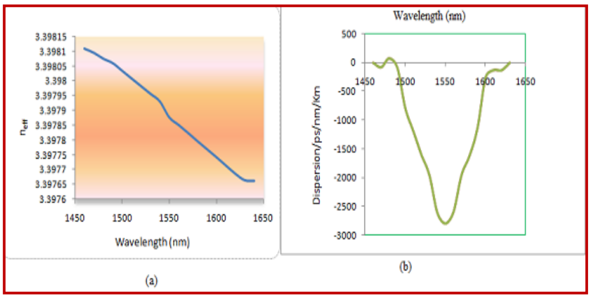

Fig 13: (a) variation of n_{eff} with λ(b) Dispersion curve

4.3 Applications of PCW Array

Two types of PCW arrays discussed above are extensively used in MachZender Interferometer,lasers,Filters,Power splitters,Directionalcouplers,Mux/Demux,Resonators,Switches ,AWG,True Time delay line,Waveguides ,waveguides with sharp bends etc.

5.RESULTS AND DISCUSSION

The PCFs and PCWs discussed in our discussion should have TE and TM bandgap (Figure 14) Using Bandsolve tool Band structure is calculated.If the device has to be polarization sensitive they should show the bandgap for hybrid polarization shown.In this case the propagation constant β remains constant for TE and TM propagation.

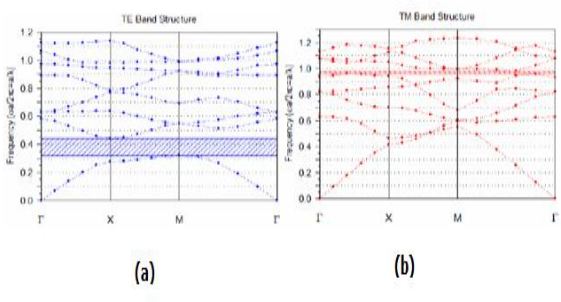

Fig 14: Band diagram for (a) PC with air holes in dielectric background (b) PC with dielectric rods in air

The operating wavelength λshould be chosen in such a way that normalized frequency a/λ falls within the band gap to ensure that PCFs and PCWs guide by Photonic band gap (PBG) effect. In case of Dual concentric core PCFs, for the phase matched wavelength ($\lambda \approx \lambda_p$),the power will beequally distributed between the inner cores resulting in large dispersion. This is ascertained by the mode profile of Dual concentric core shown in (Figure15).

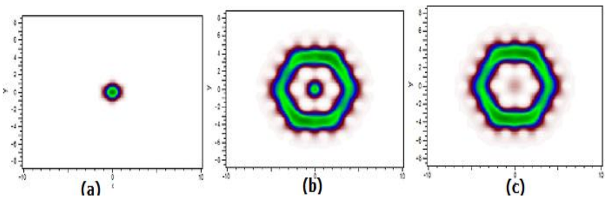

Fig 15: Mode Profile at (a) $\lambda<\lambda_p$(b) $\lambda=\lambda_p$ (c) $\lambda>\lambda_p$

This change in the mode profile shifts the beam in the o/p MMI coupler resulting in wavelength separation. Similar behavior is observed in Multicore PCF.For the phase matched wavelength, maximum power is coupled from the central core to neighbouring cores shown in (Figure 16).

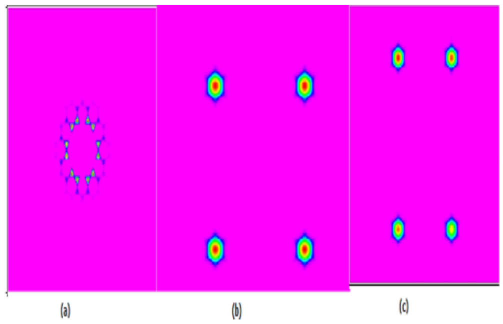

Fig 16:Mode Profile at (a) $\lambda<\lambda_p$(b) $\lambda=\lambda_p$ (c) $\lambda>\lambda_p$

Under these circumstances the PCF cores behave like parallel waveguides analogous to the array section of arrayed waveguide grating (AWG).AWG is a phasar used as Mux/Demux.

In caseof PC and PCF based Demux,light enters MMI region, diverges, propagates through the parallel waveguides and focuses at the center point of the o/p MMI region. When multiple wavelengths are fed they are separated at the o/p waveguides.(Figure 17) presents the propagation pattern.

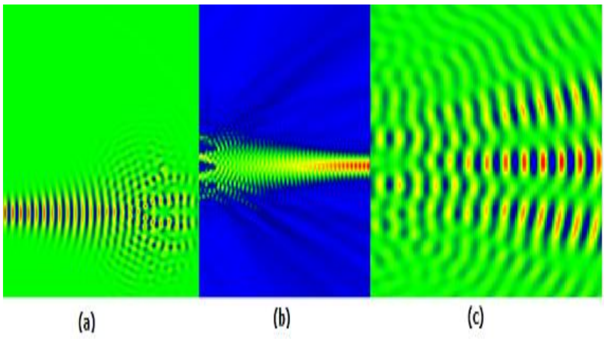

Fig 17:Light propagationat(a)i/p MMI region & PC - array(b) $\lambda=\lambda_p$convergence at the centerof o/pMMIcoupler (c) Wavelength separation at the o/p waveguides at $\lambda<\lambda_p$,$\lambda=\lambda_p$and $\lambda>\lambda_p$

For the central wavelength the electric field will be associated with the central channel in PC and PCF based Demux shown in (Figure18a) .When four wavelengths are fed at the i/p,the electric field will be associated with all four channels presented in (Figure 18b).The device cross talk in PC and PCF based devices are computed using the overlapping integral tool for the central wavelength. However the adjacent Demultiplexers shown in (Figure 19) channel cross talk is found to be -100dB in all types of novel devices.

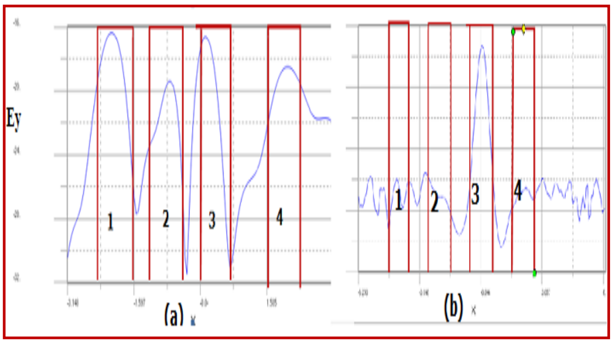

Fig 18: (a) Electric field associated with all four o/p waveguides (b) Electric field associated with central channel.

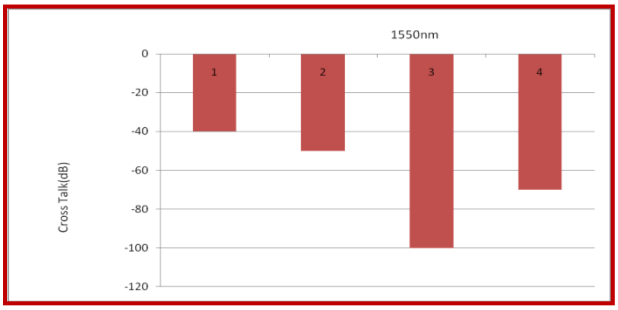

Fig 19:Adjecent channel cross talk in four o/p channels

Insertion loss of the devicedepends on the material used and device length. We have calculated the insertion loss by using the monitor for transmittance and reflectance. After the thorough analysis of all four types of Demultiplexers, we compare their performance and tabulate the results shown in (Table 1).However there may be degradation of these parameters after fabrication. Degradation of ±2% is expected depending on the degree of accuracy with which the fabrication is carried on and environmental condition.

Table 1. Performance of PCF &PCW Demultiplexers

Type	**Dispersion** ps/nm/Km	**Device length**	**Cross talk**	**Insertion loss**
PCF-Dual Core	-4200	2.2mm	-35dB	-20dB
PCF-Multicore	-3500	1.2mm	-30dB	-10dB
PCW-Rods in air	-4500	20μm	-40dB	-5dB
PCW-Air holes in Dielectric	-2500	25μm	-32dB	-10dB

The spatial shift in the image plane is less than 2μm in case of PCF and PCW with air holes in dielectric background. However incase of PCW with dielectric rods in air, the spatial shift is 2μm/nm change in wavelength.

6. CONCLUSSION

Novel designs of PCF and PCW Demultiplexers are presented here.FDTD method is used to simulate wave propagation in our devices. We have proved in our study, that when a Planar waveguide is integrated with PCF and PCW, more complex and versatile designs can be incorporated in Photonics. However the study also reveals that PCW–Demux with dielectric rods in air outperforms the rest. Otherdevice implementations based on PCFs and PCWs may be feasible by engineering the coupling parameter, waveguide modes and utilizing different excitation conditions.

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