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Photonic Crystal based Arrayed Waveguide Grating demultiplexer for Optical Network

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Abstract— A novel design of Arrayed Waveguide Grating (AWG) Demultiplexer on 2D photonic crystal is proposed. This device offers 200GHz channel separation and -32dB theoretical Cross talk.Finite Difference Time Domain Method (FDTD) is used for evaluating the device at 1550nm.The performance of the device is evaluated interms of device length, Optical efficiency and channel spacing.The novel device presented here can be used as Optical Cross Connect (OCC), True Time Delay line (TTD) and Multiplexer.

***Index Terms*—Arrayed Waveguide Grating, Finite Difference Time Domain Method, Multimode Interfernce Coupler (MMI), Photonic Crystal (PC).**

I. 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 a single fiber is known as “Wavelength division multiplexing” or WDM [1]. The key component is Mux/Demux. In 1988, M.K.Smit proposed the angularly dispersive device, based on phased array known as Arrayed Waveguide Grating (AWG), which serves as a Mux/Demux,Optical Cross Connect(OCC),Delay line etc.[2]-[5].This device is versatile and incorporated in Wavength Division Multiplexing(WDM) network,Course WDM,and Dense WDM(DWDM) network.Several designs of AWG are demonstrated to operate within telecommunication C-band[6].The attractive features of the AWG has persuaded the authors to create this device on PC,which can be used in All Optical Network.(AON).

In the last few decades much interest has been directed towards photonic crystal, in which the refractive index changes periodically. A photonic bandgap is formed in the crystal and the propagation of electromagnetic waves is prohibited for all the wave vectors.Various important scientific and engineering applications such as control of spontaneous emission [7], Zero thresholding, sharp bending of light [8], trapping of photons and so on, are expected by utilizing photonic bandgap and artificially introduced defect state and light emitters [9]. Recent advancement includes the design of True time delay line(TTD) for antenna beam steering, where PC is integrated with Multimode interference coupler[10],Realization of PC waveguides for compressing slow solitons[11],Antiresonant reflecting optical waveguides[12], Collective population inversion in three dimensional systems using photonic crystal[13],Biomedical sensors[14].Various types of Demultiplexers are reported earlier. These Demultiplexers exploit the coupling properties of parallel Photonic Crystal waveguides[15]-[16].Some of them lack dual functionality.Although various important approaches have been proposed for the realization of all these complex devices,less attention is paid to the concept of making a multifunctional device using PC, analogous to AWG.Here we explore PC based AWG which can be made multifunctional. One of the applications ie. Demux is presented in this paper.Various headings include theory, results and conclusions. Furthermore the essential modifications that are to be made for making the device multifunctional are also discussed.

II. THEORY

A. Types of Photonic Crystal

In this study we propose a novel design of AWG Demultiplexer using 2D Photonic crystal(PC).Photonic crystals are periodic systems with high dielectric and low dielectric regions as shown in Fig.1a &1b.The periodicity or spacing determines the light frequencies. Accordingly, there two types of PCs.1) Dielectric cylinders in air.2) The periodic air holes in dielectric background. Former has a TM band gap and latter has a TE band gap which means that it blocks TE or TM propagation in the normal condition. When a defect is created, light is guided, if the normalized frequency falls within the band gap.The band structure for TE and TM bandgap is shown in Fig.2a&2b.To develop PC devices, the following requirements should be satisfied.1) A photonic crystal with a complete band gap should be constructed in the optical wavelength region 2) An arbitrary defect should be introduced into the crystal.

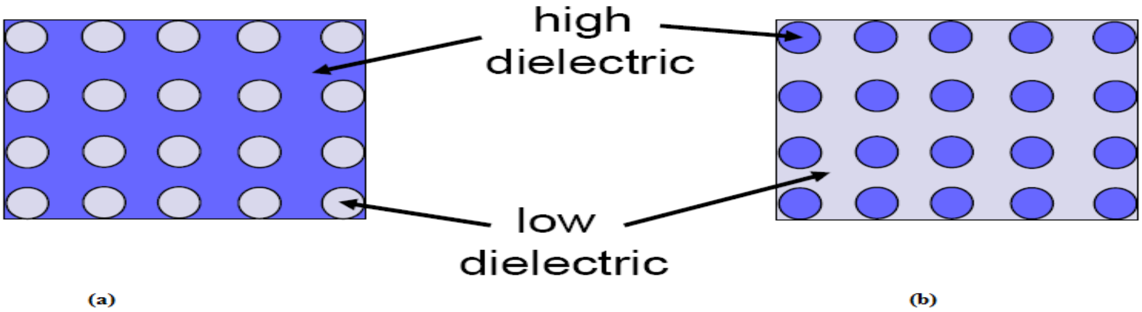


Fig.1. a)PCs with periodic airholes in dielectric background b)PC with Dieleciric cylinders in air.

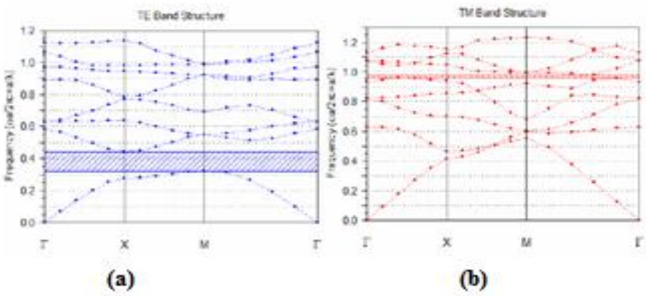


Fig.2. a) TE band structure for PC with airholes in dielectric background b) TM band structure for PC with rods in air

B. *Creating Defect in 2D PC*

We can introduce a line defect and a point defect on 2D-Phtonic Crystal. Line defect is introduced by removing a row of rods or airholes in the Γκ(Z) direction.Point defect can also be introduced by varying the size of rods or by varing the size of the airholes depending on the type of the crystal.This is depicted in Fig.3a.Losseless transmission of photon is possible for the line defect and an isolated point defect can trap the photon. The photon trapped by the defect resonates inside the defect and are emitted in the upward dirction.This phenomenon can be exploited for the design of channel –drop filter.By creating 2 or more line defects and point defects,we can realize no of photonic devices. The "Y" splitter created using line defect is shown in Fig.3b.It is also possible to create sharp bends in 2D PC as shown in Fig.3c.

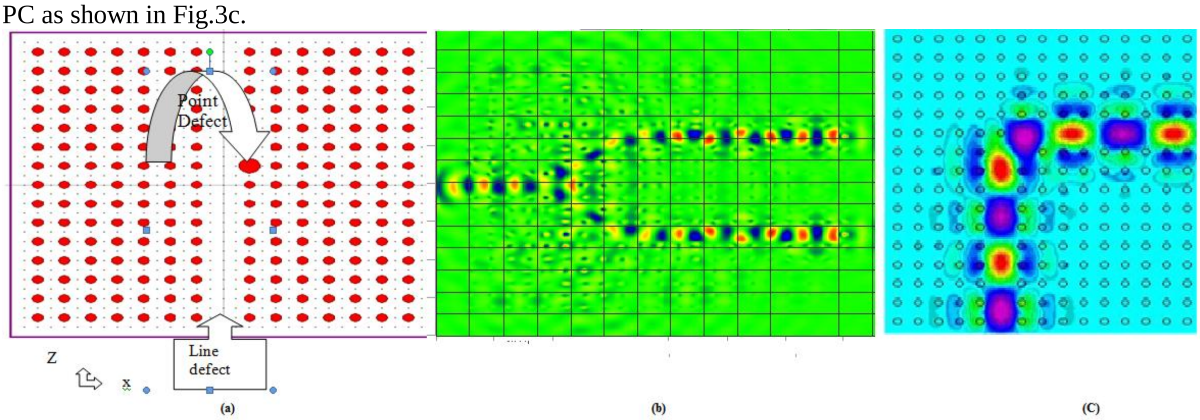
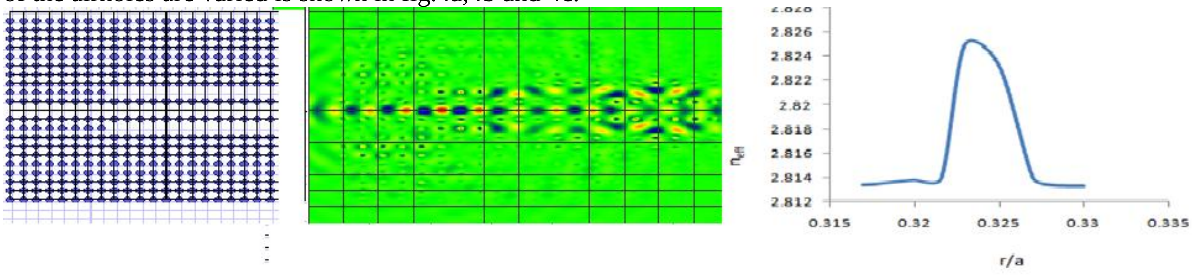


Fig.3 (a) PC with point and line defect (b) Propagation of light in Y splitter (c) Sharp bent waveguide

C. Coupling Effect

An array of PC waveguides are obtained by removing rows of holes or rods in Γκ(Z) direction.Light propagation through such a waveguide depends on the initial excitation.If a single channel is excited,then light couples evancently to neighbouring channel.The light output depends on coherently coupled light into the negihbouring waveguides and the length of the waveguide.This can be calculated using coupled mode theory(CMT)[17].Coupling coeffecient between the neighbouring waveguides can be controlled by varying the radie of the airholes /rods or the number of rows of holes/rods between each waveguide.Schematic view of the coupled waveguide , coupling between the waveguides and variation in the effective refractive index when the size of the airholes are varied is shown in fig.4a,4b and 4c.



(a) (b) (c)

Fig.4 (a) Schematic view of waveguide arrays (b) Coupling of power from central waveguide to the adjacent waveguides (c) Variation of effective index with air hole diameter.

III. DESIGN

The proposed AWG Demux on 2D PC, assuming square lattice of air holes in dielectric background is depicted in Fig.5.The radius of the air hole is 0.2a and the refractive index of the dielectric is 3.4 respectively. The parameter 'a' represents the periodicity of the lattice. An input (i/p) waveguide, Multimode interference (MMI) couplers, array waveguides and the o/p waveguides are created by introducing line and the point defects. This arrangement is similar to the conventional AWG and the Variable Width AWG.The central wavelength is 1550nm, as it falls within the band gap structure of the device. Continuous wave is launched into the i/p waveguide at different wavelengths and it is spatially separated at the o/p.Initially the device is simulated for two o/p channels followed by four o/p channels.

The proposed device in has input (i/p)waveguide(width=2a) , i/p MMI coupler with width "W=10a" and length "L=4a" which is also known as free propagation region (FPR),array waveguides ,output (o/p) MMI coupler known as the image plane and the two o/p waveguides resembling the conventional AWG.The o/p and the i/p waveguides are similar.The i/p and o/p MMI couplers are symmetric in our design.R_1-R_4 are the four rows of airholes in the array section. Each row has variable (r/a) ratio, a/λ, $a/2\lambda$, $a/3\lambda$ and $a/4\lambda$ respectively. We have three waveguides in the array section, parallel to each other. Two requirements are to be met to make the device dispersive 1) There should not be any coupling between the waveguides in the array section 2) There must be a phase difference between the waves propagating in the adjacent channels. Coupled mode theory is employed to ensure that there is no coupling between the waveguides in the array section[17].It is observed that minimum length required for coupling is 30 periods(30a)> device length=9μm. This ensures that light launched at the i/p waveguide, propagates through the array waveguides without mutual coupling.By varying the (r/a) ratio, second condition is satisfied. Since Photonic band gap (PBG) effect is exploited for designing this device, it's necessary that the proposed structure has a bandgap and the operating wavelength falls within this bandgap.The type of PC considered for this study has TE bandgap. Band Solve Tool is used to compute the band structure.Plane wave expansion (PWE) method is used for computing the bands. For the PC used in this device PBG has three band gaps as shown in Fig.6. Our operating wavelength falls well within this band gap.

The i/p waveguide, i/p MMI coupler and its integration to three o/p waveguides is analogous to 1x3 flexible power splitter.Choice of no of waveguides in the array section of the waveguides depends on two factors.1) Effective coupling of the power from the i/p MMI coupler to the array section 2)Minimum nonuniformity,which is defined as the power difference in dB between the central and the outer channels.We observed that non uniformity value increases, when we use four channels instead of three channels.This is observed by the power distribution in the array waveguides as shown in Fig .7a and Fig.7b.Therfore we have chosen 3 waveguides in the array section.In the conventional AWG the number of waveguides in the array section is three to four times than the i/p waveguides.

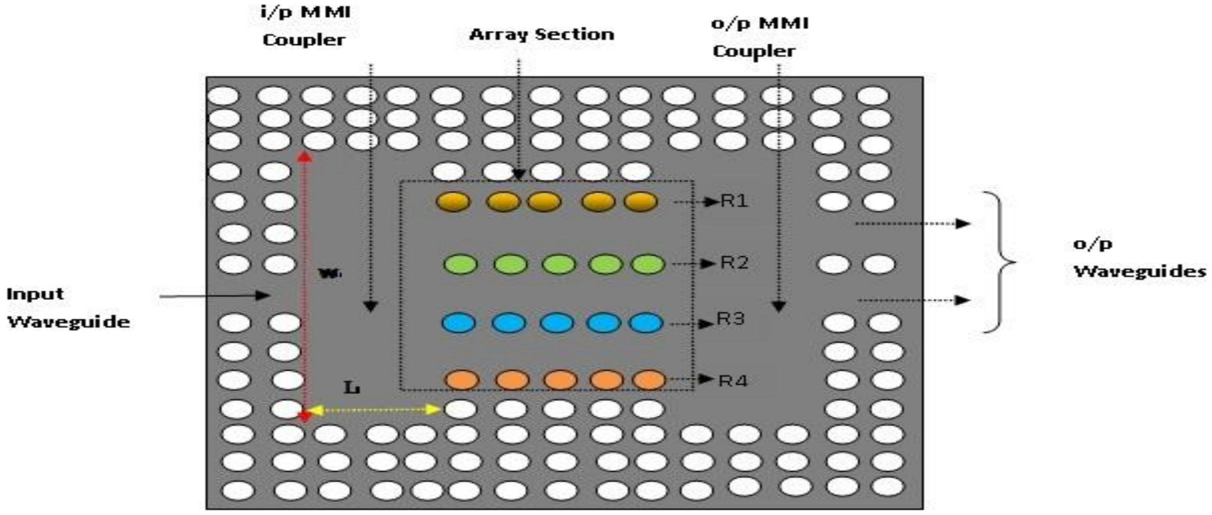
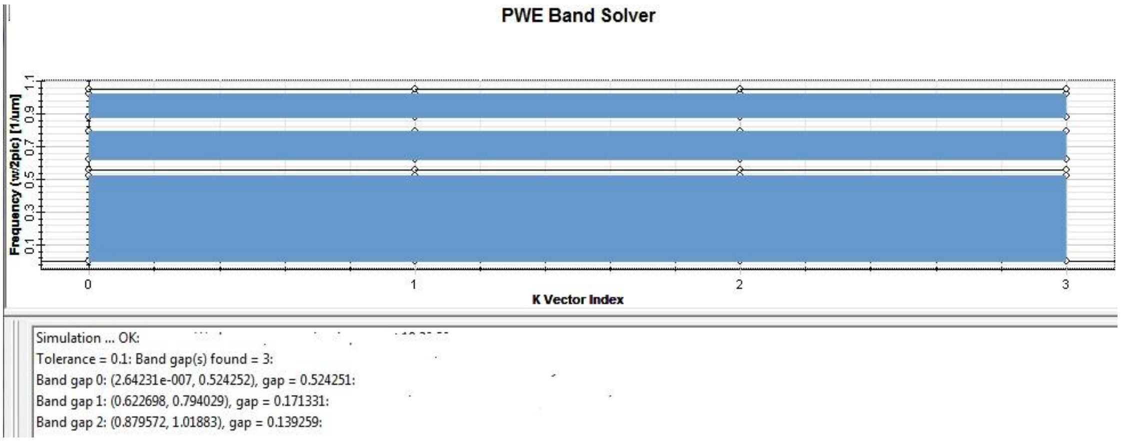


Fig.5. Schematic layout of Photonic Crystal Demultiplexer



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Simulation ... OK:
Tolerance = 0.1: Band gap(s) found = 3:
Band gap 0: (2.64231e-007, 0.524252), gap = 0.524251:
Band gap 1: (0.622698, 0.794029), gap = 0.171331:
Band gap 2: (0.879572, 1.01883), gap = 0.139259:
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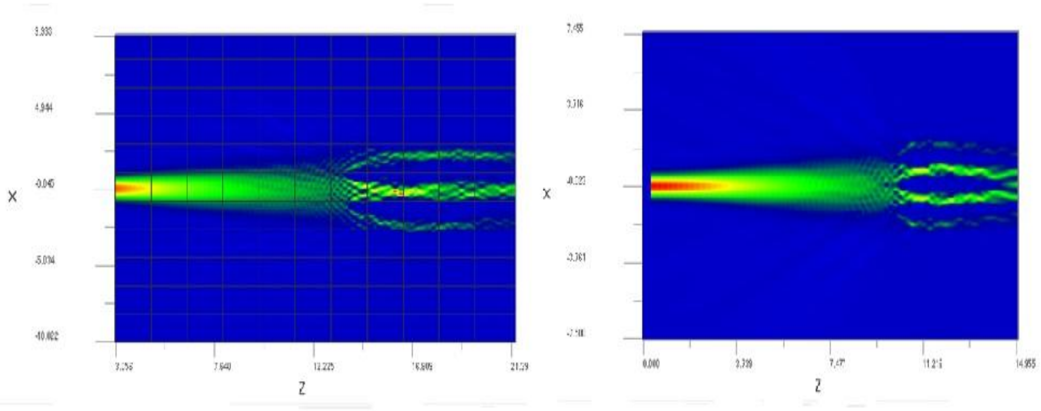
Fig.6.Band Structure for the proposed Demultiplexer



(a)

(b)

Fig.7 Power Distribution in (a) 1x3 Power Splitter (b) 1x4 Power Splitter

IV. ANALYSIS

The light enters the i/p MMI coupler through a single mode i/p waveguide. The light diverges in the i/p MMI coupler. Divergence angle of the beam can be controlled by the width and the length of the coupler. We have used symmetrical couplers at the i/p and o/p of the AWG.From the MMI region the light enters the array section,which comprises of 3 parallel waveguides.This i/p section is analogous to 1x3 flexible power splitter as the waveguide widths are varied by varying r/a ratio.The i/p section is shown in Fig.8.

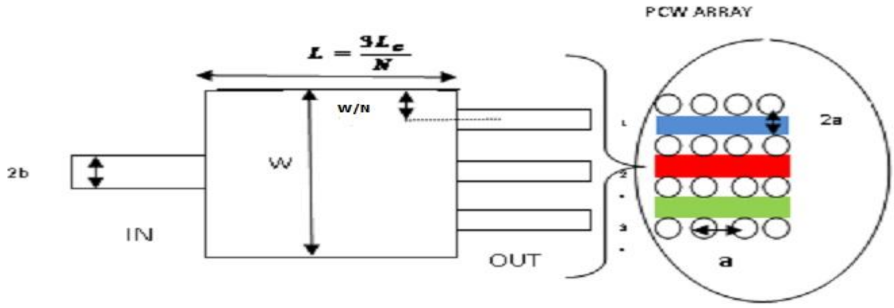


Fig.8 Input section of the PC AWG Demux

In general design of MMI coupler the device length L=3L_c/N, where L_c is the coupling length and “N” self images of the same intensity i/p that appears at the o/p.The coupling length L_c is approximately given by “1”.

$$L_c \cong \frac{4n_{eff}W^2}{3\lambda} \qquad (1)$$

Where “W” is the effective width of the MMI coupler=6a, where “a” is the period of the PC,n_{eff} is the effective refractive index and λ is the wavelength. “2b” is the width of the i/p waveguide.

In this case, effective width corresponds to geometrical width.In general the waveguide separation parameter plays a vital role in positioning the o/p waveguides. Here we have considered only two o/p waveguides.

The light diverges in the MMI coupler and enters the array section. This array section has three waveguides of different widths. This section behaves like 1x3 flexible power splitter. The splitting ratio P_c/P_b depends on the width of the PCW waveguides and the effective index of the individual waveguides.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 airholes .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 “ 2”.

$$P_c \approx Cos^2(0.5.\pi.d\Omega) \qquad (2)$$

When the beam passes through the arrayed waveguide section, the optical path length difference of adjoining waveguides is given by Δn_{eff} x *l*. Where Δn_{eff} is the change in the waveguide effective index and “*l*” is the length of array section $R_1/R_2/R_3/R_4$ shown in Fig.1.Waveguide effective index is varied due to change in “dΩ”.

“Equation 3”. has to be satisfied as the proposed structure is based on AWG principle.

$$\Delta n_{eff} \times l = m \times \lambda_0 \qquad (3)$$

Where “m” is the diffraction order of the device and “λ_o” is the central wavelength.

Nonuniformity is of prime importance in case of conventional waveguide.Nonuniformity is defined as the intensity ratio in dB between the outer and the central channel.In the novel device this is ignored, as the no of waveguides in the array section are only three. When the light enters the array section, phase shift is introduced. The propagation constant along the arrayed waveguides are β_1, β2 and β_3.

The following coupled mode equations “4”, “5” and “6” are used to compute the modes in the array section[17].

$$i\frac{d}{dz}a_n(z)+\beta_n a_n(z)+k_n[a_{n-1}(z)+a_{n+1}(z)]=0 \quad 2\le n\le N-1 \qquad (4)$$

$$i\frac{d}{dz}a_n(z)+\beta_1 a_1(z)+k_1 a_2(z)=0; \;\; n=1 \qquad (5)$$

$$i\frac{d}{dz}a_N(z)+\beta_N\, a_N(z)+k_N a_{N-1}(z)=0 \;\; n=N \qquad (6)$$

The coupling coefficient k and the propagation constant β is not same in the case of PC based AWG Demux.If all the waveguides are identical then propagation constant is taken to be same (β1=β2=β3---=β) and (k_1=k_2=k_3---=k).If one of the waveguides is excited initially ($a_{n=n0}$ (0) =a_0).Then the solution to the above equations is given by “7”

$$a_n(z)=a_0(i)^{|n-n_0|}\exp(i\beta z)J_{|n-n_0|}(2kz) \qquad (7)$$

Where J_{an}(x) Bessel function of order n.

In the novel device, length of the array section is chosen in such a way that, there is no coupling between the adjacent waveguides. All the three Waveguides behave like independent waveguides.Furthemore all the waveguides in the array sections are excited simulataneously. This is achieved by choosing the length of the array section much lesser than the coupling length (L/a). Where “ L” is the length of the device and “a” is the Period.For the proposed structure, mutual coupling occurs at the coupling length 30a>>length of the device.Thus the modal amplitude in each waveguide is given by the “8”

$$a_n(z)=(a_0)\exp(-i\beta_n z) \qquad (8)$$

Where (n=1,2,3) and the power entering each waveguide which depends on “dΩ” presented in “9”.

$$d\Omega=\frac{m.\lambda_0}{n_{eff}} \qquad (9)$$

Where “m” is the diffraction order of the array, “λ_0” is the central wavelength and “n_{eff}” is the effective refractive index. The “dΩ” of the array waveguide is chosen, such that maximum power is coupled to the individual waveguides at the central wavelength (1550nanometer).The phase difference is wavelength dependent, and the phase difference at the central wavelength is zero.When propagating through the output coupler, the outgoing beam will be tilted and the focal point will shift along the image plane. Spatial separation of the different wavelength channel is obtained. The diffraction equation of the novel device is given by “10”

$$n_{eff}\times l-n_s d_r Sin\phi=m\lambda \qquad (10)$$

Where “dr” is the space between the adjoing waveguides at the o/p, “ϕ” is the diffraction angle, “n_s” is the refractive index of the diffractive material at the output port i.e. PC material and “m” is the diffraction order.While placing the receiver waveguides, we should avoid cross talk.The position of the o/p waveguides depend on two parameters 1) Spatial shift 2) Cross talk. The cross talk specification, puts a lower limit on the receiver spacing d_r (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.

The crosstalk level in dB is related to the power overlap integral P_{over} as in “11”

$$CT(dB) = 10\log(P_{over}) \qquad (11)$$

Where “P_{over}” 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”.Where “W” is the geometric width of the waveguide and “N” is the no of output waveguides. In the proposed device the position of the o/p waveguides relies on the focusing spot.The position of the focusing spot depends on the dispersion offered by the device, which in turn controls the spatial separation of the wavelength.

The dispersion ‘D’ in “12” of the array is the lateral displacement “ds” of the focusing spot along the image plane per unit frequency change.

$$D = \frac{ds}{df} = \frac{1}{f_o} \cdot \frac{n_{eff}(array)}{n_{eff}(MMI)} \cdot \frac{d\Omega}{\Delta\alpha}. \qquad (12)$$

f_0=Central frequency, $d\Omega$= effective width of the array waveguide, n_{eff} (array) =effective index of the array waveguides, n_{eff} (MMI) =effective index of the output MMIcoupler,$\Delta\alpha$= Divergence angle of the beam in i/p MMI coupler.

Total loss in PCW Demux is given by “13” and “14”

$$L(total) = L_0 + L_p \qquad (13)$$

$$L(total) \approx -17^{e-4\pi^2 we^2} / d\Omega \qquad (14)$$

L_o=Insertion loss,L_p= Propagation loss and W_e=Width of the Gaussian modal field inside the array. This MMI region or FPR length is chosen in such a way that non uniformity value “L_u” is minimum.

V. DEVICE OPERATION

A continuous wave at 1550nm is launched at the input (i/p) waveguide.The light enters the MMI coupler and diverges. While travelling through the MMI coupler region there is a phase change. The light enters the waveguides in the array section. Due to variation in “r/a” values,n_{eff} along these waveguides are different, so does the propagation constant β. The fields in the individual waveguides arrive at the o/p aperture with equiphase and constructive interference takes place at the o/p MMI coupler which is a image plane. For central wavelength the beam is focused at the centre of the image plane and for other wavelengths the focused spot moves along the image plane enabling the separation of wavelength. Maximum power enters the central channel as compared to the outer waveguides. This effect is known as nonuniformity in Phasar, expressed in dB, which can be controlled by the divergence angle of the beam at the i/p MMI coupler.

VI. APPLICATIONS

By increasing the no of i/p and o/p waveguides, we can use this device as Mux.Optical cross connects, Modulators, Tunable Mux/Demux, Laser, Add –Drop Multiplexers, Filters, True time delay line for antenna beam steering. By adding an additional layer(analyte) in MMI region,we can use this device for DNA/RNA and Protein detection. Furthermore by using MMI region as an interaction region we can use this device as gas sensor.

VII. RESULTS AND DISCUSSIONS

The propagation of wave in the proposed PC based AWG Demux is shown in The Fig.9.Light enters the i/p waveguide, diverges in the i/p coupler, propagates through the array section and converges at the o/p MMI coupler.

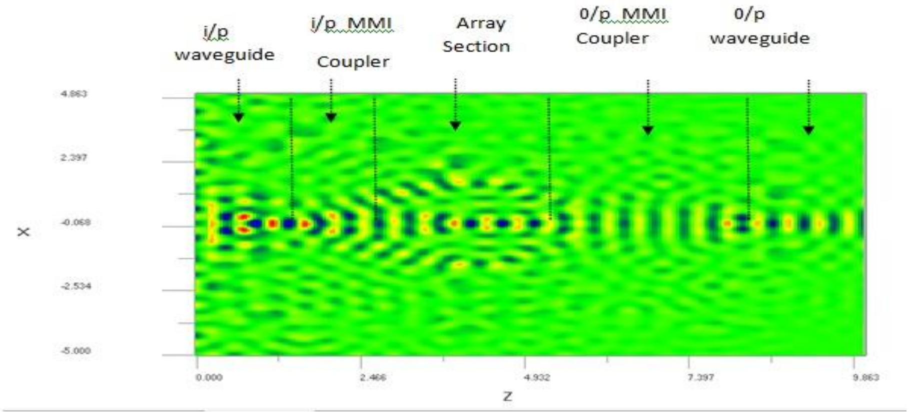
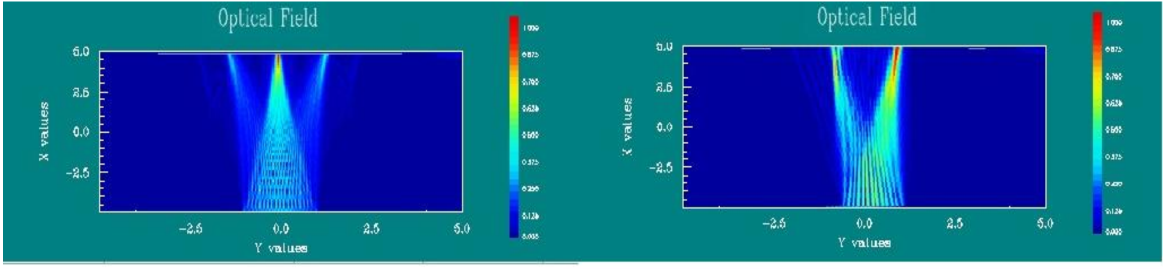


Fig.9. Propagation of light in the proposed AWG Demux at 1550nm

Using Beam Propagation tool we observed that, for central wavelength, the beam is focused at the center of the image plane as shown in Fig.10a. and for the wavelength other than the central wavelength the focusing spot moves along the image plane shown in Fig.10b.The device offers a spatial shift of 1μm/nm change in wavelength which is sufficient to provide 200GHz channel separation.

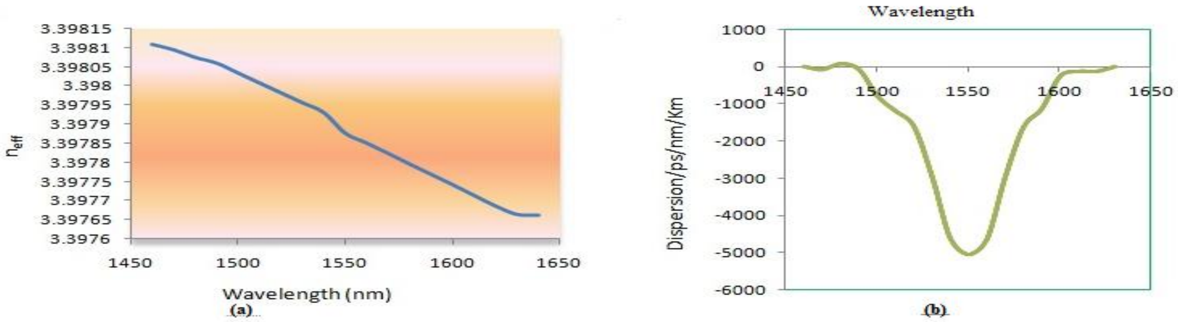


(a)

(b)

Fig.10. B.P.M simulation of the light focusing property at o/p MMI coupler (a) for central wavelength $\lambda = \lambda_0$ (b) Shifting of the beam when $\lambda < \lambda_0$

By using the overlap integral tool at the o/p, cross talk is determined ,Typical value obtained is-32dB, well within the acceptable range of the Demux.This result could be accomplished because, we are able to vary the effective index with λ and obtain high value of dispersion, -5042 ps/nm/km as shown in Fig.11a and Fig.11b.The spectral response of the device is as shown in Fig.12.We can observe from Fig.12, that space between the adjoining channels is 2nm ≈200GHz channel spacing.We can increase the no of o/p channels to four. Nevertheless for the central wavelength the field will be associated with central channel. For other wavelengths corresponding to the operating range of the Demux, field will be associated with the corresponding o/p channel as shown in fig.13a and 13b. The demultiplexers discussed earlier are not multifunctional, no provision to increase the number of output channels, longer devices and cross talk is higher than the proposed device.



(a)

(b)

Fig.11 a) Variation of the effective index with λ b) Dispersion "D" with λ

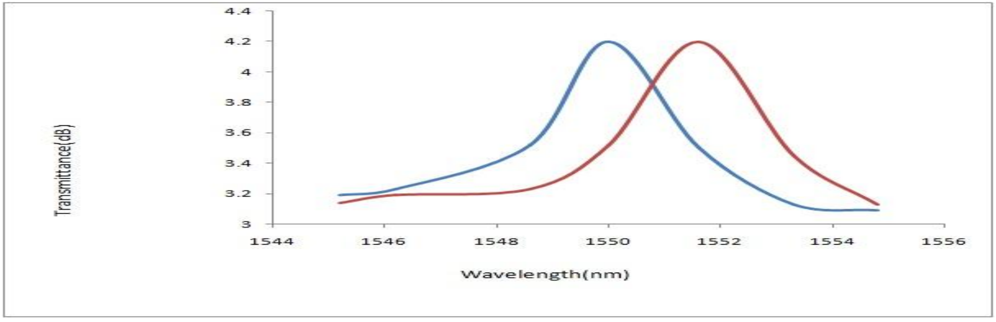
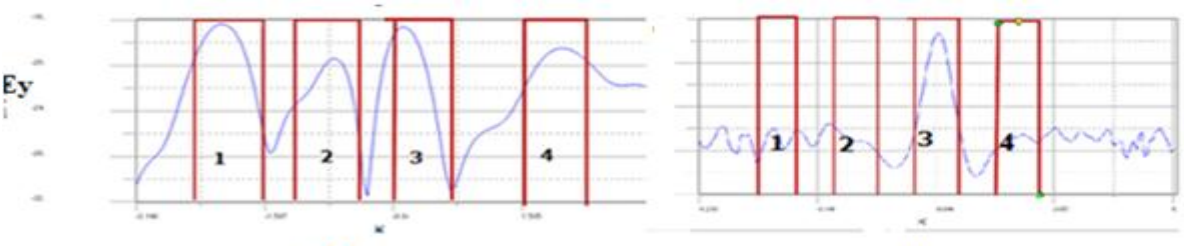


Fig.12 Spectral Response of the proposed two channel Demux



(a) (b)

Fig.13 Field associated with a) four o/p channels for a multiplexed i/p b) Field associated with central channel for $\lambda=\lambda_0$ Central Wavelength.

For central wavelength simulation the field is associated with the central channel.Far field pattern at this wavelength is shown in Fig.14

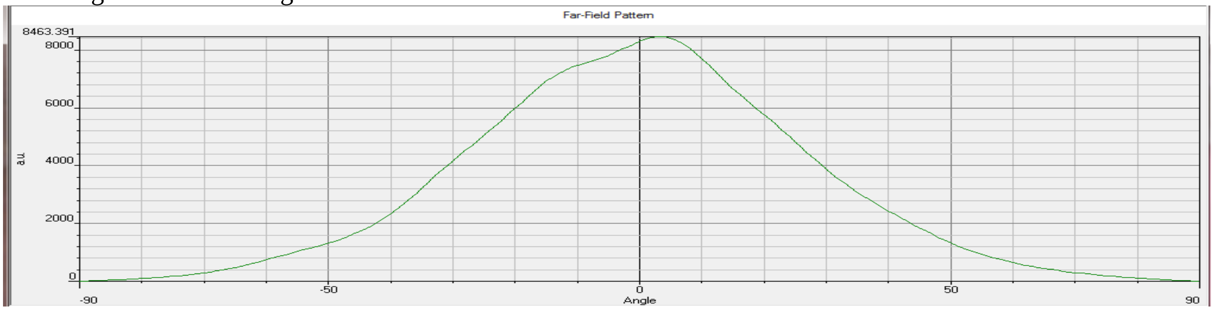


Fig.14 Far field pattern of the proposed Demux at central wavelength 1550nm

VIII. CONCLUSION

A new two channel PC Demux based on AWG principle is proposed.The proposed structure is attractive in terms of device length and channel separation.The length of the device is 9μm.Opical efficiency is 95%.The device can be transformed into a multifunctional device such as True Time Delay line(TTD),Cross Connects etc.by engineering no of inputs,outputs,coupling parameters and d/a ratio(diameter/radius) of the airhole.The device outperforms the PCF based Demux discussed earlier[16].The predictions made by the analysis are in good agreement with those observations by FDTD and BPM method. However there may be 1-2% degradation of these parameters after fabrication. Other possibilities such as PCW with dielectric rods in air, to develop similar devices are under investigation.

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