Novel Design of Photonic Crystal Devices for Optical Networks

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ABSTRACT
In this paper, we carry out the study of two-dimensional photonic -crystal based devices. The devices discussed here include simple waveguide arrays, bent waveguide, 1x2 Y splitter and demultiplexer. The coupling properties are investigated using coupled mode theory. One straightforward application of such analysis is the coupling of power launched into the channel to the side waveguides. As a result, the appropriate design of Photonic crystal waveguide arrays (PCWA) may permit the realization of efficient, compact and novel waveguides, power divider and demultiplexer.

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

General Terms
Performance, Design, Theory and algorithm

Keywords
Photonic crystal(PC),Photonic crystal waveguide arrays(PCWA), Power dividers,Demultiplexer,Coupled mode theory, Photonic Band Gap (PBG)

1. INTRODUCTION
Photonic crystals (PCs) are periodically patterned materials with strong dielectric contrast[1]-[3].There are high dielectric and low dielectric regions in the PCs as shown in Fig.1.The periodic structures forbid the wave propagation within the frequency range, which is known as photonic band gap(PBG).Because of this unique feature, optical devices like power splitters, Mach Zhender interferometer,Demux and band pass reflection filters are realized. In this paper we have presented the design of PC based devices such as Bent waveguide, Power splitters and Demultiplexer. Simulation is performed for a central wavelength of 1550nm. Band solve method is used to analyze the bandgap.Transmission characteristics are analyzed using coupled mode theory. Furthermore two dimensional (2D) finite difference time domain (FDTD) analysis is carried out to verify the theoretical analysis[4].

2. PHOTONIC CRYSTAL WAVEGUIDE ARRAYS.
In this study we implement a s waveguide arrays design using.2D Photonic crystal(PCs).Photonic crystals are periodic systems with high dielectric and low dielectric regions as shown in (Figure1).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 later has a TE band gap as shown in (Figure 2).The PC discussed here, is composed of triangular lattice of dielectric cylinders in the air (n=3.45) with radius 0.3a in air, where "a" represents the periodicity of the lattice. Perfectly matched layer (PML) boundary condition is applied to absorb outgoing waves efficiently.

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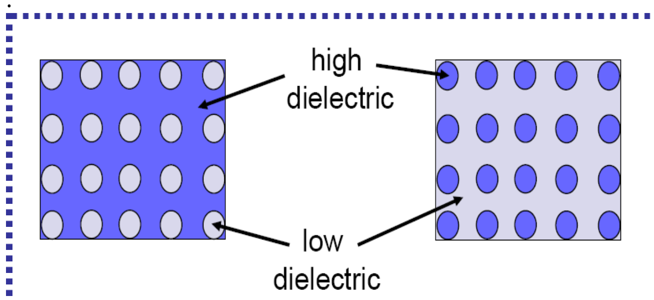
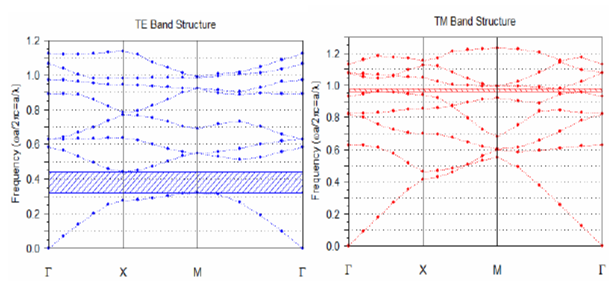


Fig1:PCs with periodic airholes in dielectric background &Dieleciric cylinders in air.



Inplane wavevector

Fig 2:TE and TM Band structure for PC

The waveguides in PC is generally obtained by removing one or more rows of dielectric rods in horizontal or vertical direction.This is considered as a line defect is shown in (Figure 3).When defect is introduced, the PC guides the light.The defect shown in Fig.3.is a line defect,which is introduced by removing a row of rods or holes 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[5].

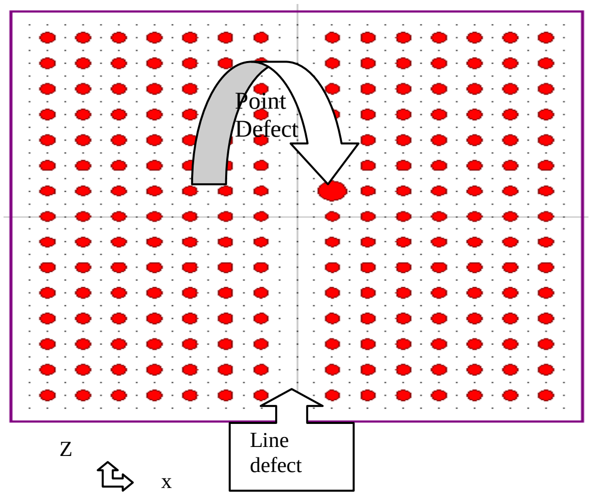


Fig 3:Schematic of 2D Photonic crystal slab showing line defect and isolated point defect.

The mechanism for the transfer of light between the constituent waveguides is as follows.The coupled structure supports a set of supermodes.The excitation of an individual waveguide means that a superposition of supermodes that is excited.This non -stationary state then evolves in such a fashion that the optical power is moved into the desired waveguide(s) following a given propagation length.(Figure4).shows the set of parallel waveguides.

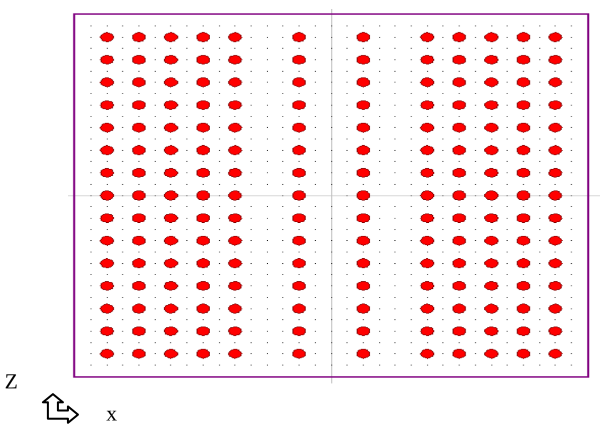


Fig 4:Schematic layout of 3 photonic crystal waveguide arrays.

3.DESIGN OF PC DEVICES

Photonic waveguide devices such as bent waveguide, Power splitter and Demultiplexer are discussed here.In this design we have used the combination of point defect and the isolated defect to enhance the ability to manipulate the flow of light. This is shown in (Figure 5),(Figure 6) and (Figure 7).

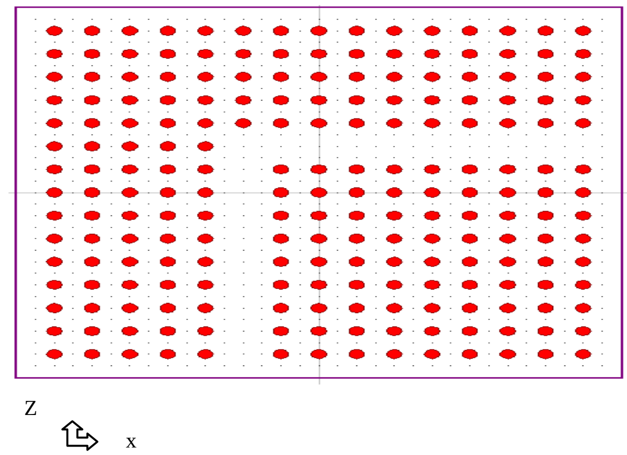


Fig 5:Schematic layout of PC bent waveguide .

In (Figure 5),bent waveguide is obtained by removing one row of rods in the Z-X direction. Power splitters plays a vital role in optical communication.Several designs have been proposed earlier. Input power is divided equally into two arms in Y splitter, as shown in Fig.6.

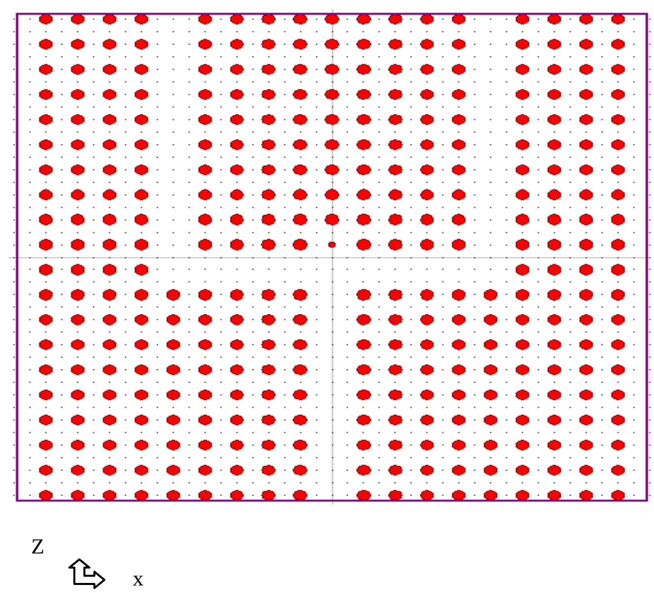


Fig 6:Schematic layout of Y Splitter with point defect and line defect.

Wavelength multiplexers and demultiplexers (MUX-DEMUX) are essential components of optical network.The strong light confinement in PC structure allows allows the design of waveguide components that can perform complex interconnections within a small area. The Demux presented here is an arrayed waveguide grating (AWG) where the array section is replaced by PCWA. The device consists of one i/p single mode waveguide with 2 µm width, four o/p single mode waveguides with 2 µm width. The spacing between the o/p waveguide is 4 µm.The length of the i/p and o/p waveguide is 80 µm.The two MMI coupler used are symmetrical and of 30 µm width.The array section consists of PCW wherein the d/Λ ratio is varied. Here "d" is the diameter of the rod and (Λ=a) is the period. The PCW in the array section is a replacement for array waveguides in the arrayed waveguide(AWG).This is shown in the fig.7.These devices find extensive applications as add drop MUX/DEMUX, Equalizers, Routers WDM channel filters,Multiwavelength lasers, Microwave Photonics switches and NxN matrix switch.

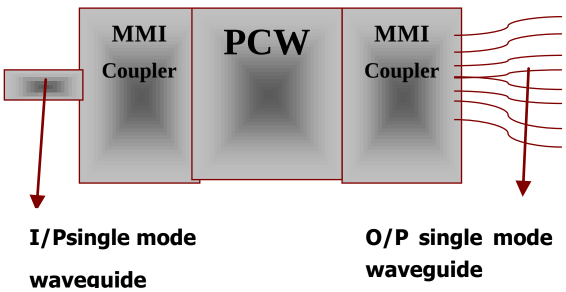


Fig 7: Schematic layout of PC based AWG Demux

Figure.8 shows the PCWA used in the array section of the AWG Demux.

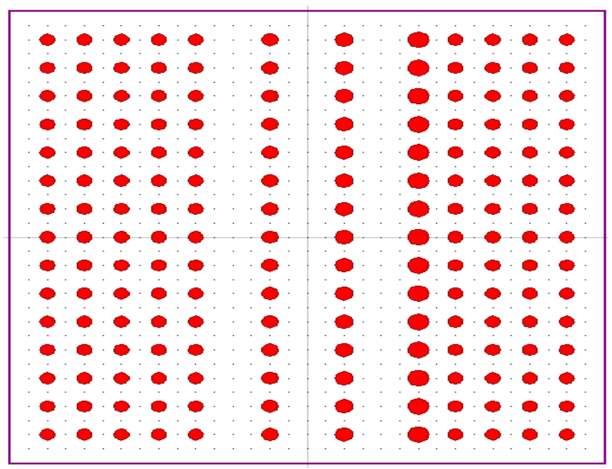


Fig 8 :Schematic layout of PCWA with variable d/Λ ratio

The variation of this d/Λ changes the effective modal index, which in turn changes the path length. The fields in the individual waveguides arrive at the o/p aperture with equiphase and constructive interference takes place at the image plane. The divergent beam is transformed into a convergent beam. For central wavelength the beam is focused on the centre of the image plane. As the wavelength is varied the beam shifts along the image plane (o/p MMI coupler).Thus enabling the separation of the wavelengths. The refractive index profile of this device is shown in (Figure 9).

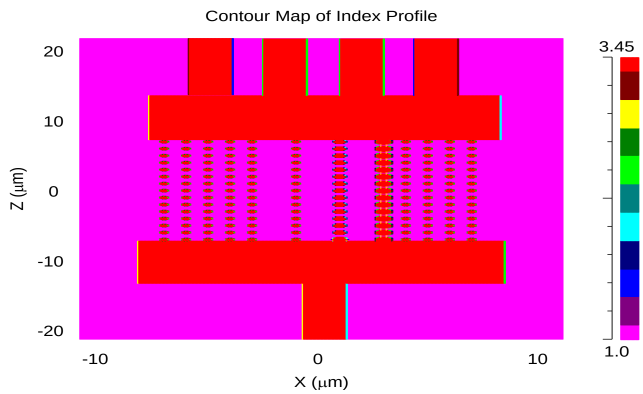


Fig 9: Index profile of PCW Demux

4. NUMERICAL METHODS

Analysis of PCW devices is done by finite difference time domain and Plane wave expansion method (PWE)[6].The power launched into the central waveguide is coupled to the neighboring waveguide. The amount of power coupled to the adjacent waveguides depends on the coupling coefficient k. [7]-[10].If there are n waveguides, light propagation in the n^{th} waveguide obeys the following first order coupled- mode equation.

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

$$i\frac{d}{dz}a_n(z)+\beta_1 a_1(z)+k_1 a_2(z)=0;\ \ n=1 \qquad \cdots(2)$$

$$i\frac{d}{dz}a_N(z)+\beta_N\ a_N(z)+k_N a_{N-1}(z)=0\ \ n=N\ (3)$$

The coupling coefficient k and the propagation constant β is not same in the case of PCW 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 waveguide is excited initially ($a_{n=n0}(0)=a_0$).Then the solution of the above equations is

$a_n(z)=a_0(i)^{|n-n_0|}\exp(i\beta z)J_{|n-n_0|}(2kz)$,where $J_n(x)$ Bessel function of order n.

4.1 Design of Demux

PHASAR's have many degrees of design freedom, and many design approaches are possible. The approach followed by M.K.Smit is explained here.

The receiver spacing d_r: We start with cross talk specification

Which puts a lower limit on the receiving spacing d_r .Cross talk level lower than than -30 to -35dB are difficult to realize. In our design -35 to -50dB is considered. The cross talk between the adjacent channel is considered to be approximately -100dB.The cross talk in dB is related to the power overlap integral P_{over} as follows;

Cross Talk (CT)dB = 10log(P_{over}) (4)

$$P_{over}(ds) = \frac{\{0.5[\int_{A\infty}(\hat{E}_1^* \times \hat{H}_1 + \hat{E}_2 \times \hat{H}_2^*)dA]\ \}}{\int_{A\infty}(\hat{E}_1 \times \hat{H}_1^*.\breve{Z})dA \sum_{A\infty}(\hat{E}_2 \times \hat{H}_2^*.\breve{Z})dA} \quad (5)$$

FPR(Free Propagation Region) length R_a : This is the i/p and o/p MMI coupler. It is chosen in such a way that nonuniformity value

Lu is minimum. Nonuniformity Lu (dB) is defined as the intensity ratio between the outer and central channel.

$Lu = -10 \log .\ (2\theta^2_{max}/\theta_o^2) \approx 8.7.\ \theta^2_{max}/\theta_o^2$ (6)

$$\theta_0 = \frac{\lambda}{N_{FPR}} \bullet \frac{1}{We\sqrt{2\pi}} \quad (7)$$

Where "W"$_e$ is the effective width of the modal field. The minimal length of the FPR is given by:

$$R_a = \frac{S_{max}}{\theta_{max}} \quad (8)$$

Where S_{max} is the S coordinate of the outer FPR and θ_{max} is the maximum acceptable dispersion angle.

Array Section: This section comprises of PCW array. Where multiple defects are created to obtain the required dispersion. Two types of PCW array can be used, either rods in air or air holes in dielectric background. Former is used in this paper.

5. RESULTS AND DISCUSION

The PC discussed here (dielectric rods in air) has a PBG for TM polarization. When the defect is created there is no PBG as shown in (Figure10) and allows the propagation of light shown (Figure 11).

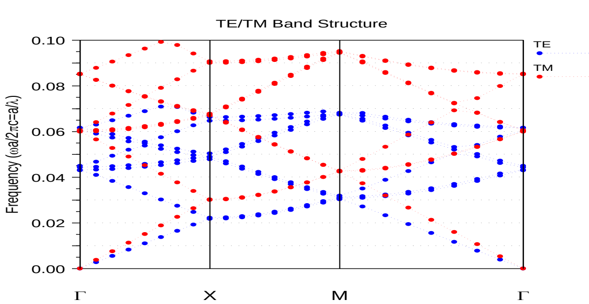


Fig10:TE and TM Band structure for PC with defect(Bent Waveguide).

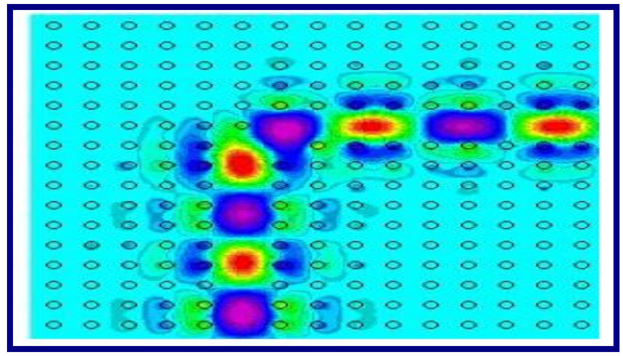


Fig11:.Propagation of the light in the Bent Waveguide

In the conventional arrayed waveguide when such sharp bend is introduced, it results in heavy loss. The loss in this case is very less, of the order of 0.01dB.The high index contrast leads to well confinement of the light. Index profile of the bent waveguide is shown in (Figure12).

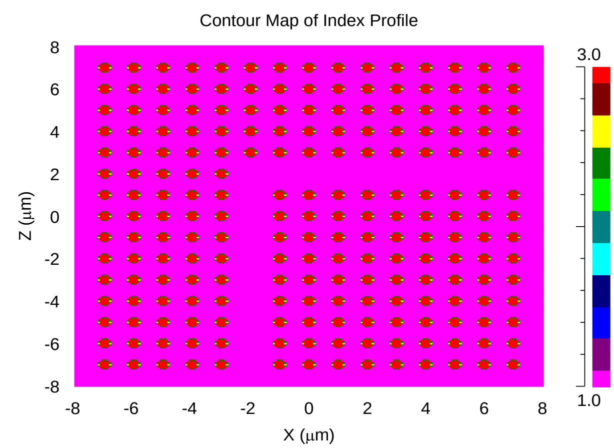


Fig 12:Index profile of Bent Waveguide

In order to find the appropriate propagation mode in the Y splitter FDTD method is used. The result is displayed in (Figure 13).

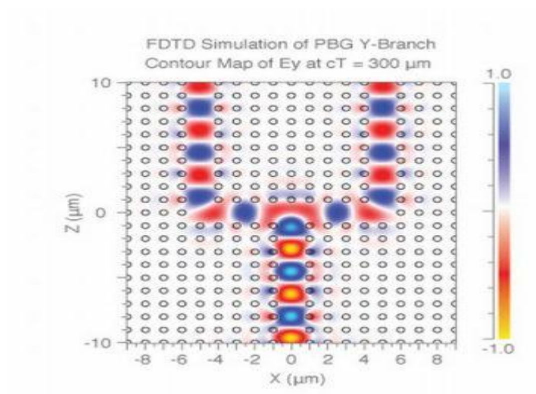


Fig13:.Propagation of light in Y branch

The Y structure supports the TM propagating modes at the normalized frequency 0.21 .The Band structure for this device is as shown in (Figure 14).

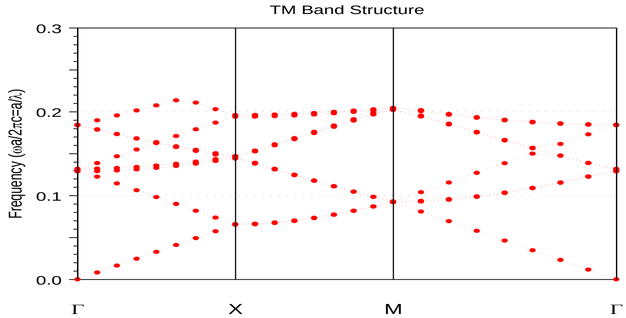


Fig14:TM band structure for Y branch.

The index profile for the band structure is shown in (Figuere15).

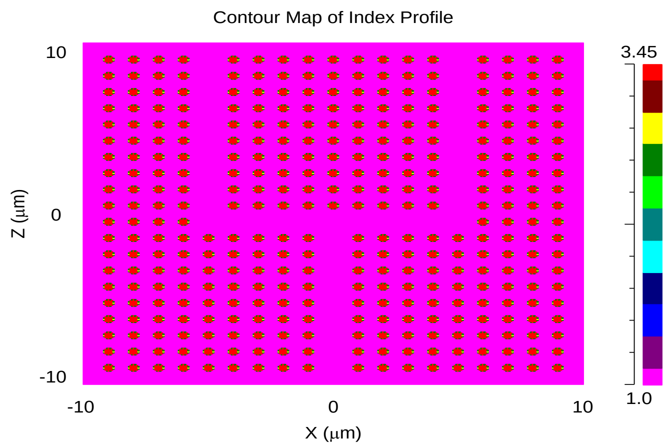


Fig 15:Index Profile for Y branch.

The PCW based AWG Demux discussed earlier, focuses beam at the center of the image plane for central wavelength 1550nm.It is displayed in (Figure 16).

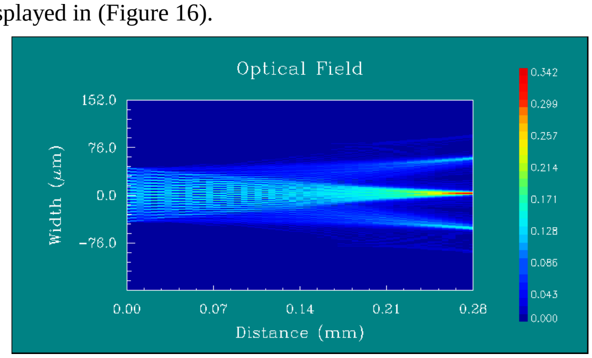


Fig16: BPM Simulation of the light focusing property in the second slab waveguide for central wavelength

For $\lambda \neq \lambda_0$, the beam shifts along the image plane as shown in (Figure 17). Modal field redistribution between the waveguides causes the effective refractive index to change rapidly with wavelength(Figure 18), thus resulting in a very high dispersion value around the phase matched wavelength of 1.55 µm around -4350ps/nm/km (Figure 19). If we place the o/p waveguide at the different focusing point we can separate the wavelengths as shown in (Figure 20).This device can be used as a true time delay line (TTD) for antenna beam steering.

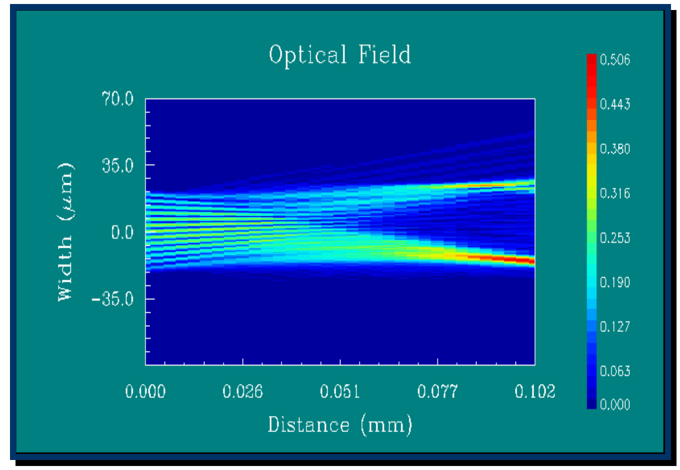


Fig 17: BPM Simulation of the light focusing property in the second slab waveguide for $\lambda \neq \lambda_0$

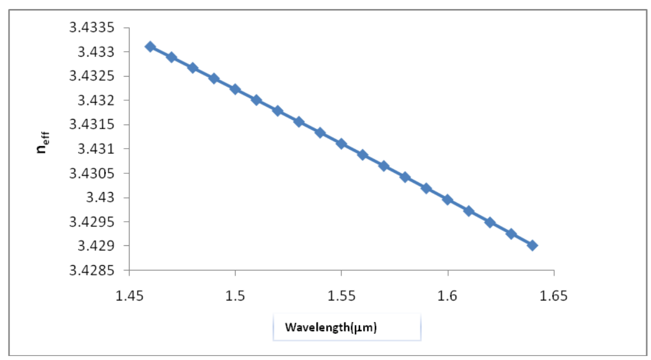


Fig 18: Change in the effective index with λ

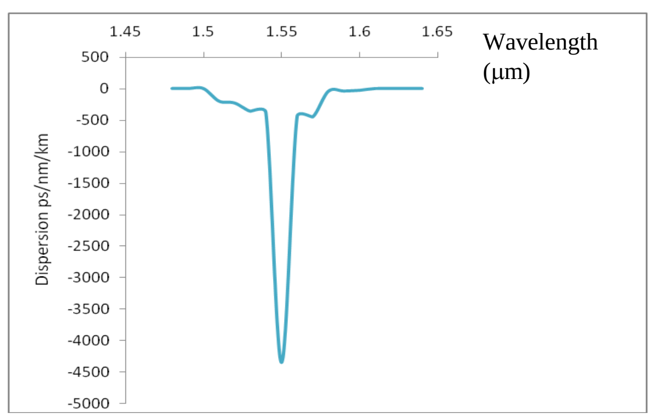


Fig19: Relationship between dispersion value D and Wavelength

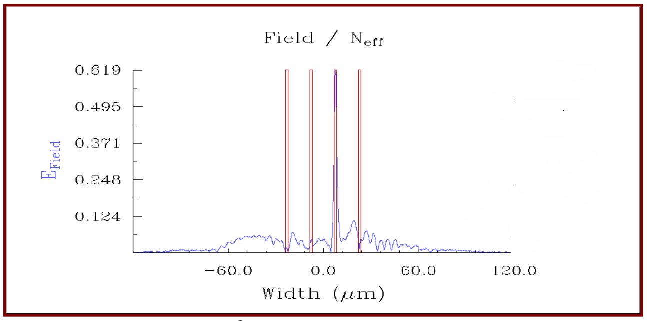


Fig 20:Electric field associated with central channel

By using the overlapping integral cross talk for the adjacent channel is calculated. This yields a value of -100dB for the central channels (Figure 21).Overall device cross talk is around -40dB.

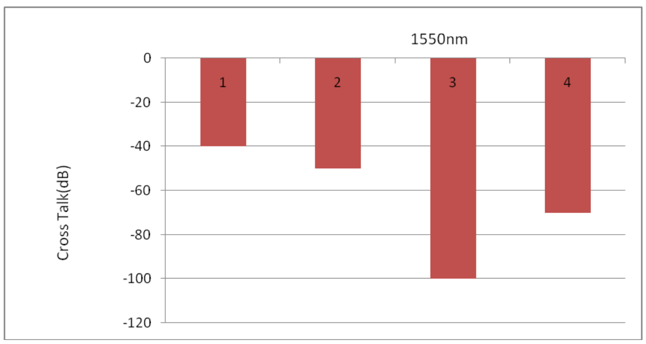


Fig 21:Adjecnt channel cross talk

6.CONCLUSION

In summary ,we have presented the study of PCWA and designed compact and efficient power splitter ,bent waveguide and Demux for optical N/W.Other device based on PCWA may be feasible by engineering the coupling parameter, waveguide modes ,changing the air hole size/rod size. The prediction made by the coupled mode theory are in good agreement with those observations by the FDTD method. Although loss and gain were excluded in present study, they can be included easily in the coupled mode theory formulation.

7. ACKNOWLEDGMENTS

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