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Photonic Crystal Waveguide 1x3 Flexible Power Splitter for Optical Network

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***Abstract*—**A compact 1x3 power splitter based on Photonic Crystal Waveguides (PCW) with flexible power splitting ratio is presented in this paper. Multimode interference coupler (MMI) is integrated with PCW. The device size reduction compared with the conventional MMI power splitter is attributed to the large dispersion of the PCW. Band Solve tool is used to calculate the band structure of PCW. Finite Difference Time Domain (FDTD) method is adopted to simulate the relevant structure at 1550nm wavelength. The device is polarization insensitive and allows the control of output (o/p) powers within certain percentage points for both polarizations.

***Keywords*—**Dispersion, MMI Coupler, Photonic Bandgap, Power Splitter.

I. 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],[4]. 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[5]. By using conventional rectangular geometry of MMI coupler only discrete power splitting ratio can be obtained even when the overlapping of the self images is introduced [6].

For several applications free choice of power splitting is adventages.In optical networks when "tap" function is required a small portion of the power is required depending on the situation. 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 concept of tapering in MMI coupler was investigated. [9].

In [10] 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.

In 1991, the idea that the well known "stop bands" in periodic structure could be 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, were fabricated. [11]. Since then several PCF based devices such as lasers, filters, switches and multiplexers and demultiplexers were realized. The concept of multicore PCF lead to the realization of 1x4, 1x8 power splitters with fixed power splitting ratio [12],[13]. This concept of multicore in PCF was extended to design the 1x4 PCF with flexible splitting ratio by modifying the core diameter [14].With the development of PCWs, several PCW based devices such as interoferometers, lasers, multiplexers, demultiplexers and power splitters were developed. Current research is to integrate MMI coupler with PCW, which allows the realization of true time delay line(TTD)[15] and other photonic devices.

In this paper, we have integrated MMI coupler and PCW array to design and analyze 1x3 power splitter with flexible power splitting ratio. The light enters the MMI coupler and diverges, finally enters the three PCWs. The amount of power coupled to the o/p waveguides depends on the width and effective index of the waveguide. The power coupled to the o/p waveguide is controlled by varying the d/a ratio of the dielectric rods. Where "d" is the diameter of the rod and parameter "a" represents the periodicity of the lattice.

This paper is separated into 4 sections. Section II explains the design and analysis. Section III describes the simulation results. Finally section IV provides some conclusion.

II. Design and Analysis

The proposed 1x3 power splitter is schematically depicted in Fig. 1. 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 15x15μm.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, and n=3.45.The three PC (Photonic Crystal) waveguides are created by eliminating three rows rods. (Creating line defect in PC) and the diameter of the rods adjacent to the waveguides are varied as a/λ,$a/2\lambda$ and $a/3\lambda$ where λ is the operating wavelength (creating point defect in PC). The thickness of the guiding layer is 150nm.Substrate thickness is 500nm. These o/p PC waveguides are replacing the conventional waveguides. This arrangement is shown in Fig. 2.

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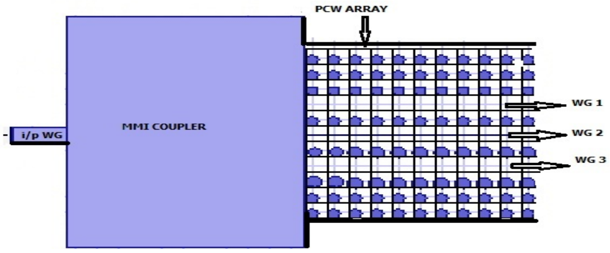

Fig. 1 Schematic of the 1x3 PCW flexible power splitter

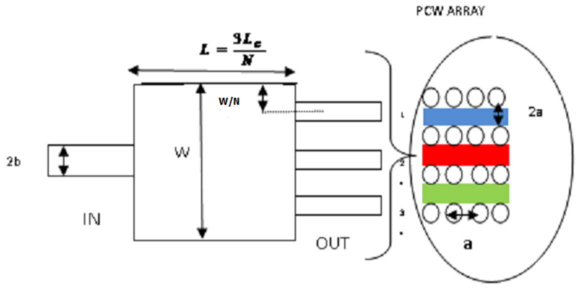

Fig. 2 PCW waveguides replaces the o/p waveguides of conventional MMI coupler

The geometry of the 1x3 flexible power splitter with one input and three o/p is depicted in Fig. 2. 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 [9].

$$L_{\frac{M}{N}} = \frac{M}{N}.L_c \quad (1)$$

with

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

Where "M" is the possible MMI lengths of overlap 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.

In our design the width of the PCW array =10a. The position of the o/p waveguides must be at "W/N". The width of the PCW waveguides are greater than or equal to 2a depending on the diameter of the dielectric rods adjecent to the waveguide. The width of the i/p waveguide is "b" µm.Length of of the coupler=(3Lc)/N=15µm and width"w"=15µm.

The splitting ratio P_c/P_b depends on the width of the PCW waveguide and the effective index of the individual waveguides. Wher in 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. 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;

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

The propagation constant β in the array section Fig. 1 of the power splitter depends on "dΩ". The propagation of light in the array section is computed using coupled mode theory[16]. The dipsersion offered by the array section contributes for phase shift in the array sections. The phaseshift varies with wavelength. However the phase shift is not important in this case. The focus is howmuch power is coupled from input(i/p) to output(o/p) waveguides.

The "dΩ" of the array waveguide is chosen such that maximum power is coupled to the individual waveguides at the central wavelength (1550nanometer).

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

m = order of the array
λ_c = Central wavelength
n_{eff} = Effective index

The power launched into the central waveguide is coupled to the neighboring waveguide in normal cases.The amount of power coupled to the adjacent waveguides depends on the coupling coefficient k. If there are n waveguides, light propagation in the n^{th} waveguide obeys the following first order coupled- mode equation.

$$i\frac{d}{dz}a_n(z)+\beta_n a_n(z)+k_n[a_{n-1}(z)+a_{n+1}(z)]=0$$
$$2\le n\le N-1 \quad (5)$$

$$i\frac{d}{dz}a_n(z)+\beta_1 a_1(z)+k_1 a_2(z)=0;\ n=1 \quad (6)$$

$$i\frac{d}{dz}a_N(z)+\beta_N a_N(z)+k_N a_{N-1}(z)=0\ n=N \quad (7)$$

The coupling coefficient k and the propagation constant β is not same in the case of PCW array of the novel power splitter. 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:

$$a_n(z) = a_0(i)^{|n-n_0|}\exp(i\beta z)J_{|n-n_0|}(2kz) \quad (8)$$

Where $J_n(x)$ Bessel function of order n.

In the proposed device, all the three waveguides are excited as the o/p from the MMI coupler enters the three waveguides simulataneously. The value of the coupling length (L/a) required =30a >> length of the PCW waveguides. Therefore all the three waveguides behave as independent waveguides without any mutual coupling. Hence equation (8) reduces to

$$a_n(z) = (a_0)\exp(-i\beta_n z) \quad (9)$$

Where (n=1,2,3) and the power entering each waveguide depends on "dΩ".

III. Results and Discussions

We first analyzed the index profile of the proposed structure, shown in Fig. 3. We employ 2D FDTD analysis to find the propagation of the light in the novel device. The device has to be polarization insensitive; this is as certained by observing the complete photonic band gap (PBG) for TE and TM polarization (Hybrid polarization). This is depicted in Fig. 4.

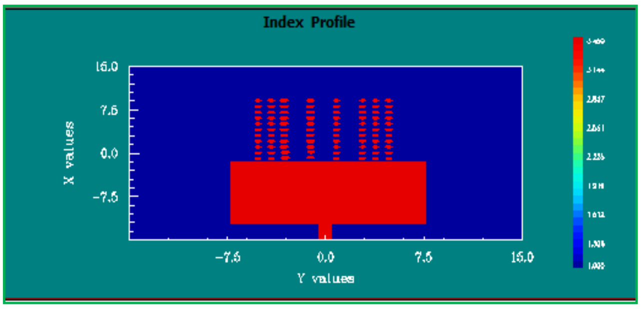

Fig. 3 Index profile of the proposed device

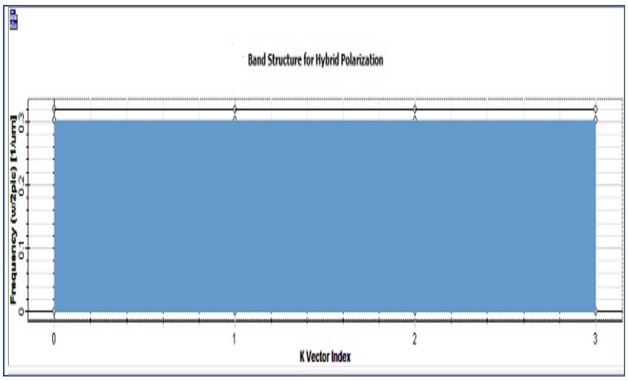

Fig. 4 Hybrid band structure of the photonic crystal

Band Solve Tool is used to compute the band strucure.For the PC used in this device PBG extends from 0-0.301459a/λ. We have chosen lattice constant a=600nm and the operating wavelength =1550nm, which falls within the bandgap. Hence the device is functional for TE and TM polarization ensuring a polarization insensitive device. This is depicted in Fig. 5(a) and (b).

To compute the guided modes in the novel device, full vectorial method is employed. We observe the exisistance of fundamental mode and the higher order modes and their modal index is shown in Fig. 6 (a), (b) &(c). By reducing the wafer thickness, only fundmental mode can be excited. All the modes are guided modes and no leaky modes which results in the loss of power.

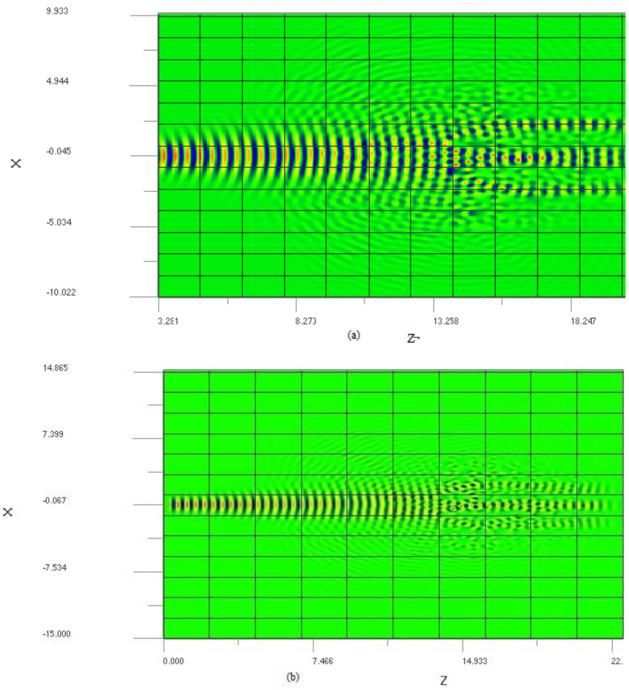

Fig. 5 (a) Propagation of light in 1x3 Power Splitter for TM polarization (b) For TE polarization

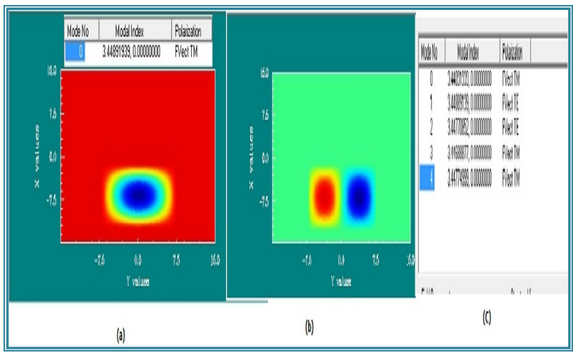

Fig. 6 (a) Fundamental mode (b) Higher order modes (c) Modal index

For any normalized frequency (Radius of the rod/wavelength) a/λ that falls within the PBG, the device will function as a flexible power splitter when two conditions are satisfied. 1) The effective index of the device should vary with wavelength. 2) The device should offer peak dispersion at the operating wavelength i.e. 1550nm.The novel device offers a peak dispersion of -4500ps/nm/km shown in Fig. 7 (a) and variation as function of λ in Fig. 7 (b).

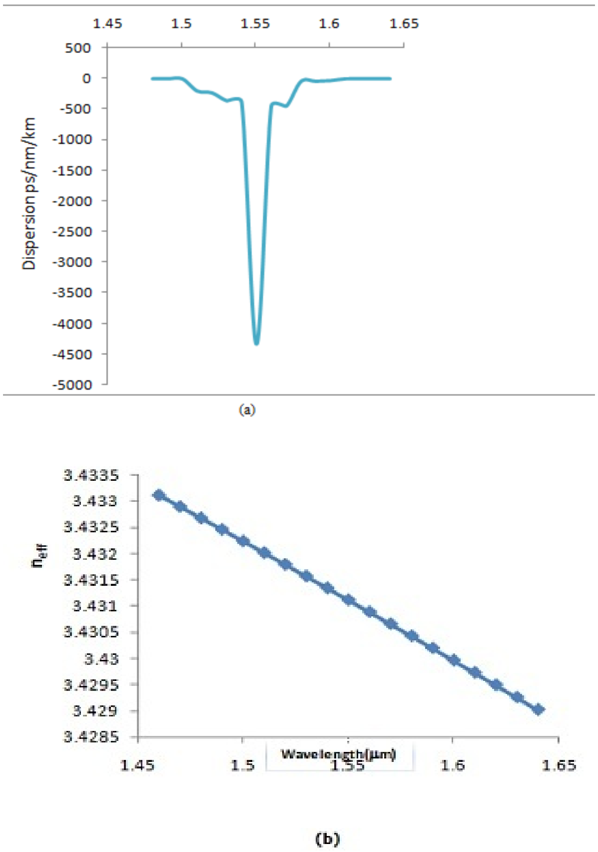

Fig. 7 (a) Dispersion diagram of the PCW (b) The variation of n_{eff} with wavelength

Fig. 8 shows the propagation of TM polarized light and the pointing vector when d/a ratio of the dielectric rods are varied. In order to tap different power, we need to vary the d/a ratio. Where "d" is the diameter of the rod.

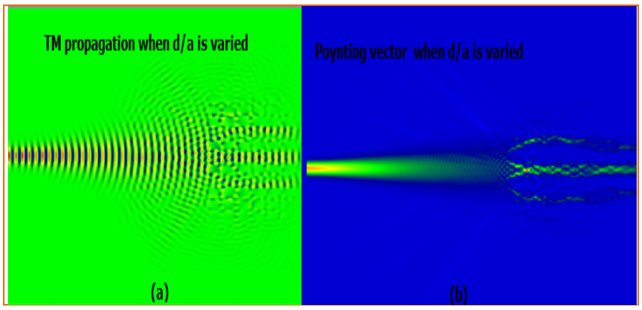

Fig. 8 (a) Propagation of TM wave when d/a is varied. (b) Power variation in o/p PCW when d/a is varied

Next we investigated the power distribution in each PC waveguide. The power distributions in percentage, when a continuous wave with 0.1w/m is launched at the i/p are 30-PCW1, 35-PCW2 and 33-PCW3.Shown in Fig. 9.

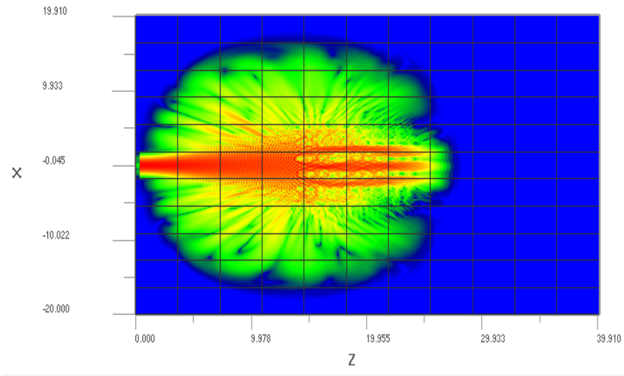

Fig. 9 Power distribution in 1x3 Power splitter

Unequal power distribution is possible provided the index distribution and the field associated with each PCW is of different intensity level. This is tested for TM polarization, equally valid for TE polarization light at 1550nm. This is indicated in Fig. 10 and Fig. 11.

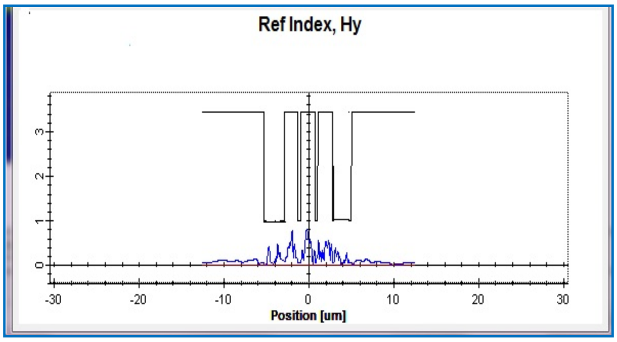

Fig. 10 Refractive index and the field Hy at the o/p PCW

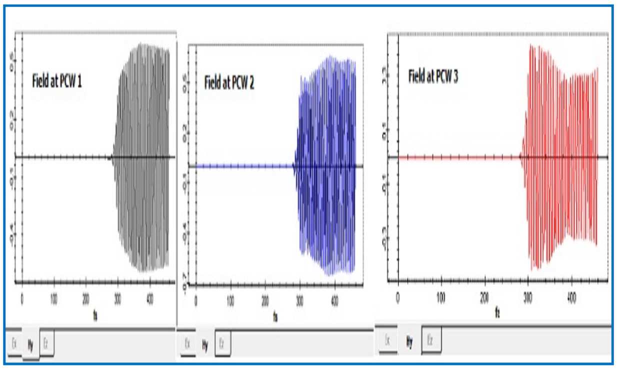

Fig. 11 Field distribution at the o/p PCWs in 1x3 power splitter

The three o/p PCWs are parallel to each other.In normal circumstances there may be mutual coupling. Here we investigated the minimum coupling length by using coupled mode theory. It is found to be 30a>length of the o/p PCWs ensuring that there is no mutual coupling between the adjacent waveguides. This is presented Fig. 12.

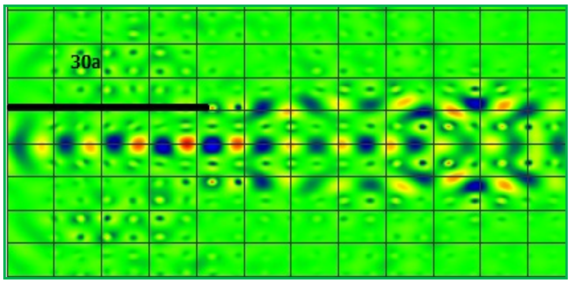

Fig. 12 Mutual coupling in three parallel PCWs

IV. CONCLUSION

A new 1x3 flexible PC power splitter has been proposed. The proposed structure is attractive in terms of device length and flexible power splitting ratio as compared to the conventional MMI power splitter. The device also outperforms the PCF based power splitters, where the device length spans in mm and the performance is dependent on the coupling parameter. Other devices such as Mux/Demux and TTD are feasible by engineering the coupling parameter and d/a ratio of the rods. The predictions made by the analysis are in good agreement with those observations by the FDTD method.Other possibilities, such as using PCW with air holes in dielectric background to develop similar devices are under investigation.

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