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Structure Optimisation of Directional Polarisation Beam Splitter

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Abstract- A new design configuration for a compact polarizing Beam Splitter (PBS) based on Photonic Crystal (PhC) is studied here using the Finite Difference Time Domain (FDTD) method . The influence of the structure parameters and their impact on the structure performances is thoroughly investigated. The obtained results show that using rectangular air holes in the coupling region of the PBS have a dramatic impact on performance and size of the device.

***Index Terms*— Directional, FDTD, Optical, Polarisation Splitters.**

I. INTRODUCTION

A polarising beam splitter (PBS) has been an area of interest for researchers over the last decades. The scientist's interest is driven by the fact that communication systems have an increasing demand for the extremely wide transmission bandwidth in optical frequencies and the utilisation of Polarisation splitting devices may help to increase the spectral efficiency and in the optimisation of frequency channel. The asymmetric Y-branch PSB proposed in [1], ~~a~~ the Mach–Zehnder interferometer PSB proposed in [2], and the multimode interference device PSB proposed in [3] are few examples of such devices. However, the main drawback of the previous mentioned designs is their relatively length, ~~(~~on the order of millimetres~~)~~ which greatly affect~~s~~ the density of integration. In order to reduce the overall device size, a compact PBS based on a hybrid photonic crystal (PhC) is proposed in [4] . Further improvement of the size of the PSB is proposed in [5], where the length of the device is reduced to 24μm by using smaller air holes in the coupling region. The focus of this paper is to propose an innovative design of the coupling region of the PhC based PBS device in order to reduce its overall length. By using rectangular holes in the coupling region instead of circular holes.

In the last few decades, various numerical modelling techniques have been proposed in the literature for the analysis of photonic devices. Beam propagation method (BPM) is a very popular method to simulate waveguide components [6][7]. However, as most of BPM algorithms rely only on forwardly- propagating waves, they are not suitable for dealing with strongly reflecting devices such as the problem in hand [8]. Alternatively, the finite difference time domain (FDTD) method is now thought to be one of the most general methods for analysing wide-class of photonic devices. For example, successful analysis using FDTD have been carried out for the dispersion properties in square hollow fibre with new cross section in [9] and optical switching using different wavelength controlling pulse using nonlinear directional coupler in [10]. Although the FDTD is computationally expensive, it is proven to be an accurate tool for simulating reflecting optical structures when Courant stability condition and numerical dispersion are considered [11]. In this paper, the FDTD has been used to analyse the polarisation beam splitter based on photonic crystal waveguides. Different investigations have been carried out to explore the effect of different parameters of the waveguide on the polarisation beam splitter performance and size. Parameters such as radius of the air holes in the coupling region and diameter of the rectangular air holes have been varied and sets of results have been presented. This paper is organised as follows. Following this introduction, a brief explanation of the theory of directional polarisation beam splitters is given in section II. The results are explained and justified in detail in section III. Then in section V conclusions are drawn.

II. THEORY

In order to achieve high efficiency compact PhC polarised beam splitter, two criteria have to be fulfilled [5]. The first criterion, both TM and TE modes must propagate with minimum loss in the PBS device. The second criterion, the propagation properties of TM and TE modes should be different to achieve the separation of the two modes after a short propagation distance. Criterion one can be easily fulfilled by using a high index photonic crystal structure with triangle air holes to create a full photonic bandgap (PBG) device[15[16]. The diameter of the air holes needs to be selected carefully, as large air holes will lead to power losses. The fact that the propagation properties of TM and TE modes are slightly different due to the size of the PBG for the TM mode is narrow relatively compared with TE mode, will help to fulfil the second criterion and the two modes may separated. However, the difference between TM and TE propagation properties will not be substantial if both TM and TE are guided through a similar PBG effect. Therefore another mechanism

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should be used in order to maximise TM and TE propagation properties differences. Fortunately, it has been proven theoretically and experimentally that the light can also be guided through the index contrast in a PhC waveguide if the average refractive index in the waveguide is higher than the average refractive index in the surrounding area [12][13]. This type of waveguides can be easily achieved by removing one raw of the air holes along the propagation direction in a triangular photonic crystal waveguide that has a lattice constant tuned to TE mode only. By removing one raw of the air holes the average refractive index inside the defected region is higher than the average refractive index in the surrounding region. While the TE light is being guided through the high index waveguide due to PBG effect, the TM mode will be confined due to the index contrast effect. In order to create the refractive index contrast to guide TM mode, two parallel waveguides separated by one raw of air holes have smaller diameters than the main air holes in the PhC structure is used.

Fig. 1 presents the diagram of the proposed polarised beam splitter [5] based on a PC directional coupler. As you may observe from the diagram in Fig. 1 the two parallel high refractive index waveguides are separated by a row of air holes smaller than the main structure air holes. The refractive index of the host material is 3.32; the period of the triangular lattice of air holes is a = 0.457µm; the radius of the lattice holes is r = 0.147µm; while the radius of the smaller holes that separate the two waveguides in the coupler region is r = 0.118µm. The top waveguide is labelled as the direct channel, while the bottom guide is called the adjacent channel. The length of the PBS achieved in [5] is about 24.2µm.

Fig. 1 represents the switching period of TM and TE modes between the two channels. Assuming that the beat is equal to π, the propagation of both TM and TE modes in ch-l is a cosine function and can be presented by the following equations;

$$\phi_{TM} = \phi_{TM(source)} \cos(\beta) \quad (1)$$
$$\phi_{TE} = \phi_{TE\,(source)} \cos(\alpha) \quad (2)$$

Meanwhile the TM and TE propagating through ch-2 is delayed by (π/2) and can be presented by the following equations;

$$\phi_{TM} = \phi_{TM\,(source)} \cos(\beta + \pi/2) \quad (3)$$
$$\phi_{TE} = \phi_{TE\,(source)} \cos(\alpha + \pi/2) \quad (4)$$

Where β and α = 0 to nπ, ϕ_{TM} and ϕ_{TE}, are the field components for TM and TE and $\phi_{TM\,(source)}$ and $\phi_{TE\,(source)}$ are the field component at the input waveguide

In order to obtain a maximum splitting ratio (100%), the periodicity of TM mode should be zero. This is not possible in this type of PBS as it does not comply with the two criteria discussed above and therefore we have to accept splitting ratio slightly less than 100% in order to design a compact PBS. If we assume 95% splitting ratio is satisfactory then TM beat can be calculated as follow;

Assuming TE beat is π , cos (α) is zero and cos (β) is equal to 0.95.

From equation (1) the value of TM power in channel 1 is given by as

$$\phi_{TM} = 0.95^* \phi_{TM\,(source)}.$$

In order to achieve the splitting of the two modes, at the same point along channel 1 at least 95% of ϕ_{TM} should exist, while ϕ_{TE} should be zero.

Assuming TE beat is shorter than TM beat both beat length for the two modes can be calculated.

$\alpha = \cos^{-1}(0) = (\pi/2)$ and $\beta = \cos^{-1}(0.95) = 18$

the beat ratio is $\frac{\pi}{36} = 5$, therefore to obtain fore very high splitting ratio TM beat should be at least five times greater than the TE beat.

As it may be observed from Fig. 1 that TE mode is fully switched from ch-l to ch-2 after propagating length of (π/2). Meanwhile TM mode is fully switched after three periods **(3 π)** of TE.

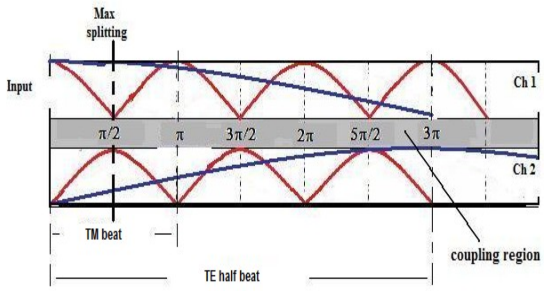

Fig. 1: switching period of TE and TM modes between the two channels

III. SIMULATION RESULTS

As indicated in Fig. 2, the TE-TM mode propagation inside the waveguide is initiated by exciting the electromagnetic field components E_z and H_z by injecting of a source-field along the input section. The fast varying frequency of the source has been set to λ = 1.55µm. The source field profile is Gaussian and it is modulated by a Gaussian pulse in time. The source expressions for both TE and TM are given by

$$E_{z_{i,j}}^{n+1} = E_{z_{i,j}}^{n} \varphi_j \sin(2\pi f n\Delta t) e^{((n\Delta t - 3T)/T)^2} \quad (5)$$
$$H_{z_{i,j}}^{n+1} = H_{z_{i,j}}^{n} \varphi_j \sin(2\pi f n\Delta t) e^{((n\Delta t - 3T)/T)^2} \quad (6)$$

Where φ_j is the fundamental field profile, n is the number of time steps, Δt is the time step size and T is the width of the Gaussian pulse and T is chosen to be 40-fs. Reference points are chosen at different locations in the structure at which the time variation of the field at each point is recorded.

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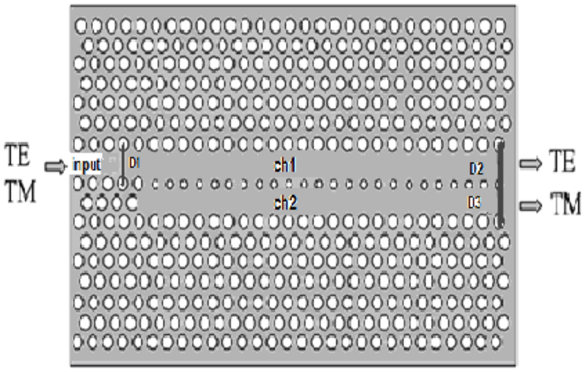

Fig. 2: Polarised beam splitter structure with circular air holes in the directional region between the two channels

As shown in Fig. 2, the reference line detectors are labelled as D1, D2 and D3 to record the incident field, transmitted power in the (ch-1) and transmitted power (ch-2), respectively. Once the transmitted power reaches the output terminals of the PBS waveguide, the ratio of FFT of the reflected to incident field is calculated to compute the spectrum variation of the switching coefficient of the TE and TM at the two channels. For the validation of the used logarithm the PBS structure proposed in [5] has been simulated number of times. Each time the radius of air holes in the coupling region is varied and the beat of TE and TM modes are obtained. It has been observed that the splitting ratio between the channels is very sensitive to the radius of the air holes in the coupling region, therefore its recommended to chose small size of discretisation cells (Δx and Δy) during the simulation, about 10nm or less.

Fig. 3 represents the relation between the radius of the air holes in coupling region and the beat length of TM and TE.

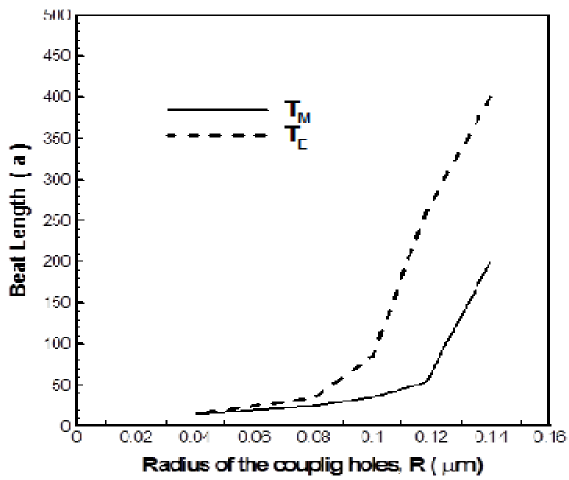

Fig. 3: Relations between the radius of coupling air holes against the beat length for the PBS

As it may be observed from the graph IN Fig. 3 that maximum difference between TE beat and TM beat is obtained when the radius (R) of the air holes in the coupling region chosen between 1.1 and 1.2μm, any values below this range will make the beat difference shorter and therefore TE and TM will overlap in both channel, in other words satisfactory splitting ratio between TE and TM cannot be achieved, on the other hand, any values of R above the stated range will increase the length of both TE and TM beats and therefore PBS size is compromised. The highest splitting ratio obtained within the range is about 97% and that achieved after TE-TM modes propagated 53 periods (24.2μm) in side the PBS.

Fig. 4 presents TE power coefficients on ch1 and ch2 at directional coupler length of 53a, (24.2μm). As may be observed from graphs the total TE power transmitted on Ch-1 at wavelength 1.55 μm, is about 98%, meanwhile the power leaked to Ch-2 is very minimum, about 2%. The obtained results as shown in Fig. 4 are in excellent agreement with the counterparts published in [5].

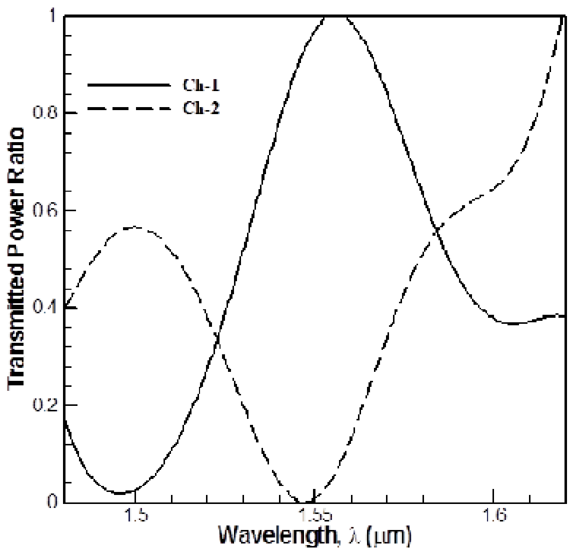

Fig. 4: TE Power ratio in both channels for the PBS presented in Fig. 1 at wavelength 1.55 μm and beat length 106a

Fig. 5 presents TM power coefficients on ch-1 and ch-2 at directional coupler length of 53a (24.2μm). As it may observed from the graphs that the total TM power switched to channel 2 at wavelength 1.55 μm, is about 96%, meanwhile the TM power propagating on Ch-1 is very minimum and it can be neglected. However because TM switching to ch-2 due to index contrast properties, power losses in side the structure is inevitable and therefore about 4% of total power is radiated outside the waveguides. The obtained results as shown in Fig. 4 are in agreement with the counterparts published in [5].

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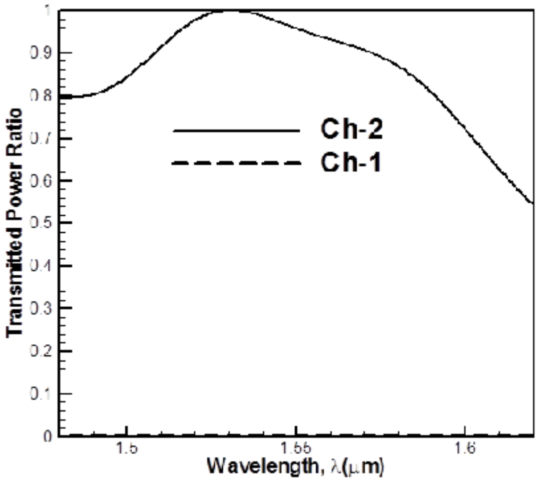

Fig. 5: TM mode power ratio in both channels for the PBS presented in Fig. 1 at wavelength 1.55 µm

In Fig. 6, the structure is modified to reduce the length of polarised beam splitter. This is assumed to be achieved by using rectangular air holes instead of circular holes for the directional coupler between the two channels. Rectangular holes can be discretised by high accuracy and can be simulated using relatively large mesh cells compared with the circular holes directional coupler proposed in [5].

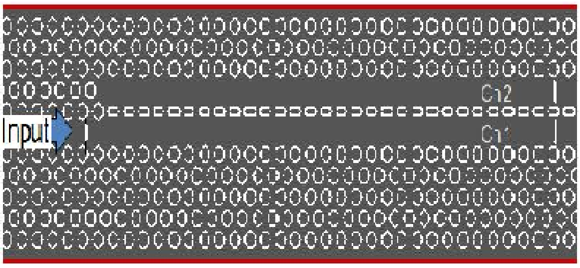

Fig. 6: The modified structure with rectangular air holes.

The radius of the air holes of the PhC is r = 0.147µm, the lattice constant a =0.457 µm, the length of the rectangular holes in the coupling region is = 0.294µm and the width =0.1.206µm. The refractive index for the waveguides ng =3.32.

As shown in Fig. 6, the three white lines in ch-1 and ch-2 are line detectors to record the incident fields at the input and transmitted power in both channels for TE and TM modes. Once the transmitted power reaches the output terminals of the channels, the ratio of FFT of the output to incident field is calculated to compute the spectrum variation of the power coefficient on both channels for both TE and TM modes.

Fig. 7 presents TM power coefficients on ch1 and ch-2 at directional coupler length of 40a (18.28µm).

As it may observed from the graphs in Fig. 7 that the total TM power switched to ch-2 at wavelength 1.55 µm, is about 99%, meanwhile the TM power propagating on (Ch-1) is very minimum and it can be neglected. In order to verify the results presented in Fig. 6, the field profile inside the structure shown in Fig. 6 is obtained by injecting the same source-fields, modulated at wavelength 1.55µm as stated in the eq. (5) and (6). Once the steady state reached, an algorithm proposed in [14] is used to obtain the field profile in the structure, based on the numerical integration of a time- dependent signal over one period.

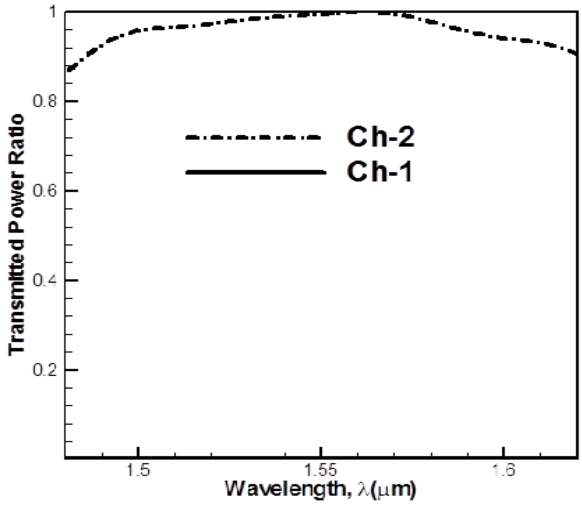

Fig. 7: TM mode power ratio in both channels for the modified PBS presented in Fig. 6 at wavelength 1.55 µm

As may be observed from Fig. 7, the density of the field profile lines in the input channel is very high. However after the TM mode travels about 40 periods, 18.28µm, TM mode completely coupled to channel 2. It is evident from the results shown in Fig. 7 and the field profile in Fig. 8 that our FDTD results are better than the results published in [5] as the coupling length is reduced to 18.28µm and the coupled power ratio obtained is about 99%.

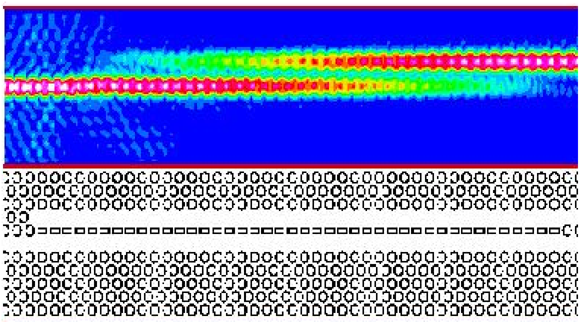

Fig. 8: TM mode field profile for the enhanced PBS presented in Fig. 6 at wavelength 1.55µm

Fig. 9 presents TE power coefficients on ch1 and ch-2 at directional coupler length of 40a (18.28µm). As it may observed from the graphs that the total TE power transmitted on ch-1 at wavelength 1.55 µm, is about 98%, meanwhile the TE power coupled to Ch-2 is very minimum and it can be neglected.

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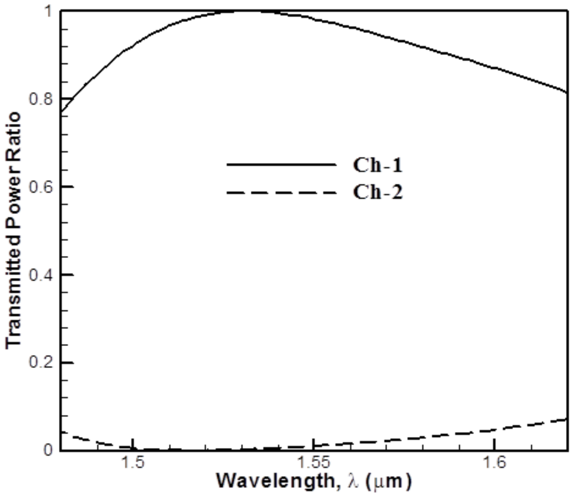

Fig. 9: TE mode power ratio in both channels for the modified PBS presented in Fig. 6 at wavelength 1.55 μm

The results presented in Fig. 9 can be verified by obtaining the field profile for the TE mode inside the proposed structure as shown in Fig. 10.

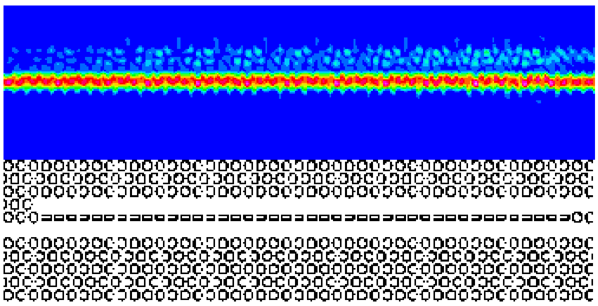

Fig. 10: TE mode field profile for the enhanced PBS presented in Fig. 6 at wavelength 1.55μm.

As may be observed from Fig. 10, the density of the field profile lines in the input channel is very high and there is no coupling between the channels within the chosen length of the directional coupler. However very small radiation can be observed on ch-2 and that may justify the 98% power coefficient on Ch-l . It is very evident from the results shown in Fig. 7 and the field profile in Fig. 8 that our FDTD results are better than the results published in [5] as the coupling length is reduced to 18.28μm and the TE power ratio obtained is about 98%.

IV. CONCLUSION

In this paper, the directional coupler polarised beam splitter (PBS) is investigated using the finite time difference domain method ,FDTD. Rectangular air holes for directional coupling are used to separate TE from TM mode. The use of rectangular coupling air holes has a significant impact on the transmitted power for TE and TM modes on channel 1 and channel 2. The variation of the rectangular coupling air holes parameters lead to dramatic changes of the splitting ratio of TE and TM at both channels. The best performance is obtained when the rectangular coupling air holes width is about 0.12 μm and their length is about 0.147μm. The minimum length of directional coupler achieved is about 40a at maximum power 99% power ratio of TE on Channel 1 and 98% power ratio of TM on channel 2.

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