Demonstration of Highly Efficient Transmission in Photonic Crystal Y-Junctions at 1.5 µm Wavelength

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Abstract: The aim of this contribution is to demonstrate a highly efficient Y-junction based on a planar photonic crystal platform is presented. The PC consists of a triangular array of holes etched into a GaAs/AlGaAs heterostructure, with a typical period of 430 nm and hole radius of 141.9 nm. The Y-junction has smaller holes positioned at the center of the junction and variation of two design parameters, typically the position and the size of the most critical holes around the proper bending region, giving rise to very uniform splitting and high transmission. The performance is very encouraging; with 2D FDTD (Finite Difference Time Domain) simulation of approximately 50 % for each arm of the Y-splitter relative to a comparable single- defect PC waveguide. This improvement relies on idea which originates from papers by Rab Wilson and K. Rauscher. Such propagation has not previously been experimentally confirmed.

1. Introduction

The development of integrated optics components based on planar photonic crystals (PhC) is an active and rapidly developing field. Following the formulation of numerical proposals for efficient waveguiding, sharp bends, and junctions in photonic lattices [1], the race is on to demonstrate these concepts in real optical systems.

Straight waveguides with respectable losses have now been demonstrated by a number of groups of researches [2, 3]. S bends [4] and the first systems that consist of guides connected to cavities [5] are also to beginning to appear. All this experimental demonstrations have raised an important point: unlike the model system of dielectric pillars in air [6], real optical systems that consist of air holes in dielectrics tend to be multimoded. Multimode lead to mode-mixing problems at intersections and to difficulties in matching input and output fields at discontinuities, thus resulting in reflections, an important problem that have received surprisingly little attention in the PhC community.

Most theoretical studies conducted so far have investigated arrays of dielectric rods in air. The advantage of this model system is that waveguides created by removing a single line of rods are single moded. Getting light to travel around sharp bends with high transmission is then relatively straight-forward, and T-junctions and Y-junctions have already been proposed [7]. Unfortunately, the rod in air approach does not provide sufficient vertical confinement and is difficult to implement for most practically useful device implementations in the optical regime [8].

In previous work [8], we have demonstrated a maximum power transmission of 40% in both arms of the Y-junction based on triple-defect waveguide which has smaller holes positioned at the centre of the junction.

In the present paper, we design three dimensional waveguides with low transmission loss and high power transmission of 50% in each arm of the Y-junction by using topology optimization. We consider the design of waveguides for scalar waves based on the Helmothz equation, that govern e.g. in plane E- or H-polarized electromagnetic waves, acoustic pressure waves, as well as out-of-plane elastic shear waves in solids. The FE model used in [9] has been extended to deal with both phononics and photonics and a topology optimization scheme based on maximization of transmitted wave-energy has been developed. We demonstrate, also, that the high bend transmission can be achieved with the addition of low-Q resonant cavity.

We use the Finite Difference Time Domain (FDTD) method to simulate propagation of optical wave in the photonic crystal.

2. Modelling

We consider wave propagation problems that are governed by the two dimensional Helmotz equation:

$$\nabla \cdot (A\nabla u) + \omega^2 Bu = 0 \qquad (1)$$

where A and B are generalized coefficients and ω is the wave frequency. The generalized coefficients vary depending on which type of wave propagation that is considered. In the case of out-of-plane elastic waves shear waves $A = \mu$ (sear modulus) and $B = \rho$ (density), whereas e.g. for E-polarized light $A = 1$ and $B = \varepsilon\mu_0$ (the dielectric constant and the free space magnetic permeability). At the domain boundaries we introduce the boundary conditions:

$$n \cdot (A\nabla u) + i\omega\sqrt{AB}u = 0 \qquad (2)$$

$$n \cdot (A\nabla u) = 2i\omega\sqrt{AB} \qquad (3)$$

The Boundary Condition (BC) in (2) specifies a radiation boundary and is applied at all exterior boundaries and BC (3) specifies an incident wave. An outward pointing unit vector at the boundaries is represented in (2) and (3).

In addition to the simple radiation BC we include so-called Perfectly Matching Layers (PML) [12] designated to absorb unwanted wave reflections from the input and output waveguide port. The governing PML equation is an anisotropic damped modification of the Helmholtz equation.

$$\frac{\partial}{\partial x}\left(\frac{S_y}{S_x}\frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{S_x}{S_y}\frac{\partial u}{\partial y}\right) + \omega^2 S_x S_y Bu = 0 \qquad (4)$$

where the two coefficients S_x and S_y govern the anisotropic wave damping behaviour of the layer. At the interface between the PML region and the computational domain $S_x = S_y = 1$ and equation (4) reduces to the ordinary Helmholtz equation (1).

We apply a standard FE discretization of the governing equations using bilinear quadrilateral elements. The resulting FE equation is given as:

$$\left(-\omega^2 M + i\omega C + K\right)u = f \tag{5}$$

where M, C and K are mass, damping, and stiffness-type matrices, f is the wave load vector and u is the unknown nodal amplitudes.

3. Optimization

We use the method of topology optimization to maximize the energy flow through the waveguide and thus reduce unwanted reflections from the waveguide bend to a minimum. We specify a design area in the vicinity of the waveguide bends and distribute the material in this domain to maximize the energy flow. Through the waveguide is found by computing the Poynting vector at the output waveguide port. The optimization procedure can be written as:

maximize Poynting vector:
x_i

$$\text{subject to:}\quad \begin{aligned}&\left(-\omega^2 M + i\omega C + K\right)u = f\\ &0 \le x_i \le 1\end{aligned} \tag{6}$$

where x_i is the element design variables, and the material properties in each element are obtained using a linear interpolation in x. The optimization problem is solved by using analytical sensitivity analysis.

4. Roles of resonators

In this section, we evaluate the relative importance of cavity resonance on the bend performance of the resonator. The idea is based on the principle of a symmetric resonator with two parts. At resonance, the transmission is complete with no reflection if the resonator is lossless. The effects of radiations can be counteracted by making the external Q of the resonator very small. This is achieved by strong coupling of the waveguide modes to the resonator mode. This concept is simply explained using coupling of modes in time [13].

Because this analysis is based on perturbation theory, it can only provide a qualitative prediction in the case of strong coupling between the cavity and the waveguide modes. Following the approach of [13], the amplitude of the mode in the cavity is denoted by u and is normalized to the energy in the mode. The decay rates of the mode amplitude due to the coupling to the waveguides are $1/\tau_{e1}$ and $1/\tau_{e2}$, respectively, related to the external Q's by $Q_{e1} = \omega_0\tau_{e1}/2$ and $Q_{e2} = \omega_0\tau_{e2}/2$, where ω_0 is the resonance frequency.

The decay rate due to radiation loss is $1/\tau_0 = \omega_0/2Q_0$. The incoming (outgoing) waves at the two parts are denoted by S_{+1} (S_{-1}) and S_{+2} (S_{-2}) (Fig. 1) and are normalized to the power carried by the waveguide mode. If the excitation is S_{+1} with $\exp(j\omega t)$ time dependence, and $S_{+2} = 0$ then at steady state we have [13]:

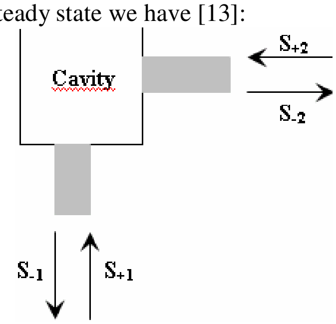

Fig. 1. Schematic of a two-port resonator connected to the waveguides of the 60^0 bend.

$$u = \frac{S_{+1}\sqrt{\frac{2}{\tau_{e1}}}}{j(\omega-\omega_0)+\frac{1}{\tau_{e1}}+\frac{1}{\tau_{e2}}+\frac{1}{\tau_0}} \tag{7}$$

and

$$S_{-1} = -S_{+1} + u\sqrt{\frac{2}{\tau_{e1}}} \qquad S_{-2} = u\sqrt{\frac{2}{\tau_{e2}}} \tag{8}$$

Which, due to (7) finally give :

$$\frac{S_{-1}}{S_{+1}} \equiv R = \frac{-j(\omega-\omega_0)+\frac{1}{\tau_{e1}}-\frac{1}{\tau_{e2}}-\frac{1}{\tau_0}}{j(\omega-\omega_0)+\frac{1}{\tau_{e1}}+\frac{1}{\tau_{e2}}+\frac{1}{\tau_0}} \tag{9}$$

$$\frac{S_{-2}}{S_{+1}} \equiv T = \frac{2/\sqrt{\tau_{e1}\tau_{e2}}}{j(\omega-\omega_0)+\frac{1}{\tau_{e1}}+\frac{1}{\tau_{e2}}+\frac{1}{\tau_0}} \tag{10}$$

At $\omega = \omega_0$ the reflection is zero and the transmission maximized if:

$$\frac{1}{\tau_{e1}} = \frac{1}{\tau_{e2}} + \frac{1}{\tau_0} \tag{11}$$

Thus asymmetric system ($1/\tau_{e1} = 1/\tau_{e2} = 1/\tau_e = \omega_0/2Q_e$) allows complete transmission provided that it is lossless. The width of the frequency response is determined by $1/\tau_e$ if the loss is present the ratio $\tau_e/\tau_0 = Q_e/Q_0$ determines the peak transmission and minimum reflection as:

$$|R|^2 = \frac{\left(\frac{\tau_e}{2\tau_0}\right)^2}{\left(1+\frac{\tau_e}{2\tau_0}\right)^2}\ ;\ |T|^2 = \frac{1}{\left(1+\frac{\tau_e}{2\tau_0}\right)^2} \tag{12}$$

5. Description of the proposal structure

The specific structure that we investigated is a Y junction formed by the intersection of three PhC channel waveguides at 60° (Fig. 2) in an otherwise uniform photonic lattice. We assume a triangular lattice of air holes etched in a dielectric substrate, with refractive index n = 3.24, having filling factor of 39 %. Since we want to use this device around 1550 nm we calculate the lattice constant to be 430 nm and obtain therefore a hole radius of 141.9 nm, respectively. The structure is assumed to be bidimensional; i.e., the air holes are infinitely long, the 2D PhC supports a photonic band gap in the region 0.203 < c/a <0.35 for TE polarized light.

In the design process, we use 2D FDTD simulation. This technique is powerful and versatile, and has been introduced and adapted to optical waveguide devices [14 -15]. In FDTD very small time step size must be used because both the carrier and the modulated envelope are included in the wave propagator.

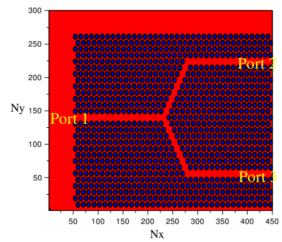

Fig.2. *non optimise Y branch structure*

We start our optimization by first looking at a wavelength scan in the non optimized case, wherein the original position of the holes remains unchanged (inset of Fig. 2).

6. Simulation results and discussion

The spectrum of transmission, after simulation FDTD-2D, is given respectively by the figure (3). Simulation FDTD 2D of this structure give a power of transmission of 10% and we considered power of reflection of 73 % thus an evaluation of losses of approximately 17 %. The weak transmission is due to the modal dissension on the level of the junction. If the incident mode has a space to be spread out in the surface of the junction, it excites the mode of a higher nature having an odd parity which is very dissipative or well it cannot be propagated in ports 2 and 3 thus most of the wave is considered and thus a weak transmission. However the excitation of the modes whose parity is odd must act like a mechanism of losses for the junction Y resulting in very poor transmission compared with that of the waveguide W1. Our conclusion is therefore as follows: the transmission through a junction depends strongly on the relationship between the modes that may propagate in the PC waveguides and the modes of the junction are not compatible with those of the waveguide, transmission will be poor.

To improve matters, the obvious choice is to modify the junction region. By adding a smaller hole at the center of the junction, we reduce the optical size of the cavity, thus eliminating multimode effects.

7. The optimised structure

The essential function of a W1 Pc Y-splitter is to convert a single mode train in the input waveguide symmetrically into two single mode trains in the output waveguides.

The small hole which is placed on a lattice site immediately in front of a single defect PC waveguide so as to perturb the incoming mode as gently as possible when dividing it to two (Fig. 4). Palamaru and Lalanne [16] originally proposed the use of such small holes as a method for mode matching between ridge waveguides and PC waveguides. They showed that a small hole,

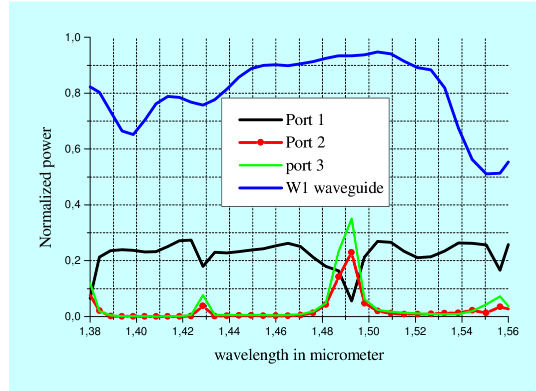

Fig.3. *2D FDTD simulation: Transmission and reflection spectra of the plain Y-junction.*

followed by a line of holes gradually increasing in size, could adiabatically convert a conventional waveguide mode into a PC waveguide mode without incurring any significant loss transmission.

In a similar way and in order to improve the transmission of the Y-branch, we achieved near-adiabatic splitting of the single input mode into two output modes by gradually varying the size of the holes at the junction. The size of the initial hole was designed to be 0.5r and the second 0.75r. To avoid the losses at the two 60° bends we do small displacements for the most critical holes around the two proper 60° bending region with increasing the radius (r) of the holes situated in the external bends. The optimised Y-branch structure resulting is showing in Fig. 4.

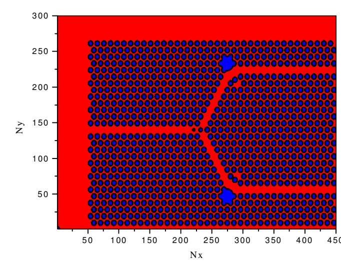

Fig.4. *Optimised Y-branch structure resulting*

8. Results and discussion

Placing additional holes at the junction then clearly increase the bandwidth and power transmission, as directly observed in our comparative simulations of a Y-junction with and without modifications. This solution has been compared to an independents proposals given by [8] and [17] who numerically studied the use of small holes placed in the centre of a W1 and the small displacement of critical holes around the proper bending respectively, in order to increase the transmission of approximately 40% for each arm of the Y-splitter. The new junction interfaces to the output arms with a mode that has a well marked even parity, and a clean field thus propagates in the output arms. The power transmission efficiency that we numerically calculated in this case is 50% for each of the each of the output arms.

The Fig. 5 presents calculated spectra for the waveguide and Y-splitter structures in order to highlight the high transmission achieved. The maximum transmission values for the W1 (a single line defect acting as a light channel in the G-K direction) and Y-splitter agree extremely favourably with the simulations. The maximum power transmission is approximately 50 % in both arms.

Arrived at the level of the two additional holes, the incident wave is divided into two parts; each one of them is channelled in a branch.

The important point, that should be noted, is the dimension of the additional holes which are used especially to distribute the single mode incident wave in two single mode waves crossing the two wearing of exits (port 2 and port 3) as it is illustrated in the Fig. 6.

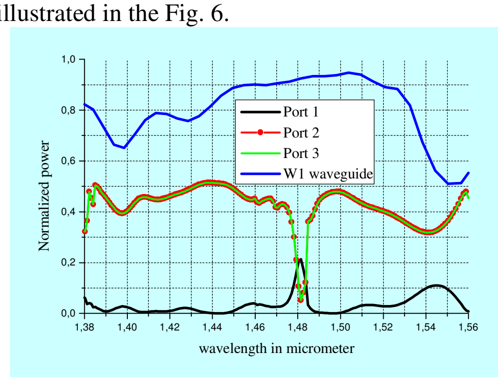

Fig.5. *The transmission spectra of the optimise Y-branch structure.*

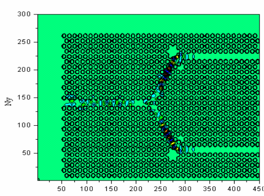

Fig.6. *Magnetic Field amplitude distribution in the optimized Y-junction when the incident wave arrives at the level of the additional holes (after 3000 iterations).*

9. Conclusion

To summarize, we have demonstrated a functional Y-junction with excellent performance based on a W1 PhC waveguide. High power transmission of up to 95% ($Y_{left}+Y_{right}$) relative to a W1 waveguide was observed.

The keys features of the device are: first, addition of smaller holes at the center of the junction in order to avoid mode expansion and excitation of higher-order modes at the output ports. Second, to avoid the mode mismatch at the bends which causes the loss of a large fraction of the power to radiation or reflected backward resulting in very poor transmission, we make variation of two design parameters, typically the position and the size of the most critical holes around the proper bending region.

10. References

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