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Optimal Design of 90° Bend in Two Dimensional Photonic Crystal Waveguides

L. Dekkiche and R. Naoum
Telecommunications and Digital Signal Processing Laboratory, Institute of Electronic,
University Djillali Liabes of Sidi-Bel-Abbes, Sidi-Bel-Abbes 22000, Algeria

Abstract: The aim of this contribution is to present the key factor that affect the transmission characteristics of the 90° bent photonic crystal waveguides. We propose a new type of two dimensional photonic crystal (2DPC) 90° bend waveguides. Within a single optimization step we already achieve very low power reflection coefficient over almost the entire frequency range of the Photonic Band Gap (PBG). A further analysis shows that there is a single critical rod in the optimized bend structure that exhibits an extraordinary high sensitivity at a given frequency. Using the Finite Difference Time Domain (FDTD) method and the absorbing boundary conditions proposed, we simulate its transmission characteristics and show an excellent transmission of light in 90° bend waveguides achieve 100% for several frequencies. This opens the door to novel topologies for compact switches and sensor applications.

Key words: Photonic crystals, finite difference time domain methods, integrated optics, optical waveguide components, waveguide bends

INTRODUCTION

Photonic crystals have inspired great interest recently because of their potential ability to control the propagation of light. They can modify and even eliminate the density of electromagnetic (EM) states inside the crystal (Yablonovich, 1987; John, 1987). Such periodic dielectric structures with complete band gaps can find many applications, including the fabrication of lossless dielectric mirrors and resonant cavities for optical light (Joannopoulos *et al*., 1995).

The realization of efficient sharp and compact waveguide bends is still a challenging task in micro optics. With the introduction of Photonics Crystals (PCs) major interest has also focused on the issue of efficient waveguide bends embedded in PCs. There are various proposals for bend design in order to minimize losses. Examples are smoothening the sharp bends (Moosburger *et al*., 2001), introducing cavities or intermediate straight sections (Olivier *et al*., 2002), or placing smaller holes around the bend (Talneau *et al*., 2002). To inhibit the modal mismatch at a Y splitter (Boscolo *et al*., 2002) an additional hole has been added at the bend. On the other hand, it has been shown that a Coupled-Defect Waveguide (CDW) composed of a chain of point defects in a PC can also have a very high transmission for a certain wavelength range at sharps bends (Johnson and Joannopoulos, 2001).

In this study, we demonstrate a novel method for guiding light around sharp corners, using photonic crystal waveguides. This method is based on the one hand on the modification in the geometry at the corner and the other hand on the use of the absorbing boundary conditions proposed by Mekis *et al*. (1999) which reduce reflection from PBG waveguide ends to under a few percent.

The FDTD method (Kunz and Luebbers, 1993) has been widely used to study EM properties of arbitrary dielectric structures.

In this method, one simulates a space of theoretically infinite extent with a finite computational cell. To accomplish this, a number of boundary conditions such as Berenger's Perfectly Matched Layer (PML) (Berenger, 1994), have been proposed that absorb outgoing waves at the computational cell boundaries. Applications of the FDTD method are to simulate photonic crystal waveguides, however, pose unique difficulties. While reflection from a PML boundary is minute for a traditional dielectric waveguide substantial reflection from the boundary is observed if a PBG waveguide is terminated so, on the order of 20-30% in amplitude (Mekis *et al*., 1996). Such reflection introduces unphysical reflected (parasite) pulses which may significantly compromise the accuracy of the simulated response. Reflected waves introduce interference and result in large errors in transmission measurements.

Corresponding Author: L. Dekkiche, 13, Rue Maarouf Larbi, Sidi bel Abbes 22000, Algeria Fax: (213) 048 56 95 46

FINITE DIFFERENCE TIME DOMAIN ALGORITHM (FDTD)

For a linear isotropic material in a source-free region, the time-dependent Maxwell's equations can be written in the following form,

$$\frac{\partial H}{\partial t} = -\frac{1}{\mu(r)}\nabla \times E \quad (1)$$

$$\frac{\partial E}{\partial t} = \frac{1}{\varepsilon(r)}\nabla \times H - \frac{\sigma(r)}{\varepsilon(r)}E \quad (2)$$

where, ε(r), μ(r) and σ(r) are the position dependent permittivity, permeability and conductivity of the material, respectively. In the two dimensional case, the fields can be decoupled into two transversely polarized modes, namely, the E polarization and the H polarization. These equations can be discretized in space and time by a so-called Yee-cell technique (Yee, 1966). The following FDTD time stepping formulas are spatial and time discretizations of Eq. 1 and 2 on a discrete two-dimensional mesh within the x-y coordinate system for the E polarization (Yee, 1966),

$$H_x\Big|_{i,j+1/2}^{n+1/2} = H_x\Big|_{i,j+1/2}^{n-1/2} - \frac{\Delta t}{\mu_{i,j+1/2}}\frac{E_z\Big|_{i,j+1}^{n} - E_z\Big|_{i,j}^{n}}{\Delta y} \quad (3)$$

$$H_y\Big|_{i+1/2,j}^{n+1/2} = H_y\Big|_{i+1/2,j}^{n-1/2} + \frac{\Delta t}{\mu_{i+1/2,j}}\frac{E_z\Big|_{i+1,j}^{n} - E_z\Big|_{i,j}^{n}}{\Delta x} \quad (4)$$

$$E_z\Big|_{i,j}^{n+1} = \left(\frac{\varepsilon_{i,j} - \sigma_{i,j}\Delta t/2}{\varepsilon_{i,j} + \sigma_{i,j}\Delta t/2}\right)E_z\Bigg|_{i,j}^{n} + \frac{\Delta t}{\varepsilon_{i,j} + \sigma_{i,j}\Delta t/2}\left(\frac{H_y\Big|_{i+1/2,j}^{n+1/2} - H_y\Big|_{i-1/2,j}^{n+1/2}}{\Delta x} - \frac{H_x\Big|_{i,j+1/2}^{n+1/2} - H_y\Big|_{i,j-1/2}^{n+1/2}}{\Delta y}\right) \quad (5)$$

where the index n denotes the discrete time step, indices i and j denote the discretized grid point in the x-y plane respectively. Δt is the time increment and Δx and Δy are the intervals between two neighbouring grid points along the x and y directions, respectively. Similar equations for the H polarization can be easily obtained.

It can be easily see that for a fixed total number of times steps the computational time is proportional to the number of discretization points in the computation domain, i.e., the FDTD algorithm is of order N.

The FDTD time-stepping formulas are stable numerically if the following conditions are satisfied (Taflove, 1995).

$$\Delta t \le \frac{1}{c\sqrt{\Delta x^{-2} + \Delta y^{-2}}} \quad (6)$$

where, c is the fastest peed of the light in all the materials involved in the simulation (In FDTD program, we always choose c be the speed of the light in vacuum). Thus, smaller Δt, this means even longer calculation time.

The number of total time steps should be chosen carefully, too. For pulse propagation, the total time steps should be larger enough, in order to allow the pulse passes the detectors. In particular, when the simulations involve cavities, the number should be sufficiently large.

BOUNDARY CONDITIONS

One approach to eliminate errors due to reflected pulses has been to increase the cell size such that the useful and the parasite pulses can be separated (Mekis *et al*., 1996). This approach, however significantly increases the computational cost in terms of memory and time. Special care must be taken to separate well the pulses since due to interference the error is proportional to the amplitude and not to the power, of the reflected pulse. In addition, in the case of steady state simulations, or when a high-Q resonance is involved, it becomes impractical or even impossible to separate the reflected signal amplitude from the useful one. In the earlier research Mekis *et al*. (1999) demonstrate that it is possible to reduce the reflection amplitude from photonic crystal waveguide ends to a few percent by using a k-matched Distributed Bragg Reflector (DBR) waveguide. This provides a simple means to reduce the computational costs associated with simulating PBG waveguides. In our work, we use this concept of absorbing boundary conditions to obtain an efficient 90° bend structure.

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. The notations employed here are those used by Manolatou *et al.* (1999). 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 (Manolatou *et al*., 1999). 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

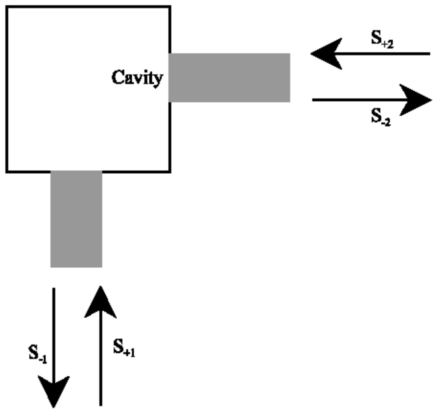

Fig. 1: Schematic of a two-port resonator connected to the waveguides of the 60° bend (Manolatou *et al*., 1999)

the approach of Manolatou *et al*. (1999), 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 τ_{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(jωt) time dependence and $S_{+2} = 0$ then at steady state we have (Manolatou *et al*., 1999):

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

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:

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

DESCRIPTION OF THE PROPOSAL STRUCTURE

The specific structure that we investigated is a 90° sharp bend formed by the intersection of two PC channel waveguides at 90° Fig. 2a in an otherwise uniform photonic lattice. We assume a square 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 PC 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 (Chutinan and Noda, 2000; Chutinan *et al*., 2002). In FDTD very small time step size must be used because both the carrier and the modulated envelope are included in the wave propagator.

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).

SIMULATION RESULTS AND DISCUSSION

The cartography of the magnetic field Hz in the non optimize structure and the transmission and reflection spectra are shown in Fig. 2b and c, respectively. We note that the transmission reached a value of only 10% (reflection 73%). The reason for this very poor transmission is twofold. First, a large fraction of the power

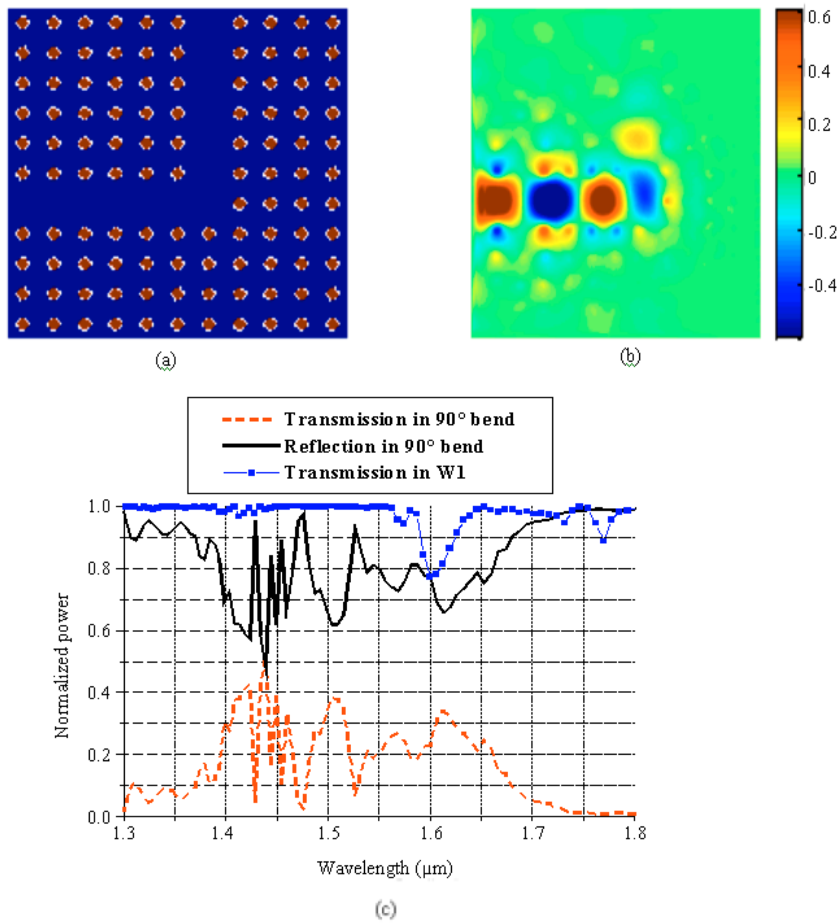

Fig. 2: (a) Non optimised 90° bend structure, (b) Magnetic field amplitude distribution in a plain 90° bend and (c) Transmission and reflection spectra of the plain 90° bend

is lost to radiation or reflected backward due to mode mismatch at the corner of the sharp bend. Moreover, the poor transmission originates from modal mismatch at the junction. In fact, if the incoming mode has space to expand in the junction area, it excites a higher mode with odd parity that is either very lossy or cannot propagate in the output waveguide, so most of the incoming light is reflected and transmission is poor. Therefore, the excitation of modes with odd parity would act as a loss mechanism for the 90° sharp bend. Our conclusion is therefore as follows: the transmission through a junction depends strongly on the relationship between the modes of 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. The resulting cartography is a mixture of the stationary mode on the level of the bend and propagative wave (Fig. 2b).

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

TOWARDS A COMPLETELY ACHROMATIC TRANSMISSION

The research of the compromise zero reflection-broad band-width was based up to now on the research of optimal topology, in terms of modal agreement between the mode of the guide and that of the bend. Insinuation, the possible improvements made to the properties of transmission, relate always to a resonant cavity and thus by definition always chromatic. We have just shown, with simple considerations, results translating of the notable improvements of the answer related to a corner: the width of the spectral range of high transmission for a bend with 60° more than was doubled compared to the improvements reported in the literature (Chutinan and Noda, 2000; Chutinan *et al*., 2002). We would however wish to use all the monomode range including that which would be located above the line of light in the 3D case. The only possible exit to transmit on all the monomode range consists in, consequently, returning to a specular approach, such as it is practised conventionally in

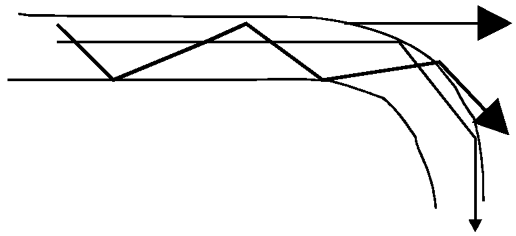

Fig. 3: Losses by curve in a conventional approach (Grillet, 2003)

integrated optics, or in other words to kill the resonance all while preserving reflections with the bend. We go, before considering the use of a specular approach, to point out the limitations of the conventional approach (case of guides ribbons for example) for the realization of turns. We can distinguish three sources from losses in a conventional approach.

The losses by curve: Certain guided rays, when the guide is right, will see their angle of reflection to pass below the limiting angle of total reflection when the guide is curved and a part of the luminous power is thus refracted outside the guide with each reflection (Fig. 3). In the case of turn to CP, these losses do not have obviously course.

The losses by transition: When we couples a mode of right guide in a curved guide, it will have an effectiveness of coupling lower than the unit because the mode of the curved guide is shifted towards the outside of the curve (Fig. 4a). Two strategies are often used in optics guided to reduce these losses: -the first consists in shifting the input of the curved guide compared to the right guide (Fig. 4b). When the right guide is shifted towards the outside of the curve, it anticipates the shift which the wave will undergo while entering the guide curves and makes thus the coupling optimal between right guide and curved guide. -the other strategy consists in producing guides with continuously variable curve (Fig. 4c) so as to pass in an adiabatic way of the right guide to a curved guide of given curve. The advantage of this method is that it can also be optimized to reduce the losses by curve. But it appears clearly that these strategies are not easily transposable with a realization of turns in a CP2D and besides do not constitute quite simply a satisfactory solution for compact applications in integrated optics.

The losses by roughness with the turns: Let us consider the light suitably installed in the curved guide and observing the conditions of total reflection interns in this

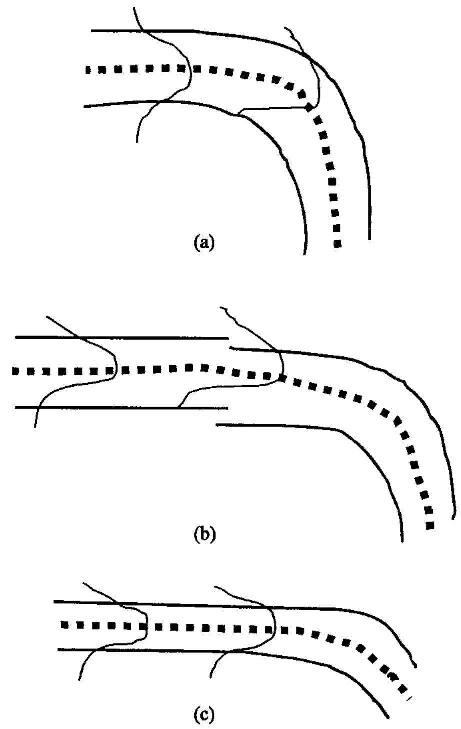

Fig. 4: (a): Losses by transitions in a conventional curved guide, (b) Configuration planned to reduce these losses by shift and (c) Curve continuement variable (Grillet, 2003)

portion: this one is not saved for as much! Roughness will induce a coupling between the guided modes and the radiative modes of the structure. That result in losses, all the more important as the fraction of luminous energy conveyed outside the guide is high.

An approach combining mirror with 45° and cavity slightly resonant, developed with MIT, rises in remarkable performances (transmission 98%, on a band-width de 10% around 1.55 mm) for the turn with 90° in a configuration with high contrast from index (Manolatou *et al.*, 1999). We took as a starting point this research, by adapting the use of the mirror to our own configuration.

The optimised structure: The essential function of W1 PC 90° sharp bend is to convert a single mode train in the input waveguide into a single mode train in the output waveguide.

In order to improve the transmission of the 90° sharp bend and to avoid the losses at the 90° bend we insert a mirror in the bend of reference, the mirror is obtained by doing small displacement for the most critical hole around the proper 90° bending region. The optimized structure resulting is showing in Fig. 5a.

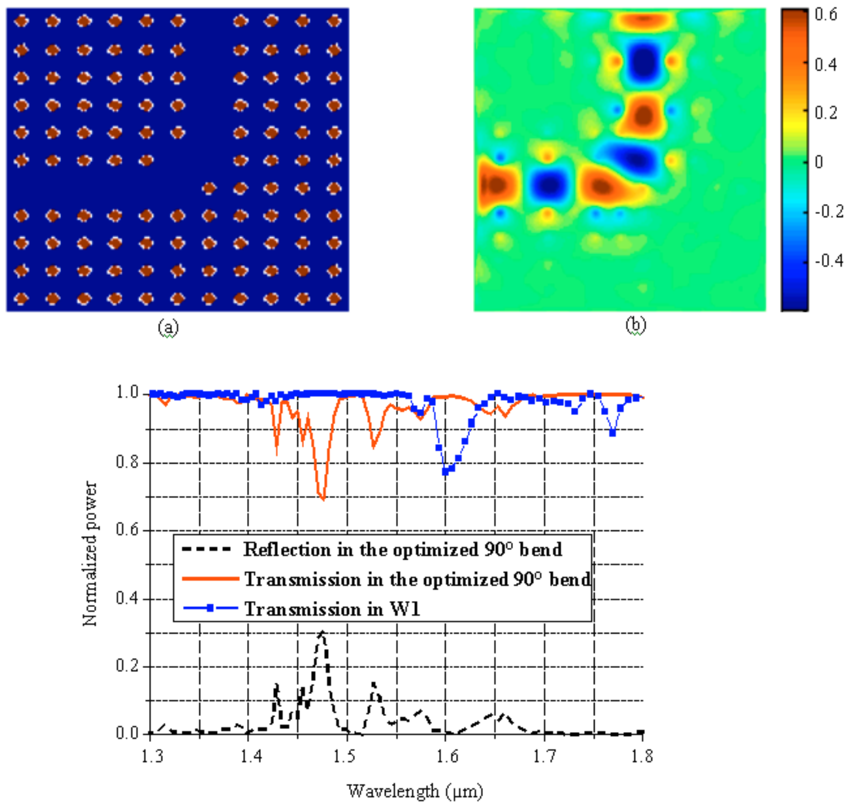

Fig. 5: (a) Optimised 90° bend structure resulting, (b) Magnetic Field amplitude distribution in the optimized 90° bend and (c) The transmission spectra of the optimise 90° bend structure

RESULTS AND DISCUSSION

Using the novel numerical scheme for the reduction of spurious reflections from photonic crystal waveguide ends and the reflections induces et the corner of the sharply bend, then clearly increase the bandwidth and power transmission, as directly observed in our, comparative, simulations of a 90° sharp bend with and without modifications. This solution has been compared to a several previous independent works.

Although, the bend's radius of curvature is less than the light's wavelength, nearly all the light is transmitted through the bend over a wide range of frequencies through the gap. The small fraction of light that is not transmitted is reflected. For specific wavelengths we can achieve 100% transmission (Fig. 5c) efficiency is that the photonic crystal waveguide be single mode in the frequency range of interest. The Fig. 5b shows clearly that the light is confined around the sharp bend and it can be seen that the radiation has been vanished compared with Fig. 2b.

CONCLUSION

While performing a simple sensitivity analysis based on FDTD code, we have obtained an efficient method for improving the frequency response of 2DPC devices. In particular we have applied this technique to a simple 90° sharp bend waveguide emerging from an underlying 2DPC with square lattice symmetry. A single optimization step has already obtained nearly zero reflection over almost the entire PBG. This technique can easily be extended to other 2DPC properties for optimization purposes, because key problem in the design of future integrated optical devices is how to balance ease of fabrication with the reduction of radiation losses.

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