Optimal Design of 60-Degree Bend in Two Dimensional Photonic Crystal Waveguides

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The bend waveguide is the key element for integrated optical signal processing waveguide devices. We propose a new type of two dimensional photonic crystal (2DPC) 60-degree 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 by Attila et al. we simulate its transmission characteristics and show an excellent transmission of light in 60\degree bend waveguides achieve 100\% for several frequencies. This opens the door to novel topologies for compact switches and sensor applications.

Keywords: Photonic Crystals, Finite Difference Time Domain (FDTD) Methods, Integrated Optics, Optical Waveguide Components, Waveguide Bends.

1. 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.\textsuperscript{1,2} 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.\textsuperscript{3,5}

In this paper, we demonstrate a novel method for guiding light around the 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 Ref. \[6\] which reduce reflection from PBG waveguide ends to under a few percent compared with the previous works.\textsuperscript{7}

The FDTD method\textsuperscript{8} 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),\textsuperscript{9} 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.\textsuperscript{10} 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.

2. 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,

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

\[
\frac{\partial E}{\partial t} = \frac{1}{\varepsilon(r)} \nabla \times H - \frac{\sigma(r)}{\varepsilon(r)} E \quad (2)
\]
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Where \( \varepsilon (r) \), \( \mu (r) \) and \( \sigma (r) \) 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. The following FDTD time stepping formulas are spatial and time discretizations of Eqs. (1) and (2) on a discrete two-dimensional mesh within the \( x-y \) coordinate system for the \( E \) polarization,

\[
H_{x}^{n+1/2} = H_{x}^{n-1/2} - \frac{\Delta t}{\mu_{i,j+1/2}} \left( E_{i+1/2,j}^{n} - E_{i-1/2,j}^{n} \right) \quad (3)
\]

\[
H_{y}^{n+1/2} = H_{y}^{n-1/2} + \frac{\Delta t}{\mu_{i+1/2,j}} \left( E_{i+1/2,j}^{n} - E_{i-1/2,j}^{n} \right) \quad (4)
\]

\[
E_{x}^{n+1} = \left( \frac{\varepsilon_{i,j} - \sigma_{i,j} \Delta t / 2}{\varepsilon_{i,j} + \sigma_{i,j} \Delta t / 2} \right) E_{x}^{n} - \frac{\Delta t}{\varepsilon_{i,j} + \sigma_{i,j} \Delta t / 2} \left( H_{x}^{n+1/2} - H_{x}^{n-1/2} \right) \Delta y
\]

\[
\times \left( - \frac{H_{x}^{n+1/2} - H_{x}^{n-1/2}}{\Delta y} \right) \quad (5)
\]

Where the index \( n \) denotes the discrete time step, indices \( i \) and \( j \) denote the discretized grid point in the \( x-y \) plane respectively. \( \Delta t \) is the time increment, and \( \Delta x \) and \( \Delta y \) 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.\(^{11}\)

\[
\Delta t \leq \frac{1}{c \sqrt{\Delta x^2 + \Delta y^2}} \quad (6)
\]

Where \( c \) is the fastest speed 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 \( \Delta t \), this means even longer calculation time.

4. DESCRIPTION OF THE OPTIMISED STRUCTURE

The specific structure that we investigated is a 60° bend formed by the intersection of two PC channel waveguides at 60° Figure 1 in an otherwise uniform photonic lattice. We assume a triangular lattice of air holes etched in a dielectric substrate, with refractive index \( n = 3.42 \), 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 < \( a/c < 0.35 \) for TE polarized light. In the design process, we use 2D FDTD simulation. 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. The essential function of W1 PC 60° 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 60° bend and to avoid the losses at the 60° 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 60° bending region. The optimized structure resulting is showing in Figure 1.

Fig. 1. Optimised 60° bend structure resulting.
5. RESULTS AND DISCUSSION

Using the novel numerical scheme for the reduction of spurious reflections from photonic crystal waveguide ends and the reflections induces at the corner of the bend, then clearly increase the bandwidth and power transmission, as directly observed in our, comparative, simulations of a 60° bend with and without modifications. This solution has been compared to several previous independent works.12–14

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 percent transmission (Fig. 3) efficiency is that the photonic crystal waveguide be single mode in the frequency range of interest. The Figure 2 shows clearly that the light is confined around the bend, and it can be seen that the radiation has been vanished.

6. CONCLUSION

While performing a simple sensitivity analysis based on FDTD home 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 60° 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.

References and Notes