



Journal of Applied Sciences

ISSN 1812-5654

science
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A Novel All-Optical Switch Based on a Photonic Crystal Coupler

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Abstract: Photonic Crystals (PCS), an analog of semiconductors for light waves, are composite periodic dielectric materials that provide novel and unique ways control many aspects of electromagnetic radiation. Harnessing the nonlinear properties of PCS offers an opportunity to create the all-optical devices. It is shown that the optical Kerr effect taking place in third order can be used effectively to obtain an ultra compact switch controlled by the intensity of a pump signal. Since the switching relies on the geometry of the 2DPC, it becomes possible to use highly nonlinear materials. The aim of this contribution is to demonstrate a highly efficient directional coupler based on the triangular lattice of circular Kerr-nonlinear dielectric rods suspended in air. We demonstrate, through a main body of the Finite Difference Time Domain (FDTD) algorithm for the third order nonlinearities the feasibility of all-optical switching in the improve structure. This study show that is possible to obtain an efficient all-optical switcher with few means and less expenses, we also compare the potentials of different photonic crystal lattices for designing single-mode waveguide and conclude that triangular structures are the best choice.

Key words: Triangular lattice, square lattice, finite difference time domain method, Kerr nonlinear material, nonlinear photonic crystal, redshift, waveguide, band gap, integrated optics

INTRODUCTION

Two Dimensional Photonic Crystals (2DPC) are receiving an increasing attention from the scientific community for their ability to control the propagation of light (Joannopoulos *et al.*, 1995). The basic building blocks for all-optical data processing such as waveguides with sharp bends, high-Q resonant cavities, perfect mirrors and so on could be integrated on a single photonic crystal chip, in order to achieve complex functions with high performances and small size (Joannopoulos *et al.*, 1997). All-optical switching in 2DPC couplers has been studied numerically in (Locattelli *et al.*, 2004), which have been simulate the 2DPC couplers based on the square lattice, however, it is very interesting to simulate the same structure but with the triangular lattice.

In this study we propose a novel all-optical switch based on a photonic crystal coupler. Switching is performed by the possibility to design a triangular Photonic Band Gap (PBG) waveguide with only one guided mode in the PBG. Such a PBG waveguide can be made single mode by choosing an appropriate thickness of the dielectric slab.

The available method to model complex nonlinear devices is the Finite Difference Time Domain (FDTD)

(Taflove, 1995). The advantages of this technique are in terms of its accuracy, generality, computational efficiency and ease of use.

NUMERICAL ALGORITHM BASED ON THE FDTD METHOD

The FDTD scheme (Taflove, 1995; Yee, 1966) has shown a great popularity for high frequency electromagnetic problems, because it is efficient and easy to program.

Since PCS are defined by two dimensional distribution of the index of refraction, the most accurate methods must treat the full 2D problem. Unfortunately, the computer memory and the time requirements are such that it is impossible to solve a realistic 3D problem on a personal computer or workstation.

Nonlinearity provides the designer with an added degree of design flexibility. With the growing complexity of nonlinear photonic device structures, approximate analytical techniques become inadequate and more accurate and efficient numerical techniques are sought.

In the past few years, the FDTD method has emerged as one of the most versatile numerical methods in PCS

analysis because of its ability to incorporate almost any type of constitutive relation describing the medium in use, including nonlinear media by directly solving Maxwell's equations simultaneously with the medium constitutive relation in the time domain. The method fully accounts for the effects of reflection, diffraction, radiation and suitable nonlinear effects that cannot otherwise be predicted by approximate analytical or other numerical techniques.

A simple application of the FDTD method to nonlinear media employs an explicit time-stepping scheme in the discretization in which the nonlinear permittivity at the unknown time step $n+1$ is approximated using the electric field value at the current time-step n (Ackerley and Chaudhuri, 1995; Kunz and Luebbers, 1993). The scheme allows the unknown field at time $n+1$ to be explicitly solved for, but it places a severe stability constraint on the time-step and mesh size. In some cases the time-step has to be reduced 20-30 times below the limit set by the Courant-Fredrichs-Lewy (CFL) condition to achieve stability in the nonlinear medium regions (Kunz and Luebbers, 1993).

In this study, we present the calculations based on the nonlinear 2DFDTD (Two Dimensional Finite Difference Time Domain). The standard implementation of Yee's mesh (Taflove, 1995) was used.

The polarization that is studied is Transverse Magnetic (TM) only, where the electric field is parallel to the rod. However the method can be used in the case of the Transverse Electric (TE) polarization.

In TM polarization the field vectors are thus: $\vec{H}=(H_x, H_y, 0)$ and $\vec{E}=(0, 0, E_z)$. The equations to be solved are:

$$\epsilon_0 \epsilon_r \frac{\partial E_z}{\partial t} = \frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} \tag{1}$$

$$\mu_0 \frac{\partial H_x}{\partial t} = \frac{\partial E_z}{\partial y} \tag{2}$$

$$\mu_0 \frac{\partial H_y}{\partial t} = -\frac{\partial E_z}{\partial x} \tag{3}$$

If we want to simulate the nonlinear case, we have to take into account an electric field dependent dielectric constant. The nonlinear model can be expressed as:

$$\epsilon_r^{nl} = \epsilon_r^l + \chi^{(3)} |E_z|^2 \tag{4}$$

Where:

$\chi^{(3)}$ = The third Kerr coefficient,

ϵ_r^{nl} = The nonlinear permittivity

ϵ_r^l = The linear permittivity.

We substitute Eq. 4 in 1:

$$\frac{\partial}{\partial t} (\epsilon_0 \epsilon_r E_z + \epsilon_0 \chi^{(3)} |E_z|^2 E_z) \tag{5}$$

However, having the nonlinear term inside the differentiation with respect to time is difficult to implement numerically.

Therefore, the assumption is made that the intensity of the light changes much more slowly than the field, so the intensity can be taken out of the differentiation. After simulations, the validity of this assumption must be checked.

The first Eq. 1 becomes:

$$\frac{\partial E_z}{\partial t} = \frac{1}{\epsilon_0 (\epsilon_r + \chi^{(3)} |E_z|^2)} \left(\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} \right) \tag{6}$$

In each time-step, a predictor corrector step is used for the intensity to improve stability. The entire window is surrounded by Perfectly Matched Layer (PML) (Berenger, 1996), which absorbs outgoing radiation. This PML only contains linear materials. In our current implementation, light is launched through the PML by prescribing the field on the outer boundary of the calculation window, ensuring that the light source does not disturb the simulation in the interior of the window (Stoffer and Kivshar, 2000).

BAND GAP: THE PARAMETER INTERPLAY

Parameter affecting band gap: The formation of a band gap is a result of coherent multiple scattering mechanisms exist (Bush and John, 1998): the microscopy scattering governed by Mie scattering, macroscopic scattering, governed by Bragg scattering. The synergetic interplay between these two mechanisms produces a band gap where no modes can exist.

In photonic band gap (PBG) structure, the parameters below may affect the two scattering mechanisms:

- Lattice geometry: The existence of a band gap on the lattice to a great degree.
- The material of the atom and the backgrounds; the refractive index contrast should be high enough, to affect the scattering strength.
- The shape of the atom: affects the macroscopic scattering pattern.
- The size of the atom: affects the Mie scattering pattern and strength.

Also, the finite size of real PBG structure affects the band gap.

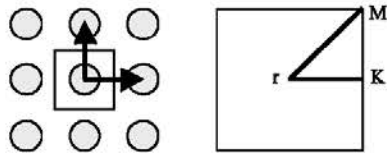


Fig. 1: 2D square lattice, unit cell and Brillouin zone. Left: unit cell and basis lattices vectors; Right: the 1st Brillouin zone and the irreducible Brillouin zone

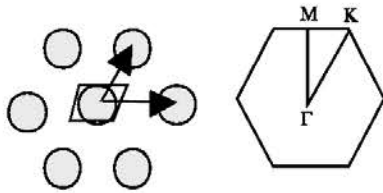


Fig. 2: 2D triangular lattice, unit cell and Brillouin zone. Left: unit cell and basis lattices vectors; Right: the 1st Brillouin zone and the irreducible Brillouin zone

Basic lattice structure: There are essentially only two kinds of 2D lattice structures; the orthogonal lattice and the oblique lattice for 2D structures. In orthogonal lattice, the two basis vectors are orthogonal, Fig. 1, which is called: 2D square lattice (Qiu and He, 2000), in oblique lattice, the two basis vectors are not orthogonal and generally the angle between these two vectors is 60°. In these oblique systems, there is the basis lattice called: the triangular lattice (also called as hexagonal lattice (Fig. 2) (Plihal and Maradudin, 1991; Sokada, 1995a,b, 1998).

Lattice geometry, especially the symmetry of the lattice is a very important factor to determine the band gap. Detailed study needs group theory (Sokada, 1995b). The choice of lattice geometry is determined by other factors: the band gap requirement (polarization, band gap width), available material, the difficulty of fabrication, etc. As a general rule, if the first Brillouin zone is close to a circle; then the structure is easier to produce a complete band gap.

In this study, we simulate the improve type of 2DPC lattices that are of practical interests: triangular lattice. Although the square lattice has been widely investigated, there have been only a few reports regarding triangular lattice structures (Cassagne *et al.*, 1996; Cassagne *et al.*, 1995). These existing reports are focused mostly on the triangular lattice.

THE IMPROVE DESIGN

Here we analysis of the effects the cell geometry is presented, showing how small variations can cause

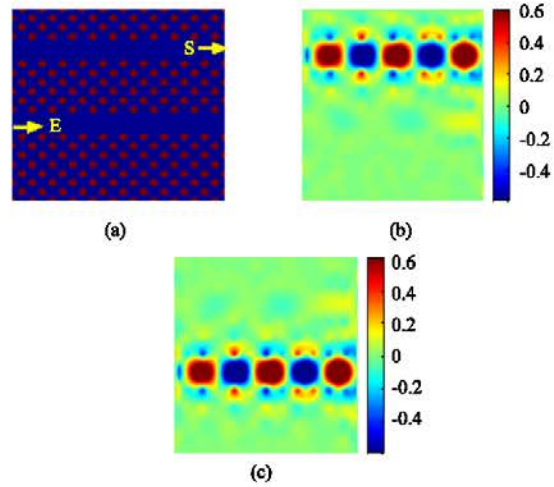


Fig. 3: (a) The proposed device based on triangular lattice, (b) intensity of the electric field in the output waveguide (S) and (c) intensity of the electric field in the input waveguide (E)

efficient switching in the distribution of the electric field inside the coupler.

In the complementary geometry, we considered a triangular lattice of rods, surrounded by air and made from nonlinear Kerr dielectric, with the same values for the refractive index and Kerr coefficients. The value chosen for structural parameter of the 2DPC was $r/a = 0.125$, where, r and a are the hole/rod radius and the lattice constant respectively. Two waveguides are formed by introducing linear defects by removing two parallel rows of rods in the ΓX direction and are separated by five rows of defects (Fig. 3a).

The simulation gives the distribution of the electric field inside the coupler in the nonlinear regime.

The intensity of the electric field in the device for a maximum input intensity I_1 . It is possible to see that all the optical energy is in the output waveguide (S) thus the coupler is in cross state (Fig. 3b).

We increase the input intensity to $I_1 > I_2$, now all the optical energy is in the input waveguide (E) and then the coupler in the bar state induced by the nonlinearity (Fig. 3c).

The mechanism that explains the switching behaviour of this directional coupler is twofold. First, the refractive index of the rows of rods between both waveguides changes owing to the Kerr nonlinearity when a high power level signal is launched as a control signal, thus it becomes possible both to tune the coupling coefficient and vary the power ratio between the 2DPC coupler outputs. Moreover, it should be noticed that the redshift of the band gap is larger in the nonlinear triangular lattice due to the impact of the geometry and the group velocity.

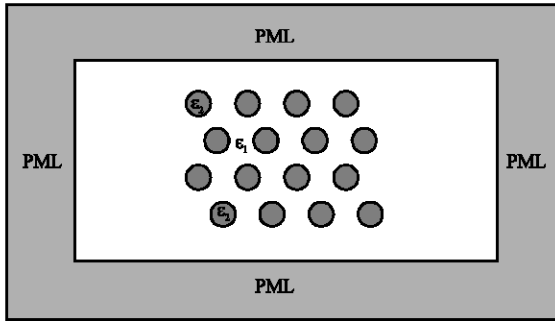


Fig. 4: Schematic of the improve 2D nonlinear photonic crystal based on the triangular lattice, all boundaries are surrounded by PML's

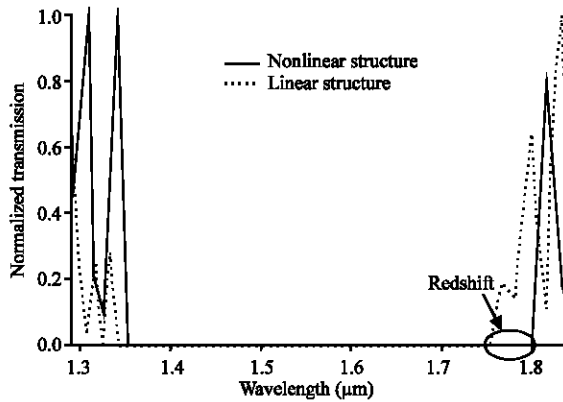


Fig. 5: Transmission spectra of linear and nonlinear 2DPBG triangular lattice

REDSHIFT DEPENDENCE ON THE GROUP VELOCITY

The properties of the redshift that we have seen in the previous subsections by simulating the structure (Fig. 4).

After the FDTD calculation process has finished, we use the Fast Fourier Transform (FFT) procedure to obtain the transmission spectrum.

The Fig. 5 shows the transmission spectrum of the linear and nonlinear 2DPBG structure shown in Fig. 4.

We can observe that, for a positive Kerr coefficient, the position of the forbidden band gap is redshifted with regard to the linear case (Maksymov *et al.*, 2005).

To explain this phenomenon mathematically, let us regard Z as being the shift towards the red of the remote objects (redshift). Its definition is connected to the translation in wavelength:

$$Z = \frac{\Delta\lambda}{\lambda_0} = \frac{\lambda - \lambda_0}{\lambda_0} \tag{7}$$

Where:

λ = The received wavelength.

λ_0 = The emitted wavelength.

The group velocity V_g and the wave vector k are given respectively by the Eq. 8 and 9:

$$V_g = c * \frac{2L}{\lambda_0^2} * \Delta\lambda \tag{8}$$

$$k = \frac{\omega}{c} * \epsilon^2 = \frac{2\pi}{\lambda} * \epsilon^2 \tag{9}$$

Where:

L = The wavelength of the structure

c = The speed of light in the vacuum.

We substitute the Eq. 9 in 8, we will have:

$$V_g = k * \frac{Lc}{\lambda\pi} * \frac{\Delta\lambda}{\epsilon^2} \tag{10}$$

Starting from Eq. 7:

$$\lambda = \lambda_0 * (Z + 1) \tag{11}$$

We substitute the Eq. 11 in 9, we will have:

$$Z = \frac{2\pi\epsilon^2}{k\lambda_0} - 1 \tag{12}$$

Taking into account the Eq. 10 and 12, we notice that the variation of the group velocity V_g is proportional to the wave vector k and the redshift expressed by the parameter Z is inversely proportional to this last. Consequently, the redshift is proportional to the intensity of the incident field.

DISCUSSION

The result suggest that a triangular lattice can be used for building integrated photonic circuits and it is possible to design a single-mode PBG waveguide within the frequency band gap. However, there are several drawbacks in using the triangular lattice photonic crystals for integrated optics application. First, single-mode propagation can be achieved only within part of the PBG, which may limit the frequency bandwidth of the integrated optics. Second, we demonstrate that the triangular lattice produce a large redshift in the nonlinear case, which leads to the slow group velocity of light in 2DPC circuits and can dramatically increase the accumulated nonlinear phase shifts that are required for the efficient performance of an all-optical switching. Without forgetting, that in the triangular structures, we found the two polarizations TE and TM, therefore presence of a complete band gap.

Having discussed the benefits and drawbacks of the triangular lattice PBG structures, it is instructive to compare it with other photonic crystal lattices.

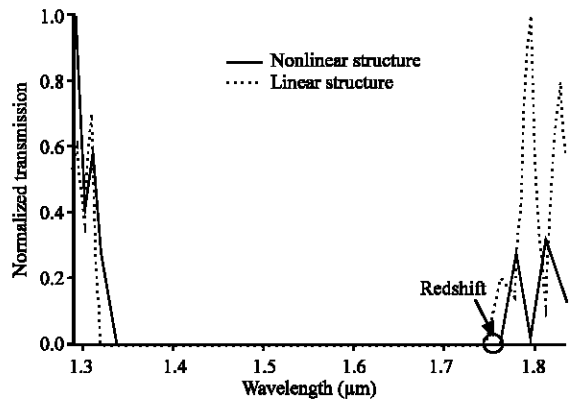


Fig. 6: Transmission spectra of linear and nonlinear 2DPBG square lattice

In fact, the result obtained is in good agreement with previous calculations (Locatelli *et al.*, 2004), which have been simulating the same design using the square geometry, in which the single-mode waveguide is obtained by introducing linear defects reducing the radius of the rods for obtaining the two waveguides of the 2DPC coupler, but we know that this way of making is expensive and very difficult in conception with regard our described design we, thus, proposed our improvement which leads to the same results with few means and less expenses.

We demonstrate so, that the factor of the triangular geometry has caused an important shift of the PBG towards the big wavelengths compared with the square geometry Fig. 6. This phenomenon is due mainly by the fact that the triangular geometry does not let pass the electromagnetic wave on the one hand and on the other hand, it has a prohibited frequency bands whatever the polarization of the light. The frequency bands are numerous for the two polarizations TE and TM. Their width reaches the maximum when the diameter of the holes is nearly equal to the distance between two close holes.

CONCLUSIONS

The performing of a novel architecture for an all optical switch based on a 2DPC directional coupler has been proposed and demonstrated. This structure may become a key building-block of a larger and more complex switching device.

Present results show that the triangular lattices photonic crystals are the best candidates and are more suited to a switching and limiting accurately than the other one. So the large redshift which appears in this kind of lattices leads to the slow group velocity of light in photonic crystal circuits, which can dramatically increase

the accumulated nonlinear phase shifts that are required for the efficient performance of an all-optical switching. The way of making in our improvement is not expensive and easy in the conception with regard to the designs which are described in earlier studies.

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