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Optical switch based on nonlinear one dimensional photonic band gap material

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ABSTRACT

In this paper we proposed an optical switch based on nonlinear one dimensional photonic band gap material. Polystyrene and SiO_2 have been chosen as constituent materials for the proposed optical switch. Propagation of optical waves through these multilayered structures has been studied for different intensities. Simulation of the device and analysis of its performance has been carried out using transfer matrix method. The study shows that the polystyrene/SiO_2 based nonlinear photonic band gap material studied here can work as an optical switch. The proposed device could also be useful in OTDM demultiplexing, all optical information processing, etc. Due to its simple geometric structure and simple operating principle, this device could be a strong candidate for the variety of applications in the field of integrated optoelectronics.

1. Introduction

With the development of high-capacity and high-speed telecommunication systems, the demand for all-optical signal processing techniques is rapidly increasing. The maximum speed of switching of electronic logic gates is of the order of 10^{10} Hz limiting the speed and bandwidth of telecommunication. On the other hand, switching speed of optical device is limited only by the speed of light passing through it and of the order of 10^{14} Hz. All-optical switches are key elements in all-optical signal processing techniques. So far, several techniques have been investigated to realize optical switches [1–4]. These approaches have shown some advantages, but which are difficult to operate at very high speed data rate. In recent years, photonic crystal based optical devices have attracted significant research efforts [5–14]. In photonic crystal structures, electromagnetic radiation with wavelength which falls within the band gap of such a crystal cannot propagate through the crystal. These devices have been widely investigated since John [5] and Yablonovitch [6] reported in 1987. Although a photonic band gap (PBG) material has photonic band gaps, the material nonlinearity can render the PBG material “transparent” for nonlinear optical propagation [8,9]. On the other hand, designs of all-optical switches and logic gates are reported based on linear and nonlinear photonic crystals [15–18]. Recently, Gupta et. al proposed the design of all-optical NOT and AND gates using counter propagating beams in nonlinear Mach–Zehnder interferometer made of photonic crystal waveguides [19].

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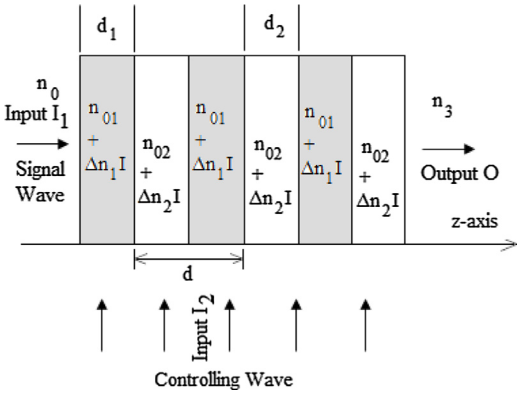

Fig. 1. Schematic diagram of the structure.

Kumar et al. had studied the behavior of group velocity of light wave in 1-D polystyrene/SiO2 nonlinear photonic crystal and proposed a scheme to trap a light wave inside the photonic crystal [20]. In the present paper, the propagation of a wave with a Gaussian spectral distribution in a polystyrene/SiO2 based one-dimensional nonlinear photonic crystal has been investigated and suggested a design of an optical switch based on the properties of such crystals. Although the concept behind this is very basic and very well known, but up to our best knowledge, we are describing this scheme for the first time. To design optical switch, a wave whose mean wavelength falls inside the photonic band gap at low intensity for the PBG material is considered here. The nonlinear layers of the photonic crystal structure considered here have different refractive indices at different intensities of controlling wave. This leads to shifting of band gaps. This shift due to nonlinearity of materials should be of the order of the spectral width of the wave. This condition allows propagation of a wave when the signal wavelengths are just inside the short wavelength edge of the gap, i.e., the gap is shifted so that the propagation of the signal without reflection through the structure is possible [21]. This property of nonlinear photonic crystal can be exploited for the design of an all-optical switch. Here, we considered that electromagnetic wave that carries the signal wave incidents perpendicular to the layers. The controlling wave, which produces the nonlinear effect, is propagating perpendicular to the direction of propagation of the signal wave. Also, we considered the amplitude of the controlling wave to be much higher than the amplitude of the signal wave thereby we can safely neglect the nonlinear effect due to the signal wave on nonlinear layers.

2. Theoretical model

Consider a one-dimensional periodic structure as a model of optical switch, in which it is assumed that the materials of alternate layers are nonlinear and select a particular axis as the z-axis which is along the direction normal to the layers. The refractive index profile of the structure has a form as given by

$$n(z) = \begin{cases} n_0\,1 + \Delta n_1 I, & 0 < z < d_1 \\ n_{02} \ + \Delta n_2 I & d_1 < z < d_2 \end{cases} \tag{1}$$

with $n(z+d) = n(z)$. Here d is the lattice constant, d_1 and d_2 are the thicknesses of the alternate layers which have refractive indices $n_{01} + \Delta n_1 I$ and $n_{02} + \Delta n_2 I$, where I is the intensity of wave. The schematic diagram of this structure is illustrated in Fig. 1.

Now, the wave equation for light propagation along the z-axis may be written as

$$\frac{d^2E}{dz^2} + \frac{n^2\omega^2}{c^2} = 0 \tag{2}$$

where n is given by Eq. (1). The solutions of Eq. (2), in any region, are the combinations of left and right travelling waves.

The characteristic matrix corresponding to one lattice period that determines the properties of the structure is given by [22]

$$m(d) = \begin{pmatrix} m_{1,1} & m_{1,2} \\ m_{2,1} & m_{2,2} \end{pmatrix} \tag{3}$$

where

$$m_{1,1} = \cos(k_{1z}d_1)\cos(k_{2z}d_2) - \frac{q_2}{q_1}\sin(k_{1z}d_1)\sin(k_{2z}d_2) \tag{4}$$