NONLINEAR PHOTONIC CRYSTAL FOR ALL-OPTICAL SWITCHING APPLICATIONS

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ABSTRACT

An all-optical switching device is a crucial component for developing high speed data transmission and signal processing in telecommunication network. The device is based on nonlinear optical material, whose refractive index depends on light intensity. Recently, photonic crystals have been considerable interest both theoretically and experimentally for optical switching devices. Due to the practical reason, we studied one-dimensional nonlinear photonic crystal for all-optical switching devices. We use transfer matrix method and nonlinear coupled mode equation to determine photonic bandgap and optical switching process. We applied them to different structures: nonlinear Distributed Bragg Reflector (DBR) and nonlinear photonic crystals which has similar linear refractive index but has opposite sign of nonlinear refractive index. By using an appropriate combination of refractive indices, it was found that the first structure can be used for all-optical switching at telecommunication wavelength (1.55 μm). The second structure can be used both for all-optical switching and optical limiter at the wavelength of 1 μm.

Keywords: all-optical switching, optical limiter, nonlinear photonic crystal, transfer matrix, nonlinear coupled mode equation.

KRISTAL FOTONIK NONLINIER UNTUK APLIKASI SAKLAR SINYAL OPTIK

ABSTRAK

Suatu piranti saklar optik merupakan komponen krusial untuk pengembangan transmisi data dan pemrosesan sinyal kecepatan tinggi dalam jaringan telekomunikasi. Piranti ini berbasis pada material optik nonlinier, dimana indeks biasnya bergantung pada intensitas cahaya. Baru-baru ini, kristal fotonik merupakan kajian yang sangat menrik baik secara teori maupun eksperimen untuk piranti saklar optik. Karena alasan praktis, kami disini mempelajari kristal fotonik nonlinier satu-dimensi untuk piranti-piranti saklar optik. Kami menggunakan metoda matrik transfer dan persamaan moda tergandeng nonlinier untuk menentukan celah pita fotonik dan proses switching optik. Dua metoda diatas digunakan dalam mempelajari dua struktur yang berbeda, yaitu reflector Bragg terdistribusi nonlinier dan kristal fotonik nonlinier yang mempunyai indeks bias linier yang sama, namun indeks bias nonlinier yang berlawanan tanda. Pemilihan kombinasi indeks bias yang sesuai, menunjukkan bahwa struktur dapat digunakan untuk switching optik pada panjang gelombang telekomunikasi (1,55 μm), sedangkan struktur yang kedua dapat digunakan untuk switching optik dan pembatas sinyal optik pada panjang gelombang 1 μm.

Kata Kunci : switching optik, pembatas sinyal optik, kristal fotonik nonlinier, matrik transfer, persamaan moda tergandeng nonlinier

INTRODUCTION

All-optical switching and optical limiter are key elements for optical signal processing in high speed telecommunication networks. All-optical switching is used for optical signal distribution that transmitted by high bandwidth and high speed optical fibers, whereas optical limiter can be used to filter, shape and multiplex optical signal and to limit the optical power. These devices are commonly based on total internal reflection, self-focusing, self-defocusing, two-photon absorption and photorefractive. A good and reliable of these devices must be fast respond, resistant to optical damage, not degrade if subjected to the high-intensity light and stable in the working environment. Many concepts have been proposed and studied for realizing these devices, such as nonlinear directional coupler, Mach-Zehnder interferometer, Nonlinear X-switch (Stegeman, 1997), nonlinear microcavities (Gubler, 2000) and nonlinear Bragg waveguide (Bader *et al.*, 2002). These devices are based on nonlinear optical materials whose refractive index depends on light incident intensity:

$$n(I) = n_0 \pm n_{nl} I \tag{1}$$

In order to realize all-optical switching and optical limiter devices, they need materials that possess high nonlinear refractive index which is very difficult to be achieved by existing materials. Therefore, as the best of our knowledge, until now there is no all-optical switching devices have been realized.

Recently, photonic crystals have been considerable interest both theoretically and experimentally. Photonic crystals are periodically structured dielectric materials with different refractive indices, generally possessing photonic band gaps (PBG): ranges of frequency in which light cannot propagate through the structure (Joannopoulos *et al.*, 1995, Sakoda, 2001). Photonic crystals structure is expected to be a key for future photonic devices. In this paper, we modeled all-optical switching and optical limiter devices rely upon one-dimensional (1D) photonic crystals consisting nonlinear optical materials. These structures are basically multilayer structures, which are easy to be fabricated into any desired substrate and integrated to the other devices. We studied two different structures, i.e. nonlinear Distributed Bragg

Reflector (DBR) and nonlinear photonic crystal composed of nonlinear optical materials with identical linear refractive index but opposite sign of their nonlinear refractive indices.
We used matrix transfer method for determining PBG and nonlinear coupled mode equation for studying electromagnetic field propagation within the structure as well as all-optical switching and optical limiter mechanism. We analyzed the devices by varying parameters, as number of layers, incident intensity, and the strenth of the nonlinear response of optically active materials.

METHOD

We studied nonlinear photonic crystals for all-optical signal processing applications theoretically using transfer matrix and nonlinear coupled mode equation. The outputs of the structure were obtained by solving those equations numerically. The structure of photonic crystal is schematically shown in Figure 1. It consist of periodically two dielectric materials with refractive indices and thicknesses n_1, d_1 and n_2, d_2, respectively. The period of the structure is Λ.

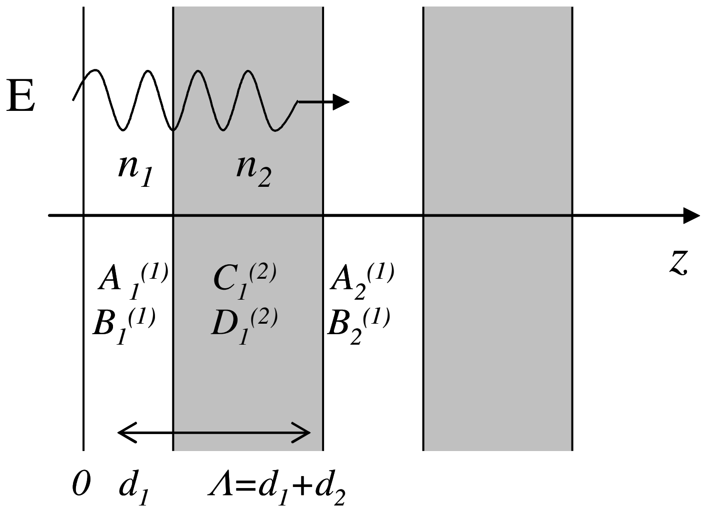


Figure 1. Structure of 1D photonic crystal with propagation direction z.

The refractive index of the structure can be expressed as :

$$n(z) = \begin{cases} n_1;\ 0 < z < a \\ n_2;\ a < z < \Lambda \end{cases} \qquad (2)$$

Matrix transfer method

We assume that the electromagnetic field E propagates to the right and to the left within the layer with refractive index n_1 has amplitudes of A_1 and B_1, respectively. Whereas the light within the layer of n_2 propagates with amplitudes of C_1 and D_1, respectively. Therefore, the propagation of light in the photonic crystal structure becomes (Yeh, 1998) :

$$\begin{aligned} E(z) &= A_1 e^{ik_1 z} + B_1 e^{-ik_1 z} \\ E(z) &= C_1 e^{ik_2(z-d_1)} + D_1 e^{-ik_2(z-d_1)} \end{aligned} \tag{3}$$

Parameters k_1 and k_2 are called propagation constants ($k_1 = \omega n_1$ and $k_2 = \omega n_2$). By applying boundary conditions at $z = d_1$ and $z = \Lambda$, we obtain :

$$\begin{aligned} \begin{pmatrix} A_1 \\ B_1 \end{pmatrix} &= \frac{1}{2} \begin{pmatrix} \left(1+\frac{k_2}{k_1}\right) e^{ik_1 d_1} & \left(1-\frac{k_2}{k_1}\right) e^{-ik_1 d_1} \\ \left(1+\frac{k_2}{k_1}\right) e^{ik_1 d_1} & \left(1-\frac{k_2}{k_1}\right) e^{-ik_1 d_1} \end{pmatrix} \begin{pmatrix} C_1 \\ D_1 \end{pmatrix} \\ \begin{pmatrix} C_1 \\ D_1 \end{pmatrix} &= \frac{1}{2} \begin{pmatrix} \left(1+\frac{k_2}{k_1}\right) e^{ik_1 d_1} & \left(1-\frac{k_2}{k_1}\right) e^{-ik_1 d_1} \\ \left(1+\frac{k_2}{k_1}\right) e^{ik_1 d_1} & \left(1-\frac{k_2}{k_1}\right) e^{-ik_1 d_1} \end{pmatrix} \begin{pmatrix} A_2 \\ B_2 \end{pmatrix} \end{aligned} \tag{4}$$

By eliminating of (C_1, D_1) matrix, we obtain :

$$\begin{bmatrix} A_2 \\ B_2 \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \begin{bmatrix} A_1 \\ B_1 \end{bmatrix} \tag{5}$$

where the components of M are :

$$\begin{aligned} M_{11} &= e^{ik_1 d_1} \left[\cos(k_2 d_2) + \frac{1}{2} i \left(\frac{k_2}{k_1} + \frac{k_1}{k_2} \right) \sin(k_2 d_2) \right] \\ M_{12} &= e^{-ik_1 d_1} \left[\frac{1}{2} i \left(\frac{k_2}{k_1} - \frac{k_1}{k_2} \right) \sin(k_2 d_2) \right] \\ M_{21} &= e^{ik_1 d_1} \left[-\frac{1}{2} i \left(\frac{k_2}{k_1} - \frac{k_1}{k_2} \right) \sin(k_2 d_2) \right] \\ M_{22} &= e^{-ik_1 d_1} \left[\cos(k_2 d_2) - \frac{1}{2} i \left(\frac{k_2}{k_1} + \frac{k_1}{k_2} \right) \sin(k_2 d_2) \right] \end{aligned} \tag{6}$$

The matrix of M is called matrix transfer of a unit cell. If the structure of photonic crystal consist of N unit cell and the light comes from the left side of the structure and interacts within the structure leads to waves which propagate to the right and to the left with amplitudes of t and r, respectively, then :

$$\begin{bmatrix} t \\ 0 \end{bmatrix} = \begin{bmatrix} \frac{1}{2}\left(1+\frac{k_0}{k_1}\right) & \frac{1}{2}\left(1-\frac{k_0}{k_1}\right) \\ \frac{1}{2}\left(1-\frac{k_0}{k_1}\right) & \frac{1}{2}\left(1+\frac{k_0}{k_1}\right) \end{bmatrix} M^N \begin{bmatrix} \frac{1}{2}\left(1+\frac{k_2}{k_1}\right) & \frac{1}{2}\left(1-\frac{k_2}{k_1}\right) \\ \frac{1}{2}\left(1-\frac{k_2}{k_1}\right) & \frac{1}{2}\left(1+\frac{k_2}{k_1}\right) \end{bmatrix} \begin{bmatrix} \frac{1}{2}\left(1+\frac{k_2}{k_0}\right) & \frac{1}{2}\left(1-\frac{k_2}{k_0}\right) \\ \frac{1}{2}\left(1-\frac{k_2}{k_0}\right) & \frac{1}{2}\left(1+\frac{k_2}{k_0}\right) \end{bmatrix} \begin{bmatrix} 1 \\ r \end{bmatrix} \tag{7}$$

The transmitted light is then expressed by T = $|t|^2$.

Nonlinear coupled mode equation

Propagation of light process in 1D photonic crystal is governed by Maxwell equations. We assume that no charge and electric current sources in the dielectric materials and no magnetic materials. Therefore, the electromagnetic wave equation can be expressed by (Sakoda, 2001):

$$\frac{d^2E}{dz^2} + \frac{\omega^2}{c^2} n^2(z)E = 0 \tag{8}$$

where $c = 1/\sqrt{\mu_0 \varepsilon_0}$ is the light velocity in vacuum and n(z) is the refractive index of the structure.

We studied two different structures, i.e. nonlinear Distributed Bragg Reflector (DBR) and nonlinear photonic crystal composed of nonlinear optical materials with identical linear refractive index but opposite sign of their nonlinear refractive indices.

(a). Nonlinear Distributed Bragg Reflector

Basically, the structure of nonlinear Distributed Bragg Reflector (DBR) is equal to the structure depicted in Figure 1, but the layer-1 is made from nonlinear optical material, therefore the refractive index of the structure becomes :

$$\begin{aligned} n(z) &= n_0 + \bar{n} \cos Gz + n_{nl}|E(z)|^2 \\ G &= \frac{2\pi}{\Lambda} \end{aligned} \tag{9}$$

where $\bar{n}$ is the depth variation of the refractive index and Λ is period. Subtitution of this equation into equation (8) leads to the wave equation :

$$\frac{d^2E}{dz^2}+\frac{\omega^2}{c^2}\left(n_0{}^2E(z)+2n_0\bar{n}\cos GzE(z)\right)+\frac{\omega^2}{c^2}2n_0n_{nl}|E(z)|^2E(z)=0 \qquad (10)$$

If the electric field and light intensity are defined, respectively, as :

$$\left.\begin{aligned} &E(z)=Ae^{i\beta z}+Be^{-i\beta z}\\ &|E(z)|^2=\left(Ae^{i\beta z}+Be^{-i\beta z}\right)\left(A^*e^{-i\beta z}+B^*e^{i\beta z}\right)\end{aligned}\right\} \qquad (11)$$

and by using slowly varying amplitude (SVA) approximation, equation (10) becomes :

$$\left.\begin{aligned} &i\frac{dA}{dz}=-n_2k_0\left[|A|^2+2|B|^2\right]A+\kappa Be^{-2i\delta z}\\ &i\frac{dA}{dz}=n_2k_0\left[2|A|^2+|B|^2\right]B+\kappa Ae^{2i\delta z}\end{aligned}\right\} \qquad (12)$$

where $n_2k_0 = \alpha$, $\kappa=\omega\bar{n}/2c$ and $\delta=\beta-\frac{1}{2}G$. Equation (12) is called nonlinear coupled mode equation. By using definition :

$$\begin{aligned} &A=|A|e^{i\phi_A(z)}\\ &B=|B|e^{i\phi_B(z)}\\ &\psi(z)=\phi_A(z)-\phi_B(z)\end{aligned} \qquad (13)$$

and subsituting it into equation (12), then by separating their real and imaginary parts, we obtain :

$$\begin{aligned} &\frac{d|A|}{dz}=\kappa|B|\sin\psi\ ;\ \frac{d\phi_A}{dz}=\kappa\frac{|B|}{|A|}\cos\psi+\alpha\left(|A|^2+2|B|^2\right)A\\ &\frac{d|B|}{dz}=\kappa|A|\sin\psi\ ;\frac{d\phi_B}{dz}=\kappa\frac{|A|}{|B|}\cos\psi+\alpha\left(|B|^2+2|A|^2\right)B\\ &\cos\psi=-\frac{3\alpha}{\kappa}|A||B|\end{aligned} \qquad (14)$$

The transmitted light is defined by :

$$|T|^2 = |A|^2 - |B|^2 \tag{15}$$

Substitution equation (15) into equation (14) leads to :

$$\left(\frac{d|A|^2}{dz}\right)^2 = 4\kappa^2|A|^2\left(|A|^2 - |T|^2\right)\left[1 - \left(\frac{3\alpha}{\kappa}\right)^2|A|^2\left(|A|^2 - |T|^2\right)\right] \tag{16}$$

By substituting the following definitions of x = 2z/L, $|C|^2 = 2/3\alpha L$, y = $|A|^2/|B|^2$ and $I_0 = |T|^2/|C|^2$, where L is the length of the photonic crystal structure and I_0 is the normalized output light intensity to $|T|^2$ into equation (16), we obtain :

$$\left(\frac{dy}{dx}\right)^2 = \left(y - I_0\right)\left\{(\kappa L)^2 y - 4\left(y - I_0\right)y^2\right\} \tag{17}$$

The solution of equation (17) is a Jacobian elliptic equation :

$$y(x) = \frac{I_0}{2}\left\{1 + \mathrm{nd}\left[2Q\left(1 - \frac{x}{2}\right)\middle| m\right]\right\} \tag{18}$$

where

$$m = \sqrt{\frac{(\kappa L)^2}{\left(I_0^{\,2} + (\kappa L)^2\right)}} \qquad Q = \sqrt{I_0^{\,2} + (\kappa L)^2} \tag{19}$$

If the normalized input light intensity is defined by I_i = y (x = 0), then the relation between output and input intensity is :

$$I_0 = \frac{2I_i}{1 + \mathrm{nd}\left(2Q|m\right)} \tag{20}$$

(b). Photonic crystal with equal linear refractive index but opposite sign of nonlinear refractive index

The structure of this 1D nonlinear photonic crystal consist of periodic dielectric materials with refractive indices :

$$\begin{aligned} n_1 &= n_{01} + n_{nl1}\, I \\ n_2 &= n_{02} - n_{nl2}\, I \end{aligned} \tag{21}$$

where n_{01}, n_{nl1} and n_{02}, n_{nl2} are linear and nonlinear refractive indices of layer-1 and layer-2, respectively. In order to obtain an analytical expression for the evolution of forward and backward propagating light inside the structure, we use the nonlinear coupled mode equation by defining $A_1(z)$ and $A_2(z)$ are amplitudes of the forward and backward propagating light and also by assuming that absorption of the materials are neglected (Brzozowski & Sargent, 2000) :

$$\begin{aligned} i\frac{dA_1(z)}{dz} &= \frac{\omega}{c}\left\{\left[(n_{0_1} - n_{0_2}) + (n_{nl_1} - n_{nl_2})I(z)\right]\exp\left(-i\frac{\pi d_2}{\Lambda}\right)\frac{\sin\frac{\pi d_2}{\Lambda}}{\pi}\, x\, A_2(z)\exp\left[i\left(\frac{2\omega n_0}{c} - \frac{2\pi}{\Lambda}\right)z\right]\right\} \\ &\quad - \frac{\omega}{c}\left[\overline{n}_{nl} I(z) x A_1(z)\right] \\ i\frac{dA_2(z)}{dz} &= -\frac{\omega}{c}\left\{\left[(n_{0_1} - n_{0_2}) + (n_{nl_1} - n_{nl_2})I(z)\right]\exp\left(-i\frac{\pi d_2}{\Lambda}\right)\frac{\sin\frac{\pi d_2}{\Lambda}}{\pi}\, x A_1(z)\exp\left[i\left(\frac{2\omega n_0}{c} - \frac{2\pi}{\Lambda}\right)z\right]\right\} \\ &\quad + \frac{\omega}{c}\left[\overline{n}_{nl} I(z) x A_2(z)\right] \end{aligned} \tag{22}$$

where $n_0 = \dfrac{n_{0_1} d_1 + n_{0_2} d_2}{\Lambda}$ and $\overline{n}_{nl} = \dfrac{n_{nl_1} d_1 + n_{nl_2} d_2}{\Lambda}$ are the average linear and nonlinear refractive indices of the structure, respectively. In this work, we assumed that $n_{01} = n_{02}$ and $n_{nl1} = n_{nl2}$, therefore, the equation (22) becomes :

$$\begin{aligned} \frac{dA_1(z)}{dz} &= -\frac{\omega}{c}\frac{2n_{nl}}{\pi}\left[|A_1(z)|^2 + |A_2(z)|^2\right]A_2(z)\exp\left[i\left(\frac{2\omega n_0}{c} - \frac{2\pi}{\Lambda}\right)z\right] \\ \frac{dA_2(z)}{dz} &= -\frac{\omega}{c}\frac{2n_{nl}}{\pi}\left[|A_1(z)|^2 + |A_2(z)|^2\right]A_1(z)\exp\left[-i\left(\frac{2\omega n_0}{c} - \frac{2\pi}{\Lambda}\right)z\right] \end{aligned} \tag{23}$$

The solution of equation (23) is taken at resonance condition ($2\omega n_0/c = 2\pi/\Lambda$), by applying the boundary conditions at the position z = L, where L is the length of the structure and $A_2(L) = 0$, i.e. no radiation is incident on the structure from the right and $A_1(L) = A_{1out}$. By taking the squared modulus of A_{1out} yield the intensity of the forward propagating within the structure :

$$I(z) = \left|A_1(z)\right|^2 = \left|\frac{1+\cos\left(\dfrac{4I_{out}n_{nl}(L-z)}{\Lambda n_0}\right)}{2\cos\left(\dfrac{4I_{out}n_{nl}(L-z)}{\Lambda n_0}\right)}\right| I_{out} \qquad (24)$$

where $I_{out} = |A_{1out}|^2$. The input light intensity is obtained at z = 0:

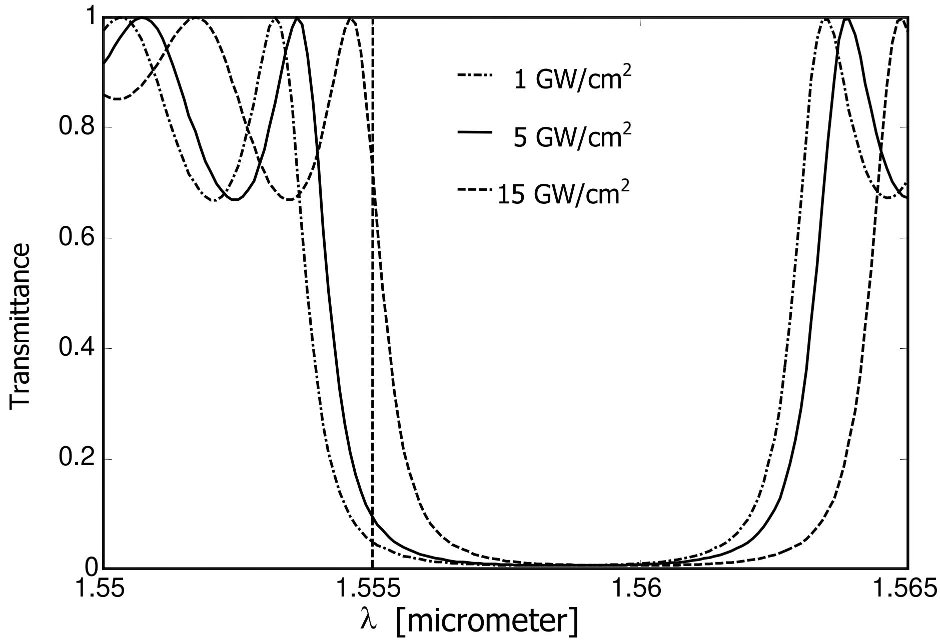
$$I_{in} = I(z)\big|_{z=0} = \frac{1}{2}\left|\frac{1}{\cos\left(\dfrac{4I_{out}}{a}\right)} + 1\right| I_{out} \qquad (25)$$

with $a = 2n_0/Nn_{nl}$ and $N = 2L/\Lambda$ is number of layers. Equation (25) is a characteristic equation of optical limiter.

RESULTS AND DISCUSSION

(a). Nonlinear Distributed Bragg Reflector

We used the combination of linear refractive indices of layer-1 and layer-2 are 1.8 and 1.6, respectively. The layer-1 is made from nonlinear optical material with nonlinear refractive index $n_{nl} = 2.2 \times 10^{-5}$ cm^2/GW. We calculated the transmittance of the structure using matrix transfer [Equation (17)] by varying light input intensity as shown in Figure 2(a). The light intensity leads to the change of photonic bandgap position to the longer wavelength. If we take the constant wavelength at 1.555 μm, it is clear that its transmission increases ~ 70% with the increase of light intensity as shown in Figure 2(b). This behaviour (change of transmittance from low to high with light intensity) is a characteristic of all-optical switching device.



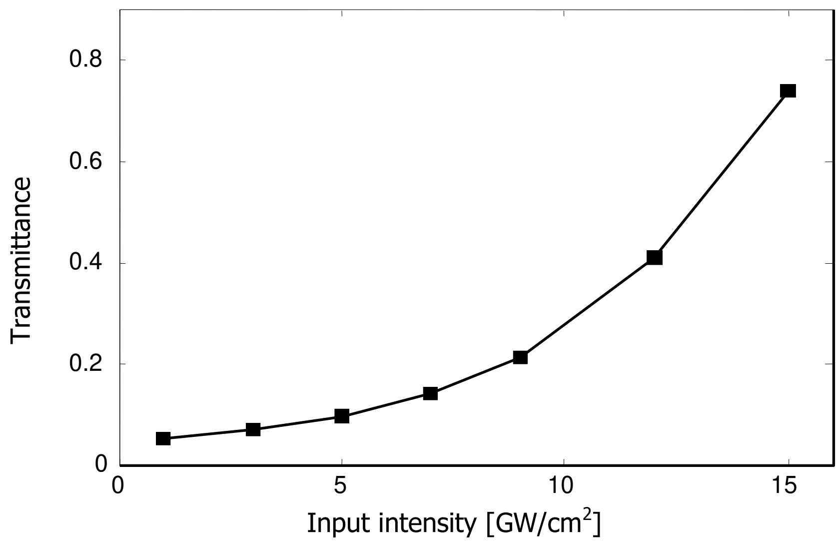


Figure 2. (a). Transmittance as function of wavelength with varying input light intensity, and (b). Transmittance of 1.555 μm as function of input light intensity

In order to study the effect of the depth variation of refractive index caused by the combination of the change of nonlinear refractive index and the length of the structure (κL) on the switching behavior, we applied equation (20) and the results are shown in Figure 3. The behavior of its switching is called optical bistability. It is clear that optical bistability depends on the value of κL; it occurs on the large value of κL. If the length of the structure is kept constant, the optical bistability occurs when the nonlinear refractive index is increased.

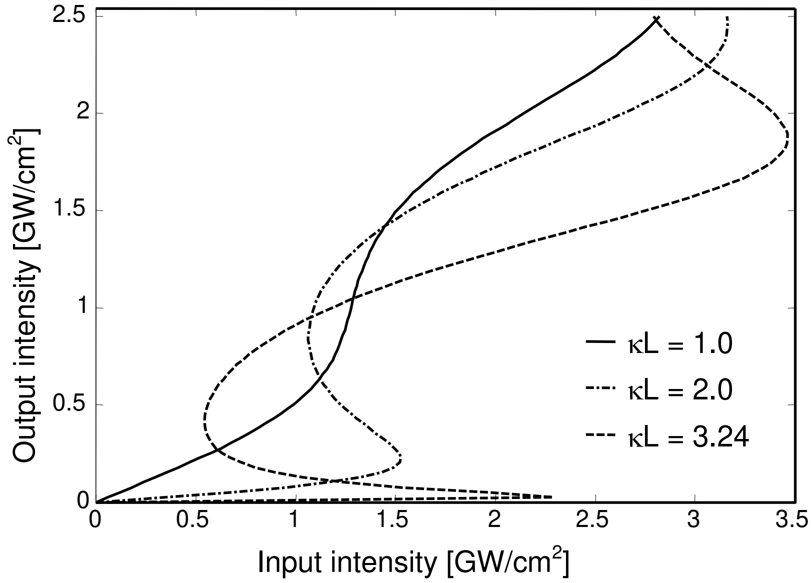


Figure 3. Optical bistability for different value of κL

(b). Photonic crystal with equal linear refractive index but opposite sign of nonlinear refractive index

In this structure, the refractive indices of each layers are $n_1 = 1.5 + 0.01\ I$ and $n_2 = 1.5 - 0.01\ I$. The thicknesses of the layers are given the values corresponding to a quarter wave structure for a wavelength of 1 μm and refractive index of $n_0 = 1.5$ ($d_1 = d_2 = 0.1667\ \mu$m). Transmittance of the structure for various numbers of layers with very low input intensity (0.5 GW/cm^2) is shown in Figure 4. For low numbers of layers, no photonic bandgap is observed. The PBG get deeper and sharper with the increase numbers of layers due to the large numbers interaction of waves which are reflected and transmitted at each interface.

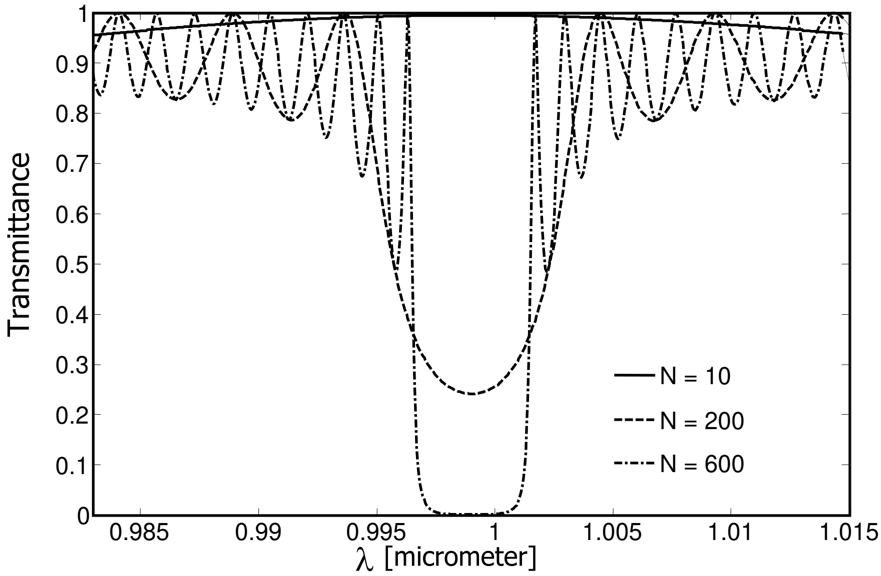


Figure 4. Evolution of transmittance spectra of the structure with n_0 = 1.5 and $|n_{nl}|$ = 0.01 cm^2/GW for different numbers of layers. The input light intensity is 0.5 GW/cm^2.

To study the potential of this structure for all-optical switching device, we plot in Figure 5(a) the transmittance spectra of this structure with 200 layers for three different values of input intensities, i.e. 0.5 , 1.0 and 1.5 GW/cm^2. The width and depth of the PBG are increased with the increase value of the input light intensity. The solid vertical line indicates the change of transmission at the wavelength of 0.995 μm with different input intensity. Its transmittance decreases allmost 100% (all-optical switching) when the input intensity is increased from 0.5 GW/cm^2 to 1.5 GW/cm^2, as shown in Figure 5(b). This behaviour is caused by the increase of different of refractive index $\Delta n = n_1 - n_2$. Therefore, the width of the bandgap also increases as $\Delta n/n = \Delta\lambda\lambda$.

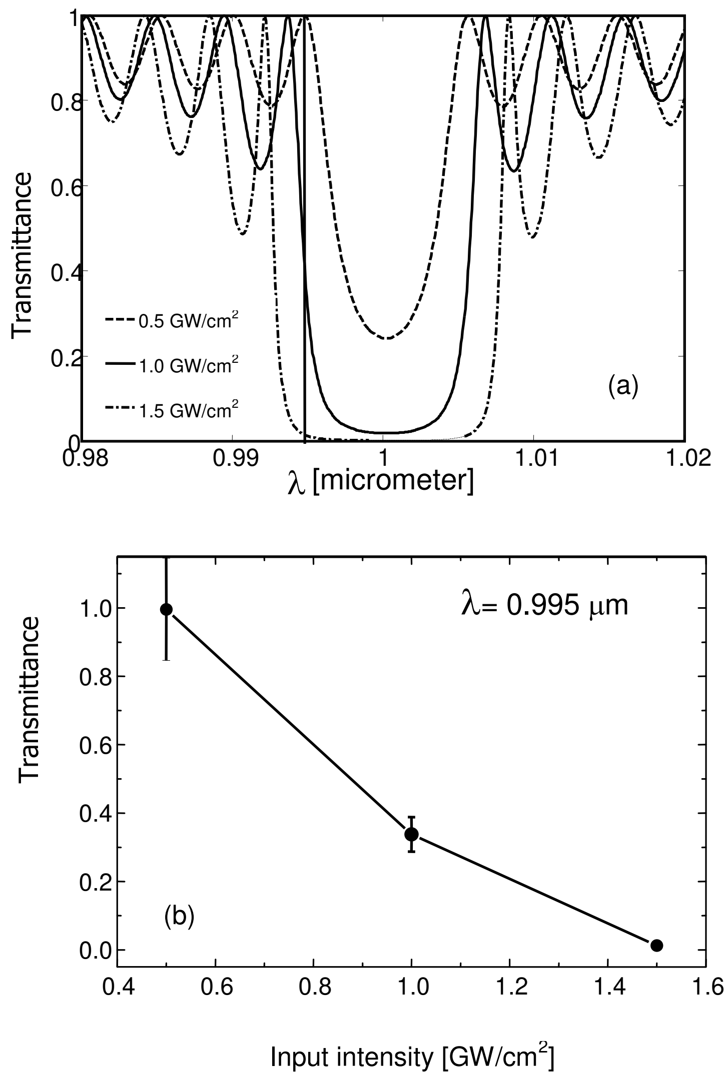


Figure 5. (a). Evolution of transmittance spectra of the structure with 200 layers for three different input intensity, (b). Transmission changes of the wavelength of 0.995 μm as the input intensity increases.

We also plot the relation between output and input light intensity in Figure 6(a) for different values of number of layers. For very low incident intensity the transmitted intensity is equal to the incident intensity. As the input intensity is increased, the output intensity begins to saturate at the limiting value. This value is the most desired for optical limiter, i.e. a device to maintain the low output intensity for the large input intensity. The limiting value is then called as limiter intensity which is decreased with the increase numbers of layers and the increase of nonlinear refractive index value as shown in Figure 6(b).

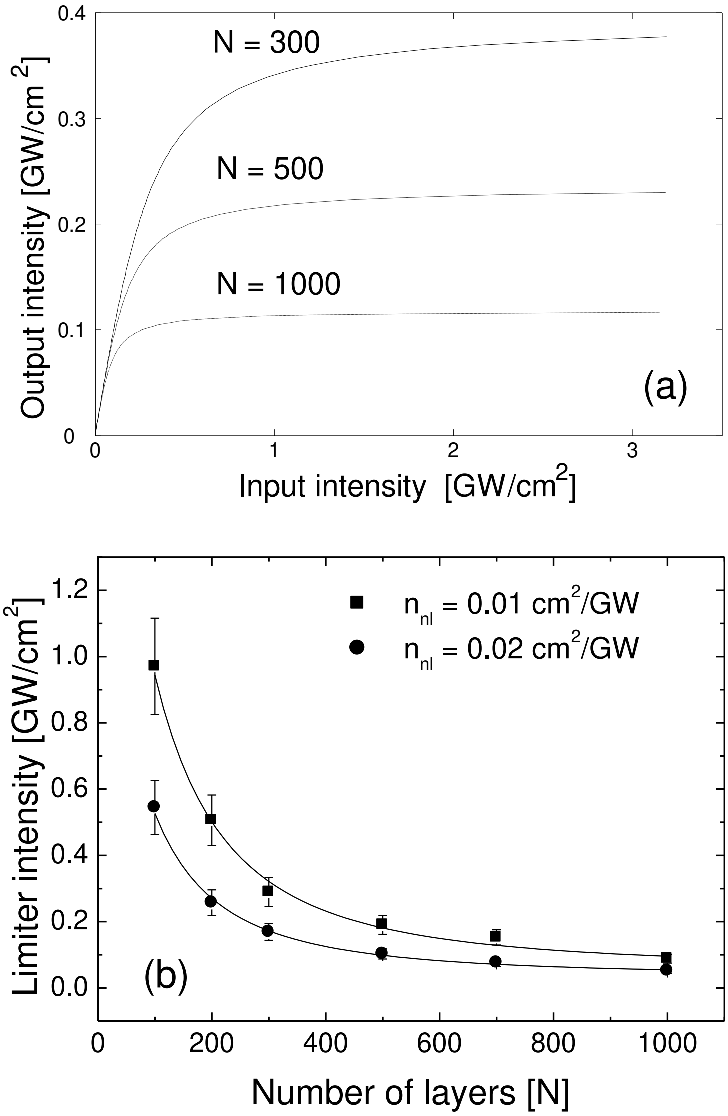


Figure 6. Output intensity as a function of input intensity for the structure (a) with numbers of layers 300, 500 and 100 layers, (b) with nonlinear refractive index of 0.01 cm^2/GW and 0.02 cm^2/GW.

CONCLUSION

Two structures of 1D nonlinear photonic crystals for all-optical switching and optical limiter devices, i.e. nonlinear Distributed Bragg Reflector (DBR) and nonlinear photonic crystal composed of nonlinear optical materials with identical linear refractive index but opposite sign of their nonlinear refractive index were studied. It was concluded that an appropriate combination of refractive indices of two materials is resulted from tuning up the position of PBG. The first structure can be used for all-optical switching at the widely used telecommunication wavelength (1.55 μm) and the second structure might be used both for all-optical switching and optical limiter devices. The limiter intensity is reduced with the increase of number of layers (N) and the magnitude of nonlinear refractive index of the layers (n_{nl}).

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