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OPTICAL BISTABILITY SWITCHING PROPERTY IN ONE-DIMENSIONAL NONLINEAR PHOTONIC CRYSTAL

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Optical bistability device based on nonlinear one-dimensional photonic crystals is designed and manufactured. The device has 20 periods and is made from ZnS and ZnSe layers alternately. When the incident power density reach threshold power density $1.0 \times 10^5\,\mathrm{W/cm^2}$, the Ar ion laser, whose wavelength is 514.5 nm, is shifted out of the optical band gap of the one-dimensional nonlinear photonic crystals, so an optical switch is made. It also can be made into an optical bistability device. The threshold power density of the optical bistability is $1.38 \times 10^5\,\mathrm{W/cm^2}$ and its switching time is about 100 ps in experiment. The experimental results are in good accordance with the theoretical ones.

Keywords: Photonic crystal; optical switch; optical bistability.

1. Introduction

Photonic crystals (PCs), also known as photonic microstructures or photonic bandgap structures were first proposed in 1987.[1,2] During the last two decades, PCs have matured from an intellectual curiosity concerning electromagnetic waves to a field with real applications in both the microwave and optical regime and have received considerable attention for fundamental physics study as well as for applications in the field of optoelectronics and optical communications. PCs have photonic band-gaps (PBGs) owing to the periodic dielectric modulation, analogous to the electronic band gaps in semiconductors due to the periodic potential modulation. If frequency of the electromagnetic wave is within the PBG of PCs, it cannot propagate in this structure. PCs are a new kind of material whose refractive index modulation period is comparable to the wavelength of light.[3] It is very difficult to fabricate three-dimensional PCs especially in the visible or near IR regime of the electromagnetic spectrum. One-dimensional or two-dimensional PCs do not have complete gaps compared with three-dimensional PCs, but they have lots of special uses and have been reported in many published papers due to their easy fabrication especially in the visible and IR regions of the electromagnetic waves.[4,5]

One-dimensional PCs consist of alternating layers with different refractive indices. When the PCs are combined with materials that have large nonlinear refractive index coefficients, they can produce many interesting properties, for example optical limiting, switching etc.[6] In this paper, an optical switch and optical bistability device based on nonlinear one-dimensional PCs is designed and manufactured. The characteristics of optical switching and optical bistability are results of the dynamic shifting of the band gap. That is to say that incident laser intensity changes causes the refractive index change of the nonlinear materials, and then the band gap edge is shifted too. The switching laser power density and switching time of the optical bistability obtained experimentally are $1.38 \times 10^5\,\mathrm{W/cm^2}$ and 100 ps respectively. The testing data agree well with the theoretical calculations.

2. Design and Manufacture

The optical bistability switch based on a one-dimensional nonlinear PC designed in this paper, is shown in Fig. 1. Two kinds of materials with different dielectric constants are alternately vaporized and deposited on the glass substrate to form a one-dimensional PC. The refractive index distribution of the PC is

$$n(z) = \begin{cases} n_2(p), & 0 < z < a \\ n_1(p), & a < z < \Lambda \end{cases} . \tag{1}$$

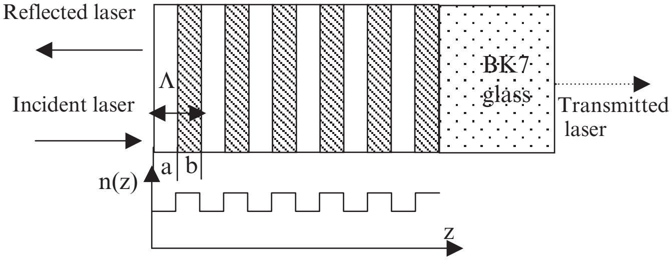

Fig. 1. Schematics of the optical bistability switch based on a one-dimensional nonlinear PC and refractive index distribution of the PC.

n_2, n_1 are the refractive indices of the two materials which make up the one-dimensional PC; a and b are the film thickness of the two materials; p is the incident laser power density; z is the laser propagation direction and is perpendicular to surface of the films of the PC; and Λ is the period of the PC. The refractive index distribution of the PC satisfies the following expression:

$$n(z) = n(z + \Lambda). \tag{2}$$

The light wave transmits in dielectric films, the electric field part of the general solution satisfies the equation $E(x, z) = E(x)\exp(i\beta z)$, where $E(x)$ denotes the amplitude of the electric field, β is the propagated constant, and x is the direction which is parallel to the surfaces of the films. As is well known, the Bloch waves propagate in one-dimensional PCs and satisfy the dispersive relation as follows:

$$K(\beta, \omega) = \left(\frac{1}{\Lambda}\right)\cos^{-1}\left(\frac{A + D}{2}\right) \tag{3}$$

where

$$A = \exp(-ik_{1x}a)\left[\cos k_{2x}b - \frac{i}{2}\left(\frac{k_{2x}}{k_{1x}} + \frac{k_{1x}}{k_{2x}}\right)\sin k_{2x}b\right], \tag{4}$$

$$D = \exp(-ik_{1x}a)\left[\cos k_{2x}b + \frac{i}{2}\left(\frac{k_{2x}}{k_{1x}} + \frac{k_{1x}}{k_{2x}}\right)\sin k_{2x}b\right], \tag{5}$$

$K(\beta, \omega)$ is the Bloch wave number, and k_{1x} and k_{2x} are the x components of the wave vectors k_1 and k_2 of the first- and second-constituent dielectric layer. When $|(A + D)/2| < 1$, then $K(\beta, \omega)$ is a real number, and the light can transmit through the one-dimensional PC. When $|(A + D)/2| > 1$, then $K(\beta, \omega) = m\pi/\Lambda + iK_i$ is an imaginary number, and the light cannot transmit through the one-dimensional PC and is totally reflected. These correspond to the band gap of the one-dimensional PC. When $|(A + D)/2| = 1$, these correspond to the edges of the band gap of the PC.

We used the nonlinear materials ZnS and ZnSe, which consist of elements in Groups II–VI of the periodic table of elements. Both have large band gaps, and are vaporized and deposited alternately on the glass substrate. The substrate was made of B7 K glass and the alternate films form a one-dimensional nonlinear PC which has 20 periods. When the light transmits in the PC, every interface between the two different films of different materials reflects the light waves, and causes wave interference. The interference of light becomes more intense or weakens depending on whether the difference in the optical path of the neighboring light wave is an integral multiple of the wavelength or not. If the incident is perpendicular to the surface (as shown in Fig. 1), we assume that $a = b = \Lambda/2$, then

$$\Lambda = q\lambda/(n_{10} + n_{20}) \tag{6}$$

where $n_{10} = n_{\mathrm{ZnS}} = 2.4$ and $n_{20} = n_{\mathrm{ZnSe}} = 2.7$ are the linear refractive indices of ZnS and ZnSe respectively, and $\lambda = 514.5\,\mathrm{nm}$ is the wavelength of the Ar ion laser.

If we let the order of diffraction $q = 3$, considering the condition of fabricating technique, then the period Λ of the one-dimensional PC is 300 nm and $a = b = \Lambda/2 = 150\,\text{nm}$. The refractive indices of ZnS and ZnSe change with the change in incident laser power density, then

$$\begin{aligned} n_1(p(t)) &= n_{10} + n_{21}p(t) \\ n_2(p(t)) &= n_{20} + n_{22}p(t) \end{aligned} \tag{7}$$

where n_{21} and n_{22} denote the nonlinear refractive index coefficients of ZnS and ZnSe respectively, and t denotes the time. ZnS and ZnSe are self-defocus dielectric, so $n_{21}, n_{22} < 0$.

3. Theoretical Calculations

According to our design, the wavelength of 514.5 nm of the Ar ion laser lies within the band gap of the one-dimensional PC when the incident laser power density is so low that it cannot lead to large nonlinearity. The refractive indices of the two materials decrease when the incident power density increases. The band gap of the one-dimensional PC will shift as the incident power density increases. When the incident power density becomes large enough, the frequency of the Ar ion laser will be shifted out of the band gap of the PC, and then the transmission will become large. Using the dynamical characteristics, we can obtain an optical switch. We calculate the band gaps that correspond to the two cases of different incident power densities, as shown in Fig. 2. The solid line denotes the incident power density that is near to $0\,\text{W/cm}^2$ and the dashed line denotes the incident power

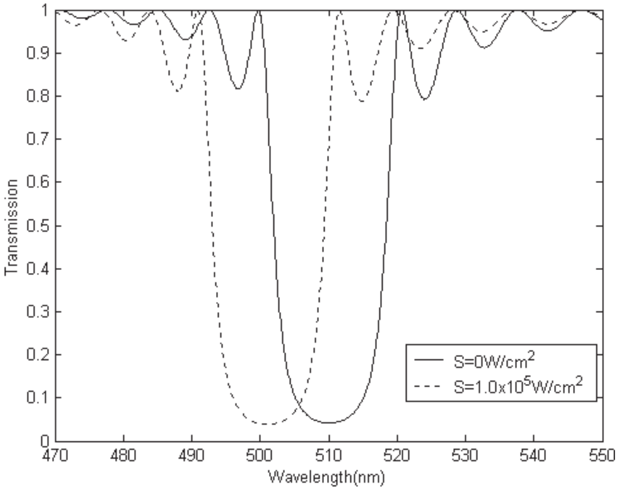

Fig. 2. The band gaps of the nonlinear photonic crystals under the two different incident power densities. The solid line denotes the incident power density that is near to $0\,\text{W/cm}^2$ and the dashed line denotes the incident power density that is $1.0 \times 10^5\,\text{W/cm}^2$.

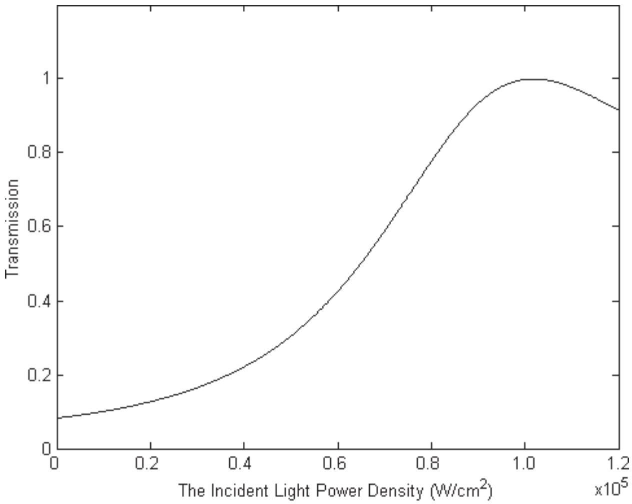

Fig. 3. Transmission curve of the nonlinear photonic crystals versus the incident laser power density.

density that is $1.0 \times 10^5\,\mathrm{W/cm^2}$. From Fig. 2, we can conclude that the band gap is shifted towards the short wavelength when the incident power density increases. The 514.5 nm wavelength of the Ar ion laser is completely shifted out of the band gap when the incident light power density reaches $1.0\times 10^5\,\mathrm{W/cm^2}$. Hence we obtain an optical switch.

We also calculated the transmission of the one-dimensional nonlinear PC versus the incident light power density, as shown in Fig. 3. When the incident light power density reaches $1.0 \times 10^5\,\mathrm{W/cm^2}$, the transmission of the nonlinear PC becomes about 1.0. That is to say that the wavelength of the Ar ion laser, 514.5 nm, is just moved out of the band gap of the PC.

Many studies have produced equations of transmission of the one-dimensional PC.[6–8] We used these equations with expression (7) in this paper to calculate the bistability of the PC, as shown in Fig. 4. In the theoretical calculation, the switching time and threshold power density of the bistability of the one-dimensional nonlinear PC is about 80 ps and $1.0 \times 10^5\,\mathrm{W/cm^2}$ respectively.

4. Experimental Measurement and Analysis

We used the experimental setup shown in Fig. 5 to test the curve of the bistability of the one-dimensional nonlinear PC. A mode-locking pulse Ar ion laser of wavelength 514.5 nm, repeating frequency 82 MHz, and pulse width 300 ps was used. The laser beam was split into two beams by the optical-splitting device 3. One of the beams was received by the light-detector 6 and translated into an electric signal which was then sent into the oscillograph 7; the other beam was vertically impinged on

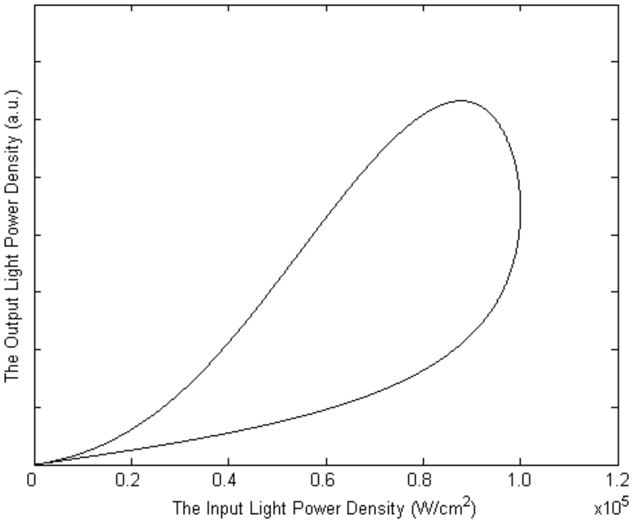

Fig. 4. The theoretical curve of bistability of the one-dimensional nonlinear PC.

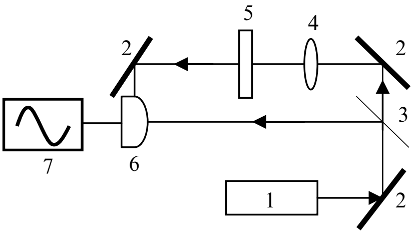

Fig. 5. The experiment testing system of the optical bistability. 1: Ar^+ Laser; 2: reflect mirror; 3: beam-split; 4: lens, 5: the PC; 6: light-detector; 7: 7904 oscillograph.

the surface of the PC and transmitted, and then reflected into light-detector 6 and translated into an electric signal which was sent into the oscillograph. At room temperature, we obtained the instantaneous waveforms of the input pulse and of the output pulse, as shown in Fig. 6. The output pulse was compressed in contrast with the input pulse. The corresponding curve of the bistability is shown in Fig. 7. The switching time is about 100 ps and the switching power density is $1.38 \times 10^5\ \mathrm{W/cm^2}$. The experimental results agree well with the theoretical ones.

We conclude that the optical bistability properties of the PC are results of the blue-shifting of the band gap, due to the decrease in the refractive indices of the materials with incident power density increase. This conclusion is supported in Fig. 2. The materials have distinct nonlinearity because of the band-filled effect.[9] Hence the one-dimensional PC has distinct optical intensity modulation and optical bistability characteristics.

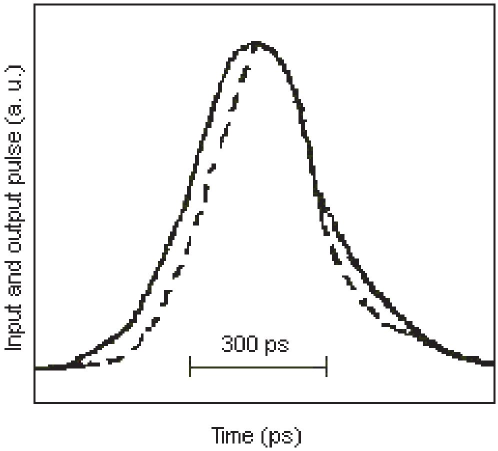

Fig. 6. The instantaneous waveform of the input pulse (solid line), and the instantaneous waveform of output pulse (dashed line).

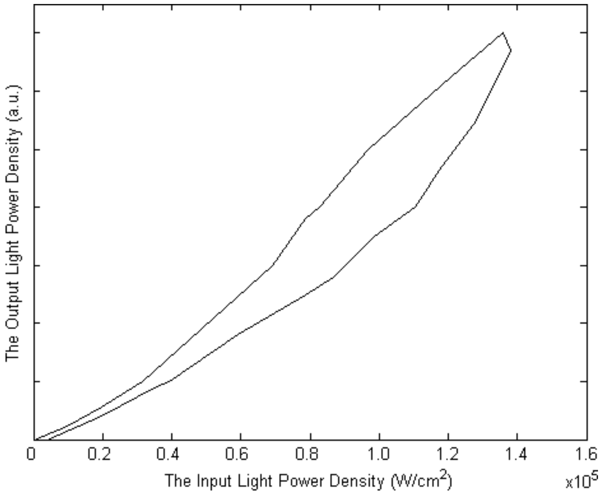

Fig. 7. The experimental curve of the bistability of the PC.

5. Conclusion

In this paper, we designed and fabricated an optical bistability switch based on one-dimensional PCs. This device has 20 periods and is made from alternating ZnS and ZnSe films. Experimently, the switching time of the optical bistability obtained is about 100 ps, while the threshold power density is $1.38 \times 10^5\,\mathrm{W/cm^2}$. The experimental results agree well with the theoretical ones. We conclude that the optical bistability properties of the PC are a result of the blue-shifting of the band gap, which is due to the decrease of the refractive indices of the materials with incident power density increase. The materials have distinct nonlinearity because of the band-filled effect.

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