Journal of Nonlinear Optical Physics & Materials
Vol. 14, No. 3 (2005) 461–468

DYNAMICAL ADDRESSING OPTICAL INTERCONNECTION BASED ON ONE-DIMENSIONAL NONLINEAR PHOTONIC CRYSTAL

MING CHEN and CHUNFEI LI
Department of Applied Physics, Harbin Institute of Technology,
Harbin 150001, China

MAI XU, WEIBIAO WANG, SHAOJIE MA, YUXUE XIA and DALI LIU
Laboratory of Excited-state Processes, Changchun Institute of Optics,
Fine Mechanics and Physics, Chinese Academy of Sciences,
Changchun 130033, China

Received 11 February 2005

A dynamical addressing device for optical interconnection based on one-dimensional nonlinear photonic crystal made on the planar waveguide was designed and fabricated. The dynamical interconnection is performed by controlling the power density of the control light. In our device, when increasing the power density of the control light from 0 to 2.60×10^5 W/cm^2, the angle of the signal beam can be changed by about 2°. This kind of devices is promising for use in all-optical interconnection, optical information processing and optical communication.

Keywords: Optical interconnection; photonic crystal; nonlinear.

1. Introduction

It has been about two decades since Goodman from Stanford University first proposed optical interconnection for very large scale integrated circuits (VLSI) technology.[1] Since then, a lot of approaches for optical interconnection have been proposed.[2,3] These can be classified into two types: passive and active. Passive interconnections offer fixed paths for interconnected lights. However, active interconnection links are dynamic and can be reconfigured by controlling lights. In this paper, a novel dynamical addressing device for optical interconnection based on one-dimensional nonlinear photonic crystal is designed and fabricated.

The first paper on photonic crystals was published in 1987.[4] Photonic crystal is a structured material whose dielectric constant exhibits translation symmetry. Such symmetry produces the energy band and the forbidden energy gap. Photons within energy gaps cannot propagate through the material. Based on this principle, the novel light-guiding devices, such as waveguide, switch, and optical fiber can be designed.[5,6] Photonic crystals can be classified as one-dimensional, two-dimensional or three-dimensional,[7] and linear or nonlinear. In this paper, we designed and fabricated a novel dynamical addressing device based on one-dimensional nonlinear photonic crystal. It can be used for all-light information process and optical communication.

2. Theory of One-Dimensional Photonic Crystal

The one-dimensional photonic crystal consists of alternated layer-type materials with different dielectric constants, as shown in Fig. 1. Assuming that the layered structure is periodic in the x direction and homogeneous in the y-z plane, the refractive index $n(x)$ of the photonic crystal is a stepwise function

$$\begin{aligned} n(x) &= n_1, \quad 0 < x < a \\ &= n_2, \quad a < x < a+b, \text{ with } n(x+m\Lambda) = n(x) \end{aligned} \tag{1}$$

where $\Lambda = a+b$ is the period of the photonic crystal, m is an arbitrary integer and a, b are respectively the thickness of the two different dielectric films. We assume that the incident light is a harmonic wave, which propagates along the x direction. The electric and magnetic fields at the two layers are connected to each other through the boundary conditions at the interfaces. The electric vector E and the magnetic vector H between the $(m-1)$th and mth periods are described by the characteristic matrix M of one primary period.[8,9] For one-dimensional photonic crystal with N period of layers, the characteristic transmittance matrix M^N can be obtained

$$\begin{bmatrix} E_1 \\ H_1 \end{bmatrix} = \overbrace{M \cdot M \cdots M}^{N} \begin{bmatrix} E_{N+1} \\ H_{N+1} \end{bmatrix} = M^N \begin{bmatrix} E_{N+1} \\ H_{N+1} \end{bmatrix}, \quad \text{with } M = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix}, \tag{2}$$

where E_1 and H_1 are the total electric and magnetic fields at the interface between the external medium with the refractive index n_3 and the left end of the photonic

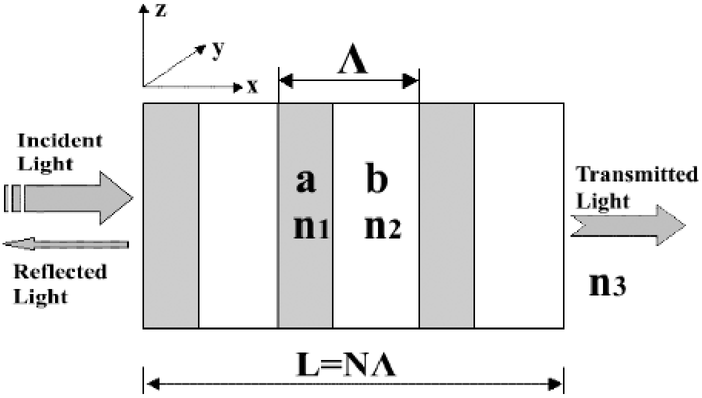

Fig. 1. Schematic diagram of one-dimensional photonic crystal with the unit cell consisting of two films with refractive indexes n_1 and n_2, and thickness a and b, respectively.

crystal, as shown in Fig. 1; E_{N+1} and H_{N+1} are fields at the interface between the photonic crystal and the external medium at the another end, and

$$\begin{aligned}
m_{11} &= \frac{\cos\beta_2\cos\beta_1 - n_1}{n_2\sin\beta_2\sin\beta_1},\\
m_{12} &= -i\left(\frac{1}{Z_1\cos\beta_2\cos\beta_1} + \frac{1}{Z_2\sin\beta_2\sin\beta_1}\right),\\
m_{21} &= -i(Z_2\sin\beta_2\cos\beta_1 + Z_2\cos\beta_2\sin\beta_1),\\
m_{22} &= \frac{\cos\beta_2\cos\beta_1 - n_2}{n_1\sin\beta_2\sin\beta_1},
\end{aligned}$$

where $\beta_1 = 2\pi n_1 a/\lambda$, $\beta_2 = 2\pi n_2 b/\lambda$, $Z_1 = \sqrt{\varepsilon_0/\mu_0}n_1$, $Z_2 = \sqrt{\varepsilon_0/\mu_0}n_2$, and λ is the wavelength in free space.

When the one-dimensional photonic crystal is made up of two kinds of nonlinear materials, whose refractive indices are respectively expressed as

$$n_i = n_{i0} + n_{i2}S, \quad i = 1, 2 \tag{3}$$

where n_{i0} is the linear refractive indices of two materials, n_{i2} is the nonlinear refractive index coefficient of the materials, and S is the light power density. Obviously, refractive indices of these materials will change with a change in incident power density. Because the band gap is a function of the refractive indices of materials,[7] the band gap of the photonic crystal will also change with a change in incident power density. As a result, the characteristics of reflection and transmission in nonlinear photonic crystal will also change with a change in incident power density.

3. Design and Manufacture of the Device

We designed and fabricated a dynamical addressing optical interconnection device based on one-dimensional nonlinear photonic crystal, as shown in Fig. 2.

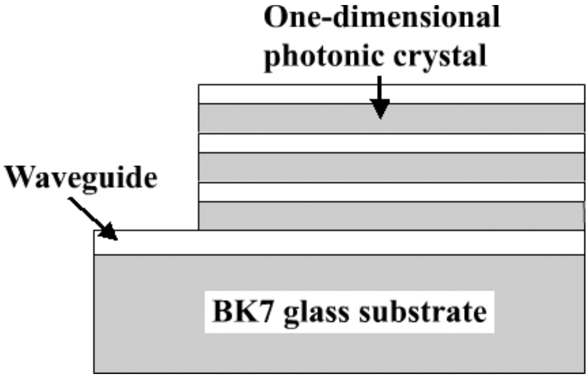

Fig. 2. Schematic diagram of one-dimensional nonlinear photonic crystal for dynamical addressing optical interconnections.

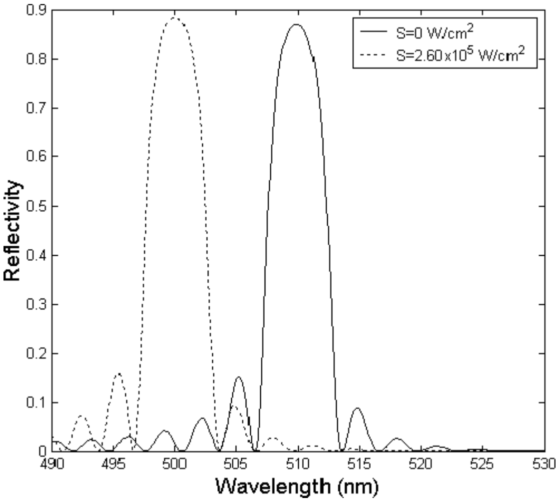

Fig. 3. Band gaps of photonic crystal with two different power densities of the control light. The solid line and the dashed line correspond to 0 and 2.60×10^5 W/cm^2, respectively.

First, we fabricated a planar waveguide on the BK7 glass substrate using Ag-Na ion exchange technique. The refractive index at the surface of the planar waveguide is 1.61. Then we alternately deposited the nonlinear materials ZnS and ZnSe on the waveguide to form a one-dimensional photonic crystal with 20 periods. The linear refractive indices of ZnS and ZnSe are 2.4 and 2.7 respectively, and since both are all self-defocus nonlinear materials, their refractive indices can decrease with an increase in light power density. In the photonic crystal designed by us, the nonlinear refractive index coefficients of the two materials are approximately the same, $-2.0 \times 10^{-11}\,\mathrm{m^2/W}$, the period Λ of the photonic crystal is 300 nm, and the thickness of the two films are 150 nm.

A control light beam is coupled into the planar waveguide to change the band gap of the photonic crystal. In Fig. 3, we show the two band gaps with two different power densities of the control light. The center of the two band gaps has maximum reflectivity. The solid line corresponds to the power density near $0\,\mathrm{W/cm^2}$; the dashed line corresponds to that of $2.60 \times 10^5\,\mathrm{W/cm^2}$. When increasing the power density of the control light, the band gap shifted to the short wavelength. In the next section we will show this dynamic characteristic in detail.

4. Experimental Testing and Analysis

The experiment setup used to test the characteristics of the dynamical addressing optical interconnection based on one-dimensional nonlinear photonic crystal is shown in Fig. 4. A mode-locked Ar-ion laser at a wavelength of 514.5 nm and pulse width of 300 ps is used as the light source. The repetition frequency of the laser is 82 MHz. The laser beam is divided into two beams: signal beam and control

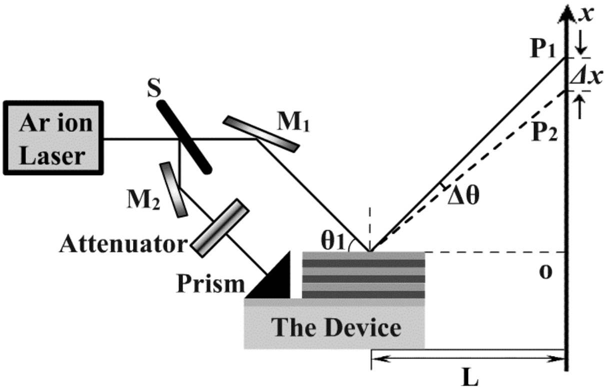

Fig. 4. Experiment setup for testing the characteristics of the dynamical optical interconnection device in which S is a beam-splitter, and M_1 and M_2 are the reflectors.

beam, by a beam splitter S. The signal beam is reflected by the reflector M_1, and then reflected again by the one-dimension photonic crystal, until finally it reaches the addressing plane. The distance between the plane and the incident point of the signal light on the photonic crystal surface is L. The control light is reflected by the reflector M_2, and then through an attenuator to be coupled into the planar waveguide by the coupling prism, and onto the nonlinear photonic crystal to control the reflected angle of the signal beam.

The control light in the planar waveguide can easily enter into the one-dimensional photonic crystal because the refractive index of the surface of the planar waveguide is smaller than that of the materials of the photonic crystal. When the power density of the control light is low enough, the nonlinearity of the photonic crystal can be ignored. We adjusted the angle θ_1 and let it satisfy the following Bragg condition:

$$2n\Lambda \sin\theta_1 = q\lambda \tag{4}$$

where $n = (an_{10} + bn_{20})/\Lambda$ is the effective index of the photonic crystal; a and b are the thicknesses of the ZnS and ZnSe films, respectively; $n_{10} = 2.4$ and $n_{20} = 2.7$ are the linear refractive indices of ZnS and ZnSe, respectively; Λ is the period of the photonic crystal; θ_1 is the angle shown in Fig. 4; λ is the wavelength of the signal light, and q is the Bragg diffraction order. Assuming $q = 2$, we obtain $\theta_1 = 42.2°$. In this case, the signal light reached the point P_1 on the plane.

When increasing the power density of the control light up to $2.60 \times 10^5\,\mathrm{W/cm^2}$, we find that the point P_1 shifts down to P_2 on the plane. Therefore, the reflected signal light is shifted in the angle of $\Delta\theta$. Measuring the distance $P_1P_2 = \Delta x$, $OP_1 = x$, we obtain $x = 45\,\mathrm{cm}$, $\Delta x = 3\,\mathrm{cm}$, $L = 50\,\mathrm{cm}$ and $\Delta\theta = \arctan((x - \Delta x)/L) - \arctan(x/L) = -1.957°$.

We use Fig. 5 to explain the characteristics of the dynamical addressing process. In this figure, β_1 is the wave vector of incident signal light; β_{d0} and β_d are wave

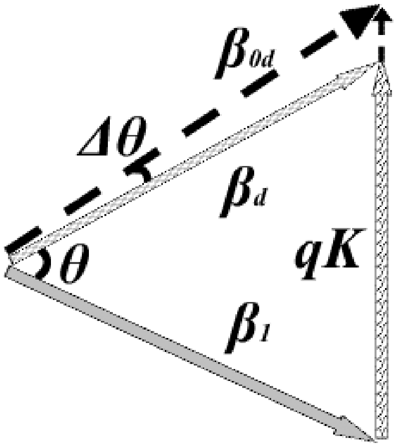

Fig. 5. Optical wave vectors for the dynamical addressing optical interconnection process.

vectors of diffractive signal lights corresponding to two different control light power densities, respectively; qK is the grating vector; and θ is the Bragg diffraction angle. When the power density of the control light is too low to consider as the nonlinearity of the materials, the vectors β_1, β_{d0} and qK can satisfy the momentum conservation law and form a closed triangle. From Eq. (4) we obtain

$$\theta = -2\theta_1 = -2\arcsin(q\lambda/2n\Lambda).$$

When the power density of the control light is increased, the angle θ will become $\theta + \Delta\theta$. Because the effective index of the one-dimensional photonic crystal $n = (an_{10} + bn_{20})/\Lambda$ becomes $n = (an_1 + bn_2)/\Lambda$, where n_1 and n_2 are given by Eq. (3), we obtain

$$\begin{aligned}\Delta\theta &= -2\frac{d}{dn}(\arcsin(q\lambda/2n))\\ &= q\lambda\Delta n[1 - (q\lambda/2n\Lambda)^2]^{-1/2}/(n^2\Lambda).\end{aligned} \tag{5}$$

In Fig. 5, vectors β_{d0} and qK all decreased when increasing the power density of the control light. The vector β_{d0} is shifted to the angle $\Delta\theta$ to satisfy the momentum conservation, as shown in Fig. 5. Assuming $q = 2$, we obtain the relation of the scanning angle of the signal light versus the increase in the power density of the control light, as shown in Fig. 6. In the calculation, we assume the power density is too small to affect the nonlinearity of the photonic crystal. The scanning angle of the signal light $\Delta\theta$ is about -2.04° when the power density of the control light is $2.6 \times 10^5\,\mathrm{W/cm^2}$. This value is very near to that from experiment. Therefore, we can conclude that the theoretical result is in good accordance with the experimental one. Since the planar waveguide can be made very narrow, we can use lower power to control the signal light.

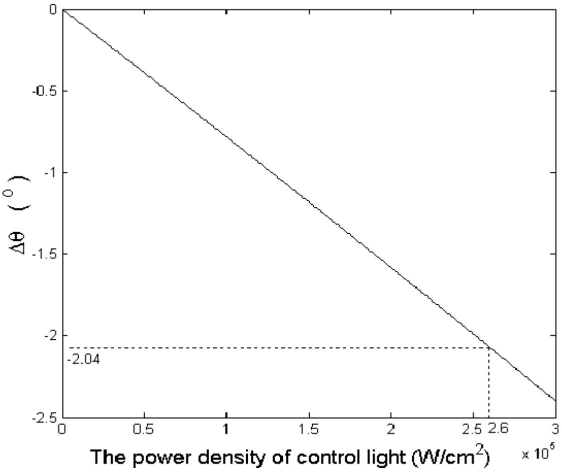

Fig. 6. Scanning angle of signal light versus the power density of the control light.

The switch time of the optical interconnection device is mainly decided by the nonlinear responding time of the materials. The ZnS and ZnSe all have very fast responding times (ns).[10] So the switch time of the device is close to ns.

5. Conclusion

We have shown a novel dynamical addressing optical interconnection device based on one-dimensional nonlinear photonic crystal. Two nonlinear materials of ZnS and ZnSe are deposited alternately on a glass planar waveguide to form a nonlinear one-dimensional photonic crystal with 20 periods. The reflected angle of the signal light is controlled by the intensity of the control light. The device can scan about 2° when increasing the power density of the control light by about $2.60 \times 10^5\,\mathrm{W/cm^2}$. This kind of all-optical controllable interconnection device has potential application in high-speed optical information processing and optical communication.

Acknowledgment

The authors would like to thank the National Nature Science Foundation of China under contracts No. 60177021 and 60277030.

References

1. J. W. Goodman, F. J. Leonberger, S. Y. Kung, *et al.*, Optical interconnections for VLSI system, *Proc. IEEE* **72** (1984) 850–865.
2. F. Sauer, Fabrication of diffractive-refractive optical interconnects for infrared operation on total internal reflections, *Appl. Opt.* **28** (1989) 386.
3. V. Moreau, Y. Renotte and Y. Lion, Planar integration of a polarization-insensitive optical switch with holographic elements, *Mater. Sci. Semicond. Process.* **3** (2000) 551.

4. E. Yablonovitch, Inhibited spontaneous emission in solid-state physics and electronics, *Phys. Rev. Lett.* **58** (1987) 2059.
5. D. Felbacq, B. Guizal and F. Zolla, Wave propagation in one-dimensional photonic crystals, *Opt. Commun.* **152** (1998) 119.
6. E. Moreno, D. Erni and C. Hafner, Modeling of discontinuities in photonic crystal waveguides with the multiple multipole method, *Phys. Rev. E* **66** (2002) 036618-1.
7. K. Sakoda, *Optical Properties of Photonic Crystals* (Springer-Verlag, Berlin, 2001).
8. D. Y. Jeong, Y. H. Ye and Q. M. Zhang, Effective optical properties associated with wave propagation in photonic crystal of finite length along the propagation direction, *J. Appl. Phys.* **92** (2002) 4194.
9. M. Born and E. Wolf, *Principles of Optics*, 7th edn. (Cambridge University Press, 1999), pp. 70–74.
10. Z. H. Zheng, Z. P. Guan, A. H. Yang, X. W. Fan and L. C. Chen, Excitonic optical bistability in ZnSe/ZnS planar waveguides, *Thin Solid Film* **249** (1994) 83.