Indian J.Sci.Res. 5 (1): 432-438, 2014 ISSN: 0976-2876 (Print)
ISSN: 2250-0138(Online)

# INVESTIGATION OF THE OPTICAL BISTABILITY IN A ONE-DIMENSIONAL LAYERED STRUCTURE CONTAINING THREE SYMMETRIC NONLINEAR DEFECT LAYERS

**H. PASHAEI ADL[a1], S. BEYGZADEH[b], N. YAZDANIPOUR[c] AND H. HAJIAN[d]**

[a]Department of Atomic and Molecular Physics, Physics Faculty, University of Tabriz, Tabriz, Iran
[b]Department of Physics, Miyandoab Branch, Islamic Azad University, Miyandoab, Iran
[c]Department of Physics, Mahabad Branch, Islamic Azad University, Mahabad, Iran
[d]Department of Solid State Physics, Physics Faculty, University of Tabriz, Tabriz, Iran

## ABSTRACT

**In this paper, using the transfer matrix method, we investigate the dependence of threshold intensity of the optical bistability to distance between the defect layers for a symmetric (and also asymmetric) one-dimensional nonlinear layered structure, theoretically. The one-dimensional nonlinear layered structure under consideration in this paper contains three coupled nonlinear defect layers. Therefore, two coupled defect modes can be created in the photonic gap of this structure. The symmetric structure for minimum value of the distance between the defect layers is referred as the special geometry. It is shown that, for the shorter wavelength defect mode created in the special geometry of the symmetric structure, the minimum threshold intensity of the optical bistability can be achieved.**

**KEYWORDS:** Optical bistability; Nonlinear layered structure; Coupled defect layers; Threshold intensity; Transfer matrix method

In the last few decades, the nonlinear responses of layered structures and also photonic crystals (PCs) have inspired considerable interest in both physics and engineering communications, because of their fantastic applications in the light control devices [1]. One finds a variety of these nonlinear responses (such as nonlinearity induced self-trapping [2-9], four-wave mixing [10-12], etc.) when these structures are illuminated by a high-power laser. The simplest example of such nonlinear responses is optical bistability (OB), in which one has situations with two (meta-) stable values for the light intensity transmitted through a nonlinear material for one value of the input intensity [12,13]. The OB is occurred because the dielectric constant of the material depends on the intensity of the electromagnetic wave [14-16]. The bistable behavior in the transmission was found to have a diode action, which may be quite useful in microwave nonlinear devices [17-19]. Also, the concept of optical bistability plays the main role in the design of all-optical transistors, switches, logical gates and optical memory devices [20, 21]. When a single nonlinear defect layer is introduced into a linear 1D PC, the OB phenomenon can be produced by the dynamic shifting of defect modes [22,23] as well. Also, the direct observation of defect modes shifting in experiment observed [24]. Further studies indicated that the basic way to obtain low switching threshold is to reach a nonlinear defect with proper physical parameters or increase the number of layers [25]. Moreover, P. Hou et al. introduced a 1D PC composed of two coupled nonlinear defect layers separated by a linear middle layer, recently [26]. In that paper, they investigated the effect of parameters variation of the linear layer on the modulation of OB threshold intensity. As far as reducing the OB threshold intensity is concerned, it is worth to introduce a structure that has lower switching threshold in comparison with the mentioned structures. To the best of our knowledge, the OB of a 1D layered structure composed of alternative linear and nonlinear layers containing three coupled nonlinear defect (TCND) layers has not been investigated. Therefore, in this paper, we investigate how the minimum value of the OB threshold intensity in the 1D TCND layered structure can be achieved. We believe that a new physics arises from the presented geometry of the structure under consideration in this paper. Also, the concluded results are appropriate for photon control devices based on 1D layered structures.

Our paper is organized as follows. In Section 2, the theoretical analysis of the nonlinear

[1]**Corresponding author**

periodic structure is presented. Numerical results are presented in Section 3 on the transmission property, the optical bistability and the electric field intensity distribution of two defect modes of the structure. In the end, the conclusion and discussion will be given in Section 4.

## BASIC EQUATIONS

As shown in Fig. 1, the layers arrangement of the symmetric 1D layered structure composed of three nonlinear defect layers under consideration in this paper is in the form of $(BA)^{13-m}A(BA)^{m}A(AB)^{m}A(AB)^{13-m}$. $A$, $B$ and $m$ represent the layers and the position of defect layers in the structure, respectively. Also, the layer thickness corresponding to the $B$ and $A$ layers are $2\lambda_0/n_b$ and $2\lambda_0/n_a^{linear}$, respectively. The central wavelength $\lambda_0$ is chosen as 4500 $A^o$, $n_b=2$ and $n_a=n_a^{linear}+\alpha I$ ($n_a^{linear}=2.5$, $\alpha$ is the Kerr nonlinear coefficient and $I$ is the intensity of the incident light).

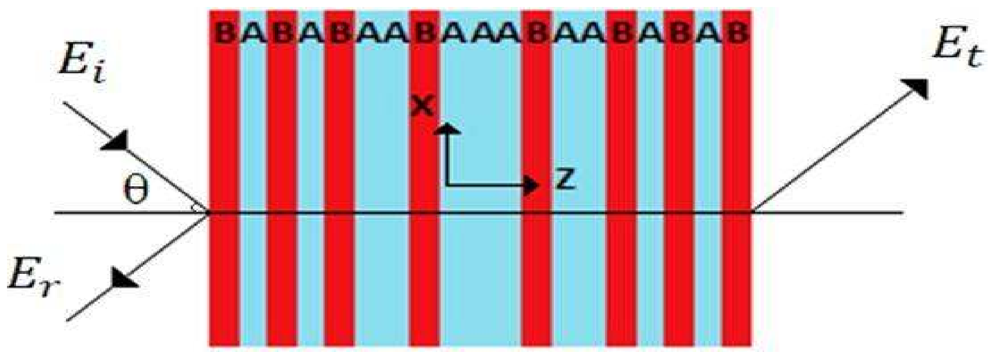


**Figure 1: (Color online) Schematic representation of the layers arrangement of the symmetric one-dimensional layered structure in the form of $(BA)^{13-m}A(BA)^{m}A(AB)^{m}A(AB)^{13-m}$. $A$, $B$ and $m$ represent the layers and the position of TCND layers in the structure, respectively**

Note that, in this paper, we only consider the case of transverse electric field. The electric fields in layers $A$ and $B$ are written as:

$$E_A(x,z)=E(z)e^{i(k_x x+k_{zA}z)-i\omega t} \quad (1a)$$

$$E_B(x,z)=E(z)e^{i(k_x x+k_{zB}z)-i\omega t} \quad (1b)$$

Here, $k_{zA}=k_0\sqrt{\varepsilon_A\mu_A(1-\sin^2\theta/\varepsilon_A\mu_A)}$, $k_{zB}=k_0\sqrt{\varepsilon_B\mu_B(1-\sin^2\theta/\varepsilon_B\mu_B)}$, $k_x=k_0\sin\theta$ with $k_0=\omega/c$, and $\theta$ is the angle of the incident light.

Inside the layers, the electric field is governed by the Helmholtz equation [27]:

$$\frac{d^2E}{dz^2}+(\varepsilon_i\mu_i\frac{\omega^2}{c^2}-k_x^2)E=0. \quad (2)$$

Here, the subscript 'i' denotes the number of the layers. At the interface between two layers, we can apply the boundary conditions:

$$E_i=E_j \quad (3a)$$

$$\frac{1}{\mu_i}\frac{dE}{dz_i}=\frac{1}{\mu_j}\frac{dE}{dz_j}. \quad (3a)$$

To get the numerical results, we divide a single layer into a large number of sub layers and hence, the permittivity of each sublayer is approximately regarded as a constant parameter for the nonlinear sublayer [17,28]. Therefore, we can employ the transfer matrix to combine the electric field at $z$ and $z+\Delta z$ [27,29,30]:

$$M_l=\begin{pmatrix}\cos(k_{zl}\Delta z) & -\frac{\mu_l\omega}{k_{zl}c}\sin(k_{zl}\Delta z)\\ \frac{k_{zl}c}{\mu_l\omega}\sin(k_{zl}\Delta z) & \cos(k_{zl}\Delta z)\end{pmatrix}, \quad (4)$$

where $l = A, B$. In the nonlinear sublayer, $\varepsilon_l$ and $k_{zl}$ are determined by the electric field magnitude at the incident surface. Then, we have the global transfer matrix:

$$M_{global} = \prod_{l=1}^{N} M_l \tag{5}$$

The tangential components of the electric and magnetic fields at incident side (z=0) and the transmitted site (z=L) are related by the following matrix equation:

$$\begin{pmatrix} E_1 \\ H_1 \end{pmatrix}_{z=0} = M_{global} \begin{pmatrix} E_N \\ H_N \end{pmatrix}_{z=L} . \tag{6}$$

## RESULTS AND DISCUSSION

In this section, at first, the linear transmissions ($\alpha = 0$) through the symmetric one-dimensional layered structure corresponding to different positions of the TCND layers is investigated in Fig. 2.

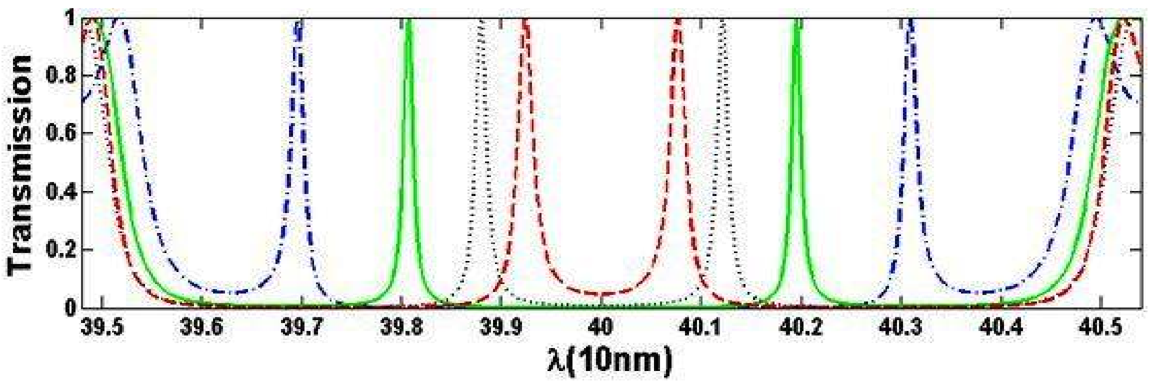


**Figure 2: (Color online) Linear transmissions through the symmetric one-dimensional layered structure corresponding to different positions of the TCND layers as m=0 (the dotted-dashed curve), m=1 (the solid curve), m=2 (the dotted curve) and m=3 (the dashed curve)**

From this figure, it can be clearly observed that the transmission spectrum of the symmetric one-dimensional layered structure contains two separate defect modes created in the photonic band gap of the structure. It is also straightforward that, the position of defect modes in the gap varies with changing the position (the 'm' parameter) of TCND layers in the structure. By increasing 'm' from 0 to 3, the coupling between the two defect modes created in the gap is also increased. Therefore in order to indicate the connection between coupling of the defect modes in the symmetric 1D TCND layered structure and the OB threshold intensity, Fig. 3 is illustrated.

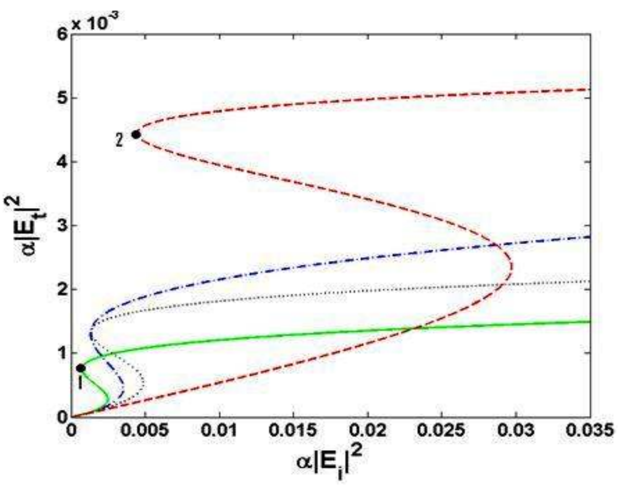


**Figure 3: (Color online) Transmitted intensity through the symmetric one dimensional TCND layers structure versus incident intensity for different values of m: m=0 (dotted-dashed curve), m=1 (solid curve), m=2 (dotted curve), m=3 (dashed curve)**

With respect to Fig. 3, it can be concluded that by decreasing the distance (decreasing the 'm') between the central defect layer and its adjacent defect layers in the symmetric 1D TCND layers structure the OB threshold intensity is also decreased. It means that the OB threshold intensity is strongly affected by the decrease or increase of the coupling between defect modes created in the photonic gap of the structure. To clarify the connection between coupling of the defect modes and the OB threshold intensity Fig. 4 is illustrated.

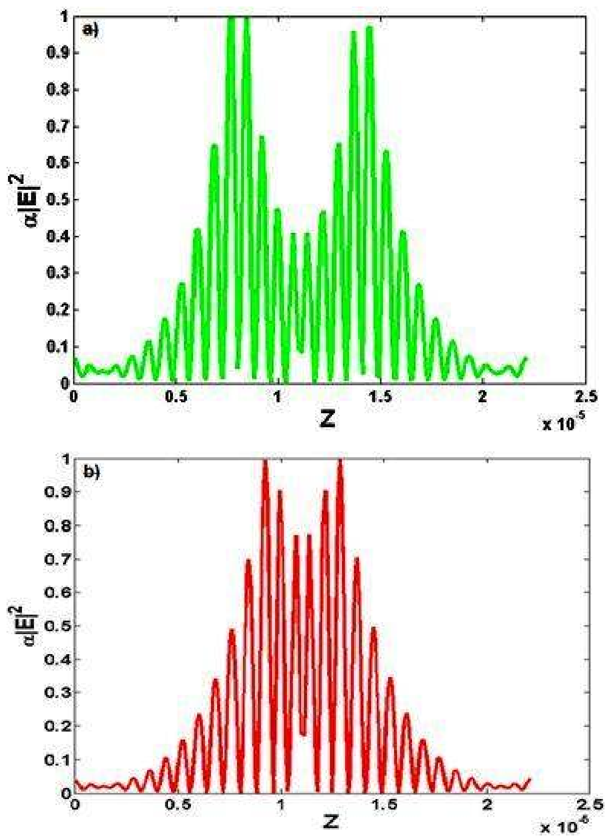


**Figure 4: (Color online) The electric filed intensity distribution of the defect modes in the symmetric one dimensional TCND layers structure. Panel a) corresponds to the point (1) in Fig. 3 and panel b) corresponds to the point (2) in Fig. 3**

In correspondence with the points 1 and 2 in Fig. 3, Figs. 4(a) and 4(b) show the electric filed intensity distribution of the defect modes in the symmetric one dimensional layered structure, respectively. Therefore, with the help of Fig. 3 and Fig. 4, it can be understood that the weak coupling of defect modes causes the decrease of the OB threshold intensity. It should be noted that in the structure corresponding to m=0, the geometry of the symmetric 1D TCND layers structure is disturbed. Therefore, we investigate this structure in Figs. 2 and 3 just to magnify the effect of m=1 structure on the OB threshold intensity. By comparing the m=0 and m=1 structures in Fig. 3, we can find that the m=1 structure supports the minimum value of the OB threshold intensity. Therefore, the new physics in the presented geometry of the structure under consideration in this paper is that for minimum coupling of the defect modes (happened in the m=1 structure), the minimum value of OB threshold intensity is obtained (see Fig. 5).

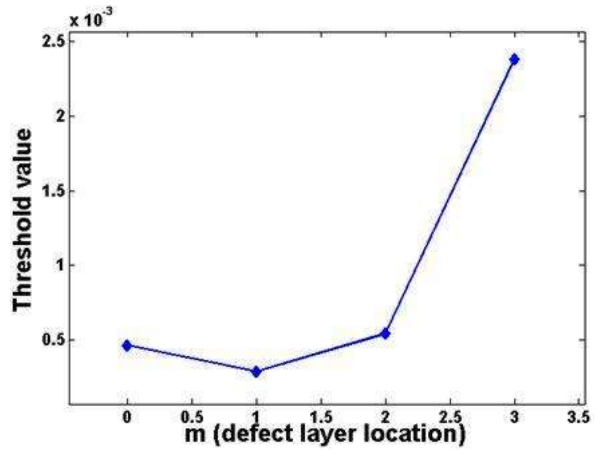


**Figure 5: (Color online) The dependence of the OB threshold intensity on the location of the TCND layers in the symmetric one-dimensional layered structure**

With respect to the mentioned explanation about the advantage of the m=1 structure to achieve the minimum value of OB threshold intensity, we investigate this structure in more details. Transmission through the m=1 structure versus intensity of the incident light ($\alpha |E_i|^2$) is plotted in Fig. 6.

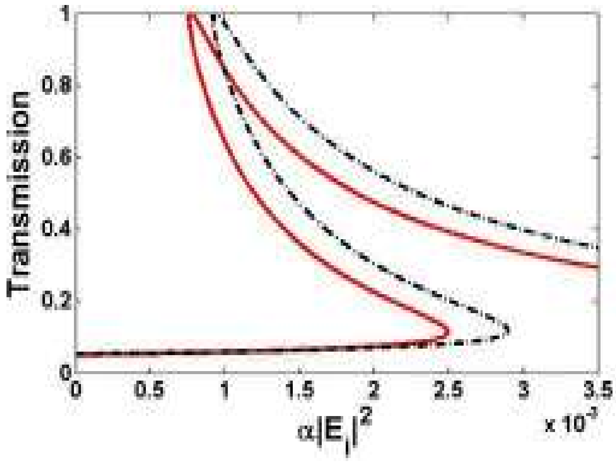

**Figure 6: (Color online) Transmission through the symmetric one dimensional layered structure versus intensity of the incident light for $\lambda = 401.9nm$ (dotted-dashed curve) and $\lambda = 398.1nm$ (solid curve). It should be noted that this figure is plotted for the two defect modes of the m=1 structure**

As it can be noticeably seen in Fig. 6 the threshold intensity of the OB in the m=1 structure for $\lambda = 398.1nm$ (the solid curve) is lower than $\lambda = 401.9nm$ (the dashed curve). To approve of this fascinating result, Fig. 7 is illustrated

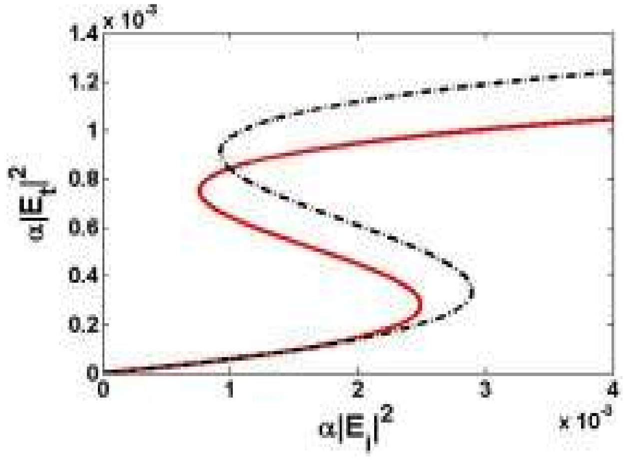

**Figure 7: (Color online) Transmitted intensity through the symmetric one dimensional layered structure versus intensity of the incident light for $\lambda = 401.9nm$ (dotted-dashed curve) and $\lambda = 398.1nm$ (solid curve). As Fig. 6, it should be noted that this figure is also plotted for the two defect modes of the m=1 structure**

From Fig. 7, and with the help of Fig. 6, it can be concluded that at the wavelength of $\lambda = 398.1nm$ minimum OB threshold intensity is possible. In other words, to achieve the OB in low threshold intensity in a symmetric 1D TCND layers structure, an incident light in short wavelength regime is needed.

Until now, in this paper, we investigate the threshold intensity of the OB in a symmetric 1D TCND layers structure. To complete the investigation, in the following, an asymmetric 1D TCND layers structure is considered.

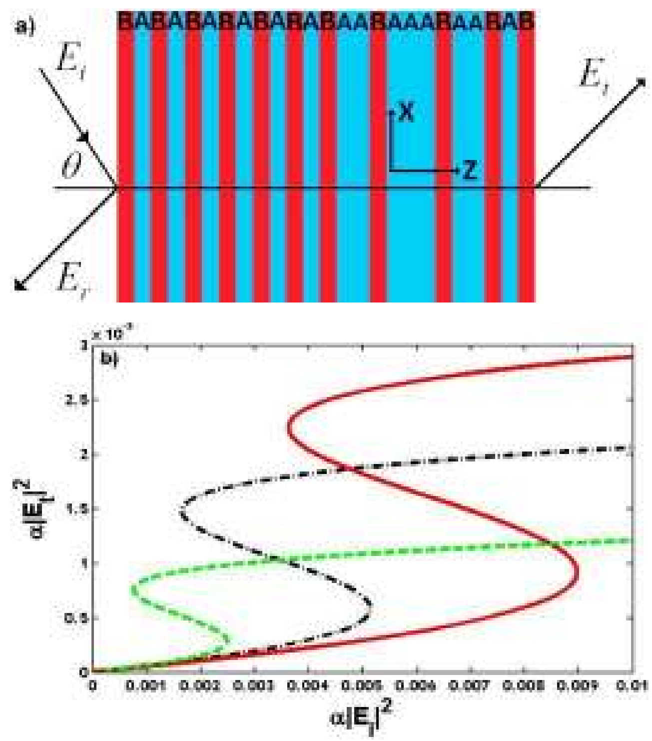

**Figure 8: (Color online) Panel (a) shows the schematic representation of the layers arrangement of the asymmetric one-dimensional layered structure in the form of $(BA)^{12+h}A(BA)\ A(AB)\ A(AB)^{12-h}$. $A$, $B$ and $h$ represent the layers and the position of TCND layers in the structure, respectively. Panel (b) shows transmitted intensity through the structure shown in panel (a), versus the intensity of the incident light. In this panel the dashed curve corresponds to h=0, the dotted-dashed curve corresponds to h=1 and the solid line corresponds to h=2**

Fig. 8(a) shows the schematic representation of the layers arrangement of the asymmetric 1D layered structure in the form of $(BA)^{12+h} A(BA)\ A(AB)\ A(AB)^{12-h}$ . $A$ , $B$ and $h$ represent the layers and the position of the TCND layers in the structure, respectively. Fig. 8(b) shows the transmitted intensity through the structure shown in Fig. 8(a) versus the intensity of incident light, for three different values of 'h'. It can be clearly seen from Fig. 8(b) that, when the structure under consideration is asymmetric the OB threshold intensity shifts to higher values in comparison with the values for symmetric structure.

## CONCLUSION

In this paper, the dependence of the threshold intensity of the optical bistability to distance between the defect layers in a symmetric (and also asymmetric) one-dimensional nonlinear layered structure is investigated, theoretically. The one-dimensional nonlinear layered structure under consideration in this paper contains the TCND layers. Therefore, two coupled defect modes can be created in the photonic gap of this structure. It is shown that, in the symmetric structure, when the distance between the central nonlinear defect layer and its two adjacent defect layers is minimum (the m=1 structure), minimum coupling of the two defect modes is possible. Consequently, for the shorter wavelength defect mode created in this special geometry of the symmetric structure, the minimum threshold intensity of the optical bistability can be achieved.

## REFERENCES


J.D. Joannopoulos, S.G. Johnson, J.N. Win, R.D. Meade, Photonic Crystals: Molding the flow of light, Princeton University Press, Princeton, 2008.

J. Martorell, R. Vilaseca, R. Corbalan, Appl. Phys. Lett. 70 (1997) 702.

F. Sasaki, S. Haraichi, S. Kobayashi, IEEE J. Quantum Elec. 38 (2002) 943.

F. Y. Wang, G. X. Li, H. L. Tam, K. W. Cheah, S. N. Zhu, Appl. Phys. Lett. 92 (2008) 211109.

M. F. Yanik, S. H. Fan, M. Soljacic, Appl. Phys. Lett. 83 (2003) 2739.

N. Large, M. Abb, J. Aizpurua, and O. L. Muskens, Nano Lett. 10 (2010) 1741.

Y. Liu, F. Qin, F. Zhou, and Z. Y. Li, J. Appl. Phys. 106 (2009) 083102.

P. Delaye, M. Astic, R. Frey, G. Roosen, J. Opt. Soc. Am. B 22 (2005) 2949.

B. Shi, Z.M. Jiang, Xun Wang, Opt. Lett. 26 (2001) 1194.

F. Zhou, Z. Y. Li, Y. Liu, and Y. N. Xia, J. Phys. Chem. C 112 (2008) 20233.

F. Zhou, Y. Liu, Z. Li, Y. Xia, Opt. Exp 18 (2010) 13337.

H.M. Gibbs, Optical Bistability: Controlling Light with Light, Academic, New York, 1985.

H. Haug, S.W. Koch, Quantum Theory of the Optical and Electronic Properties of Semiconductors, Published by World Scientific Publishing Co. Pte. Ltd., London, 2004.

C. Chen, S. Matsuo, K. Nozaki, A. Shinya, T. Sato, Y. Kawaguchi, H. Sumikura, M. Notomi, Opt. Exp. 19 (2011) 3387.

Y. Jiang, Fiber and Integrated Optics, 30 (2011) 192.

T. Pan, Ch. Tang, L. Qao, zhe. Li, phys. Let A, 337, (2005), 473.

J. He, M. Cada, Appl. Phys. Lett. 61, (1992), 18.

W.chen, D. L. Mils, phys. Rev. B, 36, (1987), 6269.

S.M. Wang, C.J. Tang, T.Pan, L. Gao, Phys. Lett. A 348 (2006) 424.

M.Z. Ali, T. Abdullah, Opt. Commun. 281 (2008) 3177.

T. Vivero, J.M. Rivas-Moscoso, A.P. González-Marco, J.A. Martín-Pereda, IEEE J. Quantum Elec. 46 (2010) 1184.

R.Wang, J.Dong, D.Y.Xing, Phys.Rev.E 55 (1997) 6301.

E.Lidorikis, K.Busch, Q.M.Li, C.T.Chan, C.M.Soukoulis, Phys. Rev.B56 (1997) 15090.

H.Inouyea, Y.Kanemitsu, Appl. Phys. Lett. 82 (2003) 1155.

C. Lixue, D. Xiaoxu, D. Weiqiang, C. Liangcai, L.Shutian, Opt. Commun. 209 (2002) 491.

P. Hou, Y. Chen, J. Shi, M. Shen, Q. Wang, Opt. Commun. 273 (2007) 441.

S.M. Wang, L. Gao, Opt. Commun. 267 (2006) 197.

R. Wang, J. Dong, D. Y. Xing, Phys. Rev. E 55(1997) 6301.

N.H. Liu, S.Y. Zhu, H. Chen, X. Wu, Phys. Rev. E 65 (2002) 046607.

L.G. Wang, N.H. Liu, Q. Lin, S.Y. Zhu, Phys. Rev. E 70 (2004) 016601.