Formation of gap soliton in negative Kerr nonlinear one dimensional photonic crystal

ARUN KUMAR[*], VIPIN KUMAR[a], G. N. PANDEY[b], KH. S. SINGH[a], S. P. OJHA[c]

Amity Institute of Telecom Engineering and Management, Amity University, Noida, India

[a]*Department of Physics, Digamber Jain (P.G.) College, Baraut, U.P., India*

[b]*Department of Applied Physics, AIAS, Amity University, Noida, UP, India*

[c]*IIMT, Greater Noida, UP, India*

Theoretical studies on the formation of gap soliton in one-dimensional negative Kerr nonlinear photonic crystal have been presented. Formation of gap soliton through the one dimensional photonic crystal has been studies for different intensities of controlling wave by solving Maxwell's electromagnetic equations and using transfer matrix method. The study shows that gap soliton form at high intensities of controlling wave and this property can be used to design optical switches.

(Received January 6, 2012; accepted July 11, 2013)

Keywords: Kerr effect, Photonic crystal, Soliton

1. Introduction

John [1] and Yablonovitch [2] reported in 1987 that a periodic variation in dielectric constant exhibits forbidden band(s) in the transmission/reflection spectrum in the optical frequency region. After this, Photonic band gap materials have been widely investigated [3-6]. Fiber Bragg grating is the simplest PBG structure, which has been widely used in the optical communication systems. Replacing the linear dielectric material(s) by nonlinear material in the conventional 1D photonic crystal can change the transmission characteristic of these photonic crystals. When a non-linear material for which refractive index depends on the intensity of the light is introduced as alternate layers in conventional one 1D photonic crystal, the transmission characteristics of the structure got changed and such structures can be made transparent at high intensity in that region of wavelength for which the composite material is opaque at low intensity [7-12]. For example, gap solitons refer to solitary localization and solitary propagation of optical waves in a nonlinear photonic band gap structure [7-9]. John et al. have studied optical solitary waves in photonic crystals extensively [7, 8]. The central frequency of a gap soliton is inside the linear photonic band gap. Experimental observations of a gap soliton has been reported in a fiber Bragg grating [9]. A nonlinear photonic band gap medium can also support solitons of an effective nonlinear Schrodinger (NLS) equation [10]. Such a soliton is called a Bragg soliton and its central frequency is close to the band gap edge [11-12]. Bragg solitons have also been successfully observed in fiber Bragg grating [11] supported by experimental results based on NLS model [12]. Recently various aspects of gap solitons have been studied by different researchers [13-17].

In this present communication, we studied the formation of gap solitons in CdS/Fe:$BaTiO_3$ based one-dimensional nonlinear photonic crystal, in which CdS is a linear material and Fe:$BaTiO_3$ is a nonlinear negative Kerr medium. For this purpose, we have considered a pulse whose wavelength falls inside the photonic band gap at low intensity for the PBG considered here. This pulse suffers cent percent reflection in linear region i.e. when the intensity of the controlling wave is low. But at high intensity, the change in the refractive index of the nonlinear region shifts the photonic band gap in shorter wavelength region. This shift in PBG should be of the order of the width of the pulse wavelength. This condition allows formation of a gap soliton when the signal wavelengths are just inside the short wavelength edge of the gap, i.e., the gap is nonlinearly shifted so that the propagation of the signal without reflection through the structure is possible [18].

We considered here that electromagnetic wave that carries the signal pulse incidents perpendicular to the layers. The controlling wave, which produces the nonlinear effect, is propagating perpendicular to the direction of propagation of the signal pulse. Also, we considered the amplitude of the controlling wave much higher than the amplitude of the signal pulse thereby we can safely neglect the nonlinear effect of the signal pulse on nonlinear layers.

2. Theoretical analysis

To study the propagation of electromagnetic waves through such a periodic structure, we assumed that the material is 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

$$n(z)=\begin{cases} n_{01}, & 0<z<d_1 \\ n_{02}+\Delta n_2 I, & d_1<z<d_2 \end{cases} \quad (1)$$

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

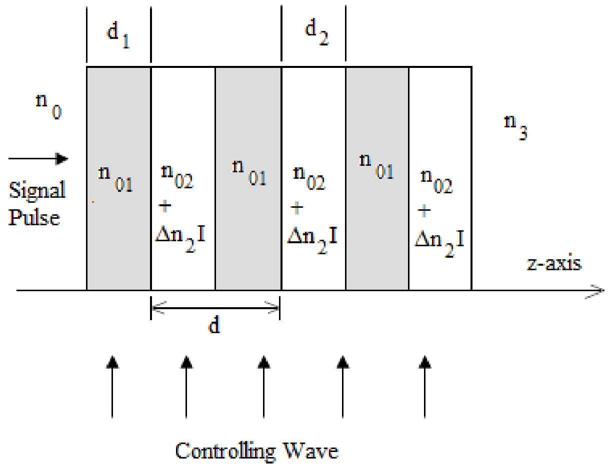

Fig. 1. Schematic diagram of the structure.

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

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

where n is given by equation 1. The solution of equation 2 in any region, are the combinations of left and right travelling waves.

The general method of transfer matrix method could not deal with the non-linear propagation problem in the presence of other high intensity controlling wave. Hence, the above equation 2 has been solved and reflectance for a proposed multilayered structure has been calculated using a modified transfer matrix method [19] for an incident signal pulse with Gaussian spectral distribution, centred at 1552 nm and for different intensities of controlling wave; and also we computed the output amplitude.

3. Results and discussion

In this section, numerical calculations on the formation of gap solitons in one-dimensional nonlinear negative Kerr photonic crystal have been presented. First, the reflection spectra of the structure for an incident signal pulse with Gaussian spectral distribution, centred at 1552 nm for different intensities of controlling wave have been discussed. Then, the transmitted pulse amplitude has been calculated. For the structure, we have considered a linear medium i.e. CdS, having refractive index n_1 = 2.32, and nonlinear medium $FeBaTiO_3$, having refractive index $n_2 = 2.3 + \Delta n_{02} I$, with third order nonlinear susceptibility –3.67×10^{-7} esu [19]. In the proposed structure, we have taken the length of structure (L) to be equal to 0.337 mm, having a lattice constant, d=337 nm out of which the thickness of CdS layer (d_1) is 0.2d and thickness of $Fe{:}BaTiO_3$ layer (d_2) is 0.8d. We have also considered that the refractive index at the input and output side of the multilayer structure is 1.5, where we used SiO_2 so that the side-bands in the reflection spectra can be suppressed. We analyzed the structure at three different intensities 2 MW/cm^2 (low), 20 MW/cm^2 (moderate) and 200 MW/cm^2 (high) of controlling wave.

When the intensity of controlling wave is 2 MW/cm^2, the reflection spectra and incident pulse is shown in Fig. 2 (a). When intensity is low, it is clear that the proposed structure has a photonic band gap from 1549.75 nm to 1554.5 nm. If a pulse with Gaussian spectral distribution, centred at 1552 nm with a FWHM of $25A^0$ is incident on this structure, then pulse will be reflected from the structure and there will be no transmission. The transmitted pulse is shown in Fig. 2 (b) and it is almost negligible. For the case in which the intensity of the controlling wave is moderate (20 MW/cm^2), the reflection spectra and the incident pulse are shown in Fig. 3 (a). At this intensity, the structure has a photonic band gap from 1542.3 nm to 1550.5 nm with some side-bands. The transmitted pulse through the structure at moderate intensity has been shown in Fig. 3 (b). It is clear from Fig. 3 (b) that some part of the pulse has been transmitted with distortion at moderate intensity of the controlling wave. However, when intensity of controlling wave is high (200 MW/cm^2), the situation is quite different. The reflection spectra at this intensity are shown in Fig. 4 (a). From this figure, it is clear that the photonic band gap, which was centred at 1552 nm at low intensity of the controlling wave, has now been shifted towards shorter wavelength side, centred at 1490.25 nm. So, a signal pulse, centred at 1552 nm incident on this structure at high intensity of controlling wave, will be propagated without distortion through the structure, as shown in Fig. 4 (b). This happens because photonic band gap has been shifted towards the shorter wavelength region, and this condition allows the propagation of a signal pulse through the structure at high intensity of the controlling wave whereas the propagation of the signal is prohibited at low intensity of the controlling wave. This indicates that there is a formation of gap soliton in a one dimensional multilayer PBG structure of nonlinear materials when subjected to a high intensity controlling wave.

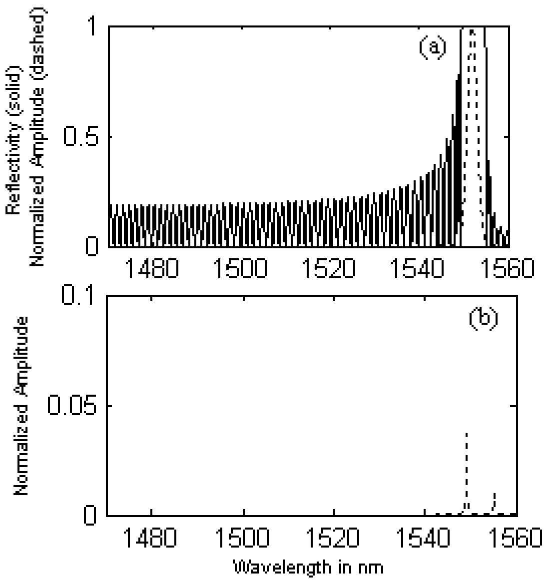

Fig. 2. (a) Reflectance spectra (solid) of the structure for normal incidence at 2 MW/cm^2 intensity of controlling wave. Normalized Amplitude of the incident pulse (dashed). (b) Transmitted Pulse from the structure at 2 MW/cm^2 intensity of controlling wave.

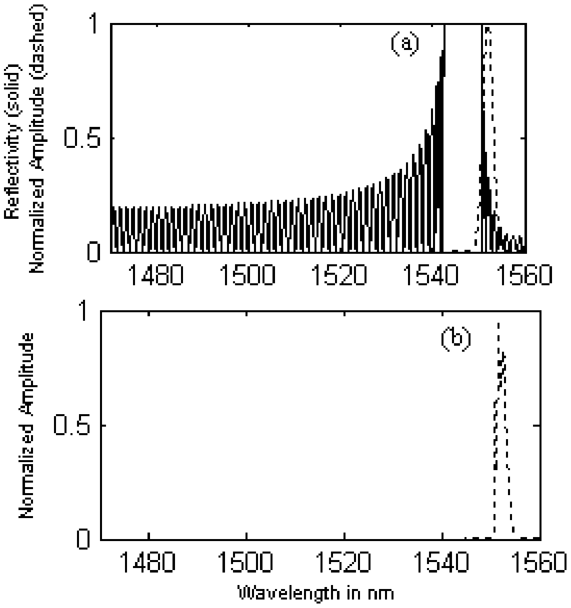

Fig. 3. (a) Reflectance spectra (solid) of the structure for normal incidence at 20 MW/cm^2 intensity of controlling wave. Normalized Amplitude of the incident pulse (dashed). (b) Transmitted pulse from the structure at 20MW/cm^2 intensity of controlling wave.

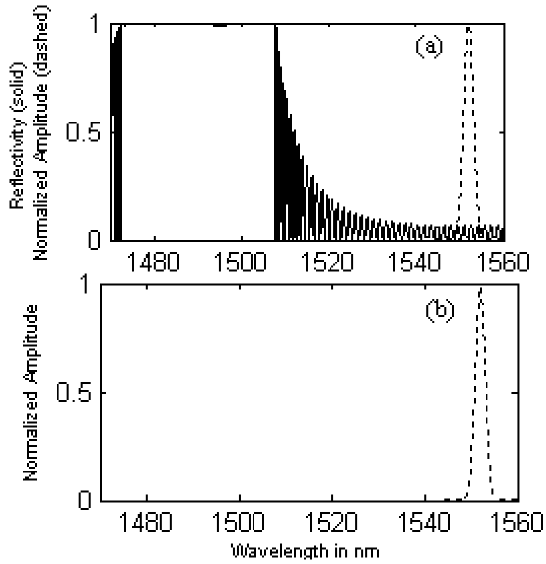

Fig. 4. (a) Reflectance spectra (solid) of the structure for normal incidence at 200 MW/cm^2 intensity of controlling wave. Normalized Amplitude of the incident pulse (dashed). (b) Transmitted pulse from the structure at 200 MW/cm^2 intensity of controlling wave.

4. Conclusion

The proposed structure exhibits a shift in the PBG towards shorter wavelength region, when the structure is subjected to a high intensity (200MW/cm^2) controlling wave. This results to the formation of gap soliton having a mean wavelength of 1552 nm, when the structure in irradiated with a high intensity cross controlling wave. At low intensity of controlling wave the structure behave like a 100% reflector at the particular wavelength discussed here. On the other hand, in presence of controlling wave, the structure becomes transparent at that particular wavelength region. Thus, by choosing appropriate intensity of the controlling wave the structure may behave like a good reflector or a transparent material at a particular wavelength. In this manner the structure behaves like a switch working in the optical region of the electromagnetic spectrum. This property can be used to design the optical switches, which can be easily integrated to the modern fiber optic technology.

Acknowledgments

One of the authors Arun Kumar is highly thankful to Dr. Ashok K. Chauhan, Founder President, Amity University, Uttar Pradesh, India for his interest in research and constant encouragements for the same. He is also grateful to Lt. Gen. P. D. Bhargava, Group Deputy Vice Chancellor, Amity University, India and Prof. R K Kapur, Head, AITEM, Amity University, Noida, India for moral support.

References

[1] S. John, Phy. Rev. Lett. **58**, 2486 (1987).
[2] E. Yablonvitch, Phy. Rev. Lett. **58**, 2059 (1987).
[3] Y.-H . Chang, Y.-Y. Jhu, C.-J. Wu, J. Optoelectron. Adv. Mater. **14**(3-4), 185 (2012).
[4] H. Huang. H. Yang, Y. Chen, T Liu, W. He, Y. Duan, P. Wang, J. Optoelectron. Adv. Mater. **14**(11-12), 871 (2012).
[5] F. Mehdizadeh, H. A.-Banaei, Z. D.-Kuzekanani, Optoelectron. Adv. Mater.-Rapid Commun. **6**(5-6), 527 (2012).
[6] S. A. E.-Naggar, N. H. Rafat, S. I. Mostafa, J. Optoelectron. Adv. Mater. **13**(7), 781 (2011).
[7] S. John, N. Akozbek, Phys. Rev. Lett. **71**, 1168 (1993).
[8] N. Akozbek, S. John, Phys. Rev E **57**, 2287 (1998).
[9] U. Mohideen, R. E. Slusher, V. Mizrani, T. Erdogan, M. Kuwata-Gonokami, P. J. Lemaire, J. E. Sipe, C. M. de Sterke, N. G. R. Brodorick, Opt. Lett. **20**, 1674 (1995).
[10] J. E. Sipe, H. G. Winful, Opt. Lett., **13**,132 (1988).
[11] B. J. Eggleton, C. M. de Streke, R. E. Slusher, J. Opt. Soc Am. B **16**, 587 (1999).
[12] C. M. de Streke, B. J. Eggleton, Phys. Rev. E **59**, 1267 (1999).
[13] A. A. Sukhorukov, Y. S. Kivshar, Phys. Rev. Lett. **91**, 113902 (2003).
[14] A. A. Sukhorukov, Y. S. Kivshar, Op. Lett. **28**, 2345 (2003).
[15] D. E. Pelinovsky, A. A. Sukhorukov, Y. S. Kivshar, Phys. Rev. E **70**, 036618 (2004).
[16] K. Motzek, A. A. Sukhorukov, F. Kaiser, Yu. S. Kivshar, Opt. Express. **13**, 2916 (2005).
[17] A. Joseph, K. Senthilnathan, K. Porsezian, P. Tchofo Dinda, J. Opt. A: Pure Appl. Opt. **11**, 015203 (2009).
[18] R. E. Slusher, B. J. Eggleton, Nonlinear Photonic Crystal, Springer-Verlag Berlin Hiidelberg (2003).
[19] H. Xiaoyong, P. Jiang, Q. Gong, J. Opt. A: Pure Appl. Opt., **9**, 108 (2007).

*Corresponding author: arun_mtech@yahoo.co.in