Existence of gap soliton in nonlinear one dimensional photonic crystal

ARUN KUMAR[*], KH. S. SINGH[a], S. P. OJHA[b]
AITTM, Amity University, Noida, India
[a]*Department of Physics, Digamber Jain (P.G.) College, Baraut (U.P.), India*
[b]*Ex Vice-Chancellor, Chaudhary Charan Singh University, Meerut, India*

Theoretical studies on the existence of gap soliton in one-dimensional GaAs/AlGaAs nonlinear photonic crystal have been investigated. Propagation of gap solitons through these multilayered structures has been studies for different controlling intensities by solving Maxwell's electromagnetic equations and using modified transfer matrix method. The study shows that gap solitons exist at high intensities and this property can be exploited in the design of an optical switch.

1. Introduction

Photonic band gap materials have been widely investigated since 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. The reason to form a photonic band gap (PBG) is the coherent multiple scattering of light in the periodic structure. The simplest PBG structure is the fiber Bragg grating, which has been widely used in the practical light wave communication systems. Although a PBG material has photonic band gaps, the material nonlinearity can render the PBG "transparent" for nonlinear optical propagation [3-13]. For example, gap solitons refer to solitary localization and solitary propagation of optical waves in a nonlinear photonic band gap structure [3-8]. The central frequency of a gap soliton is inside the linear photonic band gap. In a fiber Bragg grating, experimental observations of a gap soliton has been reported [8]. A nonlinear photonic band gap medium can also support solitons of an effective nonlinear Schrodinger (NLS) equation [9]. Such a soliton is called a Bragg soliton and its central frequency is close to the band gap edge [10-13]. Bragg solitons have also been successfully observed in fiber Bragg grating [10] supported by experimental results based on NLS model [11-13]. Sukhorukov et al predicted novel types of multigap discrete vector solitons supported by nonlinear coupling between different band gaps and studied their stability [14] and also studied the stability and generation of discrete gap solitons in weakly coupled optical waveguides [15]. Pelinovsky et al also analyzed the existence, stability, and internal modes of gap solitons in nonlinear periodic mediums described by the NLS equation with a sinusoidal potential, such as photonic crystals, waveguide arrays, etc. Also some investigators studied incoherent multi-gap optical solitons in nonlinear photonic lattices [17]. Recently, gap solitons and modulation instability in a dynamic Bragg grating with nonlinearity management has been presented [18].

In this present communication, we studied the existence of gap solitons in GaAS/AlGaAs based one-dimensional nonlinear photonic crystal. 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 longer wavelength region. This nonlinear shift 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 [19].

Here we considered 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

$$n(z) = \begin{cases} n_{01} + \Delta n_1 I, & 0 < z < d_1 \\ n_{01} + \Delta n_2 I & d_1 < z < d_2 \end{cases} \quad (1)$$

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 $n_{01} + \Delta n_1 I$ 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.
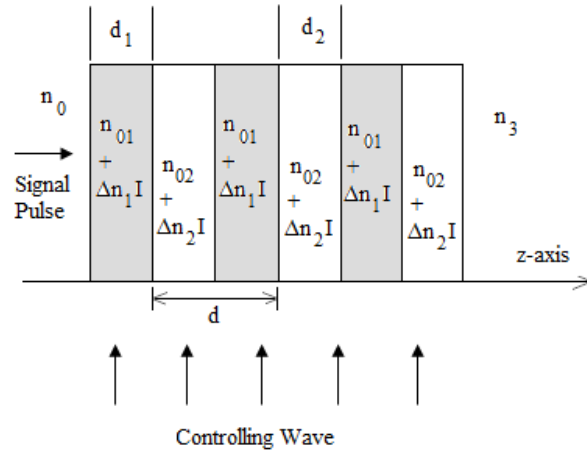

Fig. 1. Schematic diagram of the structure.

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

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

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 [20] for an incident signal pulse with Gaussian spectral distribution, centred at 1550 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 existence of gap solitons in one-dimensional nonlinear 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 nonlinear medium i.e. GaAs, having refractive index $n_1 = 3.31 + \Delta n_{01} I$, where Δn_{01} is the Kerr coefficient of GaAs, and $\Delta n_{01} = 1.59 \times 10^{-13}$ cm^2/W [21] , and another nonlinear medium AlGaAs, having refractive index $n_2 = 3.3 + \Delta n_{02} I$, where Δn_{02} Kerr coefficient of AlGaAs, and $\Delta n_{02} = 2 \times 10^{-13}$ cm^2/W [22]. Here I is the intensity of controlling wave. In the proposed structure, we have taken the length of structure (L) to be equal to 0.7mm, having a lattice constant, d=235nm out of which the thickness of GaAs layer (d_1) is 0.2d and thickness of AlGaAs 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 3, where we used As$_2$S$_3$ so that the side-bands in the reflection spectra can be suppressed. The Kerr coefficient of As$_2$S$_3$ is negligible in comparison to GaAs/AlGaAs [23]. So we can consider these layers on either sides of the multilayer structure as linear dielectric materials. We analyzed the structure at three different intensities 1 GW/cm^2 (low), 10 GW/cm^2 (moderate) and 100 GW/cm^2 (high) of controlling wave.

When the intensity of controlling wave is 1 GW/cm^2, the reflection spectra and incident pulse is shown in Fig. 2. When intensity is low, it is clear that the proposed structure has a photonic band gap from 1551 nm to 1553nm. If a pulse with Gaussian spectral distribution, centred at 1552 nm with a FWHM of 5Å 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. 3 and it is almost negligible. For the case in which the intensity of the controlling wave is moderate (10 GW/cm^2), the reflection spectra and the incident pulse are shown in Figure 4. At this intensity, the structure has a photonic band gap from 1550.8nm to 1552.8nm with some side-bands. The transmitted pulse through the structure at moderate intensity has been shown in Fig. 5. It is clear from Fig. 5 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 (100 GW/cm^2), the situation is quite different. The reflection spectra at this intensity are shown in Figure 6. 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 longer wavelength side, centred at 1561 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. This happens because photonic band gap has been nonlinearly shifted towards the longer 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 existence of gap soliton in a one dimensional multilayer PBG

structure of nonlinear materials when subjected to a high intensity controlling wave.
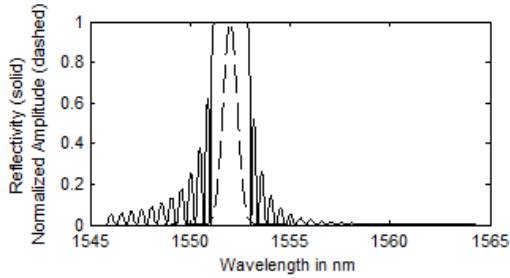

Fig. 2. Reflectance spectra (solid) of a 0.7mm long nonlinear reflector for normal incidence at 1GW/cm² intensity of controlling wave for $n_0 = 3.3$, $n_1 = 3.31 + \Delta n_{01}I$, $n_2 = 3.3 + \Delta n_{02}I$, $n_3 = 3$, d=235nm, $d_1 = 0.2d$, $d_2 = 0.8d$. Normalized Amplitude of the incident pulse (dashed).
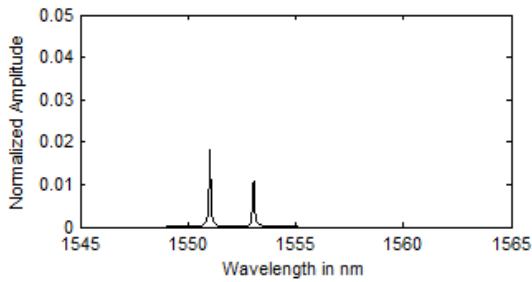

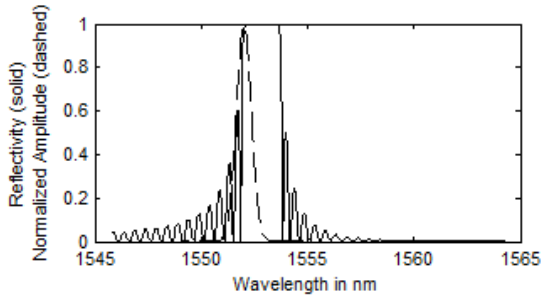Fig. 3. Transmitted Pulse from the structure at 1GW/cm² intensity of controlling wave.

Fig. 4. Reflectance spectra (solid) of a 0.7mm long nonlinear reflector for normal incidence at 10GW/cm² intensity of controlling wave for $n_0 = 3$, $n_1 = 3.31 + \Delta n_{01}I$, $n_2 = 3.3 + \Delta n_{02}I$, $n_3 = 3$, d=235nm, $d_1 = 0.2d$, $d_2 = 0.8d$. Normalized amplitude of the incident pulse (dashed).
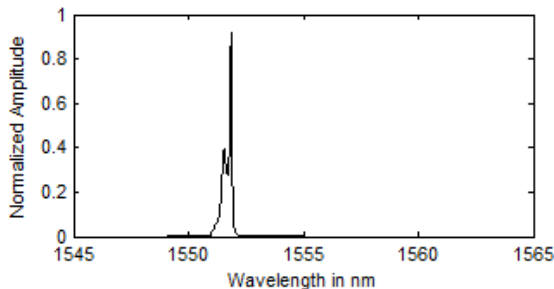

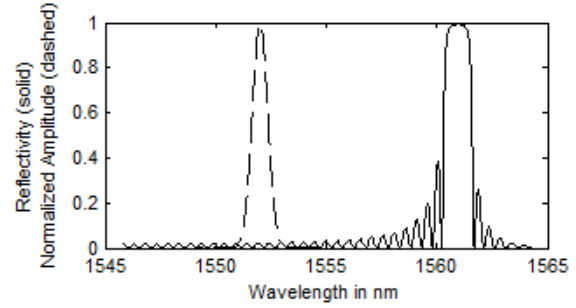Fig. 5. Transmitted pulse from the structure at 10GW/cm² intensity of controlling wave.

Fig. 6. Reflectance spectra (solid) of a 0.7mm long nonlinear reflector for normal incidence at 100GW/cm² intensity of controlling wave for $n_0 = 3$, $n_1 = 3.31 + \Delta n_{01}I$, $n_2 = 3.3 + \Delta n_{02}I$, $n_3 = 3$, d=235nm, $d_1 = 0.2d$, $d_2 = 0.8d$. Normalized Amplitude of the incident pulse (dashed).
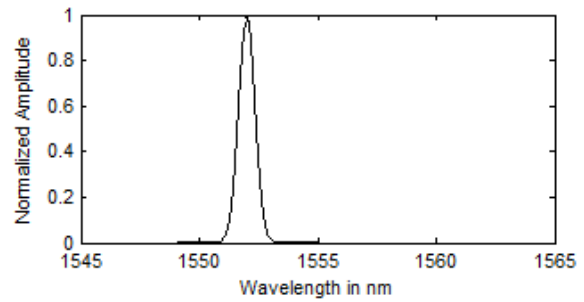

Fig. 7. Transmitted pulse from the structure at 100GW/cm² intensity of controlling wave.

4. Conclusions

The proposed structure exhibits a nonlinear shift of the photonic band gap towards longer wavelength side, particularly for the forbidden band centred at 1552nm, when the structure is subjected to a high intensity (100GW/cm²) controlling wave. This results to the existence of gap soliton having a mean wavelength of 1552nm, when the structure in irradiated with a high intensity cross controlling wave. At low intensity the structure behaves like a 100% reflector at the particular wavelength discussed here. Thus, by choosing appropriate intensity of the controlling wave the structure may behave like a good reflector or a transparent material. That is the structure behaves like a switch working in the optical region of the electromagnetic spectrum. This property can be exploited in the design of optical switch which can be easily integrated to the standard fiber optic technology.

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[*]Corresponding author: arun_mtech@yahoo.co.in