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Performance analysis of dense wavelength division demultiplexer based on one dimensional defect mode nonlinear photonic crystal

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The intensity dependent transmission characteristics of 1-D photonic crystal (PC) structure with a defect have been studied. We consider a SiO_2/GaAs multilayer structure the refractive index of GaAs layer to be dependent on intensity. The refractive indices of GaAs layer is the functions of intensity of incident light. This property can be used to tune the defect modes at desired wavelength. It is found that the average change in central wavelength of defect mode is *0.08 nm/(GW/cm^2)*. This property can be exploited in the design of a single channel wavelength division demultiplexer for application in optical communication.

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1. Introduction

A photonic crystal (PCs) was first proposed by E. Yablonovitch and S. John independently in 1987 [1,2]. After this, Photonic band gap materials have been widely investigated [3-8]. Exhibiting photonic band gap (PBGs), a frequency range in which electromagnetic waves cannot propagate is an important property of structures having periodic arrangement of materials. These structures are generally known as photonic crystals. The main importance of PBGs is the existence of forbidden bandgap in their transmission spectra, which is not possible in bulk materials. A photonic band gap in a photonic crystal (PC) is analogous to the electronic band gap in a solid. Some important applications of photonic crystals are tunable optical filters [9,10], omnidirectional reflectors [11,12], DWDM applications [13-20], temperature sensors [21] etc. When a non-linear refractive index material is introduced as alternate layers in conventional one dimensional photonic crystal, the reflection and transmission properties of the structure got changed and it gives a variety of applications [22-29].

When periodicity of a simple photonic crystal is disturbed by any method, such as, by adding another material into the structure or by changing the thickness of a layer, etc., defect modes could be generated within the photonic band gaps (PBGs) [30-32]. In a simple one-dimensional photonic crystal of $(AB)^N$, the defect mode can be obtained in a disturbed structure like $(AB)^N D(AB)^N$, where D is known as defect layer. Defect mode is a sharp and narrow transmission peak in the transmission spectrum of a simple photonic crystal.

In the present communication, we have analyzed the transmission spectra of defect modes in one dimensional non linear photonic crystal with defect. We choose SiO_2 for the materials A, GaAs for the materials B and GaAs for defect material layer D. We have also considered that the refractive index at the input and output side of the multilayer structure is 1. Here we considered that signal wave incident perpendicular to the layers. The controlling wave, which produces the nonlinear effect, is incident perpendicular to the direction of propagation of the signal wave. We also considered that the amplitude of the signal wave is very small compared to the high intensity controlling wave, so we can safely neglect the nonlinear effect of the signal wave on nonlinear layers. Also, we shall confine our study in the third transmission window of optical communication, which is the lowest loss widow for optical communication. Analysis of the structure considered here shows that this structure may be used as a single channel tunable wavelength demultiplexer for the multichannel DWDM system. Gerkin and Miller fabricated a wavelength division demultiplexer using the spatial dispersion of multilayer thin film structures [19]. They use a single 66-layer non-periodic thin film stake to separate four wavelength channels by spatial beam shifting. They demonstrate that this device can demultiplexed channels with spacing of approximately 4 nm in the first transmission window of optical communication i.e. at 850 nm wavelength. The proposed structure here requires that the number of layer is less. So, the fabrication of the proposed structure will be comparatively simpler. Also, line width of transmission peak is also less in the present case.

2. Theory

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

$$n(z) = \begin{cases} n_1 & 0 < z < d_1 \\ n_2 + \Delta nI & d_1 < z < d_2 \end{cases}, \tag{1}$$

with $n(z+d) = n(z)$. Here d is the lattice constant; d_1 and d_2 are the thicknesses of the alternate layers, which have refractive indices n_1 and $n_2+\Delta nI$, where I is the intensity of controlling wave. The schematic diagram of this structure is illustrated in Fig. 1.

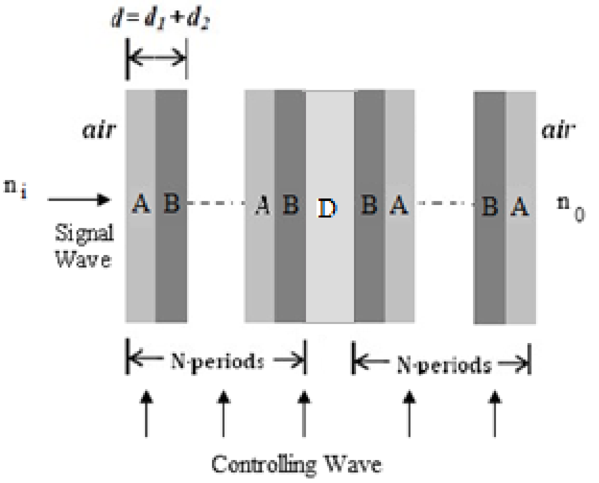

Fig. 1. Schematic diagram of one dimensional non linear photonic crystal with defect.

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

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

where n is given by Eq. (1). The solutions of Eq. (2) in any region are the combinations of left and right travelling waves.

The schematic representation of one-dimensional photonic crystal with defect is represented in Fig. 1. We consider air/$(AB)^N D/(BA)^N$/air, in which A and B represents the high and low refractive index materials, and D is the defect layer. To investigate the properties of the defect modes we shall use the transmission spectrum which can be calculated by transfer matrix method (TMM) [33]. In this method, the transfer matrix method for each layer can be written as,

$$M_i = D_i P_i D_i^{-1} \tag{3}$$

Where the dynamical matrixD_i, For TE mode of polarization it is expressed as,

$$D_i = \begin{pmatrix} 1 & 1 \\ n_i cos\phi_i & -n_i cos\phi_i \end{pmatrix} \tag{4}$$

And for TM mode of polarization,

$$D_i = \begin{pmatrix} cos\phi_i & cos\phi_i \\ n_i & -n_i \end{pmatrix} \tag{5}$$

And the propagation matrix $P_i$is defined as

$$P_i = \begin{pmatrix} e^{i\phi_i} & 0 \\ 0 & e^{-i\phi_i} \end{pmatrix} \tag{6}$$

where the phase ϕ_i is expressed as,

$$\phi_i = k_i d_i = \frac{2\pi d_i}{\lambda} n_i \tag{7}$$

For the entire structure of air/$(AB)^N D/(BA)^N$/air, the total transfer matrix is thus given by,

$$M = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} = D_0^{-1}(M_A M_B)^N M_D (M_A M_B)^N D_0 \tag{8}$$

Where, D_0 is called the dynamical matrix of air.

The reflectance (R) and transmission (T) can be calculated using the matrix elements M_{11} and M_{21} given in equation (8) is defined as

$$R = \left|\frac{M_{21}}{M_{11}}\right|^2 \quad and \quad T = \left|\frac{1}{M_{11}}\right|^2 \tag{9}$$

The general transfer matrix method [33] could not deal with the propagation problem in the presence of other high intensity controlling wave. Here, we adopted an approximate approach. Refractive index of GaAs has been computed taking proper consideration of the optical Kerr effect. With the calculated refractive index of GaAs, transmission spectrum of the defect mode of the proposed 1D photonic crystal in absence as well as in presence of high intensity controlling wave have been calculated. Johnson et al [34] and Xiaoyong et al [35] have confirmed the convergence and the correctness of this approximate approach.

3. Results and discussion

In this section, we have presented the transmission spectra for defect modes in one dimensional non linear photonic crystal with defect $[(AB)^N D(AB)^N]$. We choose SiO_2 for the materials A, GaAs for the materials B and the defect material layer D is GaAs and N = 5 in Fig. 1. So, the proposed structure will be $[(SiO_2/GaAs)^5 GaAs(GaAs/SiO_2)^5]$. Gallium Arsenide (GaAs) has refractive index $n_2 = 3.31+\Delta nI$, where Δn is the Kerr coefficient of GaAs, $\Delta n = 1.59x10^{-13}$ cm^2/W [19, 36], and another medium is silicon SiO_2 having refractive index $n_1 = 1.45$. Here, "I" represents the intensity of controlling wave. We have also considered that the refractive index at the input and output side of the multilayer structure is 1. In the proposed structure, we have taken the lattice constant, $d = 2825$ nm, out of which the thickness of SiO_2 layer (d_1) is $0.15d$ and thickness of GaAs layer (d_2) is $0.85d$. Thickness of the defect layer is $0.85d$. We have analyzed the structure at five different intensities *0 GW/cm^2* (in absence of high intensity controlling wave), *25 GW/cm^2*, *50 GW/cm^2*, *75 GW/cm^2* and *100 GW/cm^2* of the controlling wave.

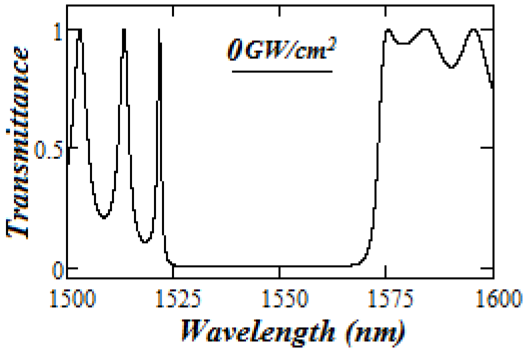

Fig. 2. Transmittance of an ideal $(SiO_2/GaAs)^{10}$ non linear photonic crystal at 0GW/cm^2 intensity.

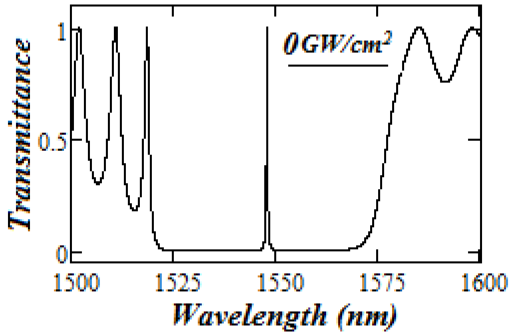

Fig. 3. The defect mode $[(SiO_2/GaAs)^5$ GaAs $(GaAs/SiO_2)^5]$ non linear photonic crystal at 0GW/cm^2 intensity.

The transmission spectra of $[(SiO_2/GaAs)^{10}]$ at *0 GW/cm^2* intensity of controlling wave (in absence of controlling wave) for normal incidence is shown in Fig. 2. The transmission spectra of $[(SiO2/GaAs)^5GaAs(GaAs/SiO_2)^5]$ at *0 GW/cm^2* intensity of controlling wave (in absence of controlling wave) for normal incidence is shown in Fig. 3. As shown in this Figure, a defect mode has been observed at *1547.74 nm* wavelength with line width of *0.32 nm*. Our aim is to study this defect mode in presence of high intensity controlling wave.

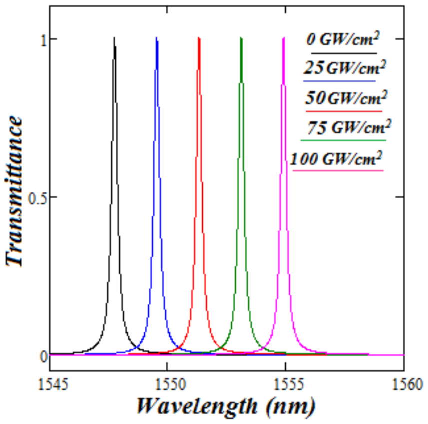

Fig. 4. Transmission spectra of defect mode $[(SiO2/GaAs)^5$ GaAs $(GaAs/SiO_2)^5]$ non linear photonic crystal at different intensity.

Fig. 4 shows the transmission spectra of defect mode $[(SiO2/GaAs)^5$ GaAs $(GaAs/SiO_2)^5]$ non linear photonic crystal at different intensity of controlling wave. From this figure, it is clear that if input radiation containing different wavelengths ranging from *1545 nm* to *1560 nm* is incident at normal incidence on the proposed structure at intensity *0 GW/cm^2*, then it will pass only an extremely narrow band of wavelength centered at *1547.74 nm* with line width *0.32 nm* and all other wavelengths will be reflected. Thus, it can work as a single channel wavelength division demultiplexer in a multichannel DWDM system. More interestingly, this defect mode can be tuned by variation of intensity of controlling wave. From Fig. 4, it is also clear that the transmission peak centered at *1547.74 nm* at *0 GW/cm^2* intensity of controlling wave (in absence of controlling wave) has been shifted to *1549.53 nm*, *1551.32 nm*, *1553.11 nm* and *1554.90 nm* corresponding to the controlling wave intensities at *25 GW/cm^2*, *50 GW/cm^2*, *75 GW/cm^2* and *100 GW/cm^2* respectively. Here, the intensity of the controlling wave has been taken arbitrarily, so we can tune centre of the defect mode at any desired wavelength by varying the intensity as shown in Table 1. It is also clear that as we increase the intensity, the defect mode of transmission shifts towards the higher wavelength region. It is found that the central wavelength of defect modes changes approximately linearly with intensity. The average change in central wavelength of defect mode is *0.08 nm/ (1GW/cm^2)*. Hence the proposed structure may be used as a single channel tunable wavelength demultiplexer in multichannel DWDM system. Also, the line-width of the transmitted wavelength is *0.32 nm*, so the proposed structure is a strong candidate to be used to demultiplex the signal with *0.8 nm* separation, which corresponds to the ITU grid for DWDM.

Crosstalk between the two adjacent channels is defined as

$$10log_{10}\frac{Power\ of\ the\ adjacent\ channel}{Power\ of\ the\ channel\ under\ consideration}$$

As output power of the photonic channel is directly proportional to the transmittance of the crystal at that wavelength, so, we can also define crosstalk as

$$10log_{10}\frac{Transmittance\ of\ the\ adjacent\ channel}{Transmittance\ of\ the\ channel\ under\ consideration}$$

It is clear from Fig. 4, that the transmittance of any adjacent channel of any transmission channel is approximately *0.07%*. Thus, crosstalk between the adjacent channel has comes out *-31.5 dB*, which is, of course, well below the standard limit of crosstalk of *-25 dB* between adjacent channel in optical communication systems.

Table 1. Central wavelength and line width of defect modes at various intensities of controlling wave.

S. No.	Intensity of controlling wave (GW/cm^2)	Central wavelength of defect mode (nm)	Separation (nm)	Line width (nm)
1.	0	1547.74	–	0.32
2.	25	1549.53	1.79	0.32
3.	50	1551.32	1.79	0.32
4.	75	1553.11	1.79	0.32
5.	100	1554.90	1.79	0.32

4. Conclusion

In this work, performance of single channel tunable dense wavelength division demultiplexer based on one dimensional defect mode nonlinear photonic crystal has been analyzed. The proposed structure used in demultiplexing scheme is based on the 1-D non linear photonic structure with defect. In this work, tuning has been achieved by the variation of intensity of the controlling wave. Detailed analysis shows that the proposed structure is suitable for single channel wavelength division demultiplexer in multichannel DWDM systems. The proposed device may also be used as a single channel drop filters, monochromator, and it may have many applications in different optical systems.

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