Investigation of Photonic Band Gap in Si-Based One-Dimensional Photonic Crystal

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ABSTRACT

A one-dimensional silicon based photonic crystal with nonlinear defect layers is examined. The linear and nonlinear optical properties are analyzed. The transmission spectrum was obtained by applying the optical transfer matrix formalism to the photonic crystal. The various transmittance peaks obtained with the defect layers are investigated. The nature of the transmittance peak is analyzed with the number of defect layers.

Keywords: Photonic Band Gap; 1D Photonic Crystal; Si-SiO₂; Transmittance

1. Introduction

The concept of photonic crystals (PCs) was first proposed by Yablonovitch and John in 1987 [1,2], who found that using periodic arrangement of dielectric materials enables us to control the propagation of electromagnetic waves. The most significant feature of a PC is the existence of photonic band gap (PBG), a frequency range in which the electromagnetic waves cannot propagate. The PBG in a PC is analogous to the electronic band gap in a solid because of the similarity between the structural periodicity of a PC and the periodic potential energy in a solid. If the periodicity of the PC is interrupted, such as the thickness of a layer being changed [3], or another medium being added into the structure [4], some defective modes could be generated within the PBGs. In a simple one-dimensional PC of \((AB)^n\), the defect mode can be obtained in a defective structure like \((AB)^m \cdot (D/B)^n\cdot (AB)^n\), where \(D\) is known as a defected layer. The defect mode is a strongly localized defect state which, in general, can be seen in the transmission spectrum with a sharp narrow resonant peak. With the presence of resonant peak in transmittance, the structure is often used as a narrowband transmission filter [5].

The PBG structures can be used in various applications, such as add-drop multiplexers, waveguides, mirrors, and resonant cavities [6-10]. Meanwhile, the optical confinement effect in photonic crystals with defects can be exploited to enhance the nonlinear optical effect. One possible method to realize a nonlinear photonic crystal structure is to insert a nonlinear optical material between two distributed-Bragg reflectors (DBRs), where each DBR consists of alternating high- and low-index layers with quarter-wave thicknesses [11]. Another possible method is to use a nonlinear optical material as a lattice element of the photonic crystal [12].

In this research, we studied the linear and the nonlinear optical properties of a nonlinear photonic crystal: \(\left(\frac{n_d}{n_l}\right)^m \cdot \left(\frac{N_{d}^{(\text{air})}}{n_l}\right)^m \cdot \left(\frac{n_i}{n_d}\right)^m\). First, we ignored the non-linear nature of the refractive index in the defect layer and investigated the linear optical properties of the photonic crystal. The transmission spectrum was obtained by applying the optical transfer matrix formalism to the photonic crystal. Next, we investigated the transmission spectrum by including the nonlinear defect layer with the order \(m = 1, 2, 3\) and studied the shift of the transmission peaks. Then, we studied the transmission variation with the spatial optical intensity distribution inside the nonlinear defect layer.

2. Linear and Nonlinear Optical Properties of Photonic Crystals

We consider a one-dimensional photonic crystal structure, as shown in Figure 1, the structure of this photonic crys-
tual constituted of high (A) and low (B) refractive index materials with m layers of defect materials. Here the thickness of A and B, i.e., SiO₂ and Si is \(d_1\) and \(d_2\), corresponding to the materials with refractive indices \(n_1\) and \(n_2\), respectively. The concept of defect in the PBG materials has led to a large number of applications as for the semiconductor materials. The suitable thickness of Ba-TiO₃, of m layers is introduced as the defect layer in the PC. For TE wave, the characteristic matrix for a single period is given by

\[
M = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} = \prod_{j=1}^{N} M_j
\]

If the \(j^{th}\) layer is characterized by the refractive index, \(n_j\), the extinction coefficient, \(k_j\), and the thickness, \(d_j\), then the individual transfer matrix, \(M_j\), is given by

\[
M_j = \begin{bmatrix} \cos \left( \frac{2\pi}{\lambda} p_j d_j \right) + ik_j d_j & 1 \sin \left( \frac{2\pi}{\lambda} p_j d_j \right) \\ ip_j \sin \left( \frac{2\pi}{\lambda} p_j d_j \right) & \cos \left( \frac{2\pi}{\lambda} p_j d_j \right) \end{bmatrix}
\]

where \(p_j = n_j \cos \theta_j\), \(N_j = n_j + ik_j\) is the complex refractive index of the \(j^{th}\) layer, and \(\theta_j\) is the angle of incidence for the \(j^{th}\) layer. For the wavelength \(\lambda = 0.633\) μm. The overall structure remains \((HL)^{m}(DL)^{m}(HL)^{m}\), where H and L remain to be Si and SiO₂, respectively. The thickness of H and L layers remains to be 50 nm and the thickness of D layer is 150 nm. The refractive indices for A and B and defect layer are 3.45, 1.45 and 2.416 respectively [13]. Here we analysed the photonic band gap by suitable absorption mechanism. A saturable absorption-based photonic crystal is described by

\[
\left( n_s/n_j \right)^4 \left( N_d^{(NL)}/n_j \right)^4 \left( n_s/n_j \right)^4
\]

where \(N_d^{(NL)} = n_d^{(NL)} + ik_d^{(NL)}\)

\[
k_d^{(NL)} = \frac{k_d^{(L)}}{1 + 4bI}
\]

\[
\beta = \frac{\omega}{c} b = \frac{2\pi}{\lambda} b
\]

Here, \(I\) is the laser-beam intensity at the sample position, and \(\beta\) is the nonlinear absorption coefficient that characterizes the saturable absorption of the nonlinear defect. To compute the defect mode in the transmission spectra, we employ the transfer matrix method (TMM) [14]. The transmission coefficient for tunneling through such as structure is given by

\[
t = \frac{4}{(m_{11} + m_{22})^2 + (m_{12} + m_{21})^2}
\]

We now turn our attention to the voltage dependence of the defect modes with a nonlinear optical material, namely BaTiO₃.

### 3. Results and Discussion

The photonic crystals consisting of Si-SiO₂ with defect layer is analysed. The schematic diagram of 1D photonic crystals is shown in Figure 1. Here, we have studied both linear effect and nonlinear effect of the photonic crystal. It was found that a photonic gap exists in the above said photonic crystal without the defect layer as suggested by some recent literature [16]. It is shown in Figure 2. The value of the gap was found between 427 nm and 630 nm. We also found that when we introduce a defect layer BaTiO₃/SiO₂ in the above said photonic crystals, an additional mode of propagation is obtained in the photonic band gap. The photonic band gap is between 420 nm and 665 nm. It can be seen that there is a sharp transmission peak at 552 nm in the gap as shown in Figure 3. The transmission peak is caused by the defect state. When the order of the defect layer increases such as \(m = 2, 3, 4\) etc, additional modes occurs in photonic band gap as shown in Figures 4 and 5. When the number of defect layers increases one of the transmittance peak goes to higher values. It almost reaches the maximum value of 1. The variation of maximum value of the transmittance.
peak with number of defect layers is plotted in Figure 6. This value of transmittance peak occurs at various wavelengths with the number of defect layers as shown in Figure 7. It is also observed there is no such variation occurs in the photonic band gap width. When the nonlinear effect is included, we observed a slight variation in the transmittance peak. For \( m = 1 \) with a structure of \( \left( \frac{n_h}{n_l} \right)^4 \left( \frac{N_d}{N_d^{(NL)}} \right)^m \left( \frac{n_l}{n_h} \right)^4 \), the voltage dependence of the transmittance peak in the PBG is analysed. The wavelengths of peaks are summarized in Table 1.
Table 1. The wavelengths of peaks for \((n_0/n_h)^4/(N_d/(n_0)/n_l)^1/(n_l/n_h)^4\).

<table>
<thead>
<tr>
<th>External applied bias (kV)</th>
<th>Wavelength of the transmittance peaks</th>
</tr>
</thead>
<tbody>
<tr>
<td>-30</td>
<td>610 nm</td>
</tr>
<tr>
<td>0</td>
<td>552 nm</td>
</tr>
<tr>
<td>30</td>
<td>490 nm</td>
</tr>
</tbody>
</table>

4. Conclusion

The linear and nonlinear optical properties of nonlinear photonic crystal are studied. The various transmittance peak occurrence is analyzed with the defect states. The defect states in the photonic crystal introduce additional modes in the photonic band gap. When the applied voltage increases the wavelength at which the maximum transmittance peak occurrence decreases. This can be greatly applied in many fields such as diode laser, non-threshold laser, dense wavelength division multiplex and PC fiber as well as the multichannel transmission filter.

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REFERENCES


