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THEORETICAL DESIGN TE-POLARIZATION ONE-DIMENSIONAL PHOTONIC CRYSTAL

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ABSTRACT

Optical properties of photonic crystal structures have attracted great interest in research area and industry field because of its capability to guide and control light propagation in compact device with feature sizes comparable to light wavelength. In this paper we describe theoretical analysis and design of one dimensional photonic crystal which has refractive index ($n_1 = 1.45$ and $n_2 = 3.45$). The program is written in MATLAB to simulate and analysis dispersions of electromagnetic waves in one dimension photonic crystal for s-polarization states. The one dimension photonic crystal has a unit cell made of different dielectric materials. The propagation angle in one medium is taken with respect to normal inside the first medium varies between 0 and $\pi / 2$.

Keywords: One Dimensional Photonic Crystal, Complete Photonic Band Gap, Group Velocity, Density of States

INTRODUCTION

A photonic crystal is a material in which the refractive index is periodically modulated on a length scale comparable to the desired operation wavelength. It is said to be a “crystal” because it is formed by a periodic arrangement of basic building blocks. The term “photonic” is added since photonic crystals are designed to affect the propagation properties of photons.

In general, the wave propagation is importantly affected when it enters into a material where some feature that concerns this wave is modulated. The wave scatters coherently at the interfaces between different featured regions. In the case of photons this feature is refractive index. For other systems propagating as waves, such as sound or electrons within a semiconductor, these features are the Young’s module and the electric potential respectively. The behavior of a photon with a certain frequency will depend on the propagation direction within the photonic crystals. The modulation of the refractive index will cause that certain energies and directions are forbidden for photons. A region of energies where the photonic crystal does not allow photons to propagate regardless of their direction and polarization is called a complete photonic band gap (cPBG) [1, 2].

Photonic crystals are said to be one-dimensional (1D) if the electric permittivity varies and is periodic in only one spatial variable, z and does not depend on x and y [3]. The idea of photonic crystals started from the notion of Bragg condition in periodic structures under which light at particular wavelengths completely reflects off such structures. As shown in Fig.1. It is this periodicity in the refractive index that gives rise to the condition under which certain wavelengths can pass through, while a select wavelength is reflected. These frequency gaps, where the propagation of electromagnetic waves is forbidden, are defined as photonic

band gaps. One dimensional crystals are periodic in only one axial direction, such as a stack of alternating refractive index planar dielectric layers [4,5].

We were motivated to explore 1D photonic crystal because (1) their structures are exceedingly simple and therefore easier to fabricate and design, and, (2) their highly anisotropic photonic band structures can lead to ultra-refraction. Fig. 1 consists of a periodic stack of alternating layers of two materials with different layer thickness (a and b) and relative permittivities (ε_a and ε_b). The period is given by $a + b = d$. In principle, there could be more than two layers per (repeating) period. The analysis described here also applies to structures having more than two layers per period. We will show that light propagating inside the photonic crystal with frequencies just outside the photonic band gaps can indeed exhibit ultra-refractive behavior. Moreover, this unconventional refraction property effectively can be used for wavelength dispersion over entire photonic bands, rather than just near the band edges [5]. It is because of this contrast between the dielectric constants of two neighboring layers that photonic band gaps exist [4].

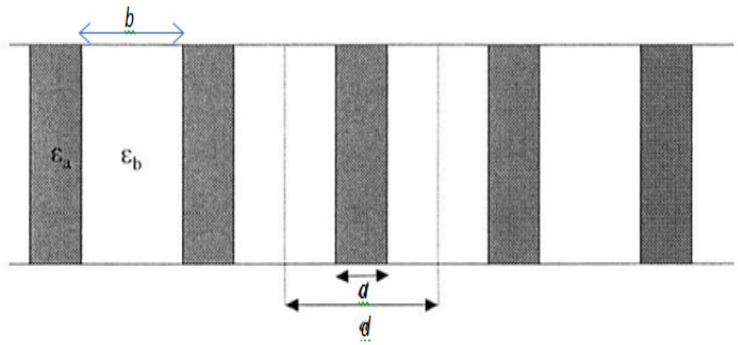

Fig. 1 A schematic view of one-dimensional photonic crystal dielectric structure [4].

When a collimated light ray of wavelength λ in a homogeneous medium (e.g. *air)* reaches the surface of the 1D photonic crystal at an incidence angle θ_{inc}. For simplicity we consider the case where the direction of wave propagation is restricted in the xy plane (Fig. 2). After entry into the photonic crystal, the light ray propagates at an angle of refraction θ_{pc}. To compute the relationship between θ_{inc} and θ_{pc} for a given wavelength, we match the frequency and tangential component of the wave vector for the incident and refracted wave across the interface using the following simple procedure. We specify the angular frequency $\omega = 2\pi f$ (f is the frequency of light) and the incidence angle θ_{inc} in the homogeneous medium. Using the relationships $\varepsilon_r \omega^2 = k_x^2 + k_y^2$ and $\tan(\theta_{inc}) = (k_y / k_x)$ we can find the wave vector in the incident medium. Here ε_r is the relative permittivity of the incident medium, and k_x and k_y are the components of the wave vector perpendicular and parallel, respectively, to the interface between the homogeneous medium and the photonic crystal. (We assume $k_z = 0$ for simplicity.) We can compute the 1D photonic crystal dispersion relationship, or photonic band structure. The angular frequency ω and the parallel component of the wave vector k_y, are the same as those in the incident homogeneous medium. The transfer matrix technique allows us to find the perpendicular component of the wave vector k_x in the photonic crystal. From $\omega(k)$ we can then compute the photonic crystal group velocity using $v_g = \nabla_k \omega(k) = (\partial\omega(k)/\partial k_x, \partial\omega(k)/\partial k_z, \partial\omega(k)/\partial k_z)$. From the components of the group velocity we can determine the angle of refraction using $\theta_{pc} = \tan^{-1}(v_{g-y} / v_{g-x})$ [5].

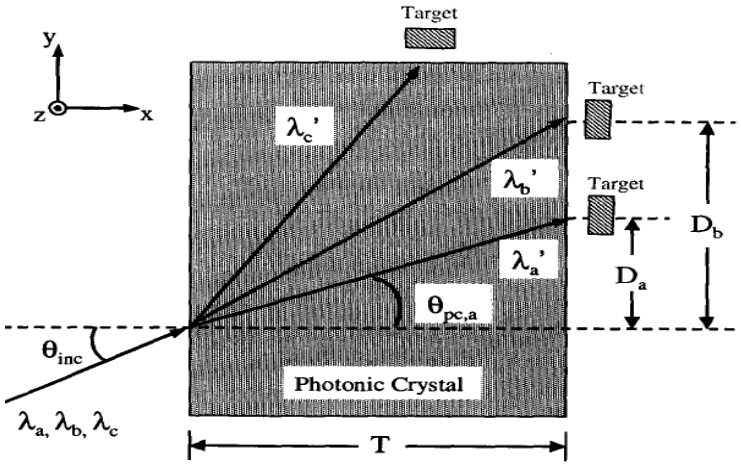

Fig. 2 Illustration of how a 1D photonic crystal might be used to disperse light of different wavelengths [5].

DENSITY OF PHOTONIC STATE IN 1D-PHOTONIC CRYSTAL

The concepts of density of states (DOS) have proven essential in the study of electromagnetic wave propagation through periodic structures. The DOS is usually defined as [6]:

$$N(\omega) = \sum_m \frac{1}{A_{BZ}} \int_{BZ} \delta(\omega - \omega_m(k)) d^2k \ldots (1)$$

where the integral is taken over the $m-th$ band and A_{BZ} is the area of the Brillouin zone (BZ). Eq. (1) can also be written as [6]:

$$N(\omega) = \sum_m \frac{1}{A_{BZ}} \int_{EFS_m} \left\| \frac{dk}{d\omega} \right\| ds \ldots (2)$$

where the integral is taken along the $m-th$ equifrequency surfaces (EFS) at frequency ω and $v_g^{-1} = dk/d\omega$ is the inverse group velocity. The DOS was first used in understanding the modification of spontaneous emission in photonic crystals. The DOS plays an important role in light trapping for solar cells and in mode confinement in photonic crystal structures. Existing methods for computing EFSs first compute the full band surface over the BZ, and then extract the EFSs as contours or surfaces from the bands. These methods are slow as they require a fine sampling of the BZ in order to accurately resolve the EFSs. Moreover, if the EFSs at a single frequency or a narrow range of frequencies are desired, then computing the full band structure represents a significant waste of effort since only those bands near the frequency of interest are needed. There are related problems in existing methods for computing the DOS of a photonic crystal. The definition in Eq. (1) suggests the typical method by which the DOS is computed: using the full band structure and binning by frequency to approximate the integral. The frequency binning method can be improved if the group velocities are also available. The DOS can also be obtained from the local density of states by an integral over the real space unit cell or from the angular density of states by an integral over the BZ. These integration methods are computationally intensive since they require repeated computation of Green's functions in the process of performing the integration [6, 7].

SIMULATION RESULT AND DISCUSSION

We proceed with the calculation of fields for TE modes. MATLAB is a great and easy tool to use to simulate optical electronics. All the results below are got after following these steps:

1. Calculate the transmittance function.
2. Implementation of dispersion relation of electromagnetic waves in 1D photonic crystal.
3. Found the normalized frequency.
4. Found the ray angle with respect to normal inside 1st medium varies between 0- $\pi/2$ and inside the 2nd medium using Snell law ($n_1 = 1.45$ and $n_2 = 3.45$). Then transform incidence angle in degrees.
5. Select points which belong to the forbidden bands.
6. In order to compute the DOS we found the inverse group velocity at each sample point and then the DOS can be directly obtained using Eq. (2).

Fig. 3 is about the transmittance function versus wavelength. Mean=0.6852, median=0.8584, mode=0.0001093 and the standard deviation (STD) =0.368. The magnitude of transmittance is go downing under within the range of infrared. Fig. 4 shows forbidden bands s-polarization, it explain the relationship between incidence angles versus normalized frequency. The incidence angle is an important parameter which affects the width of band gaps. The mean= 0.5603, median= 0.5957, mode= 0.245 and the STD= 0.2494. The thicknesses and the index contrast of the photonic crystal determinate many of its optical properties. Playing on these two parameters, we can obtain frequency ranges for which light propagation is forbidden in the material and others ranges for which light can propagate. These frequency ranges are also scale dependent. Reducing the size of the elementary cell of the periodic lattice shifts the whole frequency range to higher values. The consequence of this property is the possibility to transpose a photonic crystal design from the microwave domain to infrared or visible range. Fig. 5 represents the relationship between the normalized frequencies versus density of state for E-polarization.

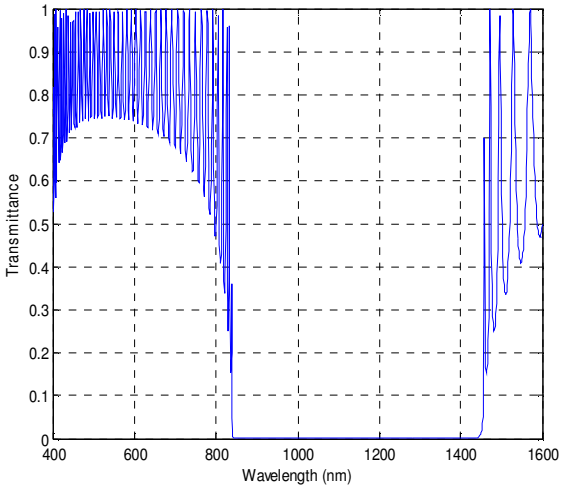

Fig. 3 Transmittance versus the wavelength. Observe there is a region near wavelength= 11250, with vanishing transmittance. This region is called the band gap.

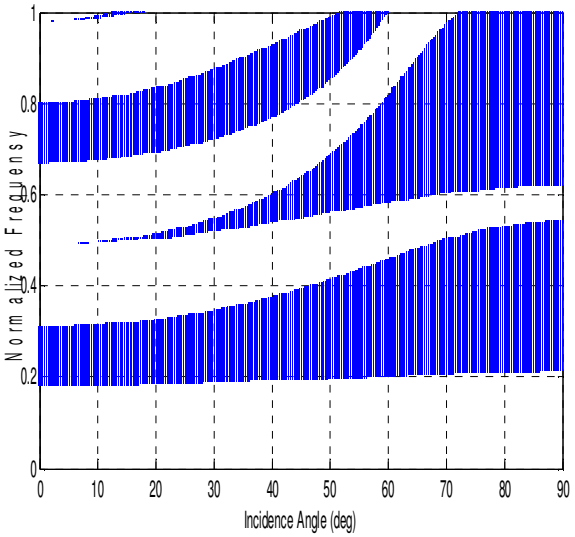

Fig. 4 Incidence angle versus normalized frequency. It shows the forbidden bands for s-polarization.

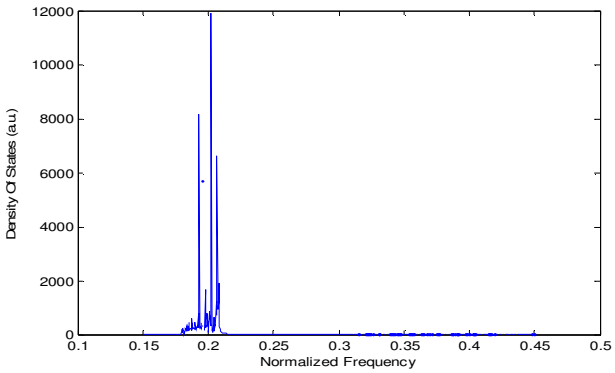

Fig. 5 Density of state versus normalized frequency. Minimum, maximum DOS are between =0.005774 to infinity.

CONCLUTION

The research presented in this paper focuses on planar one dimensional photonic structures. A 1D planar photonic crystal structure consists of alternating layers of material with different dielectric constants ($n_1 = 1.45$ and $n_2 = 3.45$). It has been shown that the larger the difference between the two indices the wider the band gaps become. Also, as the width of the air layers become smaller in comparison to the width of the dielectric layers, the width of band gaps would decrease. The angle of incidence of the light wave is also another factor which effects the width of band gaps.

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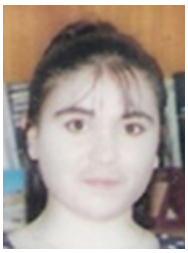

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