Photonic Crystals as Omnidirectional Infrared Reflector

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1. INTRODUCTION

Photonics is the study of the creation, control and detection of photons. The topic is of increasing interest because of projected value in new types of sensor and computing devices (Joannopoulos et al., 2008). Photonic band gap materials, also known as photonic crystals are materials which have a band gap due to a periodicity in the materials dielectric properties, shown in yellow in Figure 1. In this gap, light cannot enter the crystal and electrons cannot emit photons inside the crystal (Johnson et al., 2007). These phenomena will permit a perfect control of light propagation and radiation, thus, photonic band gap crystal acts as an insulator of light (Daniel and Peter, 2007) as shown in Figure 2. Photonic crystals can affect propagation in one, two and three dimensions, as illustrated in Figure 3.

ABSTRACT

In the present work, design and analysis of the complete omnidirectional Bragg reflector are described. Transfer matrix method (TMM) was adopted to study the unique direction spectral performance of this structure for application in the infrared spectral region (8-14μm). It was shown that omnidirectional 1D-photonic bandgap could be simply evaluated and broadened using graphical and flexible optimization methods, named as needle optimization technique. Thus, a complete wideband 1D-photonic omnidirectional reflector was achieved despite the fact that the periodicity was only in one direction.

Keywords:
Photonic Crystal
Omnidirectional reflector
Distributed Bragg reflectors
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Lord Rayleigh was the first scientist who study the propagation of electromagnetic waves in periodic structured media in 1887 (Johnson et al., 2007). He studied the reflective properties of a crystalline mineral that corresponded to a one-dimensional (1-D) photonic crystal. He observed a small band gap, through which light could not propagate through the planes of the crystal. Photonic crystals possess two types of polarizations by symmetry: the transverse magnetic (TM) in which the electric and magnetic fields are orthogonal to one another, and the transverse electric (TE) in which the electric and magnetic fields are in the same plane. By judicious placement of materials with different high and low indices inside an area or volume, hypothetical TE and TM band gap materials may be created (Joannopoulos et al., 2008), (Johnson et al., 2007). An omnidirectional photonic bandgap in one dimensional photonic crystal were studied using simple transfer matrix method (Kim and Hwangbo, 2002), (Macleod, 2001), (Southwell, 1999). Omnidirectional bandwidth was calculated by use of quarter-wave stacks with a low refractive index of 1.7 and high refractive index of 3.4 in the infrared and widened, by connecting the omnidirectional mirrors (Winn et al., 1998). A high reflection mirror for both s-(TE-) and p-(TM-) polarized light from normal to grazing incidence was studied by analysis of the Bloch wave equation for a dielectric multilayer structure. The forbidden photonic band gap was investigated in terms of angular frequency as a function of the propagation wave vector parallel to the interface (Winn et al., 1998), (Yablonovitch, 1998). Also, the reflector was fabricated as a quarter-wave stack of polystyrene (low refractive index of 1.6) and tellurium (high refractive index of 4.6) films in 10-15 µm of infrared spectrum (Fink et al., 1998).

This stack can be used as a perfect mirror inside walls of high-finesse waveguides, and air-guiding hollow optical fiber. Various applications of the omnidirectional high reflectors as a one-dimensional photonic band gap structure may be expected to improve the performance of photonic devices and thermal IR radiation control (Kawanishi and Izutsu, 2000), (Srivastava et al., 2010), (Lazarova et al., 2014). For optimizing the design of multilayer mirrors, only more sophisticated techniques started to be used: include downhill simplex algorithm, the simulated annealing systematic search in parameter space, the simulated annealing, genetic algorithms and quasi-Newton algorithm (You et al., 2004). Recently, design and evaluation of distributed Bragg reflector from 1D photonic crystal using Zemax And Teraplot was studied to function in visible and NIR spectral region (Rashid and Ali, 2017).

The aim of this paper is to describe a design procedure for a wideband omnidirectional reflectors based on 1D- photonic to be applied in the mid infrared using the transfer matrix method (TMM) and the needle variation technique (Tikhonravov, 1993), as a synthesis optimization method associated with quasi-Newton algorithm.

2. THEORY DESIGN

2.1. Band Edges and Reflectance of a Dielectric -Wave Stack

A high reflectance coating can be designed by the use of alternative high and low refractive index materials. The basic period can be (HL) or (LH), in which H and L denote the quarter-wave optical thickness of high and low refractive index materials, respectively. If the refractive index and the thickness of two materials are represented as \((n_H, d_H)\) and \((n_L, d_L)\), respectively, the TM of the basic
period (HL) at an incident angle of medium of refractive \( n_0 \) is given as (Macleod, 2001),

\[
\begin{pmatrix}
\cos \delta_H \\
\sin \delta_H \\
\sin \delta_L \\
\cos \delta_L
\end{pmatrix} =
\begin{pmatrix}
\cos \theta_H \\
\sin \theta_H \\
\cos \theta_L \\
\sin \theta_L
\end{pmatrix} \begin{pmatrix}
\cos \theta_H \\
\sin \theta_H \\
\cos \theta_L \\
\sin \theta_L
\end{pmatrix}
\]

Where \( \delta_H \) and \( \delta_L \) are the phase thicknesses of the high index, \( n_H \), and low index, \( n_L \) materials, respectively. It can be expressed as:

\[
\delta_j = \frac{2\pi}{\lambda} n_j d_j \cos \theta_j 
\]

Where \( \eta_H \) and \( \eta_L \) are the effective refractive index (or, the optical admittance) of the \( n_H \) and the \( n_L \) layers, respectively, given by:

a) For \( s \)-polarization light:

\[
\eta_j = n_j \cos \theta_j 
\]

b) For \( p \)-polarization light:

\[
\eta_j = n_j / \cos \theta_j 
\]

Where \( j=H \) or \( L \), and \( \theta_j \) is the angle of refraction in the \( j \)th layer determined by Snell's law, \( n_j \sin \theta_j = n_j \sin \theta_j \), and

\[
\cos \theta_j = \sqrt{1 - \left( \frac{n_j \sin \theta_j}{n_j} \right)^2}
\]

Reflectance of an assembly for normal and oblique incidence can be expressed in terms of amplitude electric \( E \) and magnetic \( H \) vectors of the surrounding media ( \( \eta_{q+1} \) and \( \eta_{sub} \)) and for \( q \) multilayer (Macleod, 2001),

\[
R = \left| \frac{E_{q+1}^* H_{q+1} - H_{q+1}^* E_{q+1}}{E_{q+1}^* H_{q+1} + H_{q+1}^* E_{q+1}} \right|^2
\]

Where,

\[
\begin{pmatrix}
E_{q+1} \\
H_{q+1}
\end{pmatrix} = M_q M_{q-1} M_{q-2} \ldots \ldots M_1 \begin{pmatrix}
E_0 \\
H_0
\end{pmatrix}
\]

The edge of high reflectance band can be represented by the condition (Kim and Hwangbo, 2002), (Macleod, 2001),

\[
\frac{M_{11} + M_{22}}{2} = -1 
\]

With the aid of equation (1), the condition can be expressed as:

\[
\cos \delta_H \cos \delta_L - \frac{1}{2} \left( \frac{\eta_L}{\eta_H} + \frac{\eta_H}{\eta_L} \right) \sin \delta_H \sin \delta_L = -1
\]

By simplifying the above equation, the bandwidth \( \Delta \lambda \) can be modified from its usual normal incidence definition (Macleod, 2001), to include the dependence on effective refractive index values to account the different polarization states.

\[
\Delta \lambda = \frac{1}{2} \sin^{-1} \left( \frac{\eta_H / \eta_L - 1}{\eta_H / \eta_L + 1} \right), \quad \lambda = \text{TE and TM} 
\]

2.2. Center Wavelength of Omnidirectional Reflection Band

The condition for optimum reflection (omnidirectional), called Bragg condition, from a low and a high refractive index layer pair at a given angle and polarization, is that the optical thickness should be one-half wavelength at the center of the stop band (Southwell, 1999).

\[
\frac{\lambda_c}{2} = \eta_L d_L + \eta_H d_H 
\]

Using the condition that the physical thickness of each layer is a quarter wave at the design wavelength \( \lambda_c \), i.e.

\[
\eta_L d_L = \eta_H d_H = \frac{\lambda_c}{4}
\]
Substituting equation (8) into equation (7), then \( \lambda_c \) for TE- and TM- polarization light can now be written as:

\[
\lambda_c = \frac{\lambda_0}{2} \left[ \cos \theta_L + \cos \theta_R \right] \quad \text{for TE - polarization}
\]

\[
\lambda_c = \frac{\lambda_0}{2} \left[ \sec \theta_L + \sec \theta_R \right] \quad \text{for TM - polarization}
\]

Equations (9) and (10) indicate how the center of the reflectance band shifts with angle of incidence for a quarter-wave stack.

### 2.3. Bandwidth of Omnidirectional Reflectance

From Fig. 4, the normalized omnidirectional bandwidth \( B \) with respect to design wavelength \( \lambda_0 \) of the omnidirectional band is (Kim and Hwangbo, 2002), (Macleod, 2001), (Southwell, 1999)

\[
\frac{\Delta \lambda_{\text{omni}}}{\lambda_c} = 2 \frac{\lambda^P_{\text{long}}(90^\circ) - \lambda_{\text{short}}(0^\circ)}{\lambda^P_{\text{long}}(90^\circ) + \lambda_{\text{short}}(0^\circ)}
\]

(11)

Were the omnidirectional bandwidth is given by:

\[
\Delta \lambda_{\text{omni}} = \lambda^P_{\text{long}}(90^\circ) - \lambda_{\text{short}}(0^\circ)
\]

And the center wavelength in the omnidirectional band is given by:

\[
\lambda_c = \left[ \lambda^P_{\text{long}}(90^\circ) + \lambda_{\text{short}}(0^\circ) \right] / 2
\]

Then the edge \( \lambda_E \) (longer and shorter) of the reflection band is given by:

\[
\lambda_E = \lambda_c [1 \mp \Delta g]
\]

The longer -wavelength edge of the omnidirectional reflection band is determined by the longer-wavelength TM - reflection edge at 90° angle of incidence, which was called \( \lambda_{\text{long}} \) and the short-wavelength reflection band edge at 0°, which was called \( \lambda_{\text{short}} \). Thus

\[
\lambda_{\text{long}} = (\lambda_c)_{90^\circ} [1 + (\Delta g)_{90^\circ}]
\]

\[
\lambda_{\text{short}} = (\lambda_c)_{0^\circ} [1 - (\Delta g)_{0^\circ}]
\]

(12)

(13)

The omnidirectional reflectance band width, \( B \) can now defined:

\[
\Delta \lambda_{\text{omni}} = \frac{\lambda_{\text{long}} - \lambda_{\text{short}}}{1/2 \left( \lambda_{\text{long}} + \lambda_{\text{short}} \right)}
\]

(14)

From the above equations, an expression of omnidirectional band width \( B \) in terms of high and low index values \( n_H, n_L \) will be:

\[
\Delta \lambda_{\text{omni}} = \frac{\lambda^P_{\text{long}}(90^\circ) - \lambda_{\text{short}}(0^\circ)}{1/2 \left( \lambda^P_{\text{long}}(90^\circ) + \lambda_{\text{short}}(0^\circ) \right)}
\]

(15)

### 2.4. Needle Synthesis Technique

Needle optimization is active synthesis method which works by addition of a new zero-thickness layer in to a coating design. After the new zero-thickness layer has been added, variable metric or quasi-newton local optimization method is used to improve the new design. If the zero-thickness layer has been placed in the correct position, the local optimization method will force the new layer to grow. This method may improve the existing design, but it seems to work best when it starts with a single layer.

### 2.5. Merit Function

Almost all numerical methods for the design of an optical multilayer were based on the use of merit function, which is a single value that express the current performance of the system and direction of the flow for future
calculation. So, the optimize design command tells the program to vary the thickness of the layers or their position, so that the merit function is minimized. In the present work, we have used a well-known merit function, Dobrowolski and Kamp, as given below:

$$M_F = \left[ \frac{1}{m} \sum_{i=1}^{m} \left( \frac{Q_{i}^T - Q_{i}^C}{\delta Q_{i}} \right)^2 \right]^{1/2}$$

Where $m$ is the number of target, $Q_{i}^T$ is the desired target value, $Q_{i}^C$ is the computed value of reflectance at the target wavelength and polarization mode, $1/\delta Q_{i} = w_{i}$ is the "weight" and $\delta Q_{i}$ is the tolerance.

3. RESULTS AND DISCUSSION

3.1. Reflectance of Quarter-Wave Stack at Oblique Incidence

The reflectance of $s$- and $p$-polarization light of a quarter-wave stack

Air [LH]$^{10}$ ZnSe

are shown in Figure.5 as a function of wavelength and incident angle. The design wavelength was 10 µm, high and low index materials were 3.4 and 1.7, respectively, deposited on substrate of index 2.4. The effective index values for the two materials change differently (eq.3). So, the center wavelength $\lambda_c$ of both reflection band shifts to the shorter wavelength region with different values of $s$- and $p$-polarization depending on the behaviour of the circular functions $\cos \theta$ and $\sec \theta$ [eq.9 and 10]. Furthermore, the phase thickness [eq.2] seems to be thinner as the angle of incidence increases, this will affect the band width of reflector, i.e. the TE-reflection bandwidth is broader than that at normal incidence, whereas the $p$-polarized bandwidth is narrower, this is due to change in $\Delta \varepsilon$ for both TE – and TM-polarization states [eq.6].

Photonic band gap was easily found graphically using Teraplot software, as shown in Figure 6. In this Figure, reflectance contour map was plotted versus wavelength and angle of incidence for both TE - and TM – polarizations. The red color regions in reflectance spectra for both TE and TM region represent photonic bandgap. The region between the two dashed lines, represent the forbidden wavelength range ~2µm, where light at any incident angle is perfectly reflected, i.e. omnidirectional band gap have been inspired.

3.2. Wideband Width Omnidirectional High Reflector

Introducing the "matching" concept, Omnidirectional bandgap was extended to cover the normal wavelength band as shown in Fig.7. To overcome the appearance of apparent phenomena due to oblique incidence, i.e. the blue shift in reflectance spectrum and limited photonic bandgap, two concepts were adopted, namely, matching optical thickness to normal incidence and the use of the optimization method.

At $85^\circ$ the basic period normalized to normal will be $[1.2341L, 1.0459H]$ and the reflectance is as shown in Figure 7.

To extend the omnidirectional bandwidth, the basic requirements for the design and synthesis were:

1. A program for computing the reflectance of a multilayer system with specified layer thicknesses and refractive indices entailing the evaluation of (2x2) matrix products of the form given by equation (1).
2. A means of companying the resultant reflectance at each wavelength with those of specified values (i.e. MF).
3. A systematic method of adjusting the design parameters so that the suitably chosen function for the differences is minimized.

Then the computation of the reflectance was going on as a function of layer thickness and number of layers with a prior information about the optimum condition close to design:

```
Sub/1.4936L1.288H0.5835L0.2714H0.3678L0.
4507H1.897L1.583H1.1886L1.3275H0.7035L
1.3647H0.6639L0.1079H0.4722L1.5992H1.40
55L1.0379H1.236L0.9909H1.112L1.171H
1.49L1.3096L1.084H1.4182L0.5644H0.4792L
0.8801H /Air
```

Therefore a remarkable improvement in the performance of omnidirectional reflector band for both grazing angles and the two modes of polarization, was achieved as shown in Fig.8, where the reflected rays from the stack were nearly in phase. Thus, a constructive interference was obtained within the wavelength range (8-13 µm), i.e. a complete omnidirectional photonic band gap was ~ 5 µm.

4. CONCLUSION

Quarter-wave stacks do remarkably well in providing omnidirectional 1D-photonic bandgap. The omnidirectional reflection band was broading when the matching thickness of layer was implemented as a starting design in the optimization method. In addition, results show that the proposed optimal strategy is independent of the particular example under study and in some cases produces design which was not readily amenable to solution by other known techniques. This method can be easily extended to other materials and wavelengths and predicts optimum thickness that can depart from the usual quarter-wave design to yield high performance 1D-photonic band gap.

Figure 1: Depiction of sample photonic band gap. (Yellow shaded region shows a photonic band gap on a photonic band diagram. The letters along x axis represent the different directions along the crystal lattice (Johnson et al., 2007).

Figure 2: Simulation showing how light will propagate in a photonic crystal. This can be used to guide the light in different directions (Daniel and Peter, 2007).

Figure 3: Simplified representation of one-, two- and three-dimensional crystals (Joannopoulos et al., 2008).
Figure 4: Schematic diagram showing the omnidirectional reflector parameters compared with high reflectance mirror at normal incidence for TM-polarization radiation.

Figure 5: Reflectance vs. wavelength and angle of incident, for the design: Air|LH|^{10}ZnSe, (A) TE-polarization, (B) TM-polarization.
Figure 6: Computing omnidirectional bandgap graphical method using Teraplot software.

Figure 7: Elimination of blue shift in $R_p$ spectrum using matching concept.

Figure 8: Optimum design of omnidirectional 1D-photonic bandgap
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