Int. J. Electron. Commun. (AEÜ) 68 (2014) 865–868

Contents lists available at ScienceDirect

International Journal of Electronics and Communications (AEÜ)

journal homepage: www.elsevier.com/locate/aeue

LETTER

A fast and accurate design method for broad omnidirectional bandgaps of one dimensional photonic crystals

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ARTICLE INFO

Article history:
Received 13 October 2013
Accepted 31 March 2014

Keywords:
One dimensional photonic crystals
Omnidirectional bandgap design

ABSTRACT

A fast and accurate novel design method is proposed for the design of broad omnidirectional bandgaps of one dimensional (1-D) photonic crystals (PCs). Presented method is verified with various numerical examples for 1-D photonic crystals which consist of a cascade of two quasi-periodic stacks and broad omnidirectional bandgaps are achieved. Furthermore, computation time requirement of the presented method is considerably less than that required for purely numerical approaches. The proposed algorithm is quite flexible and can easily be modified to address problems involving 1-D PCs consisting of three and more cascaded stacks and specific 2D PC structures.

1. Introduction

Dielectric and metallic mirrors have been widely used for optical devices. Dielectric mirrors which consist of multilayered dielectrics are preferred instead of metallic mirrors due to their low power loss at infrared and optical frequencies [1]. Electromagnetic wave propagation in multilayered dielectrics have been investigated in the literature [2,3]. Omnidirectional reflectivity properties of these structures have been reported in [1,4–6]. Photonic crystals yield almost perfect mirrors, providing very high reflection for any polarization and incidence angle within a specified frequency range. It has been shown that 1-D PCs are sufficient to exhibit a complete omnidirectional photonic bandgap [4–6] and they are widely used for dielectric mirrors [1,4,7]. Experimental results for total omnidirectional reflections in one dimensional photonic crystals are also given in [1,5].

In order to obtain broad omnidirectional bandgap (OBG), many methods have been proposed based on frequency domain methods and incidence angle domain methods [8–12]. Frequency domain methods require choosing materials which have larger dielectric contrast. Later, cascade connections of two or more periodic structures with different periods are used for broad omnidirectional bandgap design as an effective method. Such structures consisting of two or more incommensurate periods will be denoted as quasi periodic. Incidence angle domain methods require using lower refractive index materials and result narrow omnidirectional bandgaps with respect to frequency domain methods. Genetic algorithms have been used for the optimization process of many parameters of PCs which include two or more quasi periodic structures. Genetic algorithms have been used to design PCs for larger bandgap [13–15], and for broad omnidirectional reflectors [16,17]. Quasi periodic stacks overlap their reflection bands in the frequency domain or incident angle domain and yield broad omnidirectional bandgaps. In order to obtain larger omnidirectional bandgap a cascade of two or more quasi periodic PCs with different unit cell parameters are used in the design process [8,9,16]. Extending the omnidirectional relative bandwidth (ORB) of 1D PCs have been investigated in available literature and reported ORB values are 41.33% [9], 91.65% [8], 91.72% [16] when using four ([9]) and two ([8,16]) cascaded quasi periodic stacks. ORB values between 70.36% and 116.33% are obtained using cascades of 3 or 4 quasi periodic structures [17]. The methods given in [9,13–17] are directly based on genetic algorithms.

Conventional method to determine photonic bandgaps of 1D PCs is based on solution of an eigenvalue equation [3]. Later, the design specifications are realized by numerical or heuristic approaches which are generally not efficient as [13–17]. As an alternative method, photonic bandgaps of 1D dielectric PCs using scattering matrix approach have been determined without solving an eigenvalue equation as shown in [18]. Photonic bandgaps are determined and designed effectively by calculating two roots of analytic auxiliary functions (X_+ and X_-) with the proposed method in [18]. In this paper, it has been shown that the auxilary functions presented in [18] can effectively be used in the design of quasi periodic PCs for broad omnidirectional bandgaps with the proposed algorithm.

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http://dx.doi.org/10.1016/j.aeue.2014.03.015
1434-8411/

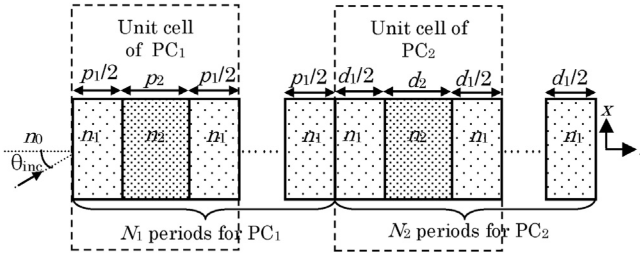

Fig. 1. Geometry of an 1-D omnidirectional reflector.

2. Theory

An omnidirectional reflector geometry is given in Fig. 1. Reflector combines two quasi-periodic stacks (PC_1 and PC_2) with symmetric unit cells. Each quasi-periodic stacks consist of two kinds of materials with refractive indexes of n_1 and n_2 and lengths of ($p_1/2, p_2$) and ($d_1/2, d_2$). PC_1 and PC_2 include N_1 and N_2 cascaded unit cells with the period's ($p_1 + p_2$) and ($d_1 + d_2$), respectively, shown in Fig. 1. Dielectric properties of media are invariant in the transverse (x, y) plane. It is assumed that TE/TM plane wave is incident with a θ_{inc} angle with respect to surface normal.

Two auxiliary functions (X_+ and X_-) can be used to directly determine band edge frequencies of photonic bandgaps of 1-D PCs observing zero transitions of the imaginary part of $S_{11} \pm S_{21}$ at band edge frequencies. The functions X_+ and X_- are defined as given in [18]

$$X_{\pm} = \mathrm{Im}\{S_{11} \pm S_{21}\} \tag{1}$$

where S_{11} and S_{21} are scattering parameters of symmetric unit cell and their analytic expressions are given in [18]. Expressions of X_+ and X_- are derived from the band edge conditions for the eigenvalue equation of 1D PC in terms of scattering parameters. The roots of X_+ and X_- yield exact values at the band edge frequencies of 1D PC and can be calculated efficiently in the interested frequency region due to well behaved functions. Therefore, by observing zero passing's of X_+ and X_- functions at band edge frequencies, unit cell dimensions of PC_1 and PC_2 (p_1, p_2, d_1, d_2) for chosen materials can be determined for given bandgap characteristics.

For normal incidence TE and TM waves will reduce to the same solution. However, when the incidence angle is increased, gap of *TE* wave increases whereas the gap of TM wave decreases [1]. As a result, determination of TM wave solutions at grazing and normal incidences is sufficient to design omnidirectional bandgap of 1D-PCs. Therefore, we will only focus on solutions of TM waves at grazing and normal incidences.

Following algorithm is proposed as a design approach for broad omnidirectional bandgaps of 1D PCs:

i. Consider construction of hybrid structure using two quasi periodic 1-D PCs with broad omnidirectional bandgap around ω_0 frequency.
ii. Choose dielectric materials which have larger dielectric contrast for symmetric PC unit cells of PC_1 and PC_2.
iii. Using zero passings of X_+ and X_- functions given in (1), determine solution set of PC_1 for unit cell dimensions which satisfy stopband at the center frequency (ω_{c1}) which is 15–40% lower than ω_0 for TM wave with 90° incidence angle. Choose appropriate solution (p_1, p_2) for the unit cell parameters of PC_1 which gives largest stopband for TM 90° and upper edge frequency of the gap, ω_1, lies around ω_0.
iv. Using zero passings of X_+ and X_- functions given in (1), determine solution set of PC_2 for unit cell dimensions which satisfy stopband at the center frequency (ω_{c2}) which is 15–40% higher than ω_0 for TM wave with 90° incidence angle. Choose appropriate solution (d_1, d_2) for the unit cell parameters of PC_2 which gives largest stopband for TM 90° and lower edge frequency of the gap, ω_2, lies around ω_0.
v. Upper edge frequency of PC_1 for TM 90° case should overlap lower edge frequency of PC_2 for TM 90° case. If the frequency overlap ($\omega_1 \geq \omega_2$) does not occur for PC_1 and PC_2 with TM 90° case, repeat step iii and iv by changing ω_{c1} and ω_{c2}.
vi. Omnidirectional bandgap of total hybrid structure will start from lower edge frequency of PC_1 for TM 90°. Upper edge frequency of omnidirectional bandgap of total hybrid structure will be upper edge frequency of PC_2 for TM 0° or upper edge frequency of second photonic bandgap of PC_1 for TM 0° depending on which is greater than the other. Determine photonic band edge frequencies of both PC_1 and PC_2 for TM 0°. Choose the appropriate solution pairs which give maximum omnidirectional bandgap and eliminate the others.

Table 1
Photonic bandgaps of PC_1.

Center freq. and UC dimensions	TE/TM wave	1st PBG of PC_1	2nd PBG of PC_1
$\omega_{c1} = 0.8\omega_0$ $\Delta\omega = 0.42\omega_0$ $p_1 = 0.24A$ $p_2 = 0.775A$	TM 90°	$0.595\omega_0$–$1.005\omega_0$	$1.568\omega_0$–$1.635\omega_0$
$\omega_{c1} = 0.8\omega_0$ $\Delta\omega = 0.42\omega_0$ $p_1 = 0.24A$ $p_2 = 0.775A$	TM 0°	$0.475\omega_0$–$0.921\omega_0$	$1.36\omega_0$–$1.438\omega_0$
$\omega_{c1} = 0.7\omega_0$ $\Delta\omega = 0.34\omega_0$ $p_1 = 0.325A$ $p_2 = 0.685A$	TM 90°	$0.535\omega_0$–$0.866\omega_0$	$1.293\omega_0$–$1.556\omega_0$
$\omega_{c1} = 0.7\omega_0$ $\Delta\omega = 0.34\omega_0$ $p_1 = 0.325A$ $p_2 = 0.685A$	TM 0°	$0.432\omega_0$–$0.824\omega_0$	$1.179\omega_0$–$1.362\omega_0$

3. Omnidirectional bandgap design examples

Using the proposed design algorithm maximally broad omnidirectional bandgaps can be obtained systematically. In the numerical examples it is assumed that PC_1 and PC_2 have only two dielectric layers with refractive indexes 4.6 (Te) and 1.6 (SiO_2). When the refractive indexes are chosen as $n_1 = 4.6$ and $n_2 = 1.6$ omnidirectional relative bandwidth (ORB) of periodic structure will be about 45% as shown in [1]. It is desired to obtain ORB value approximately 90% using two quasi-periodic stacks in tandem with the same materials.

Let's consider construction of hybrid structure using two quasi-periodic 1-D PCs with OBG around ω_0. Frequencies and lengths will be normalized as $\omega_0 = 2\pi c/D$ and p_i/A. The normalization parameters D and A are chosen $D = 655.32$ nm and $A = 200$ nm as given in [16]. Same parameter values are used in the paper for comparison purpose of ORB values. The normalization parameter A is used to show dimensions of unit cells of PC_1 and PC_2 and D is used to normalize ω_0. Same symmetric unit cell in Fig. 1 is chosen for PC_1 and PC_2. Applying steps 3 and 4, the largest first photonic bandgaps ($\Delta\omega$) of PC_1 and PC_2 for different center frequencies are given in Tables 1 and 2 together with photonic bandgap frequency regions for TM waves with 0° and 90° incidence angles. The results given in Tables 1 and 2, are combined in Table 3 for obtaining the omnidirectional bandgap of the cascade of PC_1 and PC_2.

Omnidirectional relative band gap (ORB) is defined $100\Delta\omega/\omega_m$ where ω_m is the midband value of photonic bandgap. ORB values change between 87.19% and 89.5% for chosen three different