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Narrow stop band microwave filters by using hybrid generalized quasi-periodic photonic crystals

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ABSTRACT

Using the transfer matrix method approach (TMM), the microwave transmission spectra in hybrid quasi-periodic multilayer photonic structures are studied. These structures are formed by concatenating several quasi-periodic sequences such as the generalized Cantor (GC (*a, b, c*)), generalized Fibonacci (GF (*m, n*)) and generalized Thue–Morse (GTM (*m, n*)). The results are presented for a normal incident wave with transverse electric (TE) polarization. The optimization of the sequences' parameters (*a, b, c, m* and *n*) permits us to obtain polychromatic filters that cover the frequency range of Global Systems for Mobile Communication (GSM). The manipulation of these parameters fixes the number of photonic band gaps (PBGs) and the position of the transmission peaks.

1. Introduction

Over the past few years much effort has been devoted to the study of the propagation of electromagnetic (EM) waves in periodic dielectric structures [1,2]. Photonic band Gap (PBG) materials are known to forbid the propagation of these waves within a certain frequency spectrum range. These crystals are usually composed of altering layers, having a high refractive index say n_H and a low refractive index say n_L, in an arrangement that gives rise to a series of forbidden wavelength gaps. That is, the wave is almost completely reflected by the crystal, while a series of wavelength pass bands form [3]. The simplest form of a photonic crystal is the one-dimensional (1D) periodic structure. It consists of a stack of alternating layers having low and high refractive indices, whose thicknesses satisfy the Bragg condition: $n_L d_L = n_H d_H = \lambda_o/4$ where λ_o is the reference wavelength. This is known as a Bragg mirror [4].

Quasi-periodic systems can be considered as suitable models for describing the transition from perfect periodic structures [5] to a random structure [6,7]. If made from a dielectric material, the resulting structure has interesting properties. The most important and well-known quasi-periodic structures are the Fibonacci sequence (FS) [8,9], Thue–Morse sequence (T-MS) [10] and Cantor sequence (CS) [11,12]. One can expect their properties to be able to unite the forbidden gaps in transmission spectra with strong resonances, this can localize a wave very effectively. This type of structure has many applications in different domains, such as frequency-selective filters which are based on thin-film technology, and it has been investigated for a broad range of applications [13,14 and 15].

In this work, we employ the transfer matrix method [16] to study the microwave transmission spectra in hybrid quasi-periodic multilayer structures constructed by a combination of the generalized Cantor, generalized Fibonacci and generalized Thue–Morse sequences. We extracted the transmission versus the parameters and the variables of these sequences. We study a novel procedure approach to determine a succession of multi-narrow stop band filters using hybrid quasi-periodic structures. This succession of bands

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forms a wide band gap which covers a large portion of the microwave domain.

2. Problem formulation

The method that we introduce here for calculating the transmission spectra in hybrid quasi-periodic 1D photonic crystals is the transfer matrix method (TMM) [16]. This method permits particularly to solve the standard problem of the photonic band structure (transmission, reflection and absorption) spectrum. It can be shown that the relation between the amplitudes of the incident E_0^+, reflected E_0^- and transmitted wave E_{m+1}^+ may be expressed as in the following expression:

$$\begin{pmatrix} E_0^+ \\ E_0^- \end{pmatrix} = \frac{C_1 C_2 C_3. ..C_{m+1}}{t_1 t_2 t_3. ..t_{m+1}} \begin{pmatrix} E_{m+1}^+ \\ E_{m+1}^- \end{pmatrix}. \tag{1}$$

Here C_j is the propagation matrix of each layer:

$$C_j = \begin{pmatrix} \exp(i\phi_{j-1}) & r_j \exp(-i\phi_{j-1}) \\ r_j \exp(i\phi_{j-1}) & \exp(-i\phi_{j-1}) \end{pmatrix}, \tag{2}$$

where t_j and r_j are the Fresnel transmission and reflection coefficients. The Fresnel coefficients t_j and r_j can be expressed as follows by using the complex refractive index $\hat{n}_j = n_j + ik_j$ and the complex refractive angle θ_j. For parallel (P) polarization:

$$r_{jp} = \frac{\hat{n}_{j-1}\cos\theta_j - \hat{n}_j \cos\theta_{j-1}}{\hat{n}_{j-1}\cos\theta_j + \hat{n}_j \cos\theta_{j-1}}, \tag{3}$$

$$t_{jp} = \frac{2\hat{n}_{j-1}\cos\theta_{j-1}}{\hat{n}_{j-1}\cos\theta_j + \hat{n}_j \cos\theta_{j-1}}. \tag{4}$$

Moreover, for perpendicular (S) polarization:

$$r_{jS} = \frac{\hat{n}_{j-1}\cos\theta_{j-1} - \hat{n}_j \cos\theta_j}{\hat{n}_{j-1}\cos\theta_{j-1} + \hat{n}_j \cos\theta_j}. \tag{5}$$

$$t_{jS} = 2\frac{\hat{n}_{j-1}\cos\theta_{j-1}}{\hat{n}_{j-1}\cos\theta_{j-1} + \hat{n}_j \cos\theta_j}. \tag{6}$$

The complex refractive indices and the complex angles of incidence obviously follow Snell's law: $\hat{n}_{j-1}\sin\theta_{j-1} = \hat{n}_j \sin\theta_j (j = 1, 2\ldots, m+1)$.

The values ϕ_{j-1} in Eq. (2) indicate the change in the phase of the wave between the$(j-1)$th and jth interfaces, and they are expressed by the equations

$$\phi_0 = 0 \tag{7}$$

and

$$\phi_{j-1} = \frac{2\pi}{\lambda}\hat{n}_{j-1} d_{j-1}\cos\theta_{j-1} \tag{8}$$

except for j = 1. λ is the wavelength of the incident wave in vacuum and d_{j-1} is the thickness of the $(j-1)$th layer. By putting $E_{m+1}^- = 1$, Yeh and Yariv [16] obtained a convenient formula for the total reflection and transmission coefficients, which corresponds to the amplitude reflectance r and transmittance t, respectively, as follows:

$$r = \frac{E_0^-}{E_0^+} = \frac{c}{a}, \tag{9}$$

$$t = \frac{E_{m+1}^+}{E_0^+} = \frac{t_1 t_2. ..t_{m+1}}{a}, \tag{10}$$

The quantities a and c are the matrix elements of the total product matrix:

$$C_1 C_2 C_3. ..C_{m+1} = \begin{pmatrix} a & b \\ c & d \end{pmatrix}. \tag{11}$$

By using Eqs. (9) and (10), we can easily obtain the energy reflectance R as

$$R = |r|^2 \tag{12}$$

for the (S) and (P) polarizations and the energy transmittance T as

$$T_S = \mathrm{Re}\left(\frac{\hat{n}_{m+1}\cos\theta_{m+1}}{\hat{n}_0 \cos\theta_0}\right)|t_S|^2, \tag{13}$$