Paper

Dielectric photonic quasi-crystals with doubled quasi-periodicity

Irena Yu. Vorgul and Marian Marciniak

Abstract — Optical range electromagnetic field interaction with inhomogeneous finite dielectric media is investigated. New method for analysis of this interaction in 1D case based on integral equations for fields in transient media is proposed. Some special cases of quasi-periodical structures with doubled quasi-periodicity are investigated numerically. A possibility to obtain good filtering properties in such structures for small number of quasi-periods is shown.

Keywords — photonic crystals, optical pulse transformation.

Introduction

In the last years research activities on photonic band gap (PBG) structures as artificial periodic and quasi-periodic structures whose transmission properties exhibit frequency bands where the propagation of electromagnetic waves is forbidden [1], becomes one of the most actual direction in photonics and optical communication. It is known also that such structures can display properties of bandpass filters by disruption of the periodicity [2, 3]. Classical periodic layered structures was properly investigated theoretically and experimentally for different wavebands [4, 5]. The conditions of wave propagation in them were defined as well as their reflection characteristics. Detailed description of wave behaviour in them is a fundamental base for all consequent investigations.

However, these structures are not ideal for practical applications and their development by increasing complexity of the structures (as, for example, dual periodicity) is toward the improved model. The criteria for such an optimization are the gap width and shape (preferably a rectangular-like one) as well as the structure dispersion and simplicity of their fabrication.

One of the promising way of the improvement is to use not periodical but quasi-periodical structures. Such structures in a case of small shift of thickness of the layers composing the correspondent periodical structure were considered in [6, 7].

In spite of impressive progress in the new and emerging area of PBG engineering in recent years, their development by increasing complexity of the structures (as, for example, dual periodicity) toward the improved model is still actual. The criteria for such an optimization are the gap width and shape (preferably a rectangular-like one) as well as the structure dispersion and simplicity of their fabrication. There are a lot of works on periodical and quasi-periodical structures with a great number of periods providing for some bands of frequency a full wave reflection. We tried to obtain a high reflection with sharp frequency spectrum from quasi-periodical structures considering a small number of layers, which is much more difficult to obtain but which simplifies sufficiently the structure fabrication.

Previously, we considered mainly semi-infinite structures [8, 9]. In the present paper the investigation of 1D quasi-periodic dielectric structures is carrying out toward finding optimal structures for sharp frequency filter and phase transformer. We consider a planar structure as a dielectric layer with double-quasi-periodical permittivity. An additional complexity of the structure allows to obtain high reflection for a wide band or sharp resonances on defined frequencies as well as a sufficient.

Problem formulation and solution

The considered dielectric layer $0 \le x \le a$ has a permittivity mathematically determined by

$$\begin{aligned}\varepsilon(x) &= \\ &= \sum_{n=0}^{N}\left(\alpha - \left(\frac{1}{\beta}\right)^{n}\right)\left[\theta(x-an) - \theta(x-a(n+1))\right] + \\ &+ \sum_{m=0}^{M}\left(\gamma - \left(\frac{1}{\eta}\right)^{m}\right)\left[\theta(x-bm) - \theta(x-b(m+1))\right],\end{aligned} \qquad (1)$$

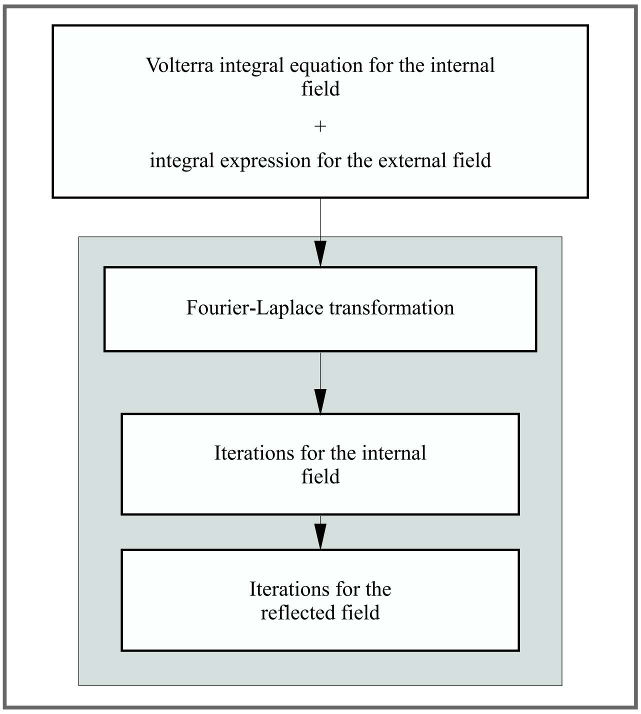

Fig. 1. Algorithm of analytical solving procedure for the problem

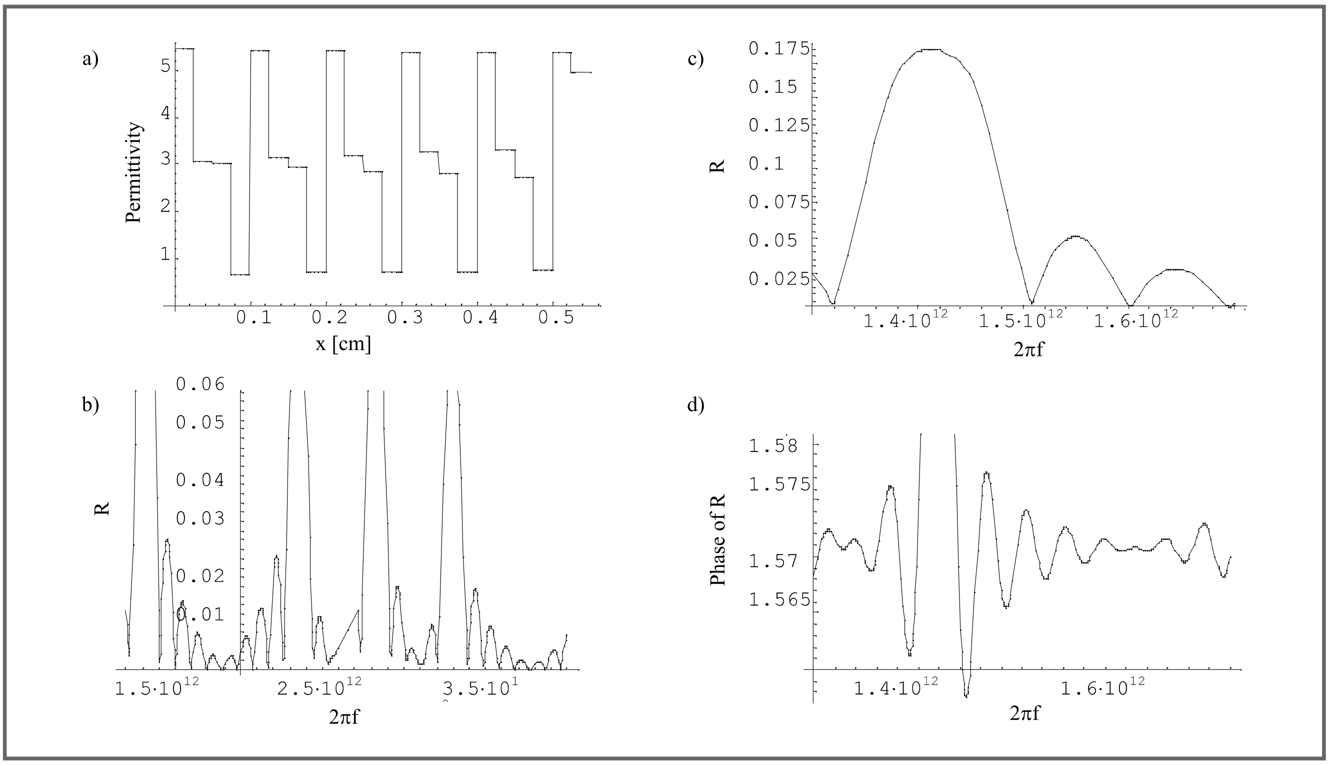

Fig. 2. Permittivity profile in the layer (a); reflection coefficient amplitude in dependence on the incident wave frequency (b), (c); reflection coefficient phase, equal to π at its maximum (d)

being essentially a superposition of two quasi-periodical structures with the composing layers widths equal to a and b, correspondingly, and slight deviation of the layers permittivity from the periodical ones.

The problem is solved based on integral equations for electromagnetic fields in nonstationary media [10]. There are some advantages in using this approach even for stationary structures because the method is based on Volterra integral equation which can be solved by iterations with improved convergence unlike Friedholm and singular equations. So we can easily control the obtained results accuracy. Initial point of the problems solutions are Volterra integral equations [10] which can be obtained from Maxwell equation for the electrical component of electromagnetic field obtained by Green function of corresponding wave equation with all nonstationarities picked up at its right hand part. In the considered 1D case it has the following form: for the internal field ($x > 0$, $t > 0$):

$$\begin{aligned} E_{in}(t,x) &= E_0(t,x) + \\ &-\theta(vt-x)\int_{t-x/v}^{t} dt'\, j(t', x - v(t-t')) + \\ &-\theta(x-vt)\int_0^t dt'\, j(t', x - v(t-t')) - \int_0^t dt'\, j(t', x + v(t-t')) \end{aligned}$$

and for the external field ($x < 0$):

$$\begin{aligned} E_{ex}(t,x) &= \\ &= B(t,x) - \theta(vt+x)\int_0^{t+x/v} dt'\, j(t', v(t-t') + x)\,, \end{aligned} \qquad (2)$$

where $j(t,x) = \frac{\partial}{\partial x}\left[\frac{\varepsilon_2(t,x)-\varepsilon_1}{\varepsilon_1} E_{in}(t,x)\right]$ for dielectric medium, θ is Heaviside step function and $v = c/\sqrt{\varepsilon}$.

Analytical iteration formula for the reflected field determined by the layer permittivity distribution was obtained according to the scheme in Fig. 1. The iteration algorithm was realized as a computer program enabling one to investigate band gap and filtering properties of the considered structures reflection for transient and stationary (as a long-time approximation for the transient one) cases. This approach is worth to be used even in a case of a stationary inhomogeneous layer, because for nonstationary problem we have a Volterra-type integral equation, for which a convergence of the iterative procedure is proved, so we can be sure in the results.

Calculation results

Calculation for different layer parameters showed that for big deviation of the structure permittivity from one of the periodic structure the reflection coefficient oscillates slightly about the value, which is not appropriate neither for anti-reflection coating nor for a good reflector.

We considered big deviations of the structure permittivity from one of periodic structure as well as small ones. In the first case, we found the oscillations of the reflection coefficient seeming not applicable to optical devices.

For small deviations of the structure from the periodical one it is possible to choose such structure parameters which provide good filtering and band gap characteristics of it (Fig. 2).

The reflection coefficient amplitude for the considered structures with doubled quasi-periodicity exceeds its maximal value for simple quasi-periodical structures, as calculated by the same program supposing the existence of only one sum in (1) (Fig. 3).

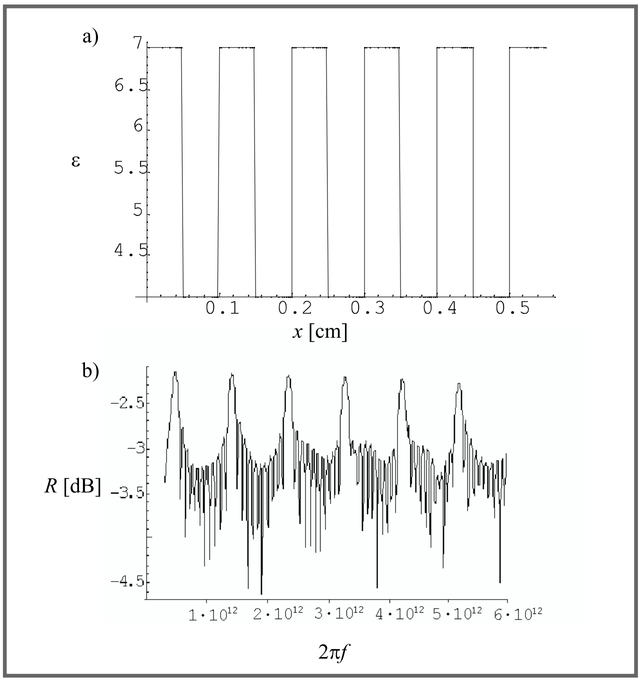

Fig. 3. Permittivity profile in the layer (a); reflection coefficient amplitude in dependence on the incident wave frequency (b)

Conclusion

An additional complexity of the structure allows to obtain high reflection for a wide band or sharp resonances on defined frequencies as well as a sufficient reflected field phase shift for some parameters combinations.

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