EVALUATION OF THE OPTICAL CHARACTERISTICS OF PHOTONIC BAND GAP STRUCTURES BY THE METHOD OF LINE BIDIRECTIONAL BEAM PROPAGATION METHOD

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ABSTRACT

The Bidirectional Beam Propagation Method based on the Method of Lines is proposed as an innovative and efficient algorithm to investigate the optical properties of photonic band gap (PBG) structures. The algorithm results are validated by comparison with the analytical ones obtained via the transfer matrix method. Passive, lossy and active PBG structures can be investigated. Moreover, in order to optimize the waveguiding effect, we consider one of the two layers constituting the periodic structure made of a three-layered waveguide having refractive index variable along the transverse direction, thus obtaining better confining performance.

INTRODUCTION

The nowadays rising interest in the research and development of new and sophisticated photonic devices needs powerful computerized design tools. The goal consists of formulating analytical and numerical techniques useful to elaborate the Maxwell equations by applying suitable approximations. To this aim, developed computer-aided modeling and simulation tools must be accurate, efficient, robust and user-friendly. On the other hand, efficient computer-aided modeling and simulations may be used to gain useful insight beyond intuition, thus assisting in detailed device design and optimization, increasing the manufacturing efficiency and reducing the costs. An interesting aspect of the electromagnetic (e.m.) propagation analysis, that demands particular attention in terms of modeling, consists of the reflection and transmission phenomena occurring at the interface between two media characterized by a very strong change of the refractive index along the longitudinal direction, such as laser diode facets, antireflection coatings, passive and active waveguides with Bragg gratings and, more recently, the Photonic Band Gap (PBG) structures [1]. Numerous numerical procedures have been implemented to account for the reflection problems in integrated optics such as the free space radiation mode technique for facet reflection and the transfer matrix method for distributed-feedback structures, as well as general algorithms such as the Finite Difference Time Domain (FDTD) [2] and the Bidirectional Beam Propagation Method (BBPM) [3]. Generally, the BBPM consists of propagating the field in both the forward and backward longitudinal directions through the structure by accounting for the reflection algorithm at the discontinuity interfaces. The BBPM based on the Fast Fourier Transform (FFT) uses two operators. The former describes the conventional one direction propagation operator, the latter determines the reflection of the spectrum of the plane waves constituting the optical signal impinging on the discontinuity interfaces. Recently the authors have investigated the performance of lasers and active switches based on Fabry–Perot cavity by means of the Beam Propagation Method (BPM) based on the Method of Lines. To this aim, the bidirectional version of Mol-BPM was implemented by home-made codes in order to account for both the forward and backward waves [4]. The MoL-BBPM with respect to the conventional FFT-BBPM gives more accurate results to parity of computational parameter numerical values and offers the possibility of reducing the computer CPU time by means of a non uniform discretization of the transversal computational window. In this paper the optical characteristics, such as transmittance and reflectance of one-dimensional (1D) PBG structures, as a function of the wavelength, are analyzed by means of a suitably modified MoL-BBPM code. The simulation results are compared with those obtained by applying the transfer matrix method.

1D-PBG MODELLING BY MoL-BBPM

The MoL-BBPM algorithm is based on two operators and works in two steps. The first operator describes the one-way propagation (positive longitudinal +z direction), while the latter determines the reflection from a generic discontinuity along the longitudinal direction structure. In the first step, the two operators are used in the forward propagation to calculate the transmitted and the reflected fields at each discontinuity along the structure by imposing the continuity of the e.m. field tangential components at the discontinuity interfaces. Successively, in the second step (negative longitudinal -z direction), the backward propagation is accounted and the new transmitted and reflected fields are evaluated, taking into account the reflection contribution calculated in the previous step. Then, all the forward and the backward waves, so calculated at each computational longitudinal section, are added up. This procedure is applied iteratively till to obtain a good convergence. The convergence criterion is based on the comparison between the fields at the output section (z=L) calculated in two successive iterations. The examined 1D-PBG stack-structure along the z longitudinal direction consists of N pair of layers of medium 1, having thickness d_1 and dielectric permittivity ε_1, and medium 2, having thickness d_2 and dielectric permittivity ε_2, and a further layer of medium 1, thus obtaining the total stack made of n=2N+1 layers. Both the reflection and transmission coefficients at the input and output discontinuities, respectively, are evaluated by launching perpendicularly to the input section a gaussian pulse having width d_g=18 μm. On this purpose, the MoL-BBPM calculation transverse window X_w along the x direction has been chosen at least equal to twice the gaussian pulse width: in our case it is X_w=60 μm for all the simulations. Moreover, in order to propagate guided modes, our home-made computer code is able to analyze the structure with each of the n layers constituted of a slab symmetrical waveguide three-layered along the x transverse direction, characterized by a guiding film having dielectric permittivity $\varepsilon_{fi} = \varepsilon_i + \Delta\varepsilon_i$ (i=1,2) and width w. Thus, by changing the refractive index of the external layer with respect to that of the central waveguiding film, the fundamental TE-mode supported by the first slab of the PBG stack can be launched in the input section. Finally, the contribution of losses and the effects of the optical gain on the transmittance and reflectance coefficient are also included by considering a complex refractive index for the layers constituting the PBG structure.

MoL-BBPM RESULT VALIDATION

A preliminary sensitivity analysis of the MoL-BBPM was carried out in order to choose the optimum value of the computation parameters: the longitudinal step Δz in each layer and the number lines N_x. This last parameter depends on both the transverse calculation window X_w and the transverse discretization step that is chosen non uniform. In particular, we adopt two values of discretization step, thicker in the central region of width d_g, where the field is more intense, and rarer in the external region. In the case of 1D-PBG stacks with homogeneous media (without three-layered waveguide) we verify that the transmittance and the reflectance values do not depend on the calculation parameters. Their choice is only imposed by the necessity of representing the three-dimensional evolution of the electromagnetic field along the PBG structure. On the contrary, the choice of the calculation parameters is critical for the case of non homogeneous stacks, for which the results are more accurate for the MoL-BBPM calculation transverse window X_w greater than twice the waveguiding film width w, while we must choice a line number N_x greater than 20. Moreover, the choice of the longitudinal calculation step Δz is not stringent owing to the semi-analytical nature of the MoL-BBPM.
Fig.1 illustrates the reflectance R (blue curve) and the transmittance T (red curve) as a function of the normalized frequency $f_n = f/f_{max}$ calculated by means of the analytical transfer matrix method applied to the examined 1D-PBG structure along the z longitudinal direction, consisting of n=11 layers having depths d_1=0.138 μm and d_2=0.098 μm, and dielectric permittivity ε_1=2 and ε_2=4, respectively. The corresponding values of R (blue asterisks) and T (red asterisks) calculated by the MoL-BBPM, are reported in Fig.1, too. The agreement is excellent and the maximum effect of the photonic band gap occurs at the frequency $f_{max} \cong 383$ THz, for which we calculate R=0.778 and T=0.222. Fig.2 reports the MoL-BBPM contour lines of the electric field evolution along the propagation direction for three different frequency values: a) f_n=1 for which we calculate R=0.778 and T=0.222; b) f_n=0.82 with R=0.476 and T=0.524; c) f_n=1.42 with R=0.038 and T=0.962. In Fig.2(a) the effect of the photonic band gap is apparent because the field contour lines concentrate in the neighbourhood of the input section, whereas for f_n=1.42 (see Fig.2(c)) the e.m. field is almost uniformly distributed along the 1D-PBG.
Similar analysis is carried out by means of the MoL-BBPM for the same 1D-PBG structure in which the layer 1 is a three-layered waveguide having the following geometrical and physical parameters: film dielectric permittivity ε_{1f}=2, substrate and superstrate dielectric permittivity ε_{1s}=1.85 and film width w=4 μm.

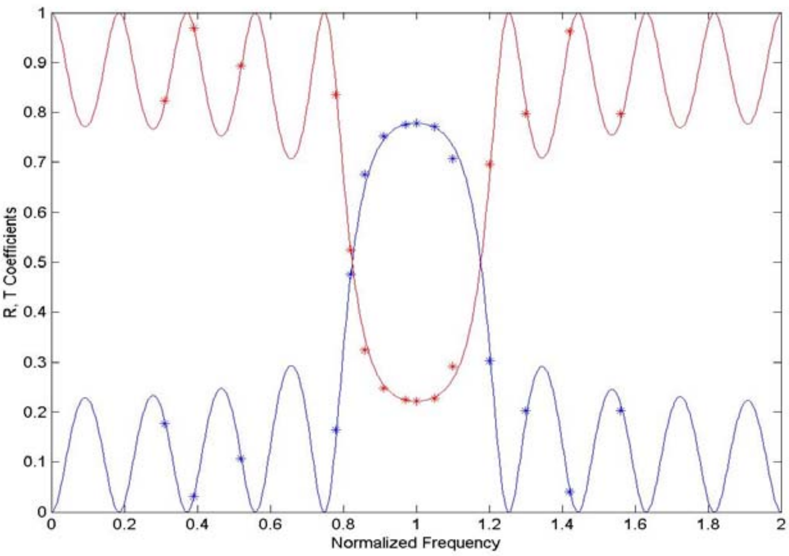
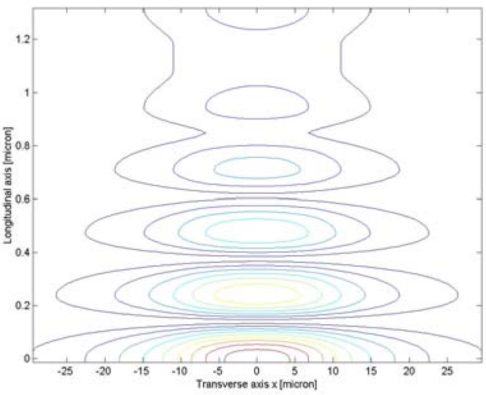
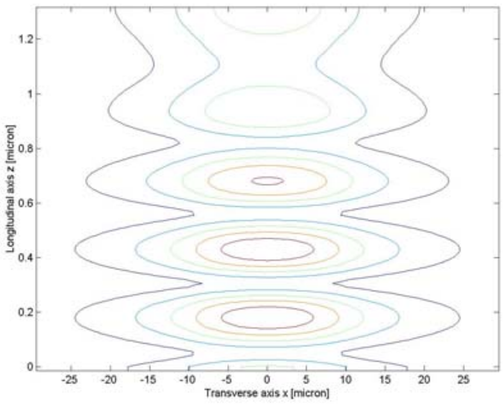


Fig.1. Reflectance and transmittance coefficients as a function of the normalized frequency calculated for both the transfer matrix method (blue and red solid curves, respectively) and the MoL-BBPM (blue and red asterisks, respectively).



(a)



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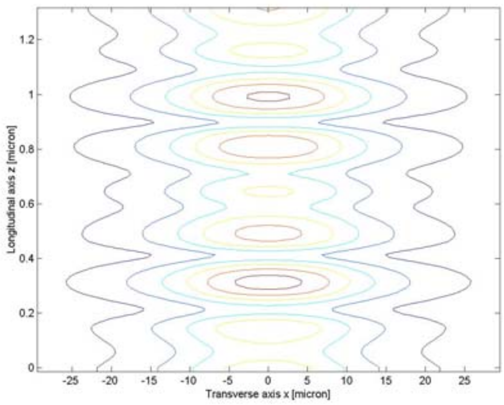
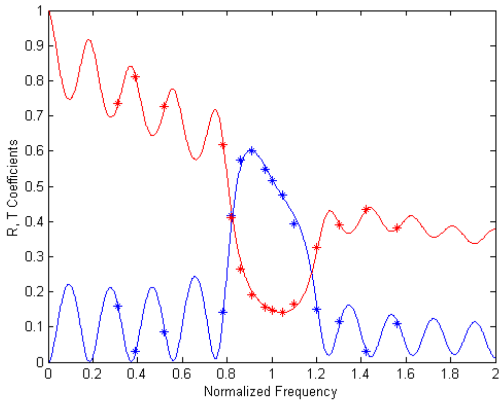


(c)

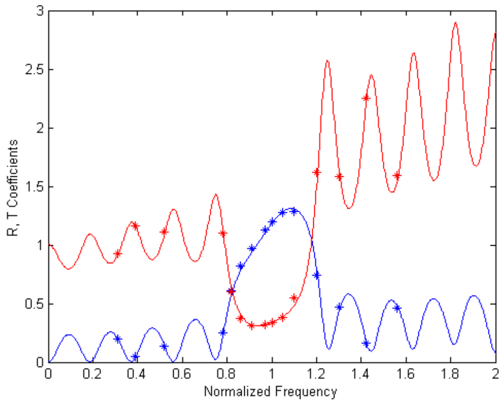
Fig.2. Electric field evolution contour lines for three frequency values: a) f_n=1; b) f_n=0.82; c) f_n=1.42.

The calculated optical characteristics of this slightly modified structure do not change with respect to those of the previous structure, but, as expected, the e.m. field shows better trapping performance, thus rendering this type of stack more efficient for integrated optics applications.

In order to account the contribution of both the gain and the loss effects in the 1D-BPG stack-structure, the medium 1 is modelled by a dielectric permittivity complex value: ε_1=2±j0.1, the signs + or – must be considered for the gain and loss effects, respectively. Fig.3 illustrates the reflectance R (blue curve) and the transmittance T (red curve) as a function of the normalized frequency $f_n=f/f_{max}$ calculated by means of the analytical transfer matrix method applied to the aforesaid examined 1D-PBG structure (stack without three-layered waveguide) for the case (a) of lossy 1D-PBG stacks and ε_1=2-j0.1 and ε_2=4 and the case (b) of active 1D-PBG stacks with ε_1=2+j0.1 and ε_2=4. The corresponding values of R (blue asterisks) and T (red asterisks), calculated by the MoL-BBPM, are reported in Fig.3, too. Also now, a perfect agreement between the two methods is apparent. In particular, for f_n=1 it is R=0.619 and T=0.142 in the lossy case and R=1.099 and T=0.251 in the active case. We can see in Fig.3 that, differently from Fig.1, the R and T behaviour is no more symmetrical around the value f_n=1, but, in the case of the lossy case, the R and T envelopes strongly decrease by increasing the normalized frequency, whereas, in the active case, they increase by increasing the frequency.



(a)



(b)

Fig.3. Reflectance and transmittance coefficients as a function of the normalized frequency calculated for both the transfer matrix method (blue and red solid curves, respectively) and the MoL-BBPM (blue and red asterisks, respectively): a) lossy 1D-PBG stack having ε_1=2-j0.1 and ε_2=4; b) active 1D-PBG stack having ε_1=2+j0.1 and ε_2=4.

CONCLUSIONS

An efficient MoL-BBPM numerical code has been set up in order to accurately evaluate the optical properties of 1D-PBG structures. The perfect agreement found with the analytical transfer matrix method makes the MoL-BBPM algorithm a valid candidate for the analysis of more complicate PBG structures including, as an example, the optical nonlinear effects. Moreover, the MoL-BBPM allows to calculate the distribution of the e.m. field evolution along the structure also in presence of arbitrary optical input signal.

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