Design of Photonic Band-Gap Devices Using the Leaky Mode Propagation Method

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Abstract: The design of some 1-D waveguiding photonic bandgap (PBG) devices has been carried out utilizing a model based on the Leaky Mode Propagation Method (LMP). This method has been implemented in a very fast computer code to optimize the design of two PBG devices, such as optical filters and resonators.

1. Introduction

The considerable interest in PBG structures arises mostly from their capability of controlling the light. The design of spectral filters, wavelength-division multiplexers, microresonators, switches, and other devices based on PBG structures has been proposed for a wide variety of applications [1-2].

In practical applications attention is paid to a one-dimensional (1-D) waveguiding photonic bandgap (WPBG) configuration, in which a resonance condition for the propagating beam is created also in transversal direction.

The main issues in the modelling of such structures are represented by the radiation loss and by a great number of numerical problems arising when very deep grooves in the etched layer and a rather strong refractive index contrast among the structure layers occurs.

The 1-D WPBG and 1-D Traversing etched WPBG (TWPBG), i.e. a structure having the core fully etched down to the substrate, can be very accurately and quickly modeled by the Leaky Mode Propagation method (LMP) [3-4] that is faster than other accurate numerical methods and does not require any analytical approximations.

The LMP approach has been recently used by the authors to develop a new and very powerful model of waveguiding PBG devices [3]. The model has been implemented in a very fast code able to provide all the parameter values in a few seconds.

Because of its accuracy and quickness our code is well oriented to the design optimization of WPBG and TWPBG-based devices, and, therefore, it has been applied to design some PBG devices such as optical filters and resonators.

In this paper, in Section 2 design examples of filtering PBG-based devices are reported, while final remarks and conclusions are in Section 3.

2. Design of WPBG and TWPBG devices

As above mentioned, the complete theory of the model can be found in Ref. [3].

The model has been validated by comparisons with other accurate numerical models, as reported in [3-4], and, then, the code has been used to design some PBG-based devices.

2.1 Design of an optical filter

First of all we have designed a filter having a transmission band around $\lambda = 1.55$ µm with negligible radiation loss.

The design approach lies in shaping the photonic band structure of the device in order to obtain one or more pass-bands between two or more stop-bands [5]. The design must be optimized by accounting for Fabry-Perot like round-trips that gives oscillations in the pass-band. These oscillations must be reduced in order to avoid the presence of ripples in the transmission coefficient spectrum.

In order to enlarge the stop-band, and making the pass-band as narrow as possible, a high index contrast must be used. So, the GaAs waveguide material having a refractive index n = 3.7 has been considered with a ridge-type configuration to obtain the alternative presence of pass-band and stop-band [5] as in Fig. 1.

When $Al_xGa_{1-x}As$ is assumed as substrate material having n > 3.5, depending on the value of x, high radiation losses are expected. To overcome this inconvenience we have designed an air-bridge configuration, i.e. a filter having air as a cover and as a substrate. The physical and geometrical parameters are shown in Table I.

The best L value to obtain a drop of the modal power reflectance, R_p, at $\lambda = 1.55$ µm is $L = 20\Lambda$. This implies a number of periods N = 20. In fact, for N < 20 we obtain a reduction of Fabry-Perot oscillations in the transmission band, but also the R_p values are higher. Calculations show that no radiation occurs in the considered range of operating wavelength, due to the particular air-bridge configuration considered.

We have also simulated the same filter realized in Si (n = 3.45), having a period Λ = 0.28 µm and we have found a quite larger pass-band centered around λ = 1.55 µm. This confirms the importance of the index contrast to widen the stop-band.

2.2 Design of an optical resonator.

The second designed device is a resonator based on the TWPBG structure.

The aim of the design is to find a device structure giving the exact resonance condition at λ = 1.55 µm. To compare our results with those obtained by other authors [6] we have choosen a Si on glass structure, etched down to the substrate.

The group velocity is given by ($\mathbf{v}_g$ = Ñw(k)) and is normal to the curves in the ω vs k diagram, in the direction of increasing frequencies. The resonance condition implies that the group velocity of the Bloch waves in the guiding plane, i.e. in the direction parallel to the substrate, vanishes. Therefore, the propagation constants of the resonant Bloch modes are placed on a maximum or a minimum points of the band structure (Brillouin diagram).

For a finite-height 1-D PBG (named TWPBG) the resonant modes having a zero group velocity in the direction parallel to the substrate are fully confined within the etched layer.

A number of simulations show that the larger is the etched region, the longer is the period of the structure useful to achieve the resonance condition. Therefore, in order to reduce the device length, we choose d = 0.8 Λ, being d the width of the high refractive index region of the perturbed layer.

By the Brillouin diagram shown in Fig. 2 we notice the circled points as resonant guided Bloch modes. The modes whose propagation constants lie on dashed bands are excited by the zero-th order mode propagating into the input slab waveguide. The others are excited by the first-order mode.

The zero-th order mode propagating into the TWPBG generates two stationary waves at the resonance condition having the propagation constants at the edge of the dielectric band (i.e. the lower one Q in Fig. 3), and at the edge of the air band (the upper one Q'), respectively. The resonator has been designed in correspondence of the two operating points Q and Q', assuming as resonance wavelength λ = 1.55 µm.

The resonance condition in corrispondence of the Q point, implies Λ = 0.249 µm. The design remaining parameters are reported in Table II. The same device design was proposed in [6] where the reported value of the period is Λ = 0.25 µm thus confirming the validity of our calculations.

At the Q point, we have determined the distribution of the resonant Bloch mode propagating into the structure. In Fig. 3 the field along one period of the device is depicted; as it can be seen the field is concentrated in the high permittivity medium. For this reason the lower band is named the dielectric band.

At the resonance point Q', for λ = 1.55 µm, we obtain Λ = 0.315 µm.

The resonant frequency guided Bloch mode along one period of the structure is depicetd in Fig. 4. Differently from what it happens at the Q point the field is concentrated in the low permittivity medium. Therefore, the upper band is named the air band.

Finally, Fig. 5 shows the field distribution into the structure at the Q resonance point. It can be observed once more that the field is concentrated in the high refractive index regions, as we expect having choosen the resonance mode in the lower band edge. Moreover, it is clear that the field propagates into the PBG region, as the resonance condition requires.

2. Conclusions

In the paper an accurate and recently proposed model based on the LMP method for the analysis of waveguide 1-D PBG devices implemented in a very fast computer code has been used to optimize the design of two PBG devices.

The code has been implemented in FORTRAN 77 language. One hundred simulations are performed in a few minutes on a 500 MHz PC.

A GaAs WPBG filter, having an air bridge configuration, was designed and simulated. The filter has no radiation losses and a very narrow pass-band was obtained between two stop-bands for the operating wavelength λ = 1.55 µm.

Moreover, a resonant, Si on glass, TWPBG device has been designed to obtain the resonance condition at the operating wavelength λ = 1.55 µm. The design was performed by the Brillouin diagram and by the α vs Λ diagram, corresponding to two resonant guided Bloch modes generated by the zero-th order mode propagating into the input slab waveguide.

We have verified that a guided resonant Bloch wave having the propagation constant in the dielectric band is concentrated in the high permittivity region of the perturbed layer, while the resonant Bloch wave having the propagation constant in the air band is concentrated in the low permittivity region of the perturbed layer, as expected.

Both the resonators exhibit negligible loss in the considered spectrum of analysis.

The resonator operating in the dielectric band shows design parameter values in good agreement with those obtained using other modelling algorithms.

References

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Table I – Parameters of the WPBG GaAs air-bridge filter.

n_c	1
n_r	3.7
n_f	3.7
n_s	1.
t_r [μm]	0.00
t_f[μm]	0.25
t_g [μm]	0.25

Table II – Parameters of the resonant device.

n_c	1
n_r	3.45
n_s	1.57
t_g [μm]	0.375
L [μm]	5.0
Λ [μm]	0.249

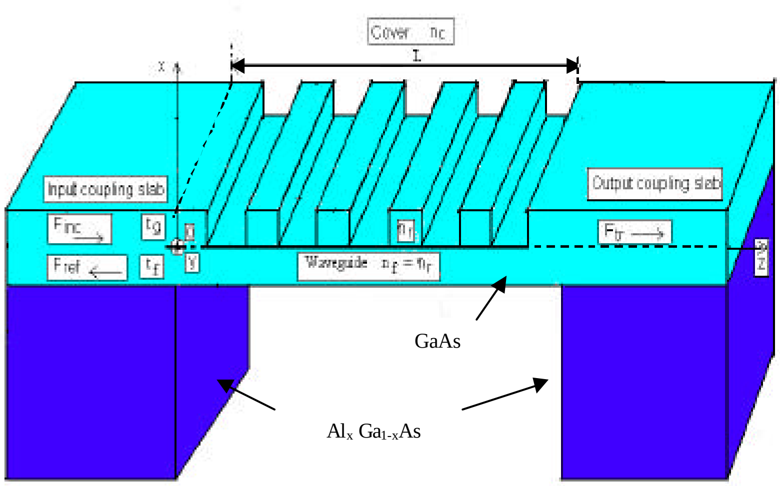

Fig. 1. The air-bridge WPBG filter structure.

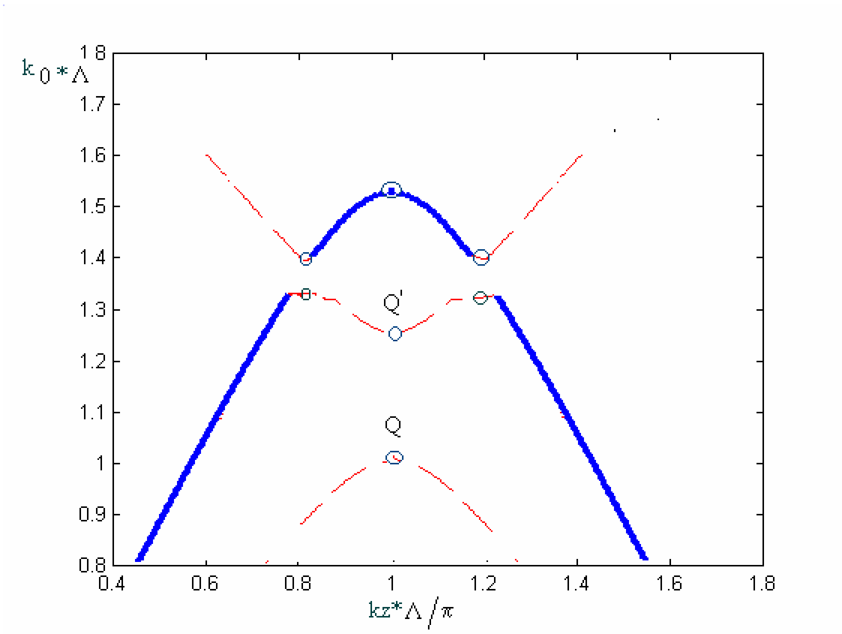

Fig. 2. Brillouin diagram relevant to the guided Bloch modes excited by the zero-th order mode (dashed line) and first order mode (bold faced line) of the input coupling waveguide. The circles denote the resonant guided Bloch modes (TE polarization)

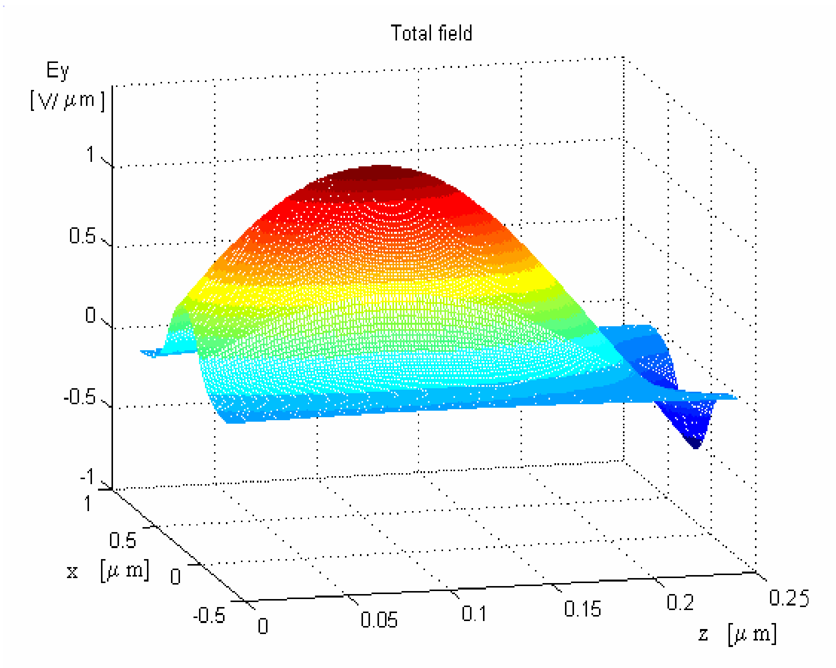

Fig. 3. Total field along one period of the resonantor operating at the Q point ($\lambda = 1.55$ μm; $\Lambda = 0.249$ μm).

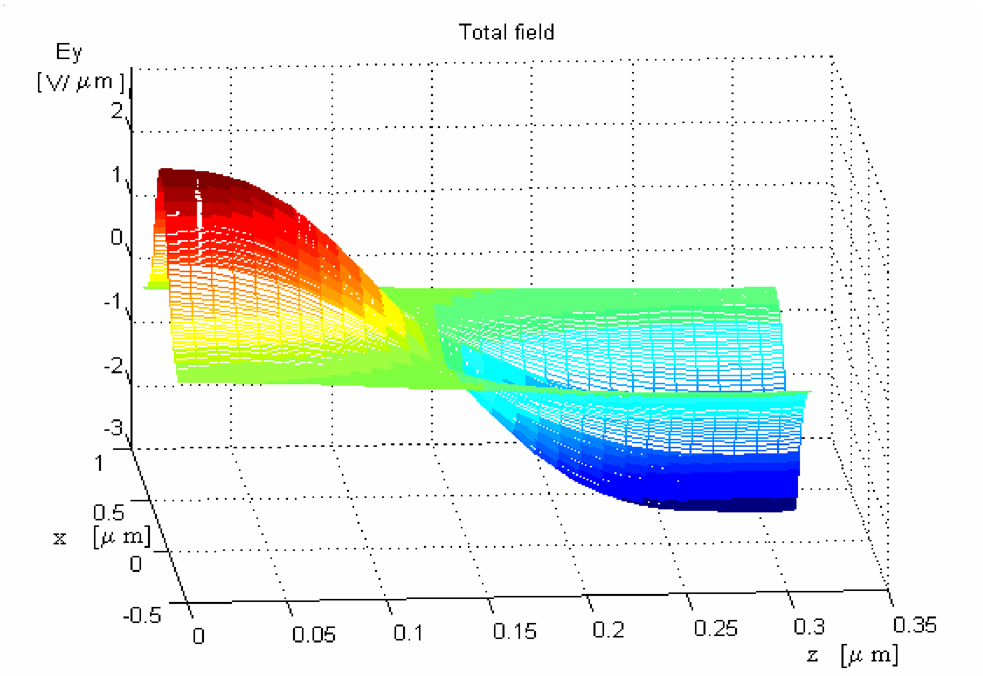

Fig. 4. Total field along one period of the resonantor operating at the Q’ point (λ = 1.55 μm; Λ = 0.315 μm).

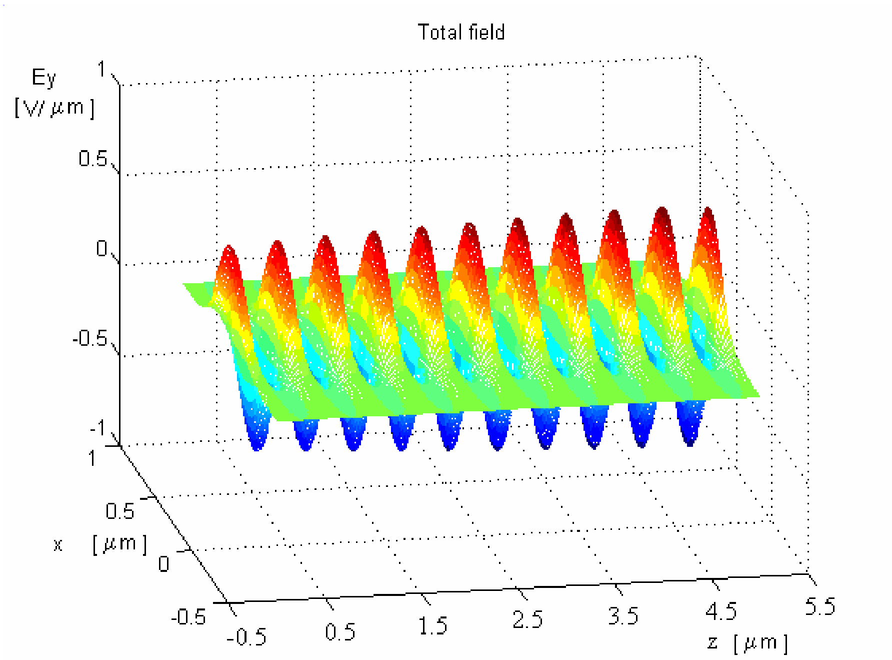

Fig. 5. Total field through the TWPBG.