ON THE SIMULATION OF
GUIDED-WAVE PHOTONIC BAND GAP FILTERS

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ABSTRACT

The Guided wave Photonic Band Gap (PBG) devices are very attractive as optical Filters. The modeling and the simulation of such structures is a topic of great interest because the classical existing optical modeling techniques, such as BPM or effective index, are not compatible with the size and propagation effects in PBG structures. In this communication two complementary simulation method are presented. The first approach uses pure numerical technique. We have simulated diffraction effects using 2D-FDTD and 3D-TLM methods. The simulation allows us to investigate the PBG mirror diffraction losses for different design parameters. The second one is a circuit approach. It is based on the modeling of the PBG as a cascade of several obstacles connected to waveguides. For each obstacle the optical S-parameters are calculated. Finally these parameters are implemented in a microwave simulator which determines the response of the PBG Filter.

INTRODUCTION

During the past decade, photonic crystals, also known as Photonic Bandgap (PBG) structures have known several technological advances and developments. They are based on the general idea that periodic structures (photonic crystals) influence photons in similar way that semiconductors crystals do to electrons. As a result, the photons in a region corresponding to a certain energy or wavelength band cannot propagate and cannot travel through the periodic structure and thus are reflected [1,2]. The development of circuits based on photonic crystals depends on the progress of integration technology as well as the Computer Aided Design (CAD) tools. Some of these tools are now available in the form of wide-spectrum simulators like the Beam Propagation Method (BPM) simulator that can be used for the analysis of conventional optical circuits: i.e. low refractive index contrast, low reflection and relatively large size device [3]. However, for a large scale integration of the optical circuits, the device dimensions need to be reduced, which results in strong guiding conditions with high refractive index contrast and high reflections. Typical examples of these circuits are optical filters, with very high selectivity, required for the WDM systems [4]. The fabrication of such filters in integrated optics requires, the use of high refractive index contrast in single mode waveguide, which could be achieved by creating air gaps (or holes) in a semiconductor waveguide using selective etching.

The analysis of such filters is a delicate problem as the dimensions of the optical spot (the guided mode of the optical waveguide) is comparable to that of the air gap (the optical discontinuity). In addition, the length of the gap is usually a fraction of the optical wavelength. In such situations, diffraction effects become very important. The incident spot will generates, into the gap, higher order modes, radiation modes as well as evanescent modes. So, an optical simulation taking into account the diffraction effects and the propagation of higher order modes is thus required.

In this communication we present two simulation techniques for application to photonic bandgap devices. The first technique is a roughly numerical method. 1D and 2D mode solvers are used, respectively with 2D-FDTD and 3D-TLM, to calculate the field distribution of the propagating mode. The obtained field distribution is thus used as an excitation in the 2D and 3D temporal methods. The 2D-FDTD and 3D-TLM methods compute the time domain response of structures to arbitrary excitations within respectively 2D or 3D space. Finally, the frequency response of the PBG structure is obtained via FFT. Such a technique is called "numerical approach". The second one is based on the decomposition of the structure in several elementary elements. Each element is represented in the form of complex scattering parameters (optical S-Matrix) to account for the magnitude as well as the phase variations of the optical field. Such a model is then integrated in a microwave simulator capable of handling the scattering parameters and the propagation phenomena. This enables to study more complex optical circuits. Such a technique is called "Circuit approach".

NUMERICAL APPROACH

The one-dimensional considered structure is a periodic one formed of air gaps which are etched into an optical waveguide fabricated in high refractive index materials. The waveguide is chosen to be single mode which imposes the transverse dimensions. The studied waveguide is represented in figure 1, where the guiding layer is made of a 0.7µm thick lattice matched InGaAsP layer on InP substrate.

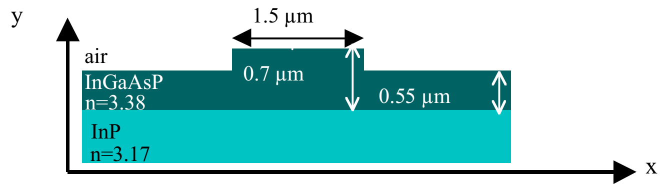

Figure 1: The transversal geometry of the simulated optical waveguide.

An optical filter based on the PBG principle (figure 2) can be obtained by using a cavity between two distributed mirrors. The later are obtained by a set of periodic air gaps etched into the waveguide. The high index contrast between the waveguide and the free space gives a good reflectivity for a large range of wavelengths with only a few periods. These mirrors will have a high reflectivity for wavelengths centered around λ, when the air gaps size is λ/4 and the guiding size parts between two air gaps is $\lambda/(4n_{eff})$, where n_{eff} is the effective index of the guided mode.

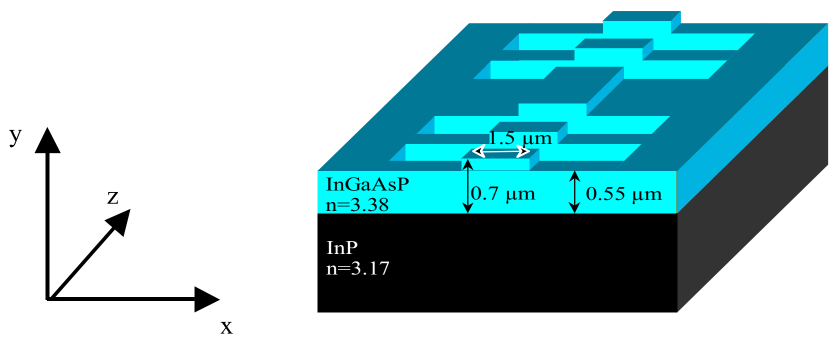

Figure 2: schematic view of studied PBG resonator.

This structure is a very compact Fabry-Perot. It is well known that the quality factor Q of the FP resonators is determined by the photon lifetime in the cavity. Among the different process reducing this lifetime, diffraction losses could be dominant. We have simulated the propagation of the light through a periodic set of air gaps in order to model the diffraction losses with an analytical approach.

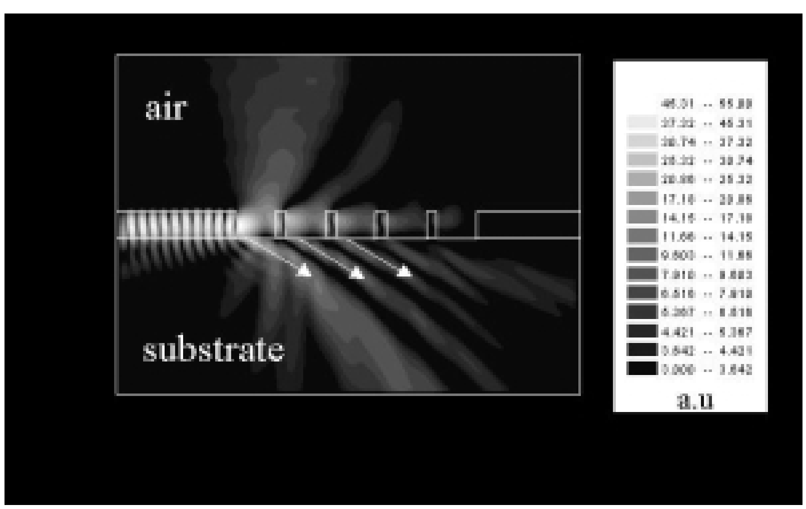

Figure 3: Field distribution for the structure described in Fig.2, calculated at λ=1.55µm using 2D-FDTD.

2D study of 1D-PBG

We have studied a 1D PBG structure. In order to study these diffraction losses, we have designed one lambda PBG (i.e. a lambda/2 air gap and a lambda/2n_{eff} semiconductor part with lambda =1.55µm) which allows light at the wavelength lambda to propagate trough the PBG structure. The “etching” is limited to the guiding layer for simplicity. A structure of five periods is simulated using 2D-FDTD and results are presented in the Fig 3. The field distribution presents a standing wave due to reflection at the first air/semiconductor interface. The figure 3 shows that light does not remain in the guiding layer but strongly diffracts into air and substrate. It is clear from this figure that some propagation directions are favored for light to spread into the substrate.

3-D study of PBG micro resonators

In this part, we study PBG resonators. The two distributed mirrors are composed of three lambda/4 air gap. The size of resonant cavity is 2.3µm. The aim of these simulations is to study the influence of etched depth on the resonator performances. For this reason two cases were simulated using 3-D TLM method. In the first case, both the guiding layer and the substrate are etched. In the second case, only the guiding layer is etched. In these simulations, the excitation is located inside the cavity of the resonator. The standing wave patterns at the resonance wavelength 1.55µm are reported in figure 4.

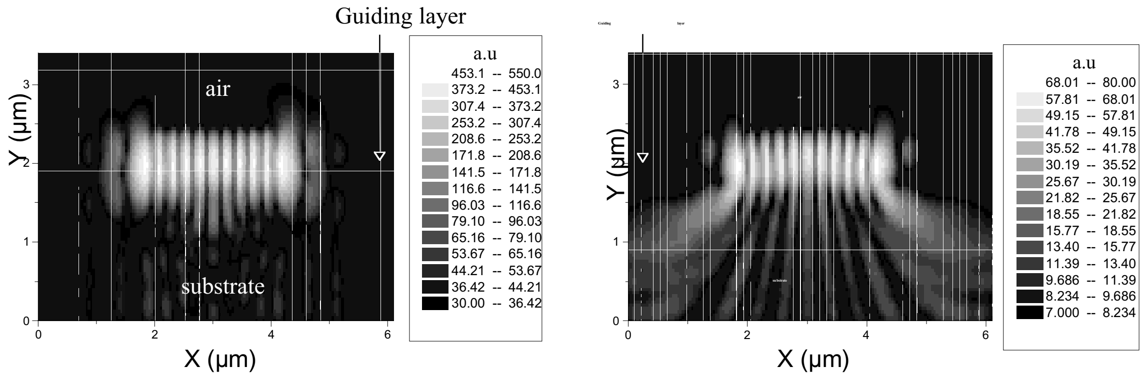

Figure 4 - Field distribution at λ=1.55µm, for the two PBG resonators investigated, using 3D-TLM.

CIRCUIT APPROACH

The considered structure is shown Fig.5. It is mainly a suspended optical waveguide that could be realized using selective etching and III-V semiconductors. The Photonic Band Gap effects are obtained by creating a periodic arrangement of air gaps (or holes) on the suspended waveguide. The circuit-oriented approach is based on the use of the S-parameters to represent the effect of the optical discontinuities in the studied circuit. To illustrate our technique we consider a simple optical discontinuity in the form of an air gap in a strongly guiding waveguide, a suspended waveguide. To model the propagation and determine the equivalent S-parameters, we used a full wave analysis i.e the Radiation Spectrum Method (RSM) [5, 6].

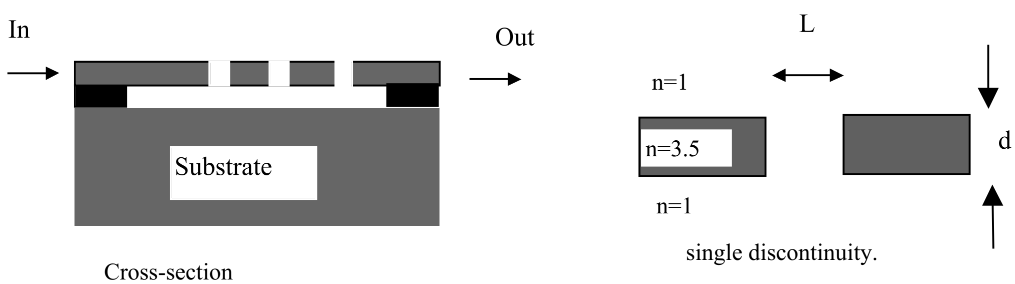

Fig. 5 - Schematic diagram of the suspended waveguide with air gaps.

Let us now apply our technique in the design of an optical filter. We consider an optical filter constructed of an optical resonant cavity formed by two Bragg mirrors. Each of these mirrors is obtained by the periodic structure of air gaps.

The air gaps used in our design are all similar with a length of 0.3875 µm corresponding to λ/4 while the semiconductor segment between the air gaps is assumed to be 5λ/4 which corresponds to about 0.55 µm.

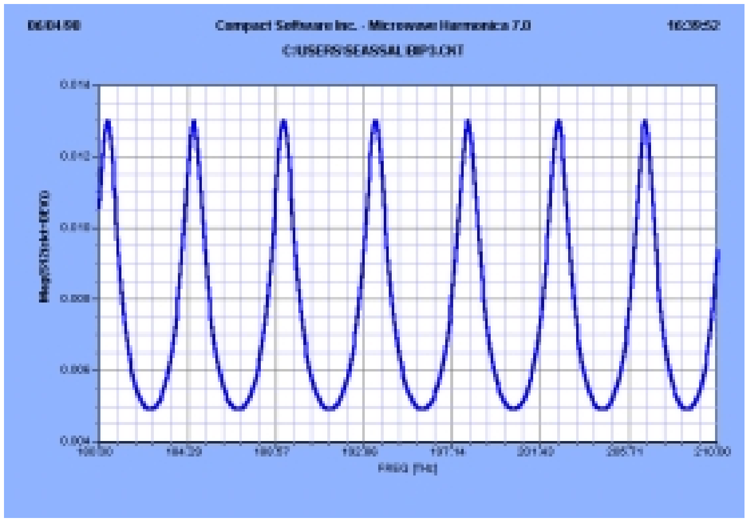

Fig. 6. Simulation of the filter frequency response for a gap length of λ/4 and a cavity length of about 10 µm.

We have thus inserted the S-parameters into a microwave simulator. The overall performance of the filter is also obtained in the form of S-parameters and it can be used in the design of other more complicated circuits. The filter response using a 0.2µm guide width with a cavity length of 23 λ, (i.e. about 10µm length of semiconductor), is shown in Fig. 6. The degradation in both the transmission and the selectivity of the filter could be observed. Such a degradation is mainly due to the losses.

CONCLUSION

We have presented two methods for the modeling of guided wave PBG structure. Two complementary techniques was used. The first one, which is a numerical technique, is very attractive for the study of the field distribution within the studied structure. It can help to understand the propagation and the behavior of the electromagnetic field inside the studied structure. The second method is more compact approach and is circuit oriented. Once the different optical elements are defined and modeled by their scattering parameters, complex structures can be simulated and opitmised.

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