PHOTONIC CRYSTAL PLANAR OPTICAL WAVEGUIDES WITH CHIGRIN-TYPE OMNIDIRECTIONAL STACKS

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1 INTRODUCTION

One of the significant emerging concepts in the field of optical telecommunications are materials with photonic band gap, also known as photonic crystals [1], [2]. These are readily applicable for highest bit transfer rates (tens and even hundreds of Gbit/s) and are inherently convenient for networks with WDM transmission. Photonic crystals were introduced by Yablonovitch in 1987 [3] and soon became one of the most important topics in optoelectronics generally, but also in numerous other fields, including e.g. microwave technique.

A photonic crystal can be defined as material whose refractive index periodically varies along one, two or three axes with a period (lattice constant) comparable to the wavelength of light. If the refractive index contrast is sufficient, in such materials a photonic band gap (PBG) appears, a range of wavelengths in which no propagation of electromagnetic radiation is possible. A 3D photonic crystal is thus a perfect omnidirectional mirror in which no propagation of electromagnetic waves within the PBG is possible.

A very important class of applications of photonic crystals in optical communication are PBG optical waveguides [4]. If a line defect is introduced in a photonic band gap structure, light is perfectly localized and guided within it, and thus a perfect (lossless) optical waveguide is obtained [5].

If a PBG guide sharply bends, light will follow its turns practically without losses, even if the bending angles are 90° and more over distances below one micrometer (as shown theoretically by Mekis et al [4] and experimentally by Lin et al [6]). This is the main advantage of PBG waveguides over conventional fiber-guides whose performance is limited by total internal reflection (TIR) and where the allowed radii of curvature are of the order of centimetres.

An ideal solution for a photonic crystal waveguide would be to use a full 3D PBG for the confinement of the localized mode (line defect). However, the need to fabricate 3D structures with accurately controlled features with the dimensions of the order ~0.1 µm and incorporating controlled line defects at the same time are well beyond today's technological possibilities [7], [8].

A practical method used to overcome this problem are 2D photonic crystal waveguides. These are fabricated by planar technologies. Various solutions for practical 2D waveguides were described in e.g. [8], [10].

Two-dimensional PBG waveguides can be used to fabricate a variety of passive components. They are utilized for waveguide intersections (crossings) with low cross-talk and high throughput [11], waveguide branches (Y-branches [12], T-branches) [13], channel add/drop filters for Wavelength Division Multiplexing (WDM) [14], etc. Their properties make them the ideal choice for low scaling of the dimensions of passive devices for optical communications.

A limitation of 2D photonic crystal waveguides is that they offer near-perfect optical confinement and guiding only within the xy plane, while being leaky along the third (z-) coordinate. This decreases the number of possible applications and limits the use of guides to only a single mode. The issue of radiation losses and leaky modes in 2D PBG waveguides is analysed in [13].

Fig. 1. 2D photonic crystal structure with triangular lattice of dielectric cylinders.
Several methods are used to suppress the leaky modes. One of them is to use only convenient light polarization and a single mode [13]. Another utilizes total internal reflection (TIR) – among the example are structures manufactured on SOI (Silicon-On-Insulator) wafers, with silica as the bottom medium, while the upper one is air [15]. This solution is valid for large incident beam angles. Finally, dielectric stacks may be deposited on the top of the waveguide cylinders/rods (forming 1D PBG along the z-axis) [11] – valid for small incident angles.

Here we use a novel approach to avoid leaky modes along the z-direction, valid for both small and large incident angles. It is based on the use of omnidirectional 1D photonic crystals. These were proposed in 1998 by Chigrin et al [15]. Basically, these are dielectric mirrors in which TIR and Bragg mirroring wavelength ranges overlap.

We propose here a combination of 2D PBG waveguides and Chigrin’s 1D omnidirectional stacks to prevent leakage in the z-direction. Thus we combine both of the methods for the leaky modes suppression in a single structure and enable practically lossless multiple mode propagation within a 2D planar guide. We describe our PBG waveguide, present calculation of some of its parameters and consider its fabrication technology issues.

II STRUCTURE DESCRIPTION AND CALCULATION

Fig. 2 illustrates the layout of our structure. An omnidirectional 1D photonic crystal is deposited on semiconductor substrate. Alternating grey and white layers represent strata with high and low refractive index, respectively. A defect layer is deposited over these stacks. A pattern of dielectric cylinders (grey) is formed in this layer. They may be arranged in a square matrix (as shown in Fig. 2), but also in triangular, graphite shape, etc. and are embedded within a medium with sufficiently contrasting refractive index (white). Thus the defect layer represents a 2D photonic crystal, but radiation is additionally confined along the z axis within the “defect” 2D structure (localized mode) by the omnidirectional stacks.

![Fig. 2. Monolithic 2D PBG waveguide enhanced by omnidirectional dielectric stacks.](image)

In Fig. 2 the 2D waveguide is shown with a built-in T-branch (black cylinders), solely for the purpose of illustration, since this can be any passive component or a combination of passive components. The described waveguide structure may be thus described as a “defect within defect”.

Controlled defects within 2D photonic crystals can be fabricated by changing the dimensions of the cylinders, by modifying their refractive index or by completely omitting them (equivalent to the filling with the embedding medium).

The structure is finished by a new set of Chigrin stacks deposited on the top of the 2D crystal. A part of the upper omnidirectional stack is removed in Fig. 2 to expose the 2D defect with waveguide.

The calculation of the required dimensions of photonic crystals for a given material pair is calculated starting from the Maxwell’s equations. The procedures for such calculation and photonic crystal band gap design are described in e.g. [17], [18], [19]. Typical result of such calculations is a photonic band gap map, i.e. the dependence of forbidden bands on photonic lattice dimensions.

Our numerical calculation proceeded as follows. For our material pair we chose silicon and silica, which offer convenient optical properties in the wavelength ranges of interest for optical communications, are well known and have a very mature technology. We utilized them both for the Chigrin stacks and the 2D defect/waveguide. We calculated the photonic band gap maps of our Si/SiO2 pair using the procedure described in [19]. Based on these calculations we chose 174 nm thick Si stack and 75 nm thick silica for the omnidirectional stack. The chosen defect mode thickness was 300 nm and the 2D crystal data were as in [15].

For our calculation of reflection and transmission coefficients of our structure we applied the transfer matrix method. We used the program TransLight, developed by Dr. A. Raynolds from the University of Glasgow, and based on the transfer matrix code by Prof. J. Pendry et al from the Imperial college, London [20].

The extinction of the leaky modes is analysed in following figures. Fig. 3 shows the spectral dependence of the Chigrin stack reflection coefficient along the z-axis in the wavelength range of interest for different numbers of layer pairs. It is seen that a relatively small number of strata is necessary to obtain high reflectivity.

![Fig. 3. Spectral reflectance of the Chigrin stack for different numbers of layer pairs and normal incidence of light. Material pair is Si/SiO2 (dielectric permittivity 11.958/2.1316), thickness 174 nm and 75 nm, respectively.](image)

Fig. 4 shows the spectral dependence of reflection coefficient for various incident angles for a Chigrin stack with the
parameters as in Fig. 3 and with 8 layer pairs. The stop band changes with incident angle, becoming narrower and shifting toward shorter wavelengths with increasing incident angle.

![Fig. 4. Spectral reflectance of Chigrin stack with 8 layer pairs for various incident angles. Data as in Fig. 3.](image-url)

![Fig. 5. Reflection coefficient of Chigrin 1D stacks with 8 layer pairs versus incident angle for different wavelengths. Data as in Fig. 3.](image-url)

Fig. 5 shows the dependence of the reflection coefficient of Chigrin 1D stacks on the incident angle for various wavelengths within the photonic band gap. The allowed angles decrease with the operating wavelength increase, which is consistent with the results presented in Fig. 4. For a wavelength outside of the photonic band gap (1.55 μm) the transmission is high for all angles, remaining between 10% and 100%. The lowest transmissions are obtained for the shortest operating wavelengths within the PBG (between 0.9 μm and 1.1 μm).

The conclusion is that properly designed PBG stacks efficiently suppress the z-components of the leaky modes in a range of frequencies near the short-wavelength bend edge, regardless of the incident angle. Thus it appears that the proposed structure could be used for improved confinement of guided modes.

### III FABRICATION TECHNOLOGY ISSUES

The crucial advantage of the proposed enhanced PBG waveguide structure is that it is relatively simple to fabricate using conventional planar technology procedures.

The main procedures to be used are thin film deposition and photolithography (either photolithography or holographic lithography). We start from a doubly polished silicon wafer. Following the preparation procedure the alternating silicon and silica layers are deposited using the rf sputtering technique as described in [19]. After the middle (defect) layer is sputtered the wafer is removed from the sputtering system and photolithographic procedure is performed to form 2D PBG structure with line defect. The required steps are spin-coating by resist, exposure through a photolithographic mask, removal of the excess photoresist, etching of the hole pattern in the defect layer for the 2D PBG crystal (including the waveguide structure), further deposition of the filling material and the removal of the excess material from the wafer surface by chemomechanical polishing. After this is performed, further sputtering of Chigrin layers is continued until the desired number of strata is deposited.

Most of the described steps represent a standard photolithographic procedure, and their utilization for the fabrication of 1D photonic crystal structures is described in e.g. [18], [19]. The only exception is chemomechanical polishing of the 2D PBG waveguide (defect) layer, which must furnish surfaces with a roughness of the order of several nanometers. Procedures for such polishing are described in detail in [21], [22], [23].

The described fabrication procedure is somewhat more complex than the fabrication of standard 1D PBG stacks. It requires an additional photolithography step with a resolution below 0.3 μm to fabricate 2D crystal, as well as chemomechanical polishing to smooth thus obtained structure. However, these are the only additional steps to be performed, and the complexity of the technology is in this manner brought to the level of fabrication of simultaneous fabrication of 1D and 2D crystals, which is quite acceptable and cannot be even compared to the complexity of fabrication of full 3D structures for the optical wavelength range.

It should be mentioned that the approach described above is by no means the only one possible. Actually, any of the various methods described in literature for the fabrication of 1D and 2D photonic crystals intended for the optical wavelength range can be utilized.

### IV CONCLUSIONS

The paper presents a proposal and a feasibility evaluation for the fabrication a novel type of photonic crystal-based planar waveguides. The structure of a conventional 2D (in-plane) photonic crystal with a localized mode (defect) is sandwiched between two Chigrin-type one-dimensional omnidirectional dielectric stacks. Basically this structure can be regarded as an omnidirectional 1D photonic crystal with a controlled defect, where the defect is photolithographically patterned to become 2D photonic crystal waveguide. The most important advantage of our structure is that it retains the simplicity of fabrication of 1D and 2D photonic crystals, while at the same time offering the functionality of 3D materials, i.e. enabling near-lossless propagation of multiple modes. The concept may be useful for a range of practical applications in optical communication networks.

### REFERENCES

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Abstract: In this paper we propose a method to improve the waveguides for optical communications based on 2-dimensional photonic crystals. To this purpose a standard channel waveguide is sandwiched between two omnidirectional Chigrin-type 1D dielectric layer stacks. The combination of total internal reflection and photonic band gap reflection enables improved confinement of optical signal along the z-axis, while retaining all the benefits of conventional 2D crystals. The structure can be fabricated utilizing standard planar technology, i.e. photolithography or holographic lithography and thin-film deposition.

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