ROMANIAN JOURNAL OF INFORMATION SCIENCE AND TECHNOLOGY
Volume **12**, Number 3, 2009, 308–316

Waveguiding in PMMA photonic crystals

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Abstract. The fabrication of two-dimensional photonic crystals (PCs) by using the electron-beam lithography (EBL) technique to directly pattern the positive PMMA electronoresist is presented. The design, simulation and fabrication of a channel waveguide in this PC is described in detail. The actual fabrication of this passive structure useful in integrated optic applications is a challenge because the PC waveguide configuration is integrated with a taper optical waveguide on the same substrate. Simulations performed with the finite difference time domain (FDTD) method predict the optical behavior, and especially the band gap, of the structure under investigation.

1. Introduction

Research in the field of photonic crystals [1] has been intensified in the last years due to an increasing interest in the basic physics and the engineering of photonic devices. Photonic crystals are artificial periodic structures consisting of at least two dielectric materials, in which the optical index of refraction is periodic in one, two or three directions. Photonic crystals are also called photonic band-gap materials since their periodic structure induces band gaps (forbidden intervals) for the propagation of electromagnetic waves with certain frequencies. The band gap width and spectral position is a function of the geometry, lattice periodicity, and the dielectric constants of the materials. PC structures with a lattice periodicity less than but comparable to the wavelength of the incident electromagnetic wave are likely to offer unexpected opportunities for the increased functionality and miniaturization of photonic integrated circuits, by reducing the cost of integrated optical systems and improving their performances. In addition, PCs can overcome many problems that limit the speed and

capability of communication networks. PCs are especially valuable in the implementation of passive photonic elements such as low-loss waveguides, splitters, bends, and filters. These structures are essential in optical communication circuits for complex signal processing.

In PC channel waveguides [2], a linear defect in the crystal, which consists of the absence or modification of one or several rows in the PC, acts as an optical guide that supports one or more propagation modes of light with frequencies in the PC band gap. In contrast to conventional waveguides, which confine the electromagnetic field by total internal reflection, the light confining mechanism in PCs is the distributed Bragg reflection. Because this wave-guiding mechanisms is much more efficient, it can be used to implement compact and highly functional PC circuits.

The goal of this paper is to present the design, simulation and manufacture of a PC channel waveguide integrated on the same substrate with an optical waveguide, using the microelectronic technology and EBL. The channel waveguide was fabricated in a PMMA PC, one of the advantages of choosing this material being that no additional technological process after EBL is required for the implementation of the guiding structure. Another advantage is that PMMA could be used for the implementation of a tunable waveguide due to its electro-optical properties [3]. For a specific geometry and dielectric constants of the materials that form the PC, FDTD simulations determined the proper dimensions and the operating wavelength of the PC waveguide.

2. Design

The PC consists of a hexagonal array of holes in the PMMA, with lattice period a and hole diameter D. The PC waveguide is formed if one or more rows in the array of holes are absent, this absence being referred to, respectively, as a single or a multiple line defect. The electromagnetic radiation is confined by the distributed Bragg reflection mechanism within the line defect for optical wavelengths within the band gap of the PC that surrounds the waveguide.

The band gap width is strongly dependent on the refractive index contrast of the materials employed. As a general rule, a PC band gap opens only if the refractive index contrast is larger than a given minimum value. In consequence, material selection for the implementation of PC waveguides is a difficult task.

Our choice of using PMMA spin-coated over SiO_2 for the fabrication of PC waveguides was motivated by two facts: technological considerations regarding the possibility of minimizing the number of fabrication steps (no additional technolo-gical process is needed after the fabrication of holes in the PMMA using EBL, in contrast to fabrication methods of PC waveguides in other materials, especially in the common SOI structures) and the potential of increased functionality of PC structures in PMMA due to the electro-optical property induced in high electric-field poled PMMA [3]. This characteristic is vital for the implementation of tunable PC structures.

For a PMMA PC waveguide working in the visible spectral region we have designed the structure choosing the diameter of the holes D to be 240 nm and their periodicity

a as 320 nm. These dimensions are also compatible with the resolution of the EBL fabrication process. Because the contrast between the refractive indices of PMMA and SiO_2 is not very high, additional simulations (presented in the next section) were needed to validate this design.

In order to ease the coupling of light into and out of the PC waveguide we have integrated it on the same substrate with input and output PMMA standard optical waveguides through taper sections, conferring a high degree of originality to the design of the structure. The tapers reduce progressively the widths of the optical waveguides until they match the width of the PC channel waveguide.

3. Simulation

Two methods were used for the simulation of the structure: the method of plane wave expansion (PWE) and the FDTD algorithm. The first step was to investigate the band structure in a two-dimensional PC consisting of a hexagonal array of holes with a diameter $D = 240$ nm and a lattice constant $a = 320$ nm fabricated in PMMA, which has a refractive index of n =1.49. The incident radiation was assumed to be TM polarized, the magnetic component of the electromagnetic field being parallel to the holes. For this geometry, PWE simulations revealed the presence of a band gap over the entire Brillouin zone centered at the wavelength λg 650. The result of band structure calculations is illustrated in Figure 1.

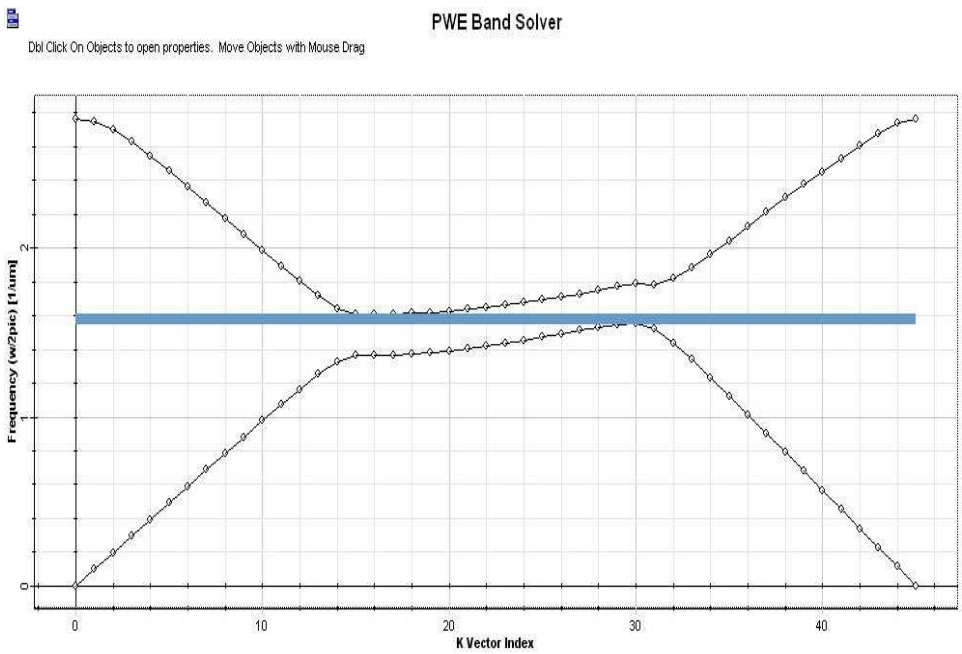


Fig. 1. The band structure of the two-dimensional PC consisting of a hexagonal array of holes in an infinitely thick PMMA layer; the band gap is represented by the blue band.

After the identification of the optimal geometrical configuration for which a band gap opens in the visible spectral range, we have improved the characterization of a realistic three-dimensional PC in a simulation second step. Instead of a two-dimensional structure, we have investigated the band gap (in fact, the reflection and transmission properties) of a three-dimensional structure composed of periodic hexagonal array of holes fabricated in a PMMA layer with a finite thickness (of 1 μm) deposited on a SiO_2 substrate. The calculation of the reflection and transmission coefficients of the three-dimensional structure was performed with the FDTD algorithm. The domain of simulation was a parallelipiped with the length $z = 6$ mm, width $x = 0.554$ mm, and thickness $y = 4$ mm, the spatial step being chosen as 0.04 mm. The simulated structure was formed from two rows of holes in PMMA with periodic boundary conditions in the $(y - z)$ plane and perfect matching layers boundary conditions in the $(x - y)$ and $(x - z)$ planes. As excitation field we have chosen a gaussian pulse with a halfwidth of 2.10^{13} s and centered at 650 nm. The spatial extension of the gaussian on the y direction was taken as 1 mm. The reflected and transmited powers were obtained from the simulation of the Poynting vector in two planes of observation along the propagation direction. From the power spectrum represented in Figure 2 one can observe the presence of a band gap centered at the wavelength of 650 nm; for wavelengths inside the band gap the incident field is strongly reflected.

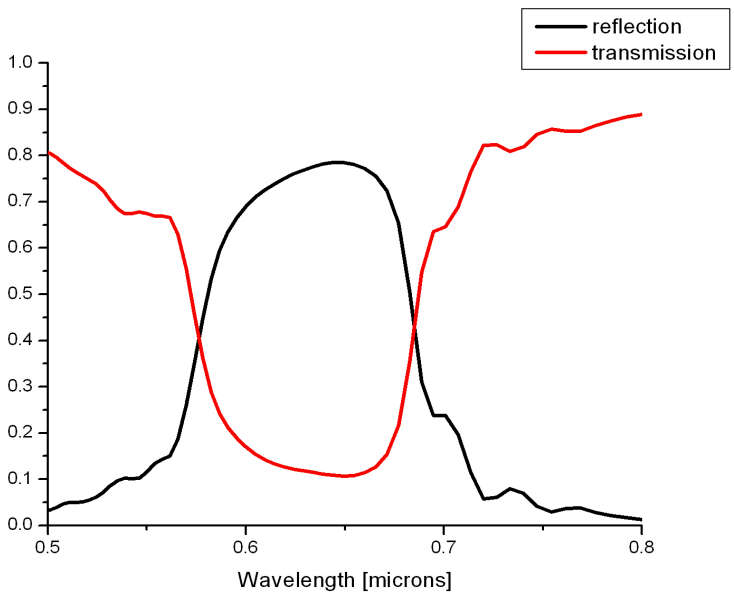


Fig. 2. Spectral dependence of the reflected (black line) and transmitted (red line) power of the three-dimensional PC.

After pinpointing the band gap of the three-dimensional structure, we have studied the waveguiding properties of a PC with a single line defect (absence of a single row

of holes). More precisely, we have performed continuous wave FDTD simulations of a PC illuminated with an optical field with a wavelength situated in the band gap. Numerically investigating the field propagation in the system, we have found that it is laterally confined, the light being guided along the line defect. The simulation results are illustrated in Figure 3.

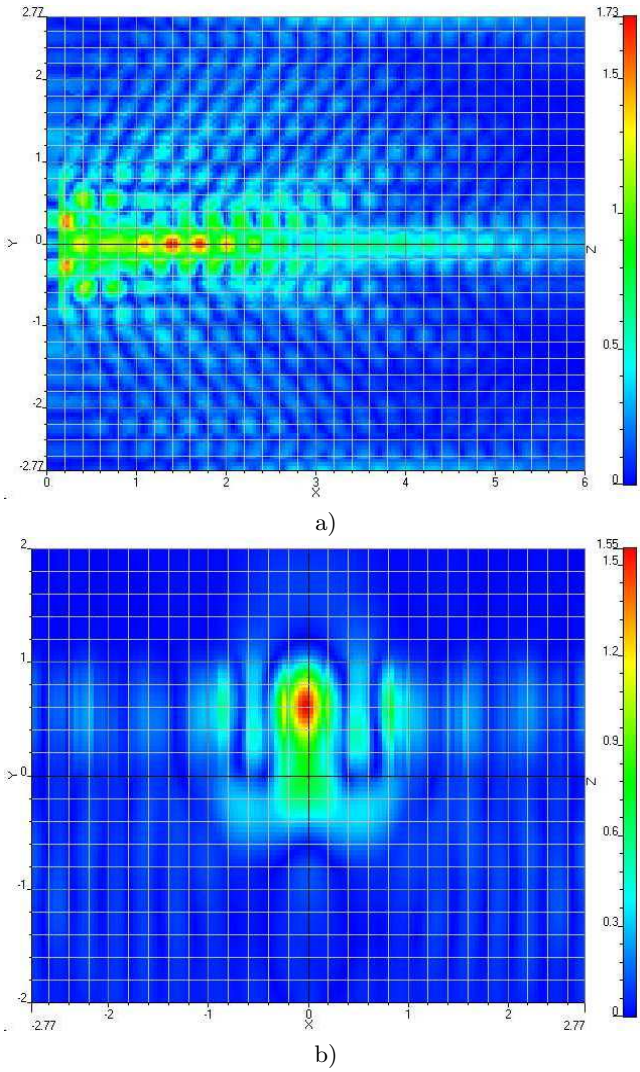


Fig. 3. Field propagation in a PC with a line defect.
Field configuration a) along the propagation direction, and
b) in a cross-section perpendicular to the propagation direction.

Figure 3-a represents the electromagnetic field configuration in the $(x - z)$ plane, and shows the strong field confinement along the line defect, parallel to the propa-

gation direction. The field configuration in a cross-section of the PC waveguide is illustrated in Figure 3-b, which reveals both the lateral and the vertical light confinement.

4. Fabrication and results

The fabrication of the PC is challenging, one of the main difficulties being the choice of the suitable processes and materials. State-of-the-art semiconductor fabrication techniques are required for the implementation of PCs for photonic applications.

Organic materials and polymers have recently demonstrated potential applications because of their easy-to-use features, low cost, and electro-optic tunability. Even if their refractive index contrast is low, it is easy to obtain a single line defect PC waveguide by EBL patterning.

In the experiments we used PMMA positive photoresist with a molecular weight of 950k (MICROCHEM). This material is used for the first time for the manufacture of PCs, despite of its low index of refraction. The PC structure was obtained without expensive and complicated technological processes.

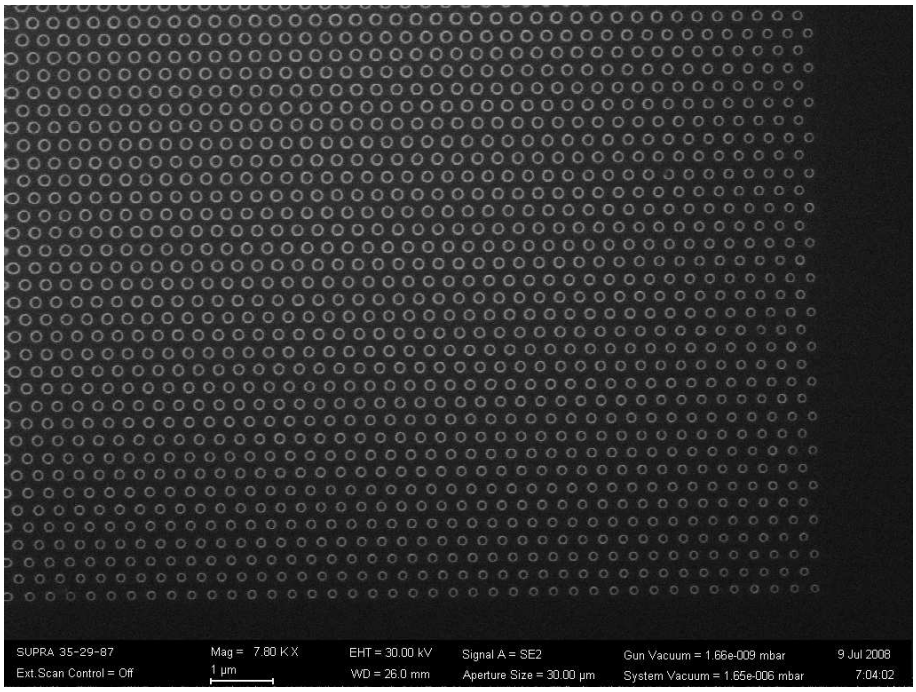
More precisely, the PMMA polymer was spin-coated on a silicon substrate, on which a SiO_2 layer was thermally grown. The thickness of the SiO_2 layer was 1.7 μm. We used 6% weight PMMA in chlorobenzene to obtain a layer of about 500 nm, two successive layers being deposited to increase the total thickness of the electronoresist to 1 μm. After spinning, the PMMA layer was introduced for two hours in an oven at 160°C. For developing the electrono-resist layer we used a solution of 3:1 IPA:MIBK.

The nanolithography was performed with a RAITH e-Line nanoengineering workstation (field emission gun – GEMINI, laser interferometer sample stage). For this application the accelerating voltage was set at 15 kV and beam current at 300 pA, the working distance being 15 nm. We used a clearing dose of 200 pC/cm^2 for areas and 0.2 pC/dot for dots.

The resulting experimental structure was investigated with a scanning electron microscope (SEM), the SEM results being presented in Figure 4. The structure in Figure 4a is a PMMA PC, Figure 4b shows a PC with a two-line defect, while Figure 4c illustrates the whole structure, including the two taper sections. A detail of the tapered region is shown in Figure 4d.

5. Conclusions

We have demonstrated the design, simulation and fabrication of a PMMA PC channel waveguide integrated on the same substrate with two taper sections that are required for launching into and extracting light from the PC waveguide. This structure has potential applications in tunable PC devices and is relatively easy to fabricate. Although the contrast between the refractive indices of the PMMA and the SiO_2 substrate is not very high, numerical simulations have confirmed that in the visible spectral region the structure acts as a waveguide.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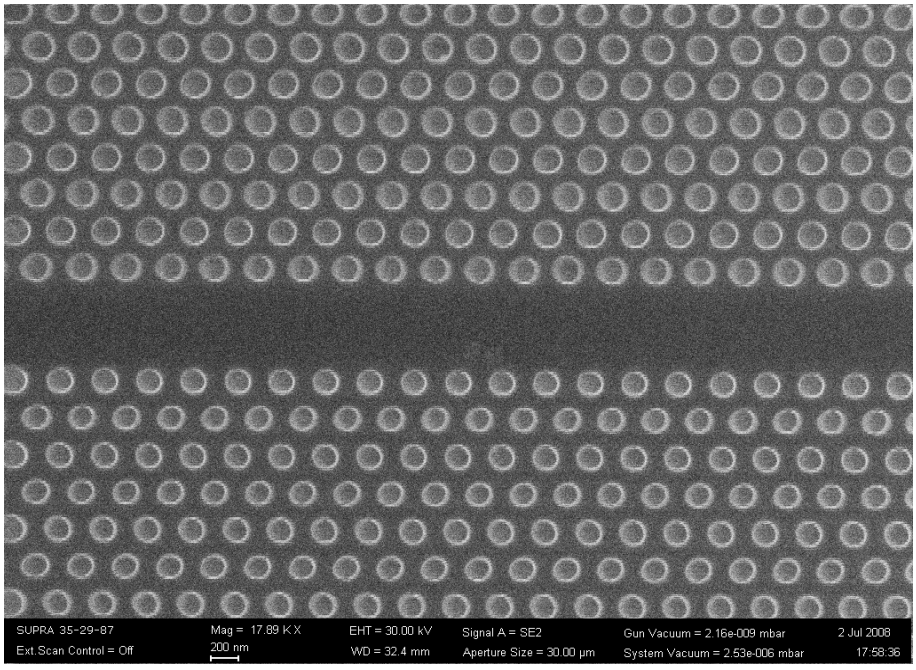
a)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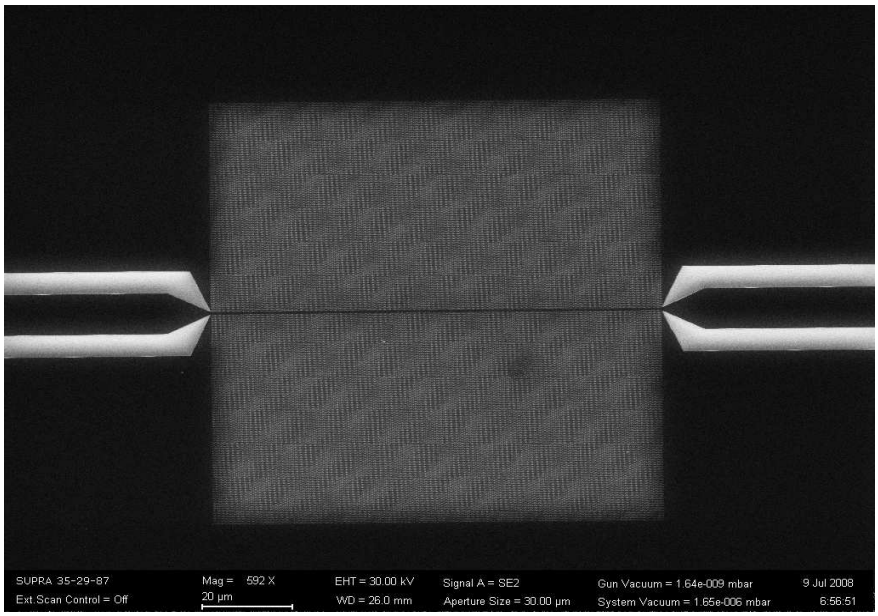
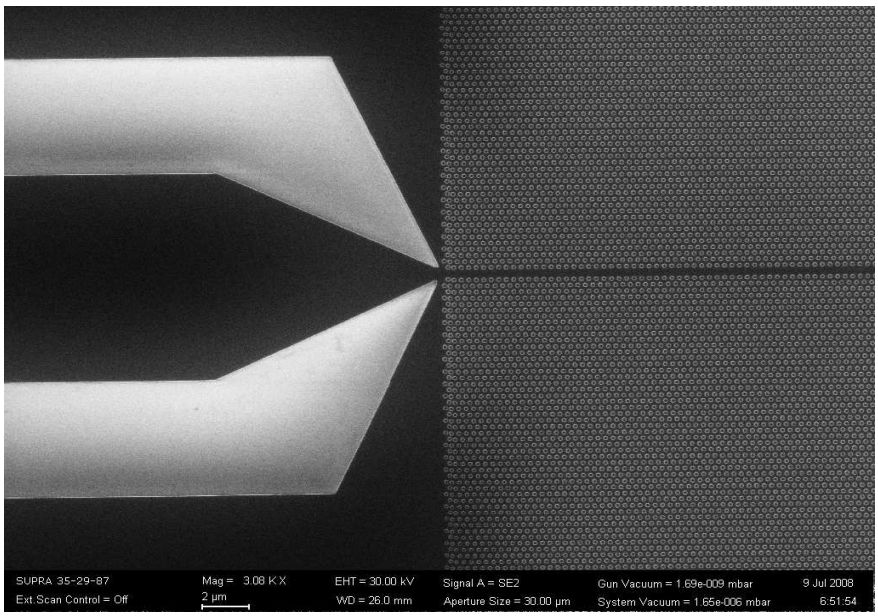


c)



d)

Fig. 4. SEM results of the fabricated structure: a) the PMMA PC, b) the two-line defect in the PC, c) the whole structure, including the taper sections, and d) detail of the tapered region.

Acknowledgments. This work has been supported by the National Romanian Project - CEEX-CALIST No. 6111/2005 (NANOSCALE- CONV).

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