Fabrication of two-dimensional photonic crystals in a chalcogenide glass

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Abstract: Two-dimensional photonic band gap structures consisting of air holes arranged to form a hexagonal lattice were patterned into chalcogenide glass thin films by Focused Ion Beam (FIB) milling. The dimensional parameters for these structures, namely type of lattice, lattice parameter and radius of the holes, were chosen so as to show a photonic band gap relevant to the infrared range, aiming at their subsequent use in the field of chemical sensing and biosensing. The optical behaviour of these structures was determined by calculating the band structure for the TM (magnetic field in-plane) and TE (electric field in-plane) modes. Furthermore, FIB milling was used to fabricate input and output waveguides coupled to the photonic crystals. The transmission spectra of the resulting structures for the TE and TM modes with two different orientations were also calculated.

Keywords: chalcogenide glass; photonic crystal; focused ion beam; band structure.

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1 Introduction

Optical communication systems must be able to process signals entirely in the optical domain to operate at high bit rates, thereby overcoming the speed limitations associated with optoelectronics conversion. Chalcogenide glasses are excellent candidates for all-optical signal processing, which involves the control of light by light. There are a number of actual and potential technological applications for these materials, given their high transmission in the infrared (IR) regime and the possibility of controlling physical and optical properties through control of composition [1,2]. This property makes them attractive materials in the areas of infrared optics, optical signal imaging and data storage. Amorphous chalcogenide materials can be deposited in thin film form in several ways, including oblique angle deposition (OAD) [3,4]. Additionally, amorphous Ge-containing chalcogenides are less toxic and easier to handle than most III-V semiconducting materials and posses extra functionality for optical fabrication and performance due to the possibility of modifying their optical band gap and index of refraction by illumination [5]. Taking advantage of these photo-induced effects, various kinds of optical elements have been patterned in chalcogenide glasses.

Moreover, recent advances in micro- and nanofabrication techniques present opportunities to control light in a way that is not possible with materials found in nature, since artificial structures built up from subwavelength elements can be fabricated with tailored spatial distribution of the effective optical constants. This offers the potential to guide and control the flow of electromagnetic radiation. In other words, the shape and size of the structural unit of a metamaterial can be tailored, and their composition and morphology can be tuned to provide new functionality [6]. Within this context, photonic crystals are defined as periodic dielectric structures that do not allow propagation at specific wavelengths [7,8]. Moreover, photons in photonic crystals can present allowed and forbidden band structures, localised defect modes, surface modes, etc. [9]. In this respect, the possibility of controlling light propagation has lead to the proposal of many novel devices [10]. Of particular interest is a photonic crystal whose band structure possesses a complete photonic band gap (PBG), i.e., overlapping photonic band gaps in the TM (magnetic field in-plane) and TE (electric field in-plane) modes. In order to achieve a complete PBG, the periodic variation of the dielectric constant of the material should be on a wavelength scale and the amplitude of the dielectric constant variation should be sufficiently high. To date, most two-dimensional photonic crystals have been fabricated using electron beam or photolithography combined with dry etching. These processes are reasonably well developed for silicon as a result of research into CMOS fabrication and silicon-on-insulator photonic devices [11]. Systems other than silicon, however, lack this level of technical maturity. For this reason, some of these high index materials have been patterned using focused ion beam (FIB) [12–14].

In this paper we report the design and fabrication of two-dimensional (2D) photonic crystals with band gaps relevant to IR wavelengths. These structures consist of hexagonal lattices of air holes drilled out in GeSbSe chalcogenide thin films. This particular arrangement was chosen since, despite the considerable amount of research undertaken on various lattice structures, a hexagonal lattice has been shown to produce the largest photonic band gap both in the TM and TE modes [15].

2 Experimental

Amorphous GeSbSe thin films were deposited by thermal evaporation on silicon dioxide-coated silicon substrates from commercially available bulk chalcogenide glasses with a nominal composition of $Ge_{28}Sb_{12}Se_{60}$. The SiO_2-coated silicon substrates were cleaned with acetone and ethanol, dried with nitrogen, and immediately loaded into the vacuum chamber. The GeSbSe was thermally evaporated using a typical current of 95 A, resulting in thin films with thicknesses in the 4–5 micron range. The base pressure was generally below 10^{-6} Torr.

An FEI Quanta 200 3D focused ion beam (FIB) was used to fabricate photonic crystals from GeSbSe coated substrates. In this technique, a fine (<25 nm) 30 kV Ga+ beam is scanned to form hexagonal lattices of submicron holes on a surface at an 11–12 mm (noneucentric) working distance. The lattice pattern was generated in a scripting interface with specified diameters smaller than the target diameters to compensate for the spreading from ion-solid interactions and the finite diameter of the beam. The target r/a ratio for the holes was 0.4; actual ratios varied from 0.3 to 0.38. Two sets of spacings, a, (1 μm and 2 μm) were fabricated. Target depths (Si reference) of 20–50 nm yielded well-defined holes. Waveguides were formed with a 430 nm probe at a 30 mm working distance.

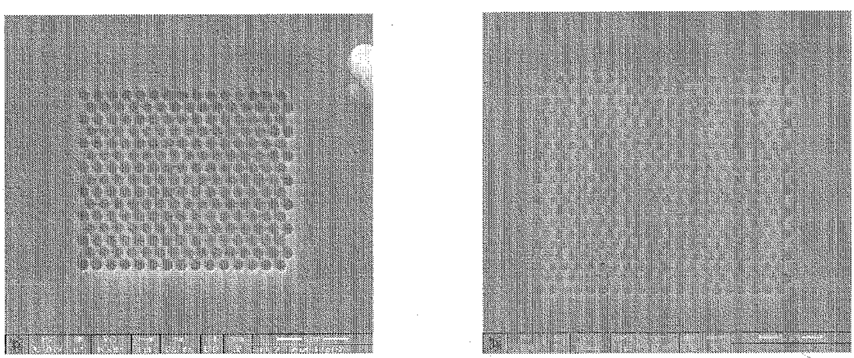
In order to calculate the photonic band structure of the chalcogenide-based 2D photonic crystals, fully vectorial eigenmodes of Maxwell's equations with periodic boundary conditions were computed by preconditioned conjugate gradient minimisation of the block Rayleigh quotient in a planewave basis [16–18]. By the use of this method it is possible to solve for interior eigenvalues without computing the many underlying eigenstates.

To determine the spectral transmission coefficients of the photonic crystals for different crystal high-symmetry directions, numerical simulations were performed with the Translight Software Code [19], a frequency domain technique. In the Translight software code, a transfer matrix-method is implemented to solve Maxwell's equations. Since solutions of Maxwell's equations are Bloch waves, eigenvectors of the transfer matrix are Bloch waves as well. The photonic band structure is then determined by diagonalising the transfer matrix. The code for this method is of particular effectiveness in the calculations of band structures of 1D and 2D photonic structures as well as for calculations of transmission and reflection coefficients of 1D, 2D and 3D photonic crystals.

3 Results and discussion

GeSbSe thin films with thicknesses in the 4–5 micron range were thermally evaporated onto SiO_2-coated silicon substrates for the subsequent fabrication of photonic crystals with high aspect ratio by focused ion beam (FIB) patterning. These structures consist of hexagonal arrays of air holes with $r/a = 0.4$, with r being the radius of the holes and a the lattice parameter. FIB milling provides single-step, rapid prototyping of photonic crystal devices without the need to optimise the conditions for dry etching as in typical lithography. Thus, FIB is here used as a powerful technique for the demonstration of the usefulness of given devices, although a production-capable patterning step would be needed before reasonable numbers of the device could be fabricated. Figure 1 is a pair of SEM micrographs of photonic crystals with two different lattice parameter and r/a ratios, patterned on GeSbSe thin films. In particular, the left image of Figure 1 shows a photonic crystal consisting in a 15 × 15 array of holes in a GeSbSe slab with $a = 1$ µm and $r/a = 0.4$, while the right image shows a 20 × 20 photonic crystal with $a = 2$ µm and $r/a = 0.3$.

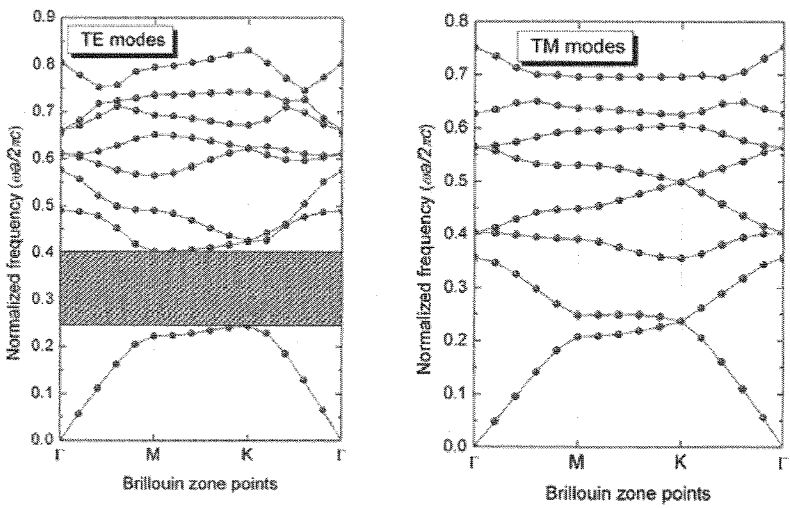
Figure 1 Top views of two different photonic crystals with different lattice parameters (a) and ratios of hole radius to lattice parameter (r/a): $a = 1$ µm, $r/a = 0.4$ (right), and $a = 760$ nm, $r/a = 0.3$ (left). The total number of periods is 15 and 20 respectively



In the fabricated systems, light is confined in the GeSbSe slabs by index guiding, while waveguiding within the slab plane is dictated by the photonic crystal. The photonic band structure of the fabricated 2D photonic crystals were calculated for air holes following a hexagonal array with $r/a = 0.4$. Given the high aspect ratio of the structures, in the computational model the height of the holes is not considered and the photonic crystals can be assumed to be effectively 2D structures. The values of the index of refraction of GeSbSe for the simulations were chosen based on our previous experience on its empirical determination from the reflectance and transmittance spectra by using computational simulation techniques [20]. The extinction coefficient was neglected given its low values in the IR regime.

Figure 2 shows the calculated band structure for the TM and TE modes of a 2D photonic crystal based on GeSbSe chalcogenide glass. In this particular case, the index of refraction of GeSbSe was taken to be $n = 3.5$ and the radius of the holes $r = 0.4a$. In Figure 2, the normalised frequency ($\omega a/2\pi c$) is represented vs. the Brillouin zone points. Only the first eight bands were calculated. From Figure 2 no band gap is observed in the case of the TM bands. However, in the case of the TE bands, a band gap is observed from band 1 to band 2, between $0.25\omega a/2\pi c$ and $0.4\omega a/2\pi c$. As expected, the low index air holes are best suited for the formation of photonic band gaps to TE light in which the electric field lines surround the holes. On the other hand, the formation of GeSbSe holes embedded into an air matrix would have favoured the formation of photonic band gaps to TM light.

Figure 2 TM and TE band structure for $n = 3.5$ and $r = 0.4a$ calculated by numerical simulations. A bandgap exists in the frequency range of $0.25\omega a/2\pi c$ to $0.4\omega a/2\pi c$ for TE modes. (see online version for colours)



Being fabricated in glass form, chalcogenides constitute a versatile platform for making planar waveguides, in addition to more traditional structures such as optical fibers. In this sense, Figure 3 shows a plane waveguide coupled to a photonic crystal for two different orientations, each of which would yield a different optical response in the IR regime. In these devices, light is guided in the third dimension by total internal reflection: SiO_2 is used for the lower cladding and air for the upper cladding. Finally, Figure 4 shows the calculated transmission spectra for TE and TM modes for the two orientations of the photonic crystals shown in Figure 3. From the simulations, a different behaviour is observed in the four different cases considered. In particular, the spectra show transmittance maxima and minima, corresponding to forbidden and allowed bands respectively. A broad bandgap is observed from 2.5 to 4.5 microns in the Γ-M direction for TE modes. Due to this bandgap, light propagation will be forbidden in this wavelength range, resulting in high reflectance. However, in the Γ-K direction light will be reflected in a similar wavelength range both for TE and TM polarisation.

Figure 3 Top view of two systems consisting of a central photonic crystal coupled to input and output waveguides ($r/a = 0.35$, $a = 1$ µm). The orientation of the photonic crystals is different in each case (Γ-M and Γ-K directions)

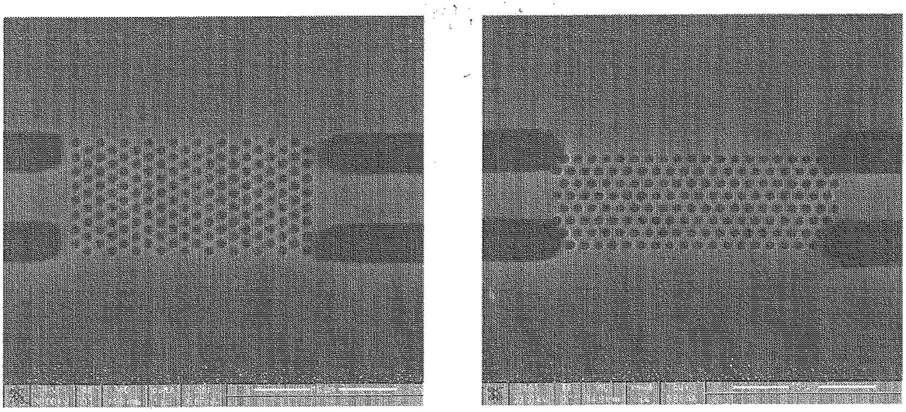
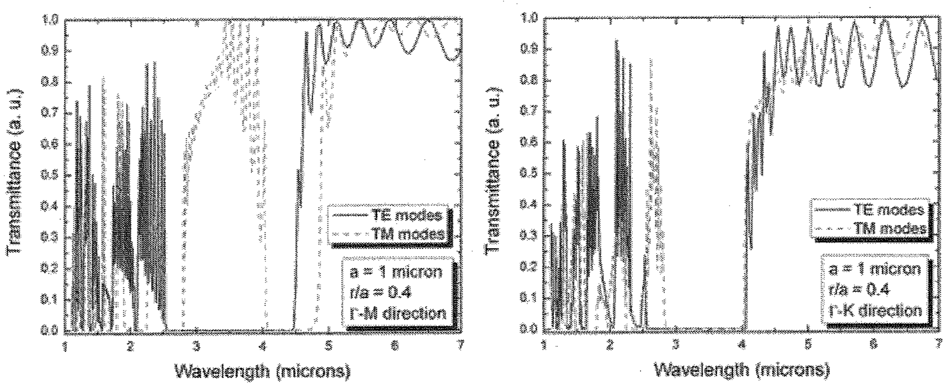


Figure 4 Calculated transmission spectra for TM and TE modes for the two high-symmetry directions shown in Figure 3 (see online version for colours)



4 Summary and conclusions

Two-dimensional GeSbSe chalcogenide glass photonic crystals were fabricated by FIB. The optical behaviour of the crystals was determined and reveals that light flow through these planar structures in the infrared regime for TE and TM polarisation can be controlled by using different lattice parameters (a) and radius of the holes (r), thus allowing the development of PBG structures with tunable optical response entirely based on chalcogenide glasses. For example, the fabrication of photonic crystals with smaller lattice parameters would lead to light control at shorter wavelengths. Finally, it should be pointed out that the FIB allows fast prototyping, avoids the use of multistep lithographic processes and allows maskless and dry etching.

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