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Photonic crystals based on amorphous chalcogenides

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Amorphous chalcogenide structures are proposed for designing meta-materials as e.g. photonic crystals with stop gaps in the far infrared and microwave range. Micrometer diameter lenslets made of As_2S_3 glass are used to this purpose. Special heat treatment is proposed to get a shrinkage of the structure built from stacks of lenslets, and creating a modulated woodpile configuration based on the photo-fluidity effect in arsenic sulphide chalcogenides. The simple procedure allows the tuning of the lattice parameter in order to reach the desired optical or microwave properties of the photonic crystal with stop band gaps.

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1. Introduction

Photonic crystals are periodic microstructures with a spatial modulation in their refractive index in specific directions. This modulation leads to the opening of photonic band gaps or stop gaps where the propagation of the electromagnetic waves is forbidden in certain frequency ranges [1-11]. Bloch-Floquet theorem for Maxwell equations implies the existence of photonic bands which consist of allowed and forbidden band regions for electromagnetic waves. These stop bands depend greatly on the wavelength of the incident light.

Last years much effort was dedicated to the design and fabrication of photonic crystals [12, 13]. In 1999 Sun et al. [14] achieved the so-called layer by layer or wood pile photonic crystals with two-photon-absorption photo-polymerization of resin. These crystals have been fabricated with a fundamental stop band at 3.9 μm wavelength. Deubel et al. [13] reported the fabrication through direct laser writing and characterization of high-quality large-scale f.c.c. layer-by-layer structures, with fundamental stop bands ranging from 1.3 to 1.7 μm.

2. The chalcogenide lenslets

The As-S chalcogenide glasses are amorphous semiconductors with high transparency throughout the near-infrared and infrared spectral region. The index of refraction lies between 2.45 and 2.53, depending on the wavelength and on the stoichiometry [14]. This index is enough to open a photonic band gap. In As_2S_3 the position of the absorption edge is situated at 530 nm leaving a broad part of the visible spectrum accessible.

Spherical lenslets of As_2S_3 have been produced with a new patented procedure [15]. Careful selection of the lenslets, to match an a pre-established diameter has been achieved using an optical microscope. The distribution of lenslet diameters exhibits a maximum around 50 μm [16]. Therefore, this diameter has been proposed for photonic crystal construction. Fig. 1 shows one typical spherical lenslet.

Fig. 1. Chalcogenide lenslet prepared according to the procedure from [14].

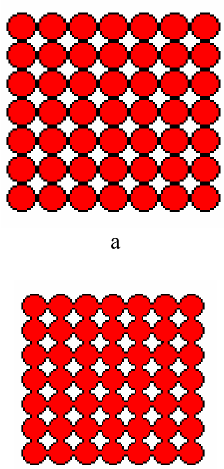
3. Making As_2S_3 photonic crystals

The lenslets can be mechanically assembled layer by layer in order to give rise to a construction similar to that of a simple cubic crystal packing. In order to maintain the lenslets of the layer in fixed positions a special optical glue could be used (e.g. ECCOBOND – 24 from Emmerson & Cumming (n ~ 1.45 – 1.55). This glue ensures the contrast of refraction indices in the assembly chalcogenide spheres – polymer matrix.

After stacking several layers, the whole chalcogenide crystal must be heat treated. If the heating temperature is carefully conduced, then the lenslets suffer firstly a photo-fluidization effect [17] and thereafter a sintering effect is produced. For higher temperatures the partial decomposition and evaporation determines the shrinking of the lenslets and all the construction shrinks, without changing the cubic configuration. Thus, a fine tuning of the stop band gap could be achieved. An other possibility to get shrinking is the illumination with light at 543 nm (He-Ne laser). This causes changes both in the refractive index and in the density of the material. Experiments show that illumination, at room temperature gives rise to an increase of the refractive index and this effect is accompanied by a ~1.5 % decrease in the film thickness.

Fig. 2 shows the chalcogenide sphere arrangement in one layer and the parameters of the photonic chalcogenide crystals. The high refractive index of the As_2S_3 makes the structure convenient in photonic applications.

To move the fundamental photonic band gaps to wavelengths in the telecommunication regime of 1.5 μm and 1.3 μm, it is necessary to have an in-plane rod spacing of the order of 1 μm and smaller. The sample area of 100 μm or 100 μm is sufficiently large for optical spectroscopy as well as for potential devices. The midgap wavelength will move towards longer wavelengths after infiltration of the template by a high index material. The success of the chalcogenide photonic crystal depends on the possibility to tune the lattice constant "a" to sufficiently low values, approaching one micrometer.



a

b

Fig. 2. Configuration of one layer chalcogenide lenslet packing. a. before sintering and shrinking b. after sintering and shrinking (gluing of the chalcogenide spheres is produced, thus forming chalcogenide slabs with modulated shape).

4. Characteristics of the chalcogenide photonic crystal

The described photonic crystal is characterized by a special configuration at variance with the exact woodpile configuration. After sintering and shrinking a structure similar, but not identical to the classical wood pile structure is produced.

A single waveguide mode spans over a normalized frequency range of a/λ = 0.380-0.417. The single mode wave-guiding bandwidth will be four times the difference 0.417 – 0.380 = 147 nm. For a =1 μm, λ will be around 2.5 μm, an infrared wavelength useful in telecommunications. For a = 50 μm, λ will be 125 μm, a value situated in the microwave range.

The degeneracy of the four lowest bands in a woodpile 3D structure at the Z-point of the Brillouin zone boundary has been shown and discussed by Chutinan and John [16]. The degeneracy between the first and second bands is a direct consequence of the symmetry of the structure in x and y directions. In our case the symmetry is more extended in z-direction. Thus, more degeneracy is expected, while the photonic band gap will be less affected. A π/2 phase shift between the first and fourth band is also expected in both structures.

The parameters of interest in a photonic crystal are the positions and bandwidths of the band gaps. These parameters are functions of the geometry of the photonic crystal and the index contrast between chalcogenide and matrix (air or polymer introduced in the interstices of the chalcogenide spheres). If the low index material is changed then the positions and the bandwidths of the band gaps will be changed.

In order to get an expression for the band gap characterization we must solve the Maxwell equation. A simple scalar approximation, valid both in the case of low or high contrast of the refraction index, for propagation along one side of the cubical configuration of the crystal is:

$$\nabla_t^2\varphi=(\beta^2-k_o^2\varepsilon(x,y))\varphi \qquad (1)$$

Where $k_o = \omega/c = 2\pi/\lambda$ is the wave vector, $\varepsilon(x,y)$ is the transverse dielectric constant profile , β is the propagation constant and φ denotes either E_x, E_y, E_z, H_x, H_y or H_z.

The transverse dielectric constant profile (x,y) can be written as

$$\varepsilon(x,y) = \varepsilon_b + (\varepsilon_a - \varepsilon_b)\, g(x,y) \qquad (2)$$

where g(x, y) =1 for chalcogenide region and g(x,y) = 0 for polymer or air region.

The propagation constant can be written as

$$\beta^2=k_o^2 n_{eff}^2 \qquad (3)$$

where n_{eff} is the effective index of the fundamental core mode.

By substituting eq. 2 and eq. 3 in eq. 1, one gets the following form for the Maxwell equation:

$$\nabla_t^2\varphi = k_o^2((n_{eff}^2-n_b^2) - (n_a^2-n_b^2)g(x,y))\varphi \qquad (4)$$

Eq. 4 can be viewed as an eigenvalue equation for the unknown value k_o and eigenvector φ with the effective index n_{eff} as a free parameter. For a given value of n_{eff} the band gap can be now evaluated by the plane wave method. Therefore, the band structure can be characterized as a function of n_{eff}.

Equation 4 can be written in a simpler form as:

$$\nabla_t^2\varphi=k_o^2(n_b^2-n_a^2)(g(x,y)-1)\varphi \qquad (5)$$

The contribution of the material is only a scaling factor of k_o. The eigenvlues of eq.5 are determined by the function g(x,y). Supposing A_{edge} is the eigenvalue that determines the photonic band edge, the wavelength of this edge (λ_{edge}) is given by

$$k_o^2(n_b^2-n_a^2) = A_{edge}$$
$$\lambda^2= (4\pi^2/ A_{edge})(n_b^2-n_a^2) = C^2(n_b^2-n_a^2) \qquad (6)$$

where $C^2 = 4\pi^2/A_{edge}$. The first term C represents the waveguide contribution, determined by the geometry of the crystal. The second term is the contribution of the material. Therefore, the relationship between the wavelength shift and the variation of the refractive index within the chalcogenide can be estimated with this explicit function.

The bandwidths of a transmission window can also be derived by subtracting two wedges of the band gap. The bandwidth is, therefore, expressed by

$$\Delta\lambda_{edge}^2 = (C_1 – C_2)^2(n_b^2-n_a^2) \qquad (7)$$

where C_1 and C_2 are the coefficients for the two edges of the band gap and W is equal to $C_1 – C_2$.

For the material data of the proposed photonic crystal the calculated width is 0.944 μm a value that demonstrates the efficiency of the selected material.

5. Conclusions

A simple procedure is proposed for making photonic crystals based on chalcogenide glasses. High contrast is achieved by using As_2S_3 glasses spherical lenslets embedded in optical glue. Due to characteristics of the procedure only large micrometric photonic crystals with photonic band gaps in the range of microwave wavelength could be obtained. A shrinking effect under heat treatment allows for shifting the main photonic band gap to lower wavelength in the far infrared region of the electromagnetic spectrum.

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