https://doi.org/10.26552/com.C.2008.2.25-29

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PHOTONIC CRYSTALS – OPTICAL STRUCTURES FOR ADVANCED TECHNOLOGY

This paper presents experimental results in the field of photonic crystals investigation. There are presented our results of experimental investigation of one-dimensional photonic crystals appearing in nature, two-dimensional photonic crystals we formed in LiNbO3 and thin photoresist layers and results of our investigation of chromatic dispersion of photonic crystal fibers as well as the influence of fiber bending on their transmittance.

1. Introduction

Submicron structures known as photonic crystals (PCs) attract great attention because of their unique optical properties. First attempts of their implementation in technology show improvement of optical and electrical properties of optoelectronic devices. Photonic crystals are formed by periodic inhomogeneities of the refractive index with periodicity near the wavelength of an interaction light. Such PC's show then typical effect of wavelength selection known as photonic band gap. The first Yablonovitch established this term as an analogy to the electronic band gap arrangement in semiconductor materials [1].

It has long been known that metallic structural coloration of birds and insects was due to the wavelength selection in PC's. Photonic crystal of one (1D), two (2D) and three dimensional (3D) arrays are found in natural world and became the topic of the scientific studies [2, 3] (Fig. 1).

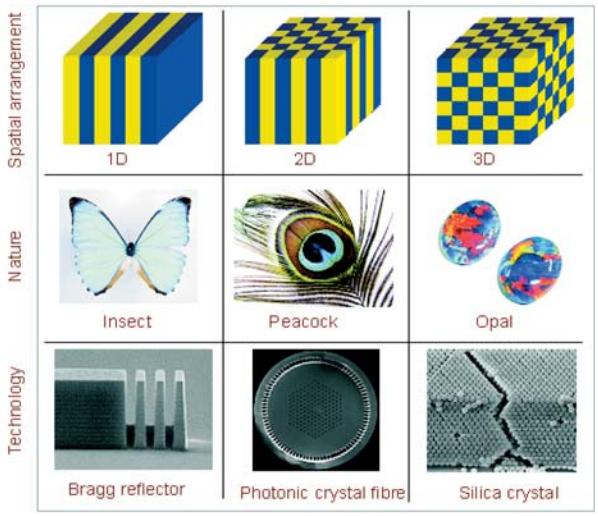

Fig. 1 1D, 2D and 3D photonic crystals in nature and technology

Inspiration in natural world started the progress in technology. Formation of 1D PC was successfully implemented 30 years ago as Bragg reflectors. 2D PC are topic of interest in optical fiber technology, where in last decade fabrication of photonic crystal fibers developed, while the 3D PC fabrication is only starting nowadays [4].

This paper presents our experimental results in the field of PC fabrication and investigation. We demonstrate experimental investigations on the 1D PCs in nature, planar 2D PCs and 2D PC formed in photonic crystal fibers.

2. Photonic crystals in nature

The surface of several beetles and other arthropods show structural colors originated from the light interference in the multilayer of alternative high and low refractive index materials [2, 3]. We investigated the structural colors, which arise in the 1D PCs in the cuticle of some species of class *Insecta*. Optical properties of studied insect were analyzed from angular spectral dependencies of the reflected light. The measured reflected spectra of samples for different incident angles are shown in Fig. 2a. In measured dependencies the individual maxima of measured spectra are in the region of visible light.

The evident blue shift of reflected spectra was observed with the increasing angle of incidence. The reflected spectrum from the sample of cuticle of dead insect was investigated under different conditions. In experiments we found that structural colors of the studied insect can be changed by the heating of samples. The blue shift of the main maximum of the reflected spectrum was observed with the increasing temperature for all investigated samples (Fig. 2b). According to a theoretical analysis the reflected spectrum from the multilayer structures (Fig. 3a) shows the blue shift as the layers thickness decreases [5].

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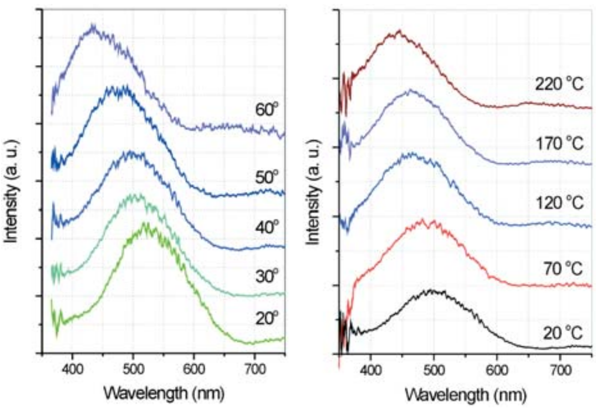
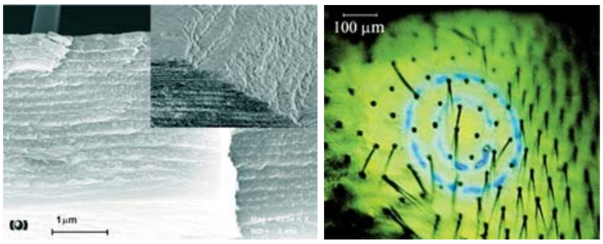


a) b)

Fig. 2 a) The angular dependence of the reflected spectra measured from the samples of Lucilia sericata. b) The temperature dependencies of reflected spectrum of cuticle of Lucilia sericata measured for 40° angle of incidence



a) b)

Fig. 3 a) SEM image of the cleaved edge of the multilayer structure of Lucilia sericata cuticle. b) The local structural color changes on the back of Lucilia sericata in the shape of sign "©" prepared by the focused HeNe laser beam

Using such experimental arrangement the sign "©"on the cuticle of *Lucilia sericata* (Fig. 3b) was created. The figure documents the local changes of the multilayer photonic structures caused by a local heating of the cuticle with the focused laser beam, what finally results in the blue shift of the reflected spectrum.

3. Fabrication of photonic crystals

Because of their unique optical properties which are advantageous for various device applications [4], the fabrication of photonic crystals has attracted a great attention. The essential for the photonics application is to have a material with properly modulated physical characteristics, e.g. refractive index. Various techniques have been used to fabricate such periodic structures [e.g. 6] but those of techniques that employ the refractive index changes induced due to illumination by light seem to be more interesting for applications.

We recognize various materials for fabrication of photonic structures such as lithium niobate – $LiNbO_3$, barium tantalate – $BaTiO_3$, photoresists and liquid crystals like polyvinylkarbazol – PVK, polymetylmetaakrylat – PMMA and so on. We focused our effort on the efficient design of simple test structures prepared in a $LiNbO_3$:Fe crystals and a positive photoresist AZ 4562 (Clariant Corp.) based on novolac resin.

In the case of $LiNbO_3$ crystals we utilize our knowledge of the photorefractive effect, i.e. the effect observed in materials that respond to light by modifying their refractive index [7, 8]. It is well-known that the non-homogeneous illumination of a crystal results in the spatial redistribution of charge-carrying electrons, including those captured in traps or donor centers. This induces a space charge field in the crystal which contributes to the refractive index changes of the crystal via electro-optic effect or via dependence of the refractive index on population of traps. The result is a spatially-varying refractive index region that occurs throughout the crystal's volume. The simplest (1D) photonic structure can be formed by a two-beam interference method [9]. The basic setup consists of an argon ion laser operating at 488 nm, a beam splitter and a sample holder (Fig. 4). Due to the construction of the splitter beams intersect each other in the place of the crystal sample seating. Laser beams form the optical field with harmonic dependence on coordinate with spatial period depending on the angle between incident beams

$$I(z) = I_0 \cdot (1 + m \cdot cos(K \cdot z)), \qquad (1)$$

where I_0 is the average intensity of light, $K = 2\pi/\Lambda$ is the spatial frequency (Λ is the spatial period), z is the coordinate along the c-axis (optical axis of the crystal) and $m = 2 \cdot \sqrt{I_1 \cdot I_2} / (I_1 + I_2)$ is the modulation index dependent on the intensities I_1 and I_2 of the interfering beams.

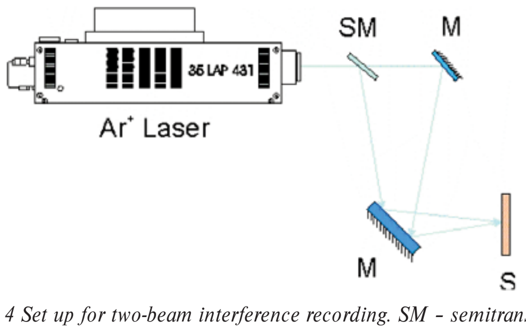
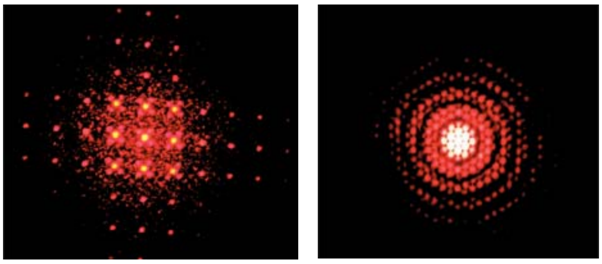


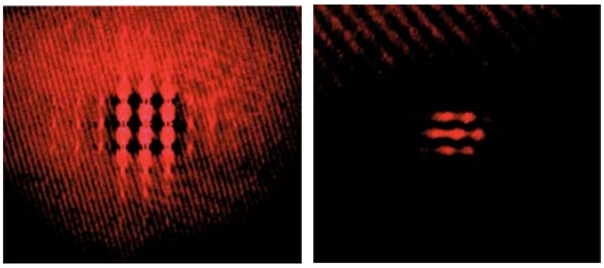
Fig. 4 Set up for two-beam interference recording. SM – semitransparent mirror, M – mirror, S – sample

This optical field creates a region with spatially modulated refractive index, which acts as the phase diffraction grating. In principle, the grating can work in both, the transmission and reflection regimes [9]. Investigation of the transmission grating formation provides the useful information such as recording time and amplitude of refractive index modulation that can be used, employing the coupled mode theory, for preparation of grating working in reflection regime. Besides the 1D structure we formed also more complex structures (Fig. 5).



a) *b)*

Fig. 5 Diffraction patterns used for recording



a) *b)*

Fig. 6 Interferograms of recorded optical fields shown in Fig. 5

However, there is the disadvantage of crystalline materials – their anisotropy. It means that one has to choose the proper orientation of the crystal with respect to the gradient of illumination during recording or choose the special form of the field according to the anisotropy in order to produce a record. The optical fields used for recording were made using one beam of Ar laser which irradiated the suitable mask. The originated diffraction pattern was then projected by a lens onto the crystal. The process of recording took from 1 minute to 2.5 minutes. The average intensity of the recording beam was 4.2 mWmm^{-2}. Recorded optical fields (Fig. 6) can be well-observed using Mach-Zehnder interferometer [10].

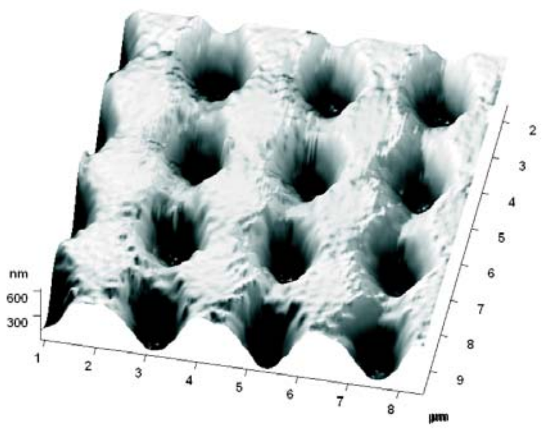


Fig. 7 AFM image of 2D structure prepared by double exposure with angle of incident laser beams α = 90°

The troubles according anisotropy can be overcome by using another type of material which is isotropice.g. a layer of a photoresist. The experimental set up for recording can be the same although the mechanism of the record formation is different. In this material light with the proper wavelength will start the sequence of chemical reactions leading to formation of regions where original monomeric material changes to polymeric one. The change of the refractive index itself or change of the optical thickness is due to process of polymerization. In addition to 1D structure we prepared also 2D structures using combination of two-beam interference method and multiple exposure technique (Fig. 7) [11].

4. Photonic crystal fibers

The unique phenomenon of photonic crystals can be used for construction of optical waveguides – called *photonic crystal fibers* (PCFs). PCFs are fibers based on Bragg reflection on the photonic crystal surrounding the "core" of the fiber, while the guiding mechanism of conventional optical fibers is based on the total internal reflection of the light in boundary of the core and its cladding. The difference between the guiding mechanisms leads to different properties of PCFs and conventional fibers. Because of PCFs ability to confine light with confinement characteristics not possible in conventional optical fibers, PCF gives new applications in fiber-optic communications, nonlinear devices, highly sensitive gas sensors and many other areas [12].

It is essential, for better utilization of PCFs, to know their geometric parameters and transmission properties. Because PCFs have a more complicated cross section area than conventional optical fibers, sometimes it is necessary to modify the methods used for measuring their parameters as chromatic dispersion, transmittance and so on.

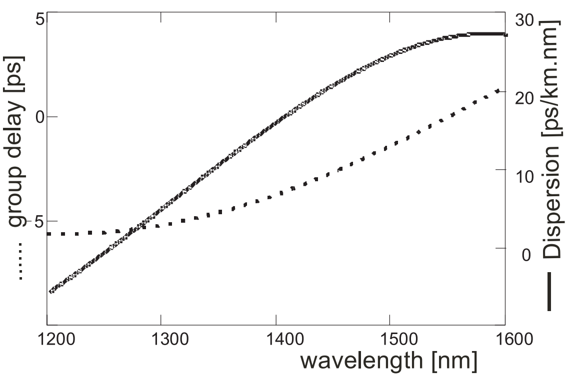


Fig. 8 Group delay $\Delta\tau_g$ and chromatic dispersion D_λ of measured photonic crystal fibre sample

Chromatic dispersion is not only an important parameter determining performance of optical fiber networks but it is also a key parameter for many other optical fiber applications, e.g. nonlinear applications using photonic crystal fibers (Fig. 8).

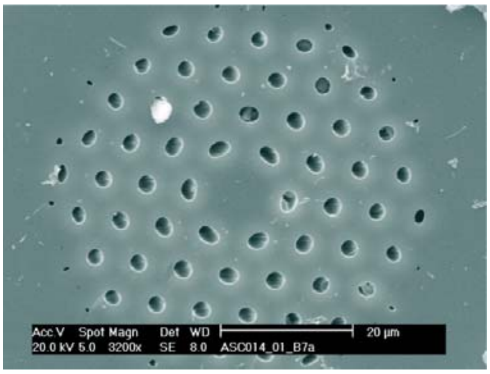


Fig. 9 SEM image of triangular structure of the photonic crystal fiber

Due to a complicated cross section area and some difficulties with shaping their faces needed at preparing mirrors we suggested to investigate the chromatic dispersion of PCF based on modified interferometric method which allows to investigate the short as well as long sample of PCFs. This method is also appropriate for determination of bend (or temperature and so on) influence on the transfer function of the fibers [13].

In our experiments we investigated photonic crystal fiber made by Centaurus Technologies, Australia (Fig. 9). The core diameter was 13 μm, average hole diameter 2.6 μm and pitch 7.1 μm.

The spectral dependence of transfer function of the fiber depends on the radius of the fiber bending. The character of this dependence is quite different from that of conventional fibers - an increasing of bending radius of conventional fibers effects the decrease of the fiber transmittance mainly in the region of longer wavelengths, while the increase of bending radius decreases transmittance of PCF in short-wave region (Fig. 10). This fact clearly shows that the mechanism of guiding the light in conventional fibers and PCFs is not the same [14].

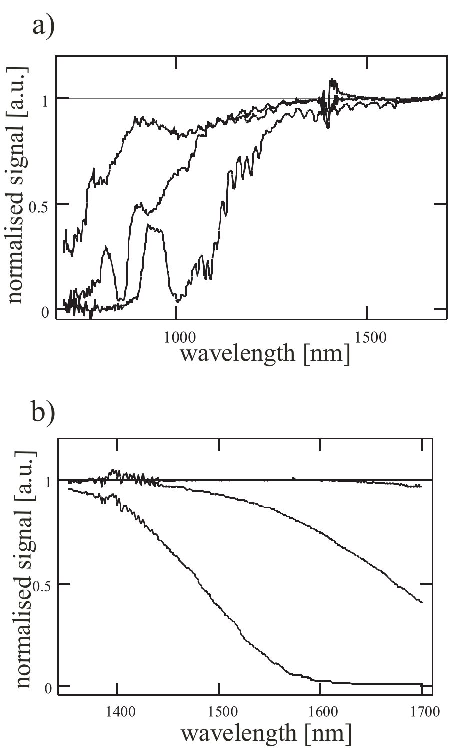


Fig. 10 Transmission functions of the PCF with different curvatures in the range (700-1700)nm and transmission functions of step-index fiber with different curvatures in the range (1350-1700)nm

The study of the intermodal interference (Fig. 11) in the fiber can also be useful. For example it allows to determine the spectral dependence of the loss coefficient for the first higher order mode as well as to determine the difference of the phase constants of interfering modes [15 17].

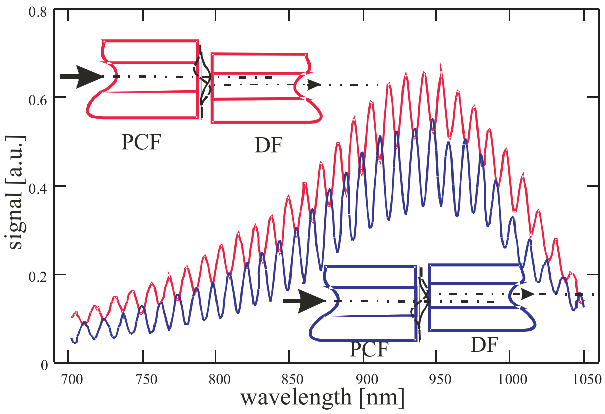


Fig. 11 Spectral dependencies of the signal interference measured in the PCF for two positions of the detecting fiber. The curves are not rectified for sensitivity of the detector and emissivity of the source

Knowledge of these parameters and their spectral dependence can provide useful information permitting a comparison between the fabricated optical fiber and the initial design upon which it was based. This includes potential information on the inhomogeneity of a fabricated fiber, which can be useful at their fabrication.

4. Conclusion

As it follows from above, the performed investigation of optical structures possessing the character of photonic crystals or photonic crystal fibers gave new results in the field of searching for the mechanisms responsible for origin of such structures in the photorefractive materials, volume and planar photonic crystals occurring in nature, or preparing structures in laboratory in materials like, for example $LiNbO_3$ crystals and photoresistive materials. Also investigation of photonic crystal fibers brought new results showing differences between guiding mechanism in photonic crystal fibers and conventional optical fibers.

ACKNOWLEDGEMENT

This work was partly supported by Slovak National Grant Agency No. VEGA 1/2048/05 and by the Science and Technology Assistance Agency contract No. APVT 20-013504.

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