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PHOTONIC CRYSTALS AND MICRO-PULLING DOWN METHOD

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The paper briefly summarizes the latest news in the area of photonic crystals. The definition, different types and properties of photonic materials are presented. It shows also how to apply this kind of materials by introducing different defects to their structures. The most interesting point is where such kind of periodic structures can be found in nature.

A new way of obtaining photonic crystals is presented. The micro-pulling method is proposed in order to grow self-organized eutectic microstructures.

1. INTRODUCTION - DEFINITION

From some time scientists try to turn to light instead of electrons as the information carrier. Light has several advantages over an electron. It can travel in a dielectric material at much greater speeds than the electron in a metallic wire. Light can also carry a larger amount of information per second [1]. The bandwidth of optical guides is significantly larger than that of metallic transmission lines: the bandwidth of fibre-optic communication systems is typically of the order of one terahertz, while that of electronic systems is only a few hundred kilohertz. Photons are not as strongly interacting as electrons, which helps to reduce energy losses. The materials, which can make the photonic technology as important as electronics is now a day, are *photonic crystals.*

A new class of optical materials called *photonic crystals (PC)* or *photonic band gap materials* is investigated since the ideas by John [2] and Yablonovitch [3]. The photonic crystal is an optical analogy of a semiconductor. Yablonovitch (inhibition of spontaneous emission) and John (localization of light) first pointed out the importance of a structure for electromagnetic proper-

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ties by drawing analogies between light and electrons. Both have a wave-like nature and can therefore be diffracted.

The semiconductor has a complete band gap between the valence and conduction energy bands. Photonic crystal has a photonic band gap where photons cannot exist, where the density of allowed states is equal zero (Fig.1).

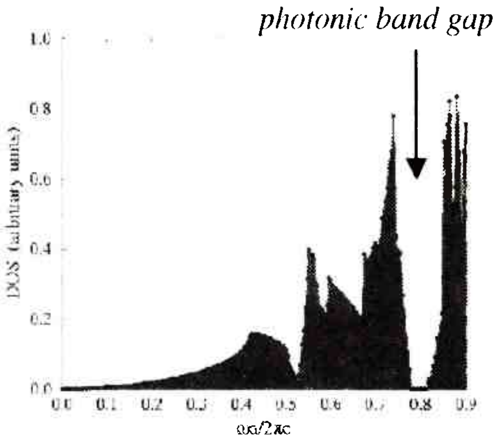

Fig.1. Density of states for fcc lattice [23].

In the semiconductor, the atomic lattice, V(r + R), presents a periodic potential to an electron propagating through the electronic crystal what results in destructive interference at certain wavelengths. The interaction of light with a material can be described by the material's refractive index or dielectric constant [4]. In the photonic crystal the periodic potential is due to a lattice of macroscopic media [5] ε(r + R), because to see diffractive effects for example for visible light the atoms have to be much bigger since visible light has a much longer wavelengths than electrons (less than 1000 nanometers as opposed to around 0.1 nanometers). PCs are formed of periodic arrays of dielectric scatters in homogeneous dielectric matrices. They can affect the properties of the photons similarly to this as semiconductors affects properties of electrons [6].

The PC crystals can be one-, two- and three-dimensional. Particularly interesting are photonic crystals with a complete photonic band gap (PBG). PBG describes a range of frequencies for which light cannot exist inside the crystal. To make the definition complete let's remind that complete photonic band gap means a direction- and polarization-independent band gap, and density of states (DOS) is the number of pathways, which are available for light modes. Since light particles are Bosons there can be more then one of them in a given state.

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Formation of photonic band gap can be regarded as the interplay between two distinct resonance scattering mechanisms. The first one is the „macroscopic" Bragg resonance from a periodic array of scatterers and the second one is the „microscopic" scattering resonance from a single unit cell of the material [7]. Photonic band gap is formed when both of the resonances happen in the same time.

I will finish the definition with words of John Pendry: "No wonder people are confused about photonic materials: We keep expanding the definition" [4].

2. TYPES AND PROPERTIES

From the point of view of space we can divide the photonic crystals on: one-dimensional (1 D), two-dimensional (2 D) and three-dimensional (3 D). Periodic structures have been playing an increasingly important role in semiconductor lasers. For example in distributed-feedback lasers the index of refraction is periodically modulated along the laser axis. In vertical cavity surface emitting lasers (VCSELs) the periodic Bragg reflectors form the cavity mirrors. The well known Bragg reflectors (mirrors) and interference filters are in fact one-dimensional photonic crystals with one-dimensional stop gap that moves with a change in the angle of incidence or other properties of the light.

2 D photonic crystals can have band gap in two dimensions in 360 degrees. They can be formed or of the shape of pillars distributed periodically in the air or periodically distributed holes in a dielectric material. The packing of the rods or holes can be quadratic, hexagonal or honeycomb [8]. The important parameter of the 2 D crystals is the 'aspect ratio', which is defined as the ratio of the sample depth (vertical direction) to the lattice constant (transverse direction). Using plasma etching or electron beam lithography people could obtain the aspect ratio 5:1. The group of Max-Planck Institute in Halle, using photochemical growth could obtain the aspect ratio equal to 200:1 (Fig.2) [8]. The control of light in a 2D photonic crystal is not as complete as in a 3D crystal, nevertheless it is possible to construct a variety of important functional devices depend on photon trapping in defects, like a novel laser with multidirectional distributed feedback (DFB) [9].

Only the three-dimensional photonic crystal can posses full photonic band gap. In 3D PCs the structural variation occurs in three dimensions and the light is controlled in a volume. The collection of 3D photonic crystals is much more rich (Fig.3). Diamond structure was the first for which the complete photonic band gap was predicted [10]. The first successful three-dimensional crystal was obtained by Yablonovitch in 1991 [11]. It was made by drilling holes in a dielectric materials, creating a diamond-like structure, called now yablonovite

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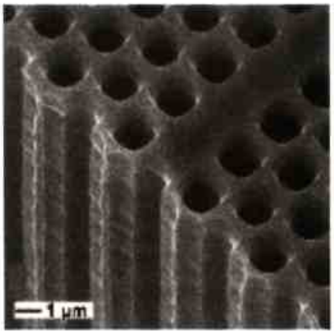

Fig.2 .Example of two dimentional photonic crystal [8].

(Fig.3a). It was discovered also that natural opal forms a photonic structure. Natural opals consist of a regular three dimensional crystalline array of colloidal silica spheres, several hundred nanometers in size (Fig.3b) [12]. Artificial opals can be grown by sedimentation of spheres from suspension, which is the basic method and give polycrystalline PCs with numerous defects and by assembling a thin layer of colloidal microspheres on a silicon substrate. A synthetic opal can act as a template into which a semiconductor material is infiltrated. Removal of the template leads to a tree-dimensional PC with periodic air-spheres embedded inside the semiconductor [13] - inverted opal structure (Fig.3c). Devices made from planar Si band gap crystals could allow on-chip manipulation of photons. The possibility to create light in the same device also exists [14]. In Fig.4 the band structure for the inverted opal is presented and the transmission measurement [15]. Opal template is quite often infiltrated incompletely. Additional air voids are formed. This helps in increasing the gap size. The next photonic structure with complete photonic band gap was first invented by the group of Iowa University and then miniaturised by Susumu Noda from Kyoto University (and Sandia National Laboratories) – „woodpile" structure showing full photonic band gap (Fig.3d). Noda [16] made this structure by stacking 0.7 µm period semiconductor stripes with the accuracy of 30 nanometers by advanced wafer-fusion technique. A band gap effect corresponding to 99.99% reflection was obtained. The smallest three-dimensional photonic crystal yet fabricated forbids propagation of light in the wavelength range around 1.5 µ, the range important for fibre optic communications. And some newly structures proposed by Toader and John – square spiral [17] and inverse square spiral – possible to obtain using glancing angle deposition method (Figs.3e-3f). Another very creative method is laser holography, which allows for generation of periodic microstructure by interference of four non-coplanar laser beams in a film of photoresist (Fig.3g) [18].

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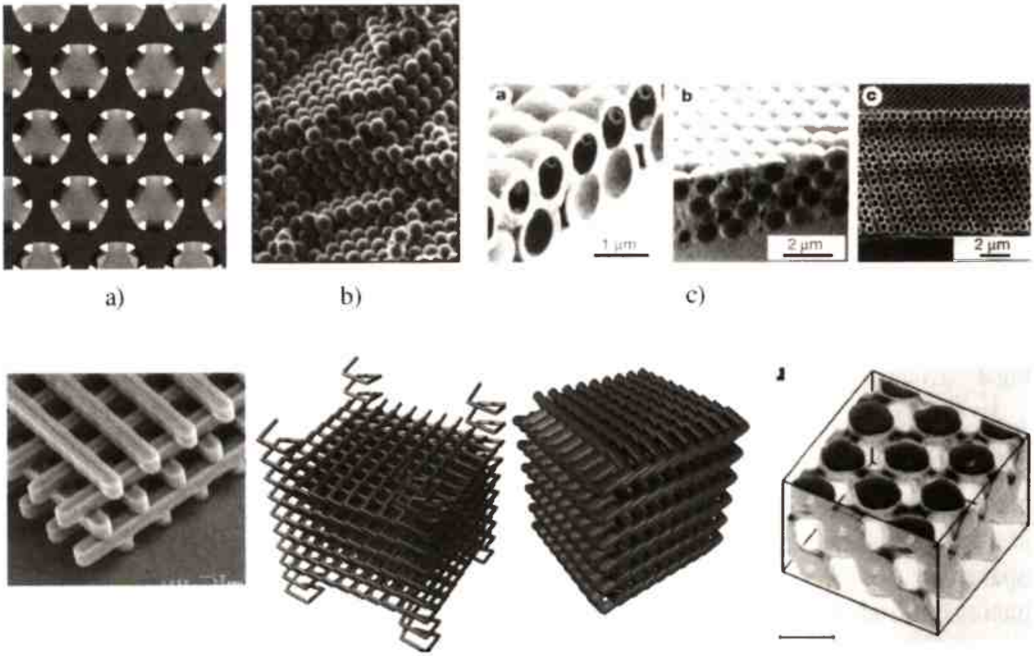

a) b) c)

d) e) f) g)

Fig.3. Examples of three dimentional photonic crystals: a) yablonovite – diamond-like structure [11], b) opal [12], c) inverted opal grown by infiltration of the opal template [13], d) woodpile [16], e) square spiral , f) inverted square spiral [17], g) model of a structure made by laser holography [18].

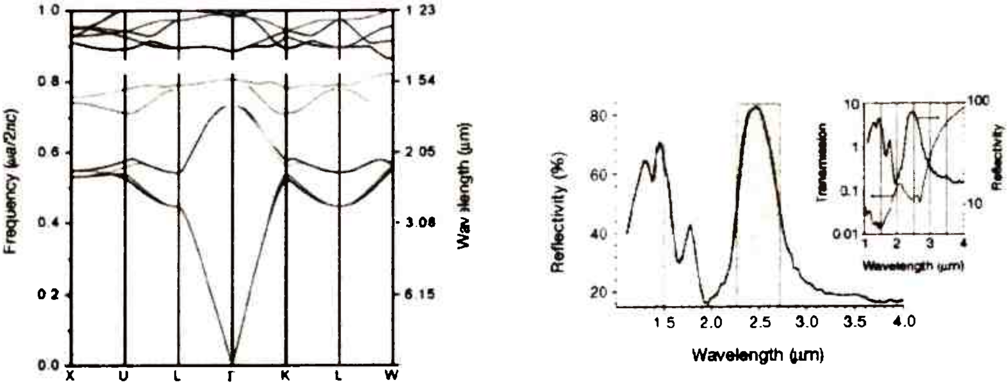

Fig.4. The band structure for the inverted opal and the transmission measurement [14].

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3. DEFECTS AND APPLICATIONS

In order to be able to apply semiconductors it is necessary to introduce defects and by the same to introduce additional allowed states in the band gap. The same situation is valid for photonic crystals. Introducing defects to a band gap structure of PC is comparable to doping in an electronic semiconductor. A defect in the photonic crystal structure can lead to a localized state of photon in the band gap. So a point defect acts like a microcavity [2], a line defect like a waveguide [5], [19] and a planar defect like a perfect mirror. Due to the nature of the Bose particle, defects in PBG materials can trap all the photons possible. So a single defect can control many photons. Photonic crystals are very attractive materials for designing new types of filters, couplers, lasers, LEDs since it is possible to tune the symmetry, frequency and localization of the defects. A hole in a thin-film crystal produces a critical element of lasers, a microcavity that can hold a local electromagnetic mode. Recently, using the two dimensional photonic crystal idea, the group from the California Institute of Technology created the world's smallest laser of 0.03 cubic micron in volume [20]. S. Noda presented the waveguide selector made of the two dimensional photonic crystal with the linear defect acting as a waveguide and single defects tuned to different light frequencies [21]. The photons with different resonant frequencies are trapped from the waveguide and emitted to free space by the corresponding single defects. Another important application of photonic crystals is the lossless waveguides with sharp bends. With photonic crystals, it is possible to create waveguides that permit 90-degree bends with 100% transmission. This phenomenon can be understood as the analogue of one-dimensional resonant tunneling phenomena in quantum mechanics. Another very useful type of incomplete band gap material is photonic crystal fibre. It has been demonstrated how to make photonic band-gap fibres by the group of the University of Bath in England [22]. Conventional fibre guide light because of the total internal reflection while the PC fibre uses the effective refractive index of the cladding region. The applications of photonic crystal fibres are endless.

The long term goal of scientists fascinated with photonic crystals are ultrasmall optical and optoelectronic integrated circuits incorporating: nanoampere laser arrays with different oscillation frequencies, waveguides that incorporate very sharp bends, optical modulators, wavelength selectors. Other applications of PCs can be: GAS sensoring, omnidirectional antireflection coating for solar cells, PC lasers, Organic Light Emitting Diodes utilizing PC crystals etc.

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4. PC HYBRIDS

Photonic crystals can be infiltrated with other material. First there was proposed a hybrid of photonic and liquid crystals, by Busch and John [23]. Liquid crystals can be found as the electrooptic display molecules in portable computers. An electric field can rotate the long molecules of e.g. nematic structure. By the rotation the refractive index of the twisted nematic liquid crystal is changed. In this way the photonic band gap of photonic/liquid crystal can be tuned and as shown by Busch and John it can be even closed and opened. There can exist different way of tuning the hybrid material since liquid crystals can be also tuned by temperature [24]. Other combinations of materials are also possible like PC and free carriers with opto-optical tuning. Nonlinear PCs can be obtained by infiltration with non-linear materials etc.

Photonic crystals are still not yet well known and rarely can be seen on the market, except the photonic crystal fibres. Since replacing existing technology is very difficult it is necessary to find new different applications for PC as for example the phenomenon of enhancement of different effect in photonic crystals as it was already published for Faraday effect.

5. NATURE

It occurs that the beautiful colours, which one can admire walking across the filed or the forest, are due to the photonic structures with which some of the animals are covered. Especially striking are the fantastic butterfly colours. Photonic crystals existed in nature long time before physicists started to think about such possibilities. Just after discovering the electron microscope biologists realised that in nature the arrays of uniform repeating structures exist that interact with light and produce the colour. First papers came already in 1942 by Anderson [25]. He called it with a term „structural colours”. Structural colours are widely distributed throughout the biological world, among animals with such nonliving investitures as feathers, scales, or insect’s cuticle. They can be found in opals, animals, peacock, butterflies,[26] fishes, and moths etc Fig.5. The first case when it was realised that the structural colours are in fact photonic crystals – was the case of the sea mouse Aphrodite (Fig.6) [27]. As A. R. Parker says „Animal structural colors are made from transparent materials which, ironically, produce the brightest optical effects seen in nature [28]. Animal’s structures are created to operate not only with the visible light but also in the range of ultraviolet and infrared. Ultraviolet is used for the communication between animals since many of them can detect wavelengths between 350-400 nm. The reflection of infrared wavelengths is probably used for

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thermoregulation by insects [28-29]. A complete band gap has excluded nature perhaps because it requires too much refractive index contrast. Nevertheless, an incomplete band gap can be very useful.

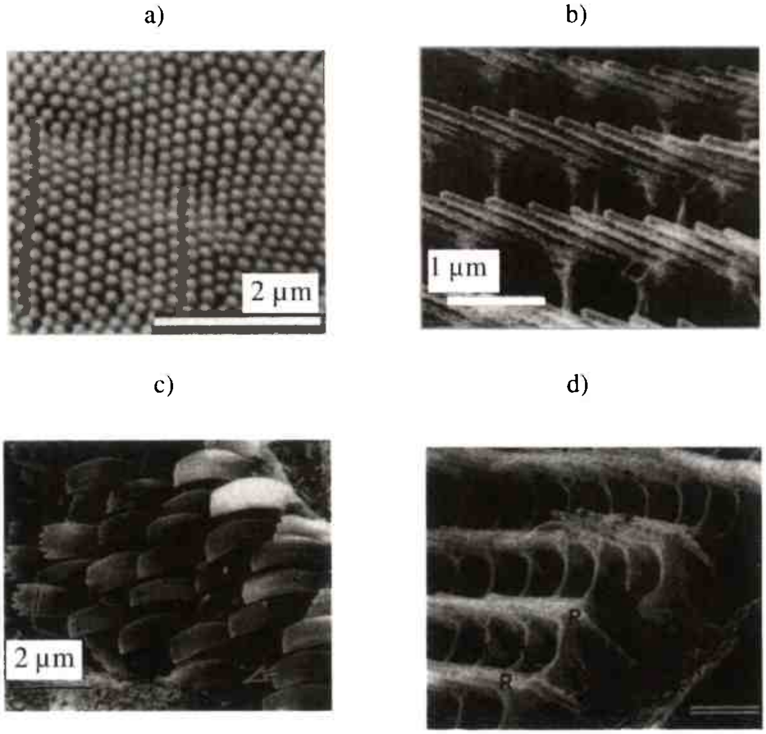

Fig.5. Photonic structures of butterflies: a) *Vanessa kershawi* [28], b) *Zeuidia amethystis*, c) *Calliona* – the scales are arranged in alternate rows, d) *Calliona* – the cross-section of a scale shown in c [26].

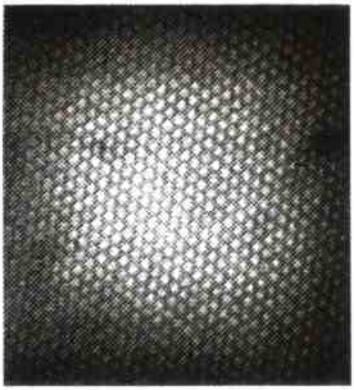

Fig.6. Structure of a sea mouse hair representing a hexagonal crystal of voids in chitin [27].

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6. MICRO-PULLING DOWN METHOD

Different kind of photonic structures are observed in nature. It is evident that photonic crystal structures can be obtained by self-organisation. And this is the way we want to go. The method, which we want to apply, is micro-pulling down (m-PD) method developed in Japan [30]. This method is mainly used to grow single crystalline fibres. It is easy and quick. The scheme of the method is shown in Fig.7. Simplifying, in the high temperature case of this method, the powders of raw materials are melted in an iridium crucible. The crucible has a small orifice in its bottom. The melt is touched with the seed at the bottom and a fibre is pulled down.

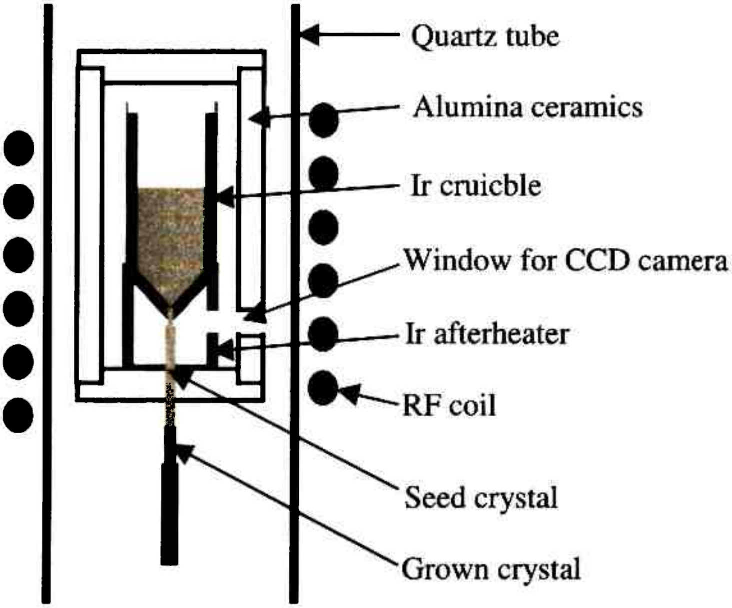

Fig. 7. Scheme of micro-pulling down (m-PD).

It was presented that by the micro-pulling down method also eutectics can be grown [31-32]. This what we would like to investigate is the growth of fibrous directionally solidified eutectics – fully aligned one phase crystallizing in the matrix of other phase. Hunt and Jackson [33] classified, investigating metals, the binary eutectic microstructures according to the entropy of melting of both phases. From this classification it can be found out that only in the

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case when both phases have low entropies of melting the fibrous growth is obtained. In the case of both phases having high entropies of melting the growth of independent crystals is observed and in the case of mixed entropies (one low, one high) the irregular of complex microstructures are formed. Such fully aligned structures can be obtained only when the crystal/melt interface is flat. The material does not need to have a eutectic composition to obtain such a structure, it can be an off-eutectic composition. The necessary conditions are the steep temperature gradient, the slow growth rate, and absence of convection [34]. All these conditions are fulfilled by the micro-pulling down method. Eutectic is our proposed way to grow self-assembled micro- and nano- photonic-like structures [35]. In Fig.8 the example of such eutectic microstructure obtained by m-PD method with high density pseudo-hexagonal packing looks almost like a ladybird. The size of structures pattern can be controlled by growth with different pulling rates. With higher pulling rate smaller size patterns are grown Fig.9. One of the crystalline phases can be etched away selectively. On Fig.10 the atomic force microscope image is shown of a sample where one of the phases was etched away. This is the state of the work until now. The subject is going to be developed for the growth of eutectics made of different kind of materials. The new idea, which exists in the proposed by us materials, is the fact that we operate with the single crystalline materials and their properties can be used. So the first of our objectives is to obtain the structures of micro fibres through which light can be transmitted in a controlled way. The next is to use materials with different properties like: a) materials showing Faraday effect [35] to observe the effects of turning polarised light (while applying the outer magnetic field) in the micro scale of micro fibres, b)

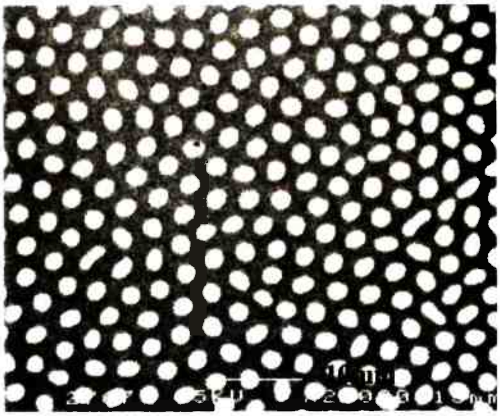

Fig.8. SEM image of the cross-section of pseudo-hexagonally packed pattern of $Tb_3Sc_2Al_3O_{12}$/$TbScO_3$ eutectic. The black color presents the garnet phase, the grey color indicates the perovskite phase [35].

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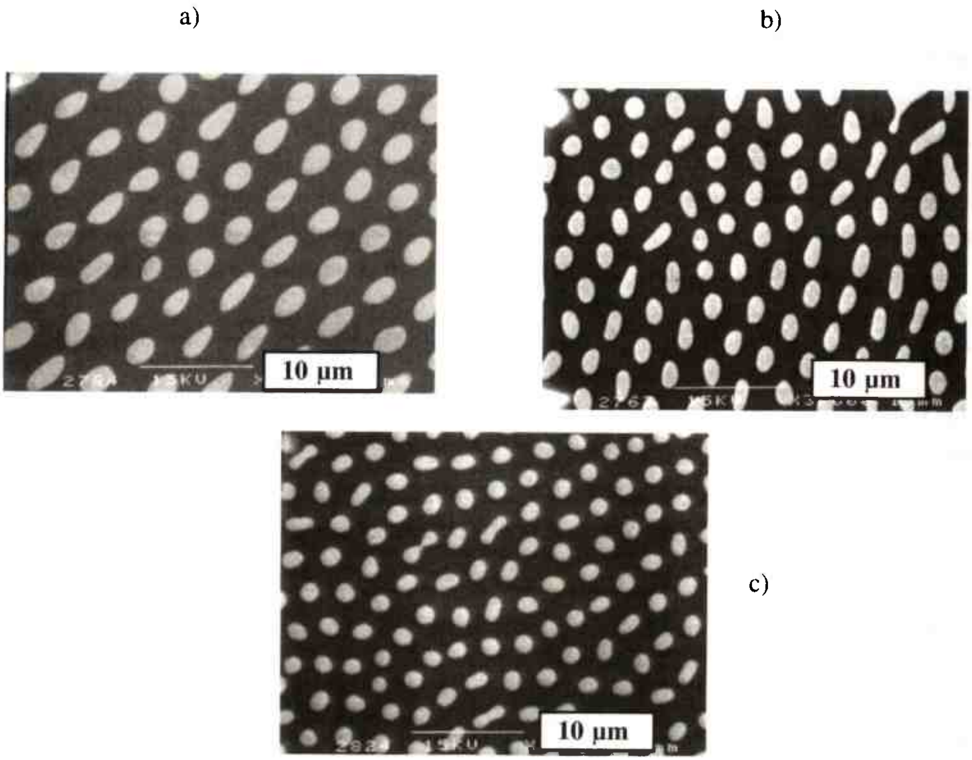

Fig.9. Decrease of the size of eutectic microstructure with different pulling rates: a) 0.15 mm/min. b) 0.30 mm/min. c) 0.45 mm/min [35].

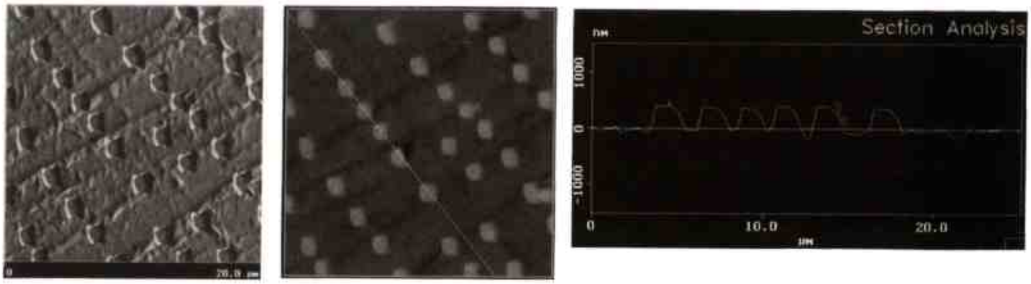

Fig. 10. AFM images of $Tb_3Sc_2Al_3O_{12}/TbScO_3$ eutectic microstructure of samples cut perpendicularly to the growth direction after polishing and etching with phosphoric acid and the cross-section of the observed «bumps» [35].

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materials doped with active elements to amplify light, c) materials with non-linear properties etc. We want to try etching of one of the phases away in 100%, so getting the air channels embedded in single crystalline oxide phase. The empty channels can be then filled in, using the capillary forces with some other kind of material like liquid crystal, biologically active material etc. In the above-described materials we want to observe the combination of the photonic crystal effect and the property of the material. Such effects were already investigated, for example it is shown that Faraday effect in the photonic of materials is enhanced significantly. The theoretical investigations were presented in many papers [36-37] and one experimental result we have found in the literature [38]. Inside the band gap the Verdet constant drastically increases, what can be understood from the fact that Faraday rotation is cumulative for reflected waves.

Current research in the Institute of Electronic Materials Technology will lead to developing of the growth of self-organized structures showing the photonic crystal properties.

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