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OPTICAL WAVEGUIDES AND FIBRES

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Surface waves on the boundary of photonic crystals and tunnelling coupling between two photonic crystals via these waves

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***Abstract*. Based on coupled $Nb_2O_5 - SiO_2$ waveguides, one-dimensional photonic crystals are fabricated and surface waves at 0.63 μm are generated at their boundary with air. A planar Bragg waveguide with an air core is fabricated due a contact of two photonic crystals through an air gap. The propagation constants of the symmetric and antisymmetric modes of the Bragg waveguide are measured and the value of the air gap of the waveguide is estimated. It is shown that, to obtain the fundamental modes of the Bragg waveguide based on the used waveguides, it is necessary to shift the working wavelength to the red and to increase the thickness of the air gap of the Bragg waveguide.**

Keywords: *surface waves, photonic crystals, tunnelling coupling*.

1. Introduction

The restricted systems of coupled waveguides attract special recent attention because surface waves can be excited at interfaces between these systems and homogeneous media and used for studying surface effects and states at these interfaces [1, 2]. Such waves are similar in many aspects to surface waves excited at the interface between a dielectric medium and a metal but differ in that they can have not only the TM but also TE polarisation because they are generated at the interface between dielectric media. The main similarity between the surface waves under study and surface waves on metals is the decreasing penetration of these waves into both boundary media: a purely exponential decay of the wave field into a homogeneous medium and an oscillating decay into a layered medium with the exponentially decaying envelope of these field oscillations. Due to the decaying penetration of the surface wave field into a dielectric medium at the boundary with the wave propagation plane, a geometrical structure can be produced in which two surface waves coupled by tunnelling will exist. Such waves excited on metal surfaces were experimentally studied in [3]. In this paper, we demonstrate the same effect, but for surface waves at the interface between one-dimensional photonic crystals.

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2. Structure of waveguides forming a one-dimensional photonic crystal, and a surface wave at the structure – air interface

As a structure carrying surface waves, we considered a restricted system of waveguides coupled by tunnelling, which consists of 10 pairs of $Nb_2O_5 - SiO_5$ layers and lies on a 1-mm-thick glass substrate with the refractive index $n_s = 1.52$ at a wavelength of 0.63 μm. The system of $Nb_2O_5 - SiO_5$ waveguides was fabricated by using a high-vacuum Aspira 150 setup for the ion-beam deposition of dielectric layers [4]. The refractive indices of the deposited Nb_2O_5 and SiO_2 films at 0.63 μm were measured to be $n_1 = 2.27$ and $n_2 = 1.48$, respectively. Because the thicknesses of Nb_2O_5 and SiO_2 layers were $h_1 = 110$ nm and $h_2 = 180$ nm, respectively, the waveguides formed in the Nb_2O_3 film at 0.63 μm were single-mode ones. Figure 1 shows the dependences of the effective refractive index n^* of modes in a restricted system on the mode number when the second medium adjacent to the restricted system is air. The dispersion dependence on the mode number is characterised by a drop in n^* on passing from the 10th to 11th mode, i.e. by the presence of the forbidden zone of the system of waveguides and the position of the 11th mode at the edge of this zone. This peculiarity of the 11th mode of the

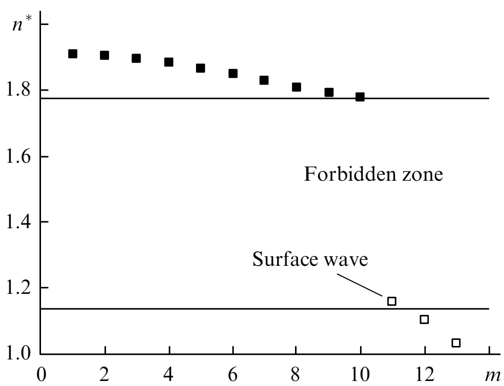

Figure 1. Dependences of the effective refractive index n^* of the mode order of a structure of coupled waveguides on the number m of guided modes (■) and radiation modes (□); the horizontal straight lines show the boundaries of the forbidden zone of the structure.

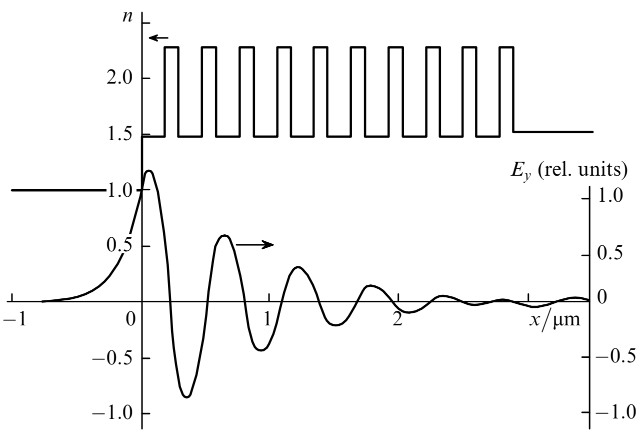

Figure 2. Distributions of the refractive index and electric field of a surface mode of the structure bordering air.

waveguide system allows us to treat it as a surface mode appearing in the system at the interface with air, which we confirmed by calculating the spatial distribution of the field of this mode by the method [5] (Fig. 2).

We excited a surface wave in the structure under study by using the Kretschman geometry with a rectangular glass prism ($n = 1.52$) in contact with a substrate with a system of waveguides applied on its opposite side. The excitation of the surface wave is caused by its leakage to the substrate, which proved sufficient to provide coupling between the incident wave from a 0.63-μm He – Ne-laser and the leaking field of the surface wave (Fig. 3). The inset in Fig. 3 also shows the m line on a screen, which demonstrates the excitation of the surface wave.

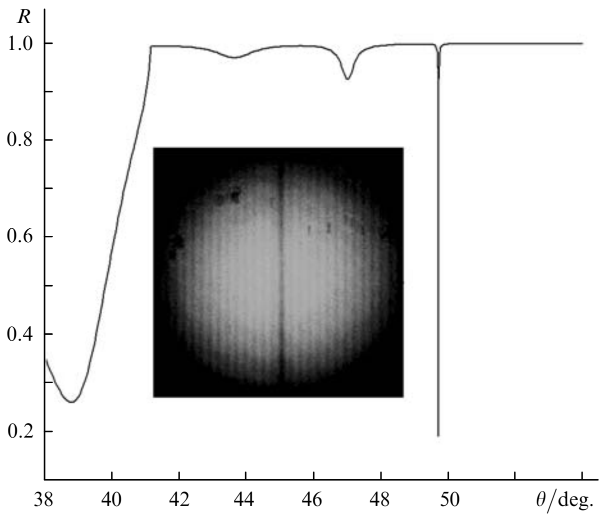

Figure 3. Angular dependence of the coefficient R of light reflection from the base of a prism used to excite the modes of the waveguide structure; θ is the angle of incidence of light in the substrate.

3. Tunnelling coupling between two photonic crystals via surface waves excited in them

Experiments on tunnelling coupling of two structures with surface waves were performed by using two rectangular glass prisms with glass substrates with applied waveguide structures placed on their bases. An air gap between the waveguide structures was produced by the deposition of buffer metal strips of the required thickness on one of the substrates. Surface waves were excited by the TE-polarised radiation from a 0.63-μm He-Ne laser. The reflected and transmitted laser radiation was detected with photodetectors PD1 and PD2, respectively (Fig. 4). In the case of a large thickness of the air gap ($h \approx 2$ μm), photodetectors recorded radiation reflected from the prism base (see inset in Fig. 3). The resonance type of the dependence $R(\theta)$ in Fig. 3 suggests that a surface wave is excited in the waveguide structure applied on a substrate in contact with the exciting prism. The absence of a signal from photodetector PD2 suggests that the thickness of the air gap between the structures is too large. By decreasing the air-gap thickness ($h < 1$ μm), we detected with photodetector PD2 the signal passing through both structures. Figure 5 presents the experimental dependence of the radiation intensity reflected from the prism base on the effective refractive index. The latter is uniquely related to the angle of light propagation in the prism ($n^* = n_p \sin\theta_p$, where n_p is the refractive index of the prism; θ_p is the angle between the

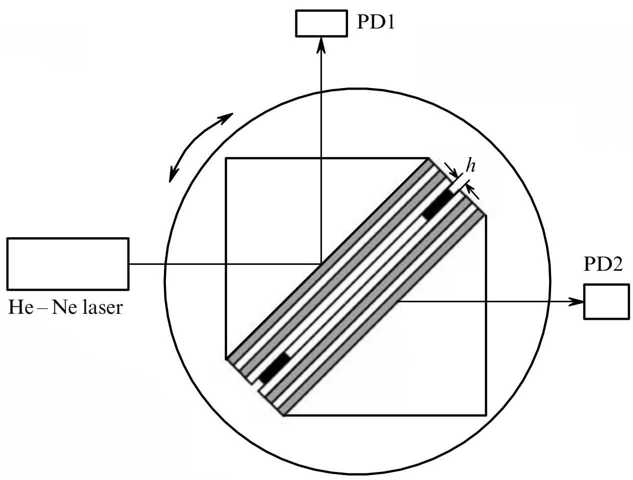

Figure 4. Optical scheme of the experiment for observing the tunnelling coupling between two one-dimensional photonic crystals.

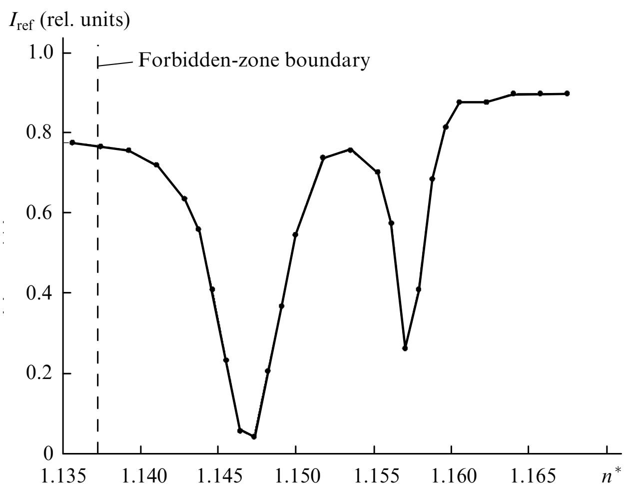

Figure 5. Reflected light intensity upon excitation of a mode in tunnel-coupled photonic crystals as a function of the effective refractive index.

normal to the prism surface and the light beam direction in the prism). These signals are characterised by the presence of the two peaks at different angles of the excited light.

4. Interpretation of the results obtained

As mentioned above, it was shown in [3] that tunnelling coupling can exist between surface waves on closely spaced thin metal plates. In the case under study, a layered planar structure is formed by closely spaced identical photonic-crystal structures separated by a narrow air gap. Such a structure is a Bragg waveguide [6] transferring radiation through the air gap or a layer of a medium with the refractive index that can be lower than that for waveguides adjacent to the gap. This Bragg waveguide has two surface TE-polarised modes. These modes propagate inside the air gap and have the maximum of the field near the photonic crystal – air interface. The field distributions in them are different. One mode has the symmetric distribution of the electric component of the field, while this distribution for another mode is asymmetric. Therefore, propagation constants for these modes are also different. We calculated the dispersion dependences of these modes on the air-gap thickness, which are presented in Fig. 6. The existence of these two modes in the complex structure under study leads to the transparency effect in the region of total internal reflection angles. Because the propagation constants of the modes are different, the angles at which the structure becomes transparent are also different. This 'bifurcation' of the signal demonstrated the presence of tunnelling coupling between the two surface structures under study. The values of the effective refractive indices obtained experimentally cannot be directly compared with calculations because real parameters of the structure (refractive indices, thicknesses) can differ slightly from theoretical values. However, the real thickness of the air gap can be estimated from the distance between experimental dips. The distance of 0.010 at the scale of the effective refractive index corresponds to the gap of 0.51 μm, in good agreement with the thickness 0.5 μm of metal strips.

Dispersion dependences presented in Fig. 6 show that the mode parameters depend on the gap thickness. The maximum sensitivity of the propagation constants corresponds to narrow gaps. By considering a planar waveguide formed by two one-dimensional photonic crystals on which electromagnetic waves are localised and which are separated by the air gap $h \approx 0.1 - 1$ μm, we see that a Bragg waveguide appears with an air core, which supports the two modes of this waveguide of symmetric and antisymmetric types. These modes penetrate deeply into periodic media surrounding the Bragg waveguide under study. However, it is known [7] that a Bragg waveguide with an air core has fundamental modes with low losses and small effective refractive indices ($n^* < 1$). Calculations of n^* for the fundamental mode of a waveguide with surrounding media, fabricated to excite surface waves by using 10 pairs of the $Nb_2O_5 - SiO_2$ waveguides of thickness $h_1 = 110$ nm (Nb_2O_5) and $h_2 = 180$ nm (SiO_2), revealed that this layered waveguide has no fundamental mode in the vicinity of $\lambda = 0.63$ μm because this wavelength falls into the forbidden zone of the structure under study. Thus, by using two structures with surface modes with $n^* > 1$ and separated by the air gap, it proved impossible to obtain a Bragg waveguide that would support the fundamental mode with $n^* < 1$ at 0.63 μm.

To study the interrelation of the fundamental modes of the Bragg waveguide formed by the structures and with air gap between them, we increased the light wavelength up to 0.73 μm. Calculations performed by using results [5] showed that for $\lambda = 0.73$ μm a Bragg waveguide with the air gap $h = 2$ μm can be formed. Figure 7 presents the distribution of the electric fields of the fundamental modes and nearest TE modes. As expected, the lowest mode of the Bragg waveguide with the air core has the effective refractive index $n^* = 0.977$, while the second-order mode has the refractive index $n^* = 0.92$. Modes, which appeared based on the former surface modes of planar structures, have $n^* = 1.0544$ and 1.0538, i.e. $n^* > 1$. For the given structure, the losses of modes produced from surface waves and the loss for the fundamental mode of the Bragg waveguide are close.

In the case of fibres with the air core, the core is usually surrounded by porous media – structural (cellular) media producing surface modes at the core boundary. The

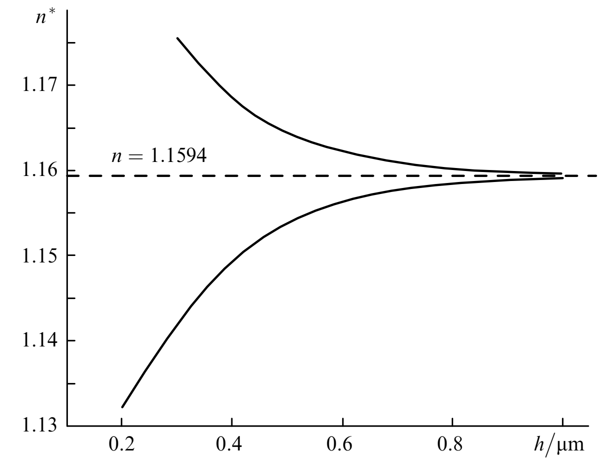

Figure 6. Calculated dispersion dependences of symmetric and asymmetric modes on the air-gap thickness.

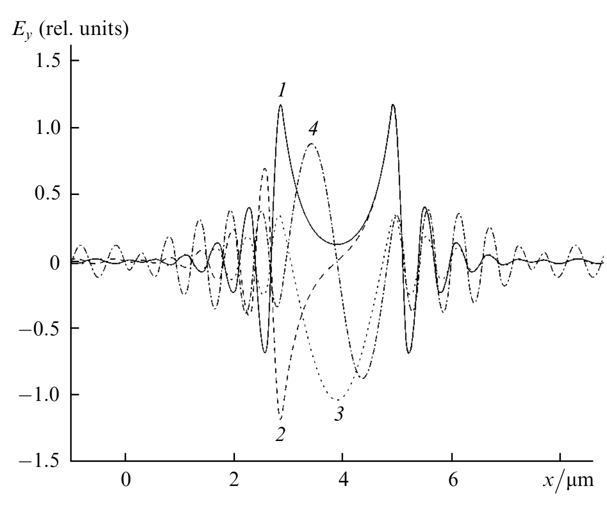

Figure 7. Distributions of the electric mode fields in the air gap between two one-dimensional crystals: symmetric (*1*) and (*2*) antisymmetric modes of a Bragg waveguide formed from surface modes, and the fundamental mode (*3*) and second-order mode (*4*) of a Bragg waveguide.

spectrum of these modes is close to the spectrum of the fundamental mode of the waveguide. This leads to additional fundamental-mode losses achieving 13 dB km^{-1} [8]. Therefore, the problem of the development of a surrounding medium for a photonic-crystal fibre with an air gap is of practical importance.

5. Conclusions

The study of the tunnelling coupling between two one-dimensional crystals on which surface electromagnetic waves can exist has shown that such waveguide structures can form a Bragg waveguide with an air core. The fundamental mode of such a structure at the surface-wave frequency is a symmetric mode with the effective refractive index $n^* > 1$. To obtain a Bragg waveguide having the fundamental mode with $n^* < 1$, it is necessary to shift the operating wavelength range to the red.

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