Surface waves on the boundaries of photonic crystals and their coupling

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Abstract. *Photonic crystal structure supporting the surface wave is considered. It is shown both theoretically and experimentally that two such structures placed close to each other can yield to resonance transmission of light through the structure. This effect is promising for sensor applications.*

Introduction

Recently bounded systems of coupled waveguides attracted attention of researchers because of the surface waves that can exist on its boundaries with the homogeneous medium. Surface waves could be a handy tool for studying the processes taking place at the surface and sensor applications [1, 2]. These wave are somewhat analogous to the surface waves that can be excited on the metal-dielectric surface (surface plasmon polaritons (SPP)), however they are not limited to TM polarization like SPP as they are excited on the boundary of dielectric media. The feature of the considered waves that is common to SPP is the exponential decay of field into the both adjacent media. While the field in the uniform dielectric media is strictly exponential, the field in the stratified media is oscillating inside the exponent envelope. This penetration of the field in the adjacent dielectric media makes possible the design of the structure that supports two surface waves evanescently coupled with each other. Earlier in paper [3] was devoted to experimental study of such waves in the case of metal-dielectric boundaries. In this paper we are demonstrating the same effect for surface waves propagation on the photonic crystal boundary.

1D photonic crystal and the surface wave on it's boundary

We use the following structure supporting the surface wave: 10 pairs of Nb_2O_5-SiO_2 were deposited on the glass substrate ($n_s = 1.52$ at wavelength of He-Ne laser $\lambda = 632.8$ nm). Waveguide system was deposited using high-vacuum ion-beam sputtering setup Aspira 150 [4]. Measured refractive indices of the films at this wavelength are $n_1 = 2.27$ and $n_2 = 1.48$ for Nb_2O_5 and SiO_2 films respectively. Layer thicknesses were chosen to be $h_1 = 110$ nm for Nb_2O_5 and $n_2 = 180$ nm for SiO_2 that correspond to single mode guiding of each

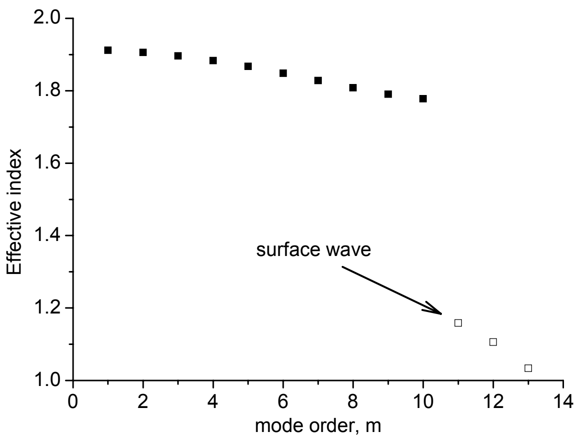

Figure 1: modes of the waveguide structure

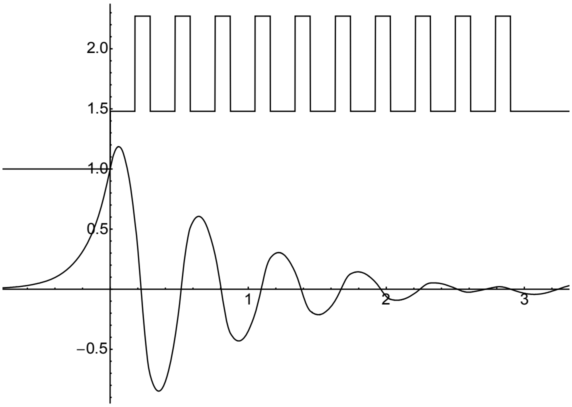

Figure 2: Field distribution of the surface wave

high-index layer. Figure 1 presents the calculated effective refractive indices of TE waveguide modes propagating in the structure in the case when the medium adjacent to the structure is air. The characteristic feature of the shown curve is the sharp drop of effective refractive index from 10th to 11th mode that corresponds to the forbidden zone of the periodic structure. Note that the 11th mode lies inside the forbidden zone that makes this mode a surface wave at the boundary between the periodic photonic crystal and dielectric medium. We confirmed the surface nature of the mode by calculating its field using the method described in [5] (see Figure 2).

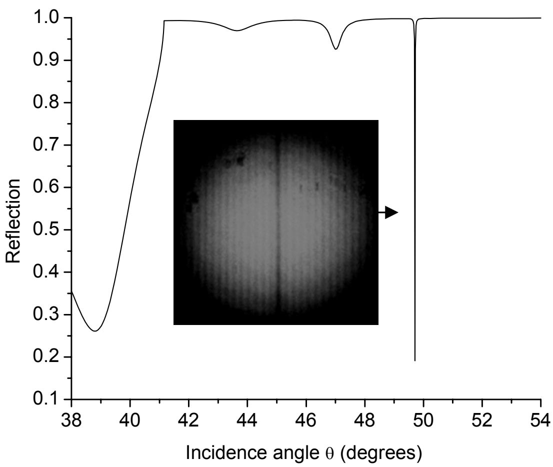

Figure 3: Reflection from the single structure

We used the Kretchmann setup for excitation of the surface wave with the prism attached to the back side of the structure substrate and having refractive index 1.52. Excitation of the surface wave in this scheme occurs due to leak of the wave into the substrate. Number of layers in the structure was chosen so that the leak is high enough to provide a sufficient coupling with the incident beam of He-Ne laser. Figure 3 presents the calculated dependence of light reflection from the structure. Dips correspond to the different modes of the structure. The sharpest dip corresponds to the surface wave. Inset on Figure 3 shows the m-line obtained in the experiment confirming the excitation of the surface wave.

Tunnel coupling of two photonic crystal with surface waves

In our experiment on tunnel coupling of surface waves between two photonic crystals used two glass prisms with substrates carrying waveguide structures attached to their bases. Air gap between the structures was created by sputtering buffer metal stripes on one of the structures. The system was excited by TE-polarized He-Ne laser beam ($\lambda =$ 632.8 nm). Figure 4 presents the scheme of the experiment. PD1 and PD2 were photodiodes registering the reflected and transmitted light beams. When the air gap was wide (about 2 mkm) we detected only the reflected beam that had one resonance dip

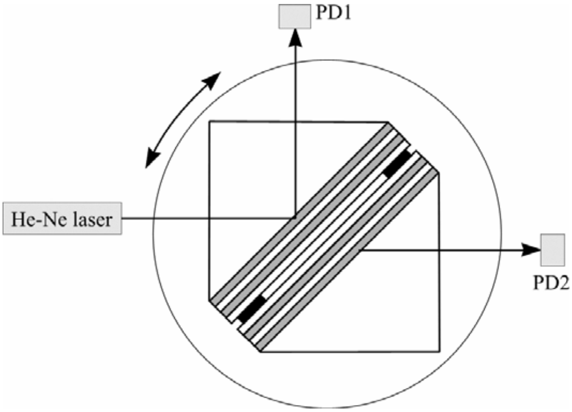

Figure 4: Experimental setup

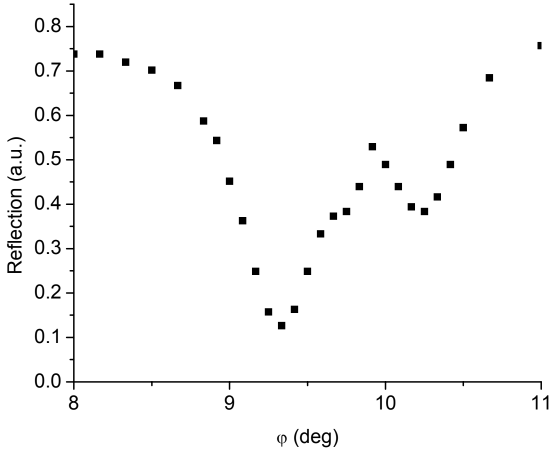

Figure 5: Reflection near the resonance

when the surface wave was excited like in the case of the single structure. At smaller gaps (below 1 mkm) we were able to detect the transmitted signal. Two peaks in this signal correspond to two dips in the reflected signal (see Figure 5). The characteristic feature of this curve is the double resonance that means that two different modes were excited. Angular distance between these two resonances increased when we applied more pressure on the structure reducing the air gap. These are very first results obtained and we will present more detailed results at the conference.

Discussion

As we said earlier paper [3] demonstrated the possibility of coupling between the surface waves propagating in two closely placed planar metallic films. In our case the structure consists of two identical photonic crystals separated by a small air gap. This structure can be considered as Bragg waveguide transmitting the light radiation in the air gap [6] (or in any other material having refracting index lower than that of the waveguides. Two surface modes exist near this gap. One has a symmetric electric field distribution in the gap and the other – anti-symmetric. Existence of these modes leads to the transparency effect that we observed in the experiment. These two modes have different effective refractive indices (see Figure 6) and thus different angles at which the structure transparency exists. Splitting of the resonance allows us to conclude that we are in fact observed tunnel coupling between the surface modes. Dispersion curves presented at Figure 6 shows that the mode parameters depends on the gap width. Effective indices are most sensitive to the gap width at small values of the width. Our calculations show that the loss in the gap (imaginary part of gap material dielectric constant) leads to strong losses in the surface modes and thus to the rapid decrease of the transparency effect. Change in the real part of the dielectric constant leads to angular shift of the resonance transparency peaks.

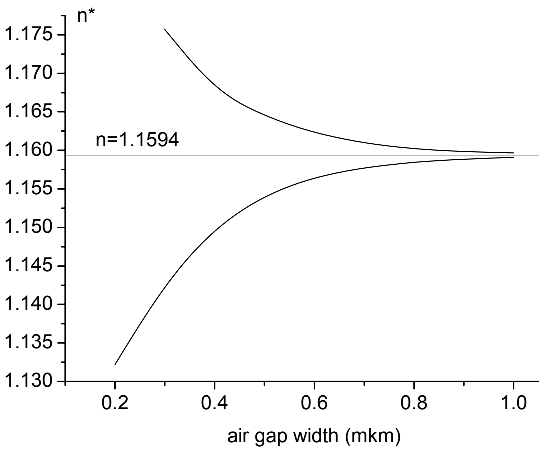

Figure 6: Effective indices of two surface waves

The observed effect of tunnel coupling between the surface waves of two photonic crystals leading to resonance transparency in the region of total reflection can be utilized in various sensor and modulating devices. This kind of waves is more attractive than the plasmonic waves in metal films due to absence of the absorbing medium. It allows to create devices with the larger sensing area and with the better sensitivity due to lower width of the resonace. If we create a cavity between the two photonic crystals like that was shown in [7] for the plasmons then it will have very high quality factor and could be used for high-sensitive sensors. Besides sensor applications it seems feasible to achieve light switching in the structure by adding nonlinearities.

Acknowledgements

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