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Surface waves at the boundary of a system of coupled waveguides

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Abstract. **Experimental investigations of surface waves at the interface between a homogeneous medium and a periodically stratified medium representing a restricted system of coupled waveguides are analysed. It is found that in all cases of the observation of surface waves a restricted system of waveguides has its own spectrum of guided modes and the spectrum of leaky modes, which become the surface waves of the system. It is shown that when two surface waves are used in a biosensor scheme, they should be realised as leaky modes of a Bragg waveguide in which a periodic system of waveguides was used as a distributed Bragg mirror of this waveguide. It is pointed out that the prism method of excitation of surface waves can be used in sensors, where these waves are employed as a detecting tool.**

Keywords: *surface waves, coupled optical waveguides, biosensors.*

1. Introduction

A system of coupled waveguides is called homogeneous if it is formed by equidistantly arranged identical waveguides with the propagation constant independent of longitudinal and transverse coordinates. The simplest example of such a waveguide system is an array of channel waveguides formed on a planar film lying on a surface with a lower refractive index. Channel-waveguide systems attract recent interest in laser optics because they can provide an increase in the output power [1]. The propagation of light in homogeneous systems of coupled waveguides was investigated earlier in papers [2, 3].

It was pointed out in [2] that in a restricted waveguide system, along with the light propagation bands, forbidden bands appear where light cannot propagate. In the case of single-mode waveguides, the light propagation bands are divided into bands where guided modes propagate and bands where leaky modes propagate. In addition, it was shown that each restricted waveguide system has two Bragg modes appearing at the boundaries of the forbidden band, the field distribution in these modes being different and dependent on the band edge to which they adjoin. In particular, it was pointed out that Bragg modes in a restricted waveguide system can be of special interest for improving the directivity of laser radiation [2].

It was shown in essence in [4] that Bragg modes appear in a waveguide system due to the violation of its uniformity caused by edge effects. It was demonstrated in [5, 6] that the violation of the uniformity of a system of coupled waveguides produces surface waves at the boundaries of this system, which can have important practical applications. In this connection we discuss in this paper the properties of these 'new' surface waves and the conditions of their generation. The novelty of these structures for sensor applications is that they can operate with TE-polarised waves in a medium with low losses, whereas plasmons used earlier can exist only in the case of TM-polarisation and are inevitably subjected to the influence of losses in a metal.

2. Mode composition of a system of coupled waveguides maintaining surface waves

Surface waves in a system of coupled waveguides were first observed in 1978 [7]. A periodic structure was obtained in [7] by the method of molecular epitaxy by growing 12 pairs of alternating 0.5-μm-thick GaAs and 0.5-μm-thick $Al_{0.2}Ga_{0.8}As$ layers on a GaAs substrate. A surface 1.15-μm wave was recorded on the surface of a sample with the period of layers $\Lambda = 1$ μm upon end excitation through a microobjective. For a sample of length 15 mm, of the four calculated modes of a surface wave only the fundamental mode was observed. Note that the violation of the uniformity of the waveguide system was manifested in its drastic break on the air side, whereas the average refractive index of the medium only weakly differed from that of the GaAs substrate.

Surface waves in the visible range (at 0.63 μm) were observed in 1984 [8] in a multilayer periodic waveguide structure prepared from the 0.4 – 0.6-μm-thick layers of zinc sulfide (with the refractive index $n = 2.37$) and cryolite ($n = 1.34$).

A model of a sensor device based on surface waves was recently demonstrated in [6]. The sensor is made on the basis of the $TiO_2 - SiO_2$ waveguide structure deposited on a glass prism and consisting of 13 pairs of alternating 117.3-nm-thick titanium dioxide and 182.4-nm-thick silicon dioxide layers, and also a finishing pair of 117.3-nm-thick TiO_2 and 156.5-nm-thick SiO_2 layers. In this paper, the violation of

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the uniformity of the waveguide system was manifested not only in a drastic break of the layered structure on the air side but also in a change in the thickness of the finishing pair of layers. Because the violation of the uniformity of this waveguide system has the most general nature, we consider its mode composition in more detail.

Figure 1 shows the scheme of the sensor studied in [6]. A surface wave was excited at the air – finishing SiO_2 interface by using the known Kretschman scheme through a prism on which a waveguide structure was deposited. We calculated preliminary by the method [9] the dependence of the effective refractive indices n^* on the mode number m in this waveguide system for $\lambda = 0.63$ µm. Because waveguides were single-mode, the number M of guided modes was equal to the number of waveguides $M = N = 14$.

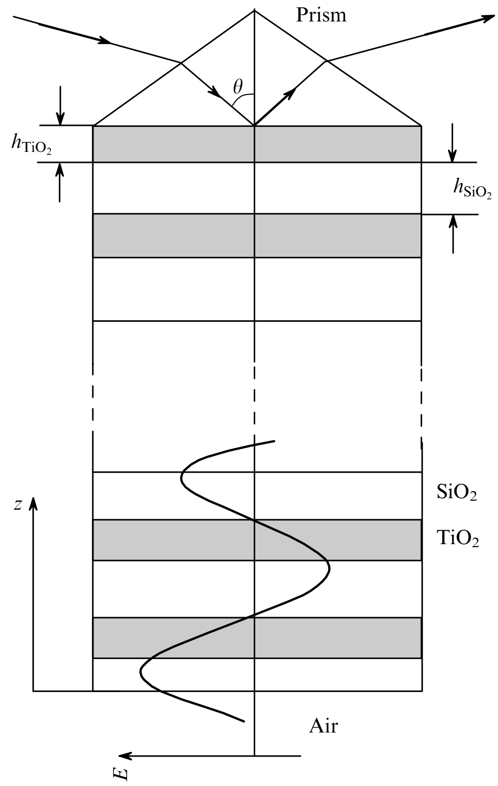

Figure 1. Scheme of a sample with a waveguide structure upon excitation of a surface wave at the waveguide structure – air interface (E is the electric field strength).

Figure 2 presents the dependence $n^*(m)$ for all modes of the system. The guided modes in the system are located before the jump, i.e. before the first forbidden band. Then, the leaky modes of the system are located, among which only four modes have efficient refractive indices above unity. The leaky modes with $n^* < 1$ leak to air, and therefore we will not consider them. The effective refractive index of a surface wave was determined by calculating [10] the angular dependence θ of the reflection coefficient of light from the base of a prism (Fig. 1) used to excite guided modes in the waveguide system ($n_{pr} = 1.518$), and searching for dips in this dependence. It was found that $n^* = 1.1436$, i.e. it is located in the second allowed band of the waveguide system, and the excited mode is in fact a usual leaky mode rather than a surface mode. The calculated field distribution

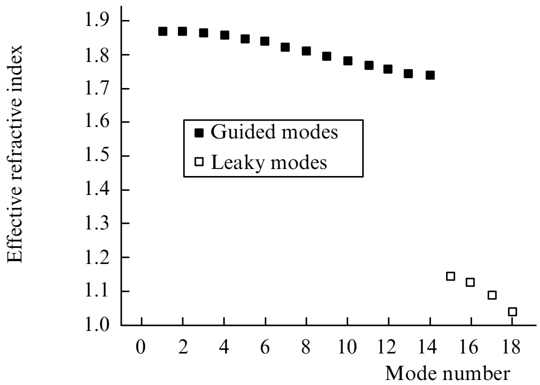

Figure 2. Dispersion dependence of the effective refractive index n^* on the mode number m of the waveguide structure [6].

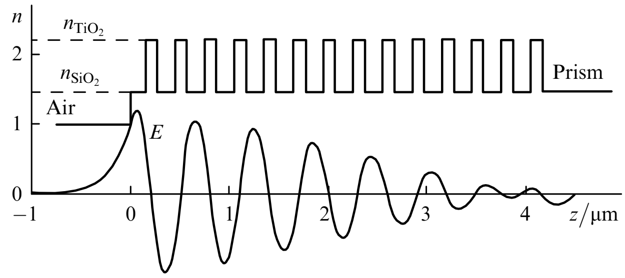

Figure 3. Distribution of the mode field E with $m = 15$ in the structure presented in [6].

presented in Fig. 3 shows that the field maximum is achieved in the finishing SiO_2 layer. The wave field in air, i.e. in the medium adjoining the SiO_2 layer is also rather strong, and this wave can be used to detect thin coatings on the SiO_2 finishing layer surface, as was done in [6].

Note, however, that the use of a waveguide structure consisting of 14 pairs of TiO_2 – SiO_2 layers of thickness indicated above allows the operation of the sensor at a real surface wave with $n^* = 1.15906$. However, the transverse resonance becomes considerably narrower due to exponential decay of the surface wave with distance from the surface and a weak coupling of the surface wave with a wave incident from the prism caused by the exponential decay.

A biosensor operating on surface waves propagating in a one-dimensional photonic crystal is described in paper [11] reported at the ICONO/LAT-2007 conference (Minsk, June 2007). Surface waves were excited in the waveguide structure by the 532-nm radiation in the Kretschman scheme with a K8 glass prism. The waveguide system was deposited on a K8 glass substrate. The first layer deposited on the substrate was a 154-nm-thick SiO_2 layer and the first waveguide layer was prepared from a 89.4-nm-thick Ta_2O_5 layer with the refractive index $n = 2.12$ ($\lambda = 532$ nm). The waveguide structure consisted of three pairs of SiO_2 – Ta_2O_5 layers and a 638.5-nm-thick SiO_2 finishing layer on which surface waves were excited. The SiO_2 finishing layer surface was in contact with an aqueous solution of biomolecules. The analysis of the mode composition of the layered structure showed that three guided modes and three leaky modes are maintained at a wavelength of 532 nm in the structure, the two of which have refractive indices falling to the first forbidden band.

3. Field distribution in a surface wave

The first- and second-order surface modes had the refractive indices $n^* = 1.448$ and 1.341, respectively. Figure 4 presents the field distributions for these modes that we calculated by the method described in [12]. The authors of paper [11] call these modes the surface modes of a photonic crystal; however, in our opinion, which coincides with the classification presented in [12], such modes should be better called the modes of a Bragg waveguide in which a multilayer structure (photonic crystal) operating as a distributed mirror.

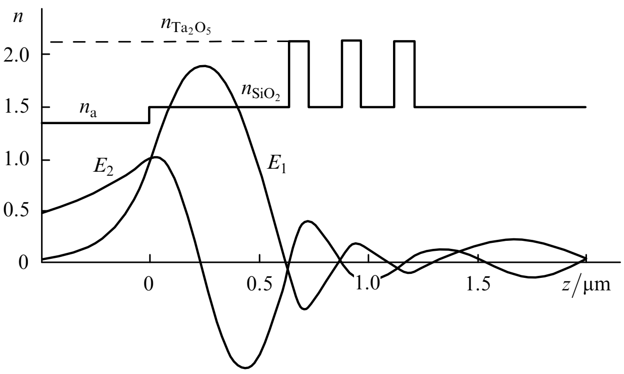

Figure 4. Distributions of the fields E_1 and E_2 of surface modes used in paper [11]; n_a is the refractive index of the adjacent medium.

Such a waveguide, in which modes appear on one side due to total internal reflection at the interface with the environment and on the other side – due to Bragg reflection at the interface with a periodic layered structure, is theoretically described in [12]. The dispersion relation for a Bragg waveguide has the form [12]

$$k_g\left(\frac{q_a\cos k_g t - k_g \sin k_g t}{q_a \sin k_g t + k_g \cos k_g t}\right) = -\mathrm{i}k_{1x}\frac{\exp(-\mathrm{i}K\Lambda) - A - B}{\exp(-\mathrm{i}K\Lambda) - A + B}, \quad (1)$$

where k_{1x} is the transverse component of the wave vector in a lattice layer with a low refractive index; K is the modulus of the Bloch vector; Λ is the period of structure layers; and A and B are the coefficients of the characteristic matrix of the unit cell. The left-hand side of Eqn (1) contains only parameters of the SiO_2 finishing layer (subscript g) and the environment (subscript a), whereas its right-hand side depends on parameters of the periodic medium. For the real parameters of the surface wave localised near the waveguide boundary (propagation constant β, decay constant q_a in the adjoining layer, and the transverse component k_g of the wave vector in the finishing layer of thickness t), the left-hand side of Eqn (1) is real. The right-hand side of Eqn (1) becomes real only for complex values of the modulus of the Bloch wave vector K, which are realised for values of n^* in the forbidden band of the system. The imaginary part of K determines the penetration depth of the exponentially decaying surface wave in the periodic part of the Bragg waveguide.

Thus, the guided modes of a Bragg waveguide can exist if the standard condition of the transverse resonance in the finishing layer of the structure and the Bragg reflection condition at the periodic medium-finishing layer interface are fulfilled simultaneously. A great difference between the refractive indices of layers allowed us to obtain a broad forbidden band ($1.10573 < n^* < 1.61558$), and the enlarge thickness of the SiO_2 finishing layer provided the existence of two modes in the structure. The dependence of the modulus of the Bloch vector K on n^* is presented in Fig. 5.

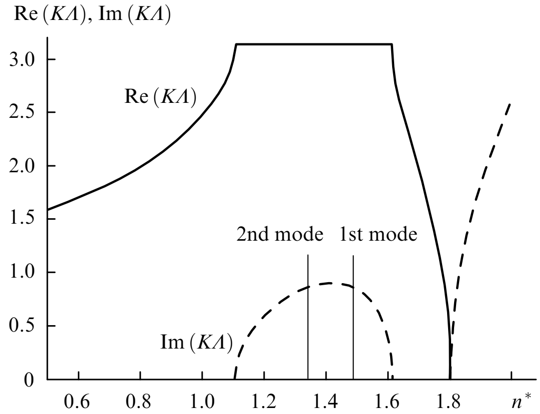

Figure 5. Dependence of the modulus of the Bloch vector K on the effective refractive index n^* for the structure taken from [11].

Note that the penetration depth l of the wave power to the adjacent homogeneous medium is determined by the expression

$$l = \frac{\lambda}{4\pi(n^{*2} - n_a^2)^{1/2}}, \quad (2)$$

where $n_a = 1.335$ is the refractive index of the adjacent medium (water). One can see from (2) that the depth of penetration of the second-order surface mode into water is considerably larger than that for the first-order mode.

The 532-nm sensor described in [11] was used to measure the concentration of biotin molecules bonded with a streptavidine monolayer, demonstrating the real advantage of the use of surface waves excited on the surface of a photonic crystal.

4. Conclusions

Analysis of the experimental studies of surface waves existing at the homogeneous medium – periodically stratified medium interface has shown that these waves can be successfully used in spectroscopic investigations of thin layers located at the interface, in particular, for studying biological layers.

The possibility of prism excitation of surface waves on the surface of a photonic crystal is an important advantage of these waves in spectroscopic investigations of unknown surfaces.

The method for simultaneous measurements of the refractive index of a liquid (aqueous) medium and the thickness of the boundary layer of biological molecules was proposed in [11]. This method is based on simultaneous excitation of two surface waves with different depths of penetration into a liquid medium, which allows one to take into account temperature variations in the liquid and to improve the accuracy of concentration measurements of biological molecules.

An important advantage of 'new' surface waves is the extension of the spectral range of radiation used in experiments due to the possibility of creating surface structures of the required type. Another advantage of surface waves of the new type is the possibility of the preparation of a chemically neutral surface on which these waves can be produced. Finally, the last advantage of 'new' surface waves is the possibility to obtain a large propagation length of these waves on the surface of a photonic crystal; however, this property still can be realised only in the future.

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