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Optical excitation of surface plasmon polariton and waveguide modes resonances on prismatic structures

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The prismatic structures for excitation surface plasmon polariton and waveguide modes resonances were investigated. The first structure consists of a glass prism and thin metallic layer deposited on the prism. The second one includes an additional dielectric layer. Plasmon polariton resonance can be observed only for TM polarization at finely tuned structure parameters. Waveguide modes resonance is possible for both polarizations in the presence of the dielectric layer. We show that the first structure has the highest sensitivity of angle minimum reflectivity, whereas the second one has the highest reflectivity sensitivity to the probed liquid refractive index changes.

Keywords: surface plasmon polaritons, waveguide mode, resonance, sensitivity.

1. Introduction

A surface plasmon polariton (SPP) is a fundamental electromagnetic excitation, which may exist at the interface between a metal and a dielectric. When the frequency of the SPP matches the frequency of external electromagnetic waves, there is a strong absorption of the electromagnetic waves. A conventional description of a surface plasmon resonance (SPR) instrument is best understood in terms of a prism-based configuration [1]. Therefore, this configuration allows the light to exploit reflecting properties of a glass prism. In 1968, both OTTO [2] and KRETSCHMANN and RAETHER [3] developed prism-coupling configurations for SPR excitation based on concepts involving attenuated total reflectance. In the Otto configuration, the prism and metal surface are separated by a dielectric (usually air). In the Kretschmann configuration (Fig. 1**a**) the metal film is placed between the dielectric and the prism.

The SPP resonance appears when refractive index of the prism material exceeds the refractive index of the medium adjoining the metallic film. The reflectivity from the metallic film in this case can be zero at properly set structure parameters [4].

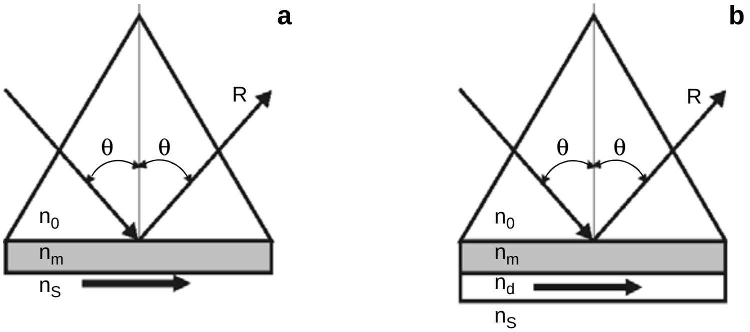

Fig. 1. The prismatic structures of the plasmon polariton (**a**) and waveguide (**b**) resonances, where n_0 – refractive index of prism, n_m – refractive index of metallic film, n_s – refractive index of surrounding media, n_d – refractive index of dielectric film, R – reflectivity.

The large field enhancement of SPP localized at the metal surface makes SPP very sensitive to changes in the permittivity of the adjacent dielectric. The biological molecules or chemicals can be selectively bound to the surface, causing the shifting of the wavelength of the SPP resonance [5–8].

If an additional dielectric layer is incorporated onto the metal film (see Fig. 1**b**), the incident light excites likewise weakly guided modes in a waveguide structure. Both TE and TM polarizations exhibit waveguide modes. However, the plasmon polariton is observed for TM polarization only. The laser beam reflectivity from the metallic film is about zero for both SPP and waveguide-modes resonances. The minimum reflectivity shifts upon change of the refractive index medium adjoining to dielectric film. The experimental analysis showed that change of the angle of minimum reflection is a few tenth parts of the degree of arc at the change of the refractive index of biochemical water liquid [9].

The refractive index change can be experimentally studied by other method where incident angle of laser beam is the resonant angle at which the reflectivity is minimum (desirably, approaching zero). Reflectivity is different from zero when refractive index changes occur.

We would like to point out that SPP-based technology has a very broad spectrum of potential applications. Surface waves play an important role in many fundamental resonant phenomena, such as, *e.g.*, the anomalous optical effects in the reflectivity and transmission [10] of periodically corrugated metal samples, and are already exploited in a wide range of practical devices. Research in this field is quite intensive and advanced and sensors relying on the effect of the SPP resonance shift are commercially available.

The prismatic reflection optical waveguide device may, for example, be used as an optical waveguide sensor for measuring the refractive index of a sample medium. The sensitivity of such an optical waveguide sensor may be adjusted according to a particular application.

The present work aims at a theoretical comparison between characteristics of the two types of prismatic structures and determination of their parameters for obtaining higher sensitivity to refractive index change of medium being analyzed. The use of metallic and dielectric films of certain thicknesses can enhance the refractive index sensitivity of SPR and waveguide-mode sensors by large resonance wavelength shifts and sharp reflection resonance peaks. An impact of the analyzed medium refractive index on sensitivity of such structures was investigated using matrix method. The matrix method is widely used for the calculation of optical properties of multilayer structures [11]. The purpose of this work is to predict optimal design of such devices.

2. Matrix method for analysis of multilayer structures

Consider a thin-film system consisting of L layers, as shown in Figure 2 [11]. The structure parameters comprise not only the refractive indices n_j and the thicknesses d_j of the layers $j = 1, 2, \ldots, L$, but also the refractive indices n_s and n_m of the substrate and the above medium. The angle of incidence θ, the wavelength λ, and the plane of polarization of the incident radiation are external variables of the system.

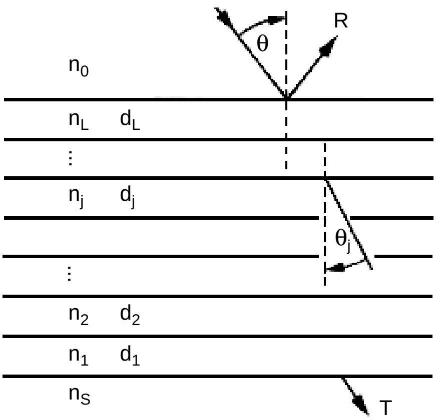

Fig. 2. Composition of multilayer structure.

It can be shown that the coefficients of amplitude reflection r and transmission t of a multilayer coating consisting of L layers bounded by a semi-infinite medium are given by

$$r = \frac{\eta_0 E_0 - H_0}{\eta_0 E_0 + H_0} \tag{1}$$

and

$$t = \frac{2\eta_0}{\eta_0 E_0 + H_0} \tag{2}$$

where

$$\begin{pmatrix} E_0 \\ H_0 \end{pmatrix} = M \begin{pmatrix} 1 \\ \eta_S \end{pmatrix} \tag{3}$$

and E_0 and H_0 are the electric and magnetic vectors, respectively, of incident wave, and M is a matrix given by the following product

$$M = M_L M_{L-1} \ldots M_j \ldots M_2 M_1 \tag{4}$$

In the preceding equation, M_j is a 2×2 matrix characterizing the j-th film:

$$M_j = \begin{pmatrix} m_{11} & im_{12} \\ im_{21} & m_{22} \end{pmatrix} = \begin{pmatrix} \cos(\delta_j) & \frac{i}{\eta_j}\sin(\delta_j) \\ i\eta_j \sin(\delta_j) & \cos(\delta_j) \end{pmatrix} \tag{5}$$

where

$$\delta_j = \frac{2\pi}{\lambda} n_j d_j \cos(\theta_j) \tag{6}$$

The quantity $n_j d_j \cos(\theta_j)$ is the effective optical thickness of the layer j for refraction angle θ_j. Throughout the text, η denotes the effective refractive index of the medium, substrate, or layer, and is given by

$$\eta = \begin{cases} \dfrac{n}{\cos(\theta)}, & p(\mathrm{TM})\text{-polarization} \\ n\cos(\theta), & s(\mathrm{TE})\text{-polarization} \end{cases} \tag{7}$$

depending on whether the incident radiation is polarized parallel (p) or perpendicular (s) to the plane of incidence. The angle θ_j is related to the incidence angle θ_0 by the Snell law

$$n_m \sin(\theta_0) = n_j \sin(\theta_j) \tag{8}$$

The intensities of transmittance and reflectance are

$$T = \frac{\eta_S}{\eta_0} |t|^2 \tag{9}$$

$$R = |r|^2 \tag{10}$$

The structure in Fig. 1**a** includes one layer only, the structure in Fig. 1**b** includes two layers; therefore, transfer matrices for these layers (M_1 in the first case, M_1, M_2 in the second case) are calculated according to Eq. (5).

3. Sensitivity to refractive index variations in prismatic structure

3.1. Dependence of reflectivity upon angle of incidence

We employed computer simulations to determine optimum parameters of the system. The structure here consists of a glass prism $n_{prism} = 1.76$ on which a silver film (with dielectric permittivity of –17.62 – 0.42*i* [12, 13]) and a dielectric layer ($d = 0.8$ μm, $n_d = 1.479$) were deposited. Water was used as a medium ($n_S = 1.333$), and the laser beam wavelength was $\lambda = 0.6328$ μm. The reflectivity minimum is observed for TE polarization at thickness of the metal film 50.4 nm, for TM polarization – 56.4 nm. The parameters of the metal film are in agreement with those of volumetric samples with such thicknesses [14, 15]. Figure 3 represents the dependence of reflectivity on laser beam incidence angle at the metal film. The angles indicated by arrows correspond to

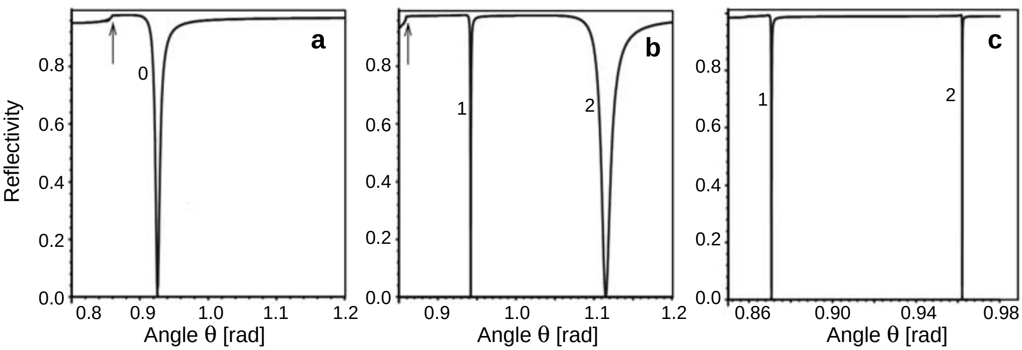

Fig. 3. Reflectivity vs. laser beam angle of incidence at the metal film: TM polarization, dielectric thickness equals zero (**a**), TM polarization, dielectric thickness is 0.8 μm (**b**), TE polarization, dielectric thickness is 0.8 μm (**c**).

angles of the total internal reflection described by the expression $\theta = \text{asin}(n_S/n_0)$. The reflectivity minimum ($R_{min} = 7.7\times10^{-5}$, $\theta_{min} = 0.9258$ rad) is observed at plasmon-‑polariton resonance, as shown in Fig. 3**a**. It is obvious that the following condition must be satisfied for the reflectivity minimum angle:

$$\theta_{0\min} > \text{asin}\left(\frac{n_S}{n_0}\right) \tag{11}$$

Figure 3**b** illustrates existence of two reflectivity minima for the TM polarization in the presence of dielectric layer. The first minimum ($R_{1\min} = 5.5\times10^{-5}$, $\theta_{1\min} =$

= 0.942017 rad) appears as a result of the waveguide resonance. It can be possible if the following conditions hold:

$$\operatorname{asin}\left(\frac{n_d}{n_0}\right) > \theta_{1\min} > \operatorname{asin}\left(\frac{n_S}{n_0}\right) \tag{12}$$

The cause of the second minimum ($R_{2\min} = 6.9\times10^{-5}$, $\theta_{2\min} = 1.115$ rad) is resonance of the SPP. This resonance can be obtained if the angle satisfies:

$$\theta_{2\min} > \operatorname{asin}\left(\frac{n_d}{n_0}\right) \tag{13}$$

The angles $\theta_1 = \operatorname{asin}(n_S/n_0) = 0.8593$ rad, $\theta_2 = \operatorname{asin}(n_d/n_0) = 0.9979$ rad define boundaries between the regions of possible resonance phenomena and separate phenomena based on plasmon polaritons or waveguide resonances.

Figure 3**c** indicates that two reflectivity minima ($R_{1\min} = 1.7\times10^{-5}$, $\theta_{1\min} =$ $= 0.8708$ rad, $R_{2\min} = 4.74\times10^{-3}$, $\theta_{2\min} = 0.9621$ rad) appear as a result of waveguide mode resonance in a 0.8-μm thick dielectric layer for the TE polarization. Minima are bounded by θ_1 and θ_2 angles.

Reflectivity minima will be shifted to the left in angle dependence upon decreasing the thickness of dielectric layer at waveguide modes resonance. The number of reflectivity minima will be decreasing until they totally disappear. It is worth noting that such a situation is common for both polarizations. The minimum reflectivity for the TM polarization (SPP resonance) does not disappear with decreasing the dielectric layer thickness.

3.2. Reflectivity sensitivity to the medium refractive index changes

The change of the refractive index n_S of a medium adjoining a dielectric layer or metallic film induces a shift of the reflectivity minimum. The dependence of sensitivity S_m of the shift minimum reflectivity on the change of n_S may be given by the equation:

$$S_m = \frac{\theta_{\min}(n_S + \Delta n_S) - \theta_{\min}(n_S)}{\Delta n_S} \tag{14}$$

It is obvious that n_S must be low in this case. We obtained $n_S = 10^{-4}$ after numerical calculations with initial value n_S equal to 1.333.

Calculations of sensitivity were done according to Eq. (14) for the same conditions and angle dependences of reflectivity (see Fig. 3). Thus, sensitivity S_m of the SPP resonance is 1.12 rad in the absence of dielectric layer. Nevertheless, sensitivity decreases abruptly and practically equals zero (minimum two in Fig. 3**b**) due to the SPP resonance in the presence of dielectric layer. The angle of reflectivity minimum with accuracy of 10^{-4} does not shift even at a change n_S by 0.1. The electromagnetic field decreases rapidly when passing through the metallic film in the SPP resonance. Therefore, the field in the medium with a refractive index n_S will be very low in the presence of dielectric waveguide. The analyzed medium refractive index change practically does not influence the distribution of electromagnetic field in a prismatic structure with dielectric layer.

The reflectivity minimum in Fig. 3**b** appears due to the waveguide modes resonance in the dielectric layer. In this case, the electromagnetic field is the same in cross-section of the waveguide. This field decreases rapidly in the medium considered moving from dielectric-liquid interface. Therefore, as one expects, there is certain sensitivity of the reflectivity angle minimum to a change of n_S. The sensitivity is 0.1 rad according to Eq. (14) and it is one order of magnitude lower than at the SPP resonance. Thus, the field at dielectric-liquid interface is smaller in the case of the waveguide resonance than in the SPP resonance.

The sharp reflectivity minimum from metallic film can be obtained at waveguide modes resonance for the TE polarization. The waveguide modes resonance can appear in the presence of dielectric layer with certain thicknesses only. The sensitivity is 0.32 rad for the first minimum, for the second one – 0.0423 rad (see Fig. 3**c**) according to Eq. (14). The difference between the values of sensitiveness for the two minima can be explained by the fact that the first minimum is located closer to the angle of the total internal reflection θ_1 than the second one. The field in the liquid decays slower for the first minimum than for the second one. Change of thickness of the dielectric layer can move the first minimum to the total internal reflection angle θ_1 and increase the sensitivity. The angles of the reflectivity minimum $\theta_{1\min}$ and sensitivity S_m to a change of n_S for certain thicknesses of dielectric layer at an angle of the total internal reflection $\theta_1 = 0.8593$ rad and $n_S = 1.333$ are collected in Tab. 1.

T a b l e 1. Sensitivity of the waveguide modes resonance and angle of the reflectivity minimum in prismatic structure

d_d [μm]	0.22500	0.23000	0.73000	0.80000	1.22400
$\theta_{1\min}$ [rad]	0.85931	0.85950	0.85993	0.87080	0.85986
S_m [rad]	0.86000	0.81000	0.65000	0.32000	0.61000

It should be noted that a good correlation between sensitivity and closeness of the reflectivity minimum angle $\theta_{1\min}$ with the total internal reflection angle θ_1 is observed. However, the sensitivity $S_m = 0.86$ rad at the waveguide modes resonance for the TE polarization is lower than the sensitivity $S_m = 1.12$ rad of the SPP resonance with missing dielectric layer. A higher sensitivity of such a structure to change of water solution characteristics under waveguide resonance for TE polarization [9] is conditioned by the pores in the dielectric layer. The molecules of organic origin penetrate the pores that reduce the change of refractive index not only in the considered liquid but in dielectric waveguide layer too.

Our previous research, as described above, was performed for a prism with refractive index $n_0 = 1.76$. Optimization (determination of maximum sensitivity S_m) of the SPP resonance without dielectric waveguide can be conducted only due to

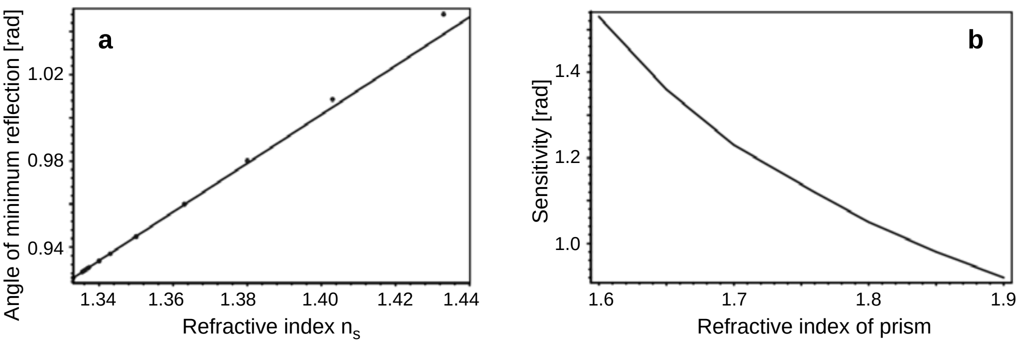

Fig. 4. Dependence of the minimum reflectivity on the analyzed liquid refractive index (**a**) and dependence of the sensitivity S_m on the prism refractive index n_0 (**b**).

the change of the prism refractive index. Figure 4**a** represents a linear dependence of the minimum reflectivity angle on a change n_S. The points are calculated using Eq. (14); the straight line is calculated by analytical dependence $\theta_{1\min} =$ $= 1.12(n_S - 1.333) + 0.9258$ for $n_0 = 1.76$; all other data correspond to Fig. 3**a**. We observed linearity of this characteristic in a wide domain of the change n_S, up to 1.37.

The sensitivity S_m depends on the prism refractive index n_0, as shown in Figure 4**b**.

Our analysis shows that the sensitivity increases when n_0 decreases. The prism refractive index can decrease down to 1.479 (fused silica) for a laser beam of wavelength 0.6328 μm in water solutions. The sensitivity S_m is 2.52 rad for the TM polarization. The reflectivity minimum angle $\theta_{1\min}$ equals 1.254163 rad for $n_S = 1.333$.

3.3. Reflectivity sensitivity to the refractive index changes n_S for metal film

The parameters of prismatic structure are selected in such a way that the reflectivity versus angle is almost zero (see Fig. 3). Figure 5 shows dependences reflectivity from n_S at the resonance disturbance. The curve 0 in Fig. 5**a** is calculated for the structure without a dielectric layer. The curves 1 and 2 in Fig. 5**a** are calculated for a 0.8-μm thick dielectric layer for TM polarization. The curves 1, 2 and 3 in Fig. 5**b** are calculated for a 0.8-μm and 0.73-μm thick dielectric layers for TE polarization.

Therefore, the maximum of the sensitivity was obtained for SPP resonance in the prismatic structure without the dielectric layer for TM polarization (see curve 0 in Fig. 5**a**). The curve 2 in Fig. 5**a** indicates that when the structure contains a dielectric layer then the sensitivity is practically zero for SPP resonance. The electromagnetic field decays exponentially as the distance to the metal film increases. The value of the field is negligible in the medium as a result of the dielectric layer presence between the metal film and the medium. The sensitivity of the structure with the dielectric layer for waveguide resonance (see curve 1 in Fig. 5**a**) is smaller than in the structure without the dielectric layer for SPP resonance.

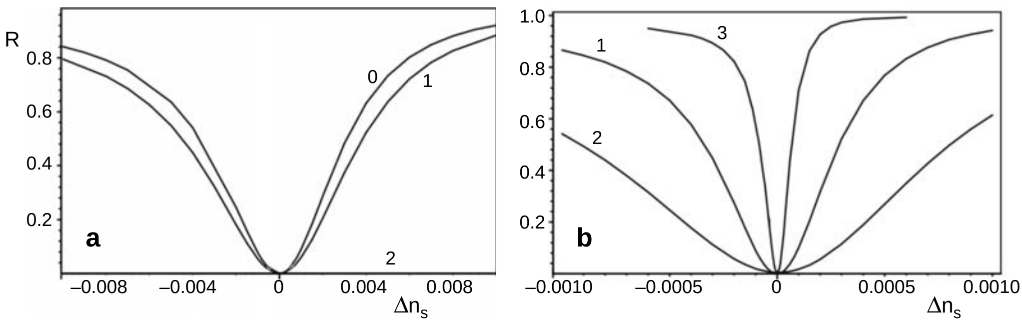

Fig. 5. Dependence of reflectivity on refractive index of the liquid: TM polarization (**a**), TE polarization (**b**).

The refractive index sensitivity is considerably smaller for TM-polarization than in the case of disturbance of the waveguide resonance for TE polarization (see Fig. 5**b**). The sensitivity is higher for resonances located near the total internal reflection angle θ_1. Maximum sensitivity is observed for a 0.73-μm thick dielectric layer, since angle $\theta_{1\min} = 0.8599$ rad is close to $\theta_1 = 0.8593$ rad. As a result, our detailed analysis of the disturbance resonance at change n_S concerns only TE polarization. It is necessary to note that the change of reflectivity ΔR is proportional to Δn_S^2 in the resonance vicinity. Therefore, the dependence of R on n_S is nonlinear. It is possible to select an incident angle for $n_S = 1.333$ such that the reflectivity equals 0.5 and to obtain a linear dependence of R on n_S (see Fig. 5**b**). The sensitivity S_R can be calculated as:

$$S_R = \frac{R(n_S + \Delta n_S) - 0.5}{\Delta n_S} \tag{15}$$

The sensitivities S_R were calculated by this method for the following parameters of the prismatic structure: $n_d = 1.479$, $d_{\text{silver}} = 50.4$ nm, $\lambda = 0.6328$ μm. These data are presented in Table 2.

The second row of Table 2 corresponds to the case of $n_d = 1.76$, the third one – to $n_d = 1.6$. The sensitivity increases as the laser beam incident angle approaches the total internal reflection angle. If the prism refractive index decreases then the sensitivity increases, too. This method is sensitive to the changes of n_S of an order of 10^{-7}.

The TE polarization sensitivities S_m and S_R according to Eqs. (14), (15) can increase because of the dielectric layer refractive index decreasing, for example, to 1.38.

T a b l e 2. Reflectivity sensitivity to the refractive index changes n_S.

d_d [μm]	0.225	0.230	0.730	0.800	1.224
S_R (n_d = 1.76)	3.200×10^4	0.950×10^4	5.600×10^3	1.400×10^3	6.100×10^3
S_R (n_d = 1.6)	4.100×10^4	1.100×10^4	6.500×10^3	1.600×10^3	6.800×10^3

Sensitivities S_m and S_R equal 1.1 rad and 5.7×10^4 for the layer thickness of 0.43 μm for n_0 = 1.6. These values of sensitivity are higher than those presented in Tabs. 1 and 2.

4. Conclusions

The consideration of optical excitation of surface plasmon polariton and waveguide modes resonance described in this work allows maximum refractive index sensitivity to be obtained in prismatic structures without waveguide layer. The sensitivity increases when the prism refractive index decreases for both TM and TE polarizations.

The results strongly indicate that the sensitivity of the prismatic structure is practically equal to zero at SPP resonance with structure that contains a dielectric layer. The sensitivity change of the reflectivity as a function of refractive index is higher for TE polarization than for TM polarization and increases when the angle of the reflectivity minimum approaches the total internal reflection angle. It should be noted that the sensitivity increases when refractive indices of the prism and the dielectric layer decrease.

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