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MODELLING THE 2D PLASMONIC STRUCTURES WITH ACTIVE CHALCOGENIDE GLASS LAYER

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Abstract. The paper contains the description of light propagation in plasmonic structure coupled with planar waveguide. The Fresnel's reflectance is calculated by matrix method and the calculations of the waveguide propagation constants are provided by the solution of the dispersion equation with complex refractive indexes. The result evaluates the conditions when a prism with as low as 1.51 (BK7) refractive index is used to couple plasmon-waveguide modes with an As_2S_3 film which have the refractive index 2.47. The film may experience photoinduced modification of the refractive index that may be used for the realization of 2D optical memory cells.

Key words: chalcogenide amorphous materials, As_2S_3, plasmonics, photonics.

1. INTRODUCTION

The plasmons represent a new form of light-matter interaction which is manifesting by collective elementary excitations corresponding to electron oscillations in a metal. When an incident *p*-polarized light beam that satisfies a certain resonance condition excites the charge density oscillations the resulting wave may propagate along a thin film at metal-dielectric interface and a surface plasmonic wave is generated. The phenomenon is known as the surface plasmon resonance (SPR). Usually, the light coupling is carried out in the Kretschmann-Raether arrangement for which the configuration is based on angular interrogation in which a prism for the excitation of surface plasmons by light is used [1–4].

The surface plasmonic wave propagates parallel with the metal-dielectric interface due to the border conditions. Any variation of the refractive index near the metal-dielectric interface determines a shift of the resonance angle. In the case of a coupled plasmon-waveguide resonator (CPWR) the plasmonic waves and the excited modes in the waveguide are coupled. For certain experimental conditions in the CPWR *p* (transversal magnetic) and *s* (transversal electric) polarized waves may be excited, so the energy of the incident radiation is absorbed resonantly.

The unique optical properties of ChGs are used for a range of important applications, focusing on recent examples in mid-infrared sensing, integrated optics and ultrahigh-bandwidth signal processing [5, 6]. Also, using the SPR method combined with a ChG films characterized by reversible optical transmission changes it is possible to realize devices having optical memory.

The resonance angle changes was obtained by depositing a thin amorphous chalcogenide glass (ChG) layer on the substrate surface who's refractive index may be modified by the external irradiation [7]. The authors use a rutile prism which has the refractive index higher than the refractive index of the GaLaS film, necessary condition for the excitation of surface plasmon.

This situation is inconvenient from several respects. First, the number of materials with refractive index over 2.5 and transparent in the visible range is very limited. Secondly, the vacuum deposition on the prism base is very inconvenient in terms of technology. Third, gold films with standard thickness of 50 nm deposited on conventional glass (like microscope slide) is commercialized as a standard chipset for plasmonic sensors.

All these aspects lead to the need to develop appropriate methods for coupling light into structures which contain chalcogenide films with a high refractive index. This may be obtained by realize of the interaction in CPWR.

2. NUMERICAL SIMULATIONS OF CPWR FRESNEL REFLECTIONS IN KRETSCHMANN CONFIGURATION

Software for numerical SPR calculations of four layer structure was developed by use of the transfer matrix formalism [8, 9]. Calculations of the reflectivity Rp and Rs for p-polarization and respectively s-polarization were performed for a four-layer system made up of BK7 (prism) – Au (50nm metal film) - As_2S_3 (thin layer structure with variable thickness)-Air. The relation between the reflectivity spectra and the incidence angle θ was simulated for the 632.8 nm wavelength (the irradiation of HeNe laser).

For As_2S_3 layer thickness of 250 nm, the plasmonic pick at the approx. 65^0 resonance angle corresponds to a bound plasmon-planar waveguide mode. A waveguide mode resonances for s-polarisation also exists (Fig. 1). Up to four resonance picks may be highlight in the case of 400 nm film thickness.

The reflectance spectra $R(\theta)$ are done for p-polarization and s-polarization Two ChG film thicknesses (50 nm and 250 nm) were taken into consideration. Only one pick exists for small thickness that corresponds to true plasmonic interaction. Our results show the possibility of more convenient silica or borosilicate glass to be used as prism material. The simulations denote that waveguide coupled mode resonances are sharper than plasmon-polariton modes. Such peculiarity indicates to greater sensitivity.

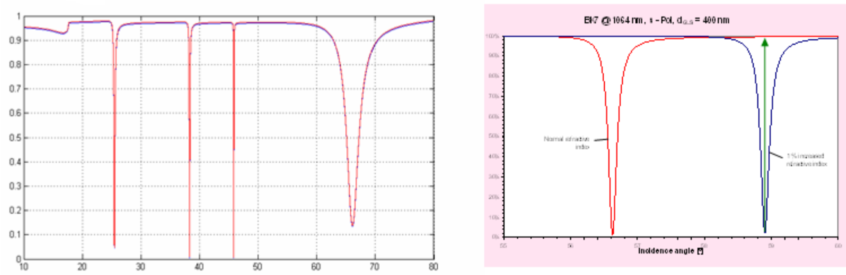

Fig. 1 – Resonance angles with As_2S_3 film (n = 2.47) on gold 50 nm film and BK7 prism (n_p = 1.51) as substrate. The shift of the resonance pick position (right picture) due to 1% refractive index change.

A reflectivity change of 100% may occur when the values of the As_2S_3 film refractive index have 1% or less variation. Such variations of the refractive index usually occur as result of the film irradiation with light. All features of the interaction may be highlighted by solving and analyzing the equation of dispersion. The information about propagation length is especially important since this parameter establishes the space resolution of 2D cells.

2. PLANAR WAVEGUIDE MODE SIMULATIONS FOR KRETSCHMANN PLASMONIC CONFIGURATION

The planar waveguide consists of a structure of long and large layers in the plan YZ and have four regions in each of which the refractive index may be considered as constant. The structure schematic is shown in Fig. 2. The four constituent regions are as follows: a thick, semi-infinite, substrate region with an refractive index n_4 equal to that of the prism; a thin dielectric film (optical waveguide) of an index n_2; a thin metallic layer with an complex refractive index n_1 and a thick, considered semi-infinite, cover region with an index n_3. The thin optical waveguide layer has the largest index $n_2 > n_1$ and n_3.

Since the optical waveguide region has the largest index, the optical fields are mainly confined in this region. The film thickness d is comparable to the operating wavelength λ. The metallic film thickness is adjusted to spark dip crash in the resonance picks. The thickness depends weakly on the working wavelength and the type of the metal used. The thickness value for gold and silver films is closed to 50 nm in visible and near IR spectral domain, as indicated by the plasmonic experiments.

Fig. 2 – The schematic of the plasmonic-waveguide coupling structure.

The calculations provided in paper [10] show that the penetration depth of the electromagnetic field in metals like Au, Ag constitute 22 to 25 nm. It means that the metallic film of 50 nm can be considered thick, because the field does not penetrate to the upper part of the film. Such an approximation considerably simplify the form of the dispersion equation and also simplify the finding of solutions in the complex plan. Finally, we will write the electromagnetic field relations for the 3-layer waveguide system as the fields are weakly linked with the prism medium. The cover (may be air) and substrate regions are much thicker than λ and we consider these thick regions as infinite.

Based on the model presented in paper [11] the propagation equation for the electric/magnetic fields, E/H in the three regions characterized by the refractive indexes n_1, n_2 and n_3, respectively may be written in the form:

$$\frac{\partial^2 E(x,y)}{\partial x^2} + \left(k_o^2 n_{1,2,3}^2 - \beta^2\right) E(x,y) = 0\,, \tag{1a}$$

$$\frac{\partial^2 H(x,y)}{\partial x^2} + \left(k_o^2 n_{1,2,3}^2 - \beta^2\right) H(x,y) = 0\,, \tag{1b}$$

where k_0 is the vacuum wave vector and β represents the propagation constant along the z axis. In the case of TE mode the electromagnetic field is characterized by the components E_y, H_x and H_z while in the case of TM mode the field is characterized by H_y, E_x and E_z.

From the continuity boundary conditions one obtained the expressions of the electric and magnetic field components within each region. For the optical waveguide the field components E_y, H_x and H_z of the TE mode can be written as

$$E_y\left(x,z\right)=(A\cdot \mathrm{e}^{\mathrm{i}k_2x}+B\cdot \mathrm{e}^{-\mathrm{i}k_2x})\exp(-\mathrm{i}\beta z)\,, \tag{2}$$

$$H_x\left(x\right)=-\frac{\beta}{\omega\mu_o}E_y(x,z)=-\frac{\beta}{\omega\mu_o}\left(A\cdot \mathrm{e}^{\mathrm{i}k_2x}+B\cdot \mathrm{e}^{-\mathrm{i}k_2x}\right)\exp\left(-\mathrm{i}\beta z\right), \tag{3}$$

$$H_z\left(x\right)=\frac{i}{\omega\mu_o}\frac{\partial E_y}{\partial x}=-\frac{k_2}{\omega\mu_o}\left(A\cdot \mathrm{e}^{\mathrm{i}k_2x}-B\cdot \mathrm{e}^{-\mathrm{i}k_2x}\right)\exp(-\mathrm{i}\beta z)\,, \tag{4}$$

where k_2 is the wave number within the optical waveguide along the X direction, ω represents the pulsation, μ_o is the magnetic constant and A and B are two constants which are obtained from the boundary conditions in $z=0$ and $z=d$.

The wave number within the optical waveguide is given by the relation $k_2^2=n_2^2k_o^2-\beta^2$. The dispersion equation for the TE modes can be obtained from the continuity conditions of the electric field E_y and of the magnetic filed H_z (or the spatial x derivative of the electric field) components at the two boundaries of the waveguide, being given by:

$$k_2\cdot d=\arctan\left(\frac{k_1}{k_2}\right)+\arctan\left(\frac{k_3}{k_2}\right)+m\pi\,. \tag{5}$$

Here, $k_{1,2,3}$ are the wave numbers along the X axis for metal film, waveguide (high refractive index dielectric, As_2S_3 for example) and cover, respectively; d is the waveguide thickness and m represents the mode number. The wave numbers for metal film and cover are given by the relations: $k_1^2=\beta^2-n_1^2k_o^2$, $k_3^2=\beta^2-n_3^2k_o^2$.

The propagation constant β is the same in all of the three layers due to the continuity condition of the electromagnetic field components E_y and H_x at the boundaries. Based on the plasmonic structure presented in Fig. 2 the numerical simulations were performed in Matlab and the some results are presented in Figs. 3, 4 and 5.

The thickness of the As_2S_3 film (the planar waveguide) is varied between 100 and 2000 nm, the refractive indexes of the As_2S_3 film and for a gold layer as a function of wavelength being taken from [12,13]. For λ = 632.8 nm the refractive indexes of Au is $n_1=0.18-2.99i$ and As_2S_3's is $n_2=2.60$ (whereas for λ = 1310 nm wavelength the refractive indexes are n_1 = 0.41-8.38i and n_2 = 2.44, respectively).

The electric field distributions across the waveguide (i.e. the transverse x direction) corresponding to the propagating modes is given in Fig. 3 for 0.2 μm and 0.5 μm waveguide thickness, respectively. The calculations indicate that the 3^{rd} order mode cannot propagate within the 200 nm thick guide while the 5-th order mode cannot propagate within the 500 nm waveguide thickness.

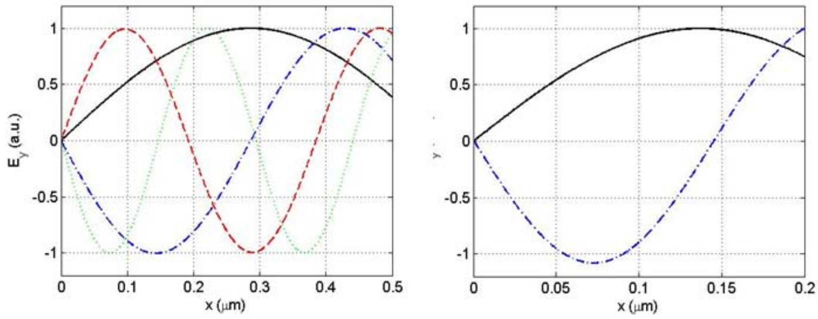

Fig. 3 – Electric field distribution (E_y) in transverse direction of the TE_0 (black curves), TE_1 (blue curves), TE_2 (red curve) and TE_3 (green curves) modes in the planar waveguides with the thicknesses 0.5 μm (left plot) and 0.2 μm (right plot).

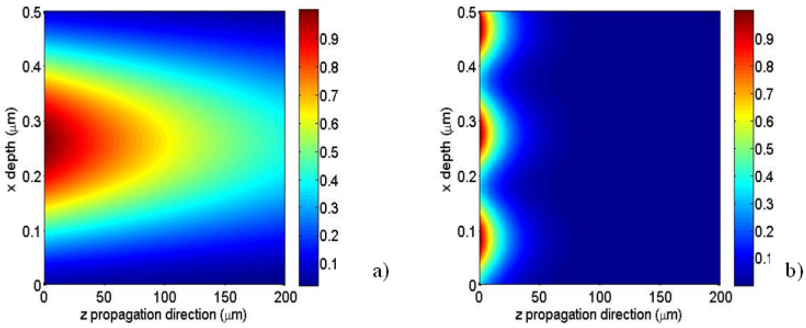

Fig. 4 – Intensity field distribution within the waveguide for the first (a), and third (b) TE modes in the planar waveguides with 500 nm thickness.

We can see from Fig. 4 that the propagation length for the first TE_0 mode is large enough, around 100 μm. This is because the power of the first mode propagates mainly through the waveguide center. The higher TE_2 mode propagates more in the vicinity of metal border and the propagation length is smaller, i.e. around 10 μm. For higher modes there are even bigger losses so as the wave propagation distance is only a few micrometers.

The calculations indicate that β and k_2 characterizing the propagation of modes within the waveguide are complex quantities. The real and imaginary parts of β as a function of waveguide thickness are presented in Fig. 5. The effective refractive index $N_{ef} = \beta/k_0$ for the waveguide mode is within limits of 1.5 to 2.5, that is much smaller than the effective refractive index of pure plasmon mode. The provided simulations show large possibilities in the manipulation with propagation conditions and may be used in practical applications.

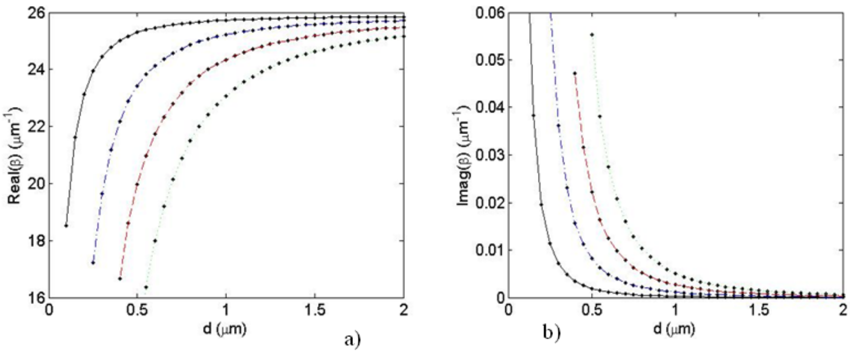

Fig. 5 – The real (a) and imaginary (b) parts of the propagation constant as a function of waveguide thickness, for the first four modes TE_0 (black), TE_1 (blue), TE_2 (red) and TE_3 (green). The incident wavelength is 632 nm.

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