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Excitation of waveguide modes in plasmonic waveguide, formed by electron beam in glass

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By methods of computer simulation the features of excitation of waveguide modes in plasmonic waveguide, formed by electron beam in glass, were studied. The waveguide is the thin layer of silver, or silver nanoparticles under the glass surface. It is shown that the efficiency of transformation of volume electromagnetic wave to waveguide mode can reach 0.8. The influence of geometry factors on the efficiency of transformation was studied.

Keywords: plasmonic waveguide, waveguide mode, glass, electron beam.

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Introduction

Inorganic glasses are a suitable material to form optical waveguides in them. They are adaptable to streamlined production methods and transparent in visible and near-IR ranges. Glass waveguides can be fabricated by the ion exchange method [1], as well as can be written by laser radiation [2]. As it is shown in [3,4], focused electron beam can be used to write waveguides in silicate glasses that contain mobile ions of metal, for example, Na^+ or Ag^+. The diffusion coefficient of Na^+ ions in silicate glasses at $T = 320^\circ$C is $2.6 \times 10^{-15}\,m^2/s$ [5]. The diffusion coefficient of Ag^+ ions is about 10 times lower. When a glass is irradiated by electrons with a relatively high energy (10−50 keV), thermalized electrons form a negatively charged area under the glass surface. This results in field migration of mobile ions of metal into this area and their neutralization by thermalized electrons. It leads to a local increase in the refractive index of the glass [4]. However, the charge in the irradiated area is not distributed monotonously, but in layers where the minimum thickness has the closest to the surface layer [6,7]. Thus, an optical waveguide written by an electron beam is a layered structure of alternating layers with high and low refractive index. Depth of the layers depends on the electron energy. Modulation of the refractive index in the layers can be 0.01−0.04, depending on the radiation dose [6]. In addition, when silver-containing glasses are irradiated by electrons with subsequent heat treatment at a temperature exceeding the glass transition point in the air, silver nanoparticles are formed in the layers with high silver content [6] (Fig. 1). This makes it possible to form plasmonic waveguides in such glasses, along which surface electromagnetic waves can propagate [7,8]. When a glass is irradiated by electrons and heat-treated, a continuous film of silver can be formed under the glass surface as well [9].

The goal of this work was to use numerical simulation methods to study peculiarities of waveguide modes excitation in a plasmonic waveguide formed by an electron beam in a silver-containing silicate glass.

Method of numeric simulation

Fig. 2 shows geometry of a waveguide structure formed on the basis of the data presented in [4–6]. Parameters of the layers are given in the table. The numerical simulation was performed for a wavelength of 0.65 μm. In the calculations, the prism model with $n = 1.7$ (STK15 optical glass) was used for the radiation coupling to the waveguide structure. It was assumed that the air gap between the prism and the waveguide structure is much lower than the wavelength, and refractive indices of layers had rectangular profiles.

The numerical simulation of plasmonic waveguide mode excitation in such layer used a continuous silver film approximation. The possibility to create such layers under electron irradiation is shown in [9]. In the calculations, we used the complex refractive index of silver $n^* = 0.12 + i4.2$ for a wavelength of 0.65 μm taken from [10]. Since in the case of prismatic radiation coupling, surface plasmons can be only excited for the TM-polarization, the numerical simulation was performed for the TM-polarized incident

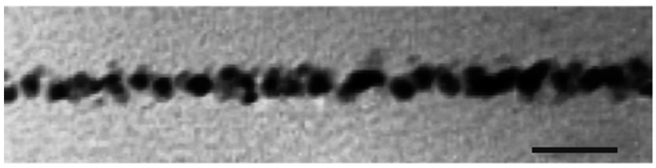

Figure 1. TEM-image of a layer of silver nanoparticles in a silicate glass after irradiation by electrons and heat treatment at a temperature over the glass transition point. Scale 50 nm. Adapted from [6].

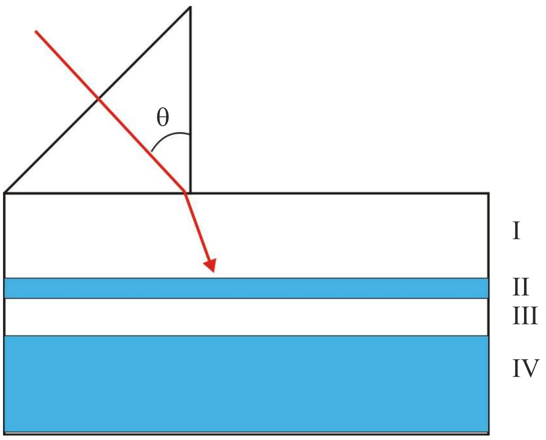

Figure 2. Geometry of the waveguide structure model formed on the basis of the data presented in [4-6].

Parameters of layers of the waveguide structure shown in Fig. 2

Layer	Refractive index	Thickness, μm
Prism	1.7	–
I	1.5	0.35
II	$0.12 - i4.2$	0.02
III	1.5	0.05
IV	1.54	∞

Let us consider the peculiarities of the excitation of a plasmonic waveguide mode for the case that layer II is a silver film with a thickness of 20 nm. Fig. 3 shows calculated angular dependencies of reflection coefficient for the plasmonic waveguide structure with a silver film for various thicknesses of layer I. It can be seen from the figure that the plasmonic waveguide mode is excited at a radiation incident angle greater than the total internal reflection angle.

The calculation has shown that an increase in thickness of layer I results in an increase in the efficiency of transformation of space electromagnetic wave to surface radiation. Taking into account the fact that in case of electron irradiation the electric field transfers silver ions into the waveguide from its surrounding areas, the refractive index in these areas becomes lower. Therefore refractive indices of layers I and III are lower than the refractive index of the glass body.

In the numerical simulation, the transfer matrix method [11] was used for the TM-polarization of the incident radiation. In this method, field amplitudes at the input (E_1, H_1) and output (E_2, H_2) of the layers boundaries are described by the following matrices:

$$\begin{bmatrix} E_1 \\ H_1 \end{bmatrix} = \begin{bmatrix} \cos\alpha & -i\frac{\sin\alpha}{U} \\ -iU\sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} E_2 \\ H_2 \end{bmatrix} = M_1 \begin{bmatrix} E_2 \\ H_2 \end{bmatrix},$$

$$U = n\sqrt{\varepsilon_0/\mu_)}\cos\theta.$$

Here n — refractive index of the layer, θ — incident angle, $\alpha = 2\pi/\lambda nd\cos\theta$ — phase delay of the wave passage through the layer, d — thickness of the layer. Transfer matrix M of the entire multilayer structure with N layers is described as $M = M_1 \cdot M_2 \cdot M_3 \ldots M_{2N}$.

Results and discussion

The calculations have shown that the critical angle corresponding to the total internal reflection for the given multilayer structure is 61.9°.

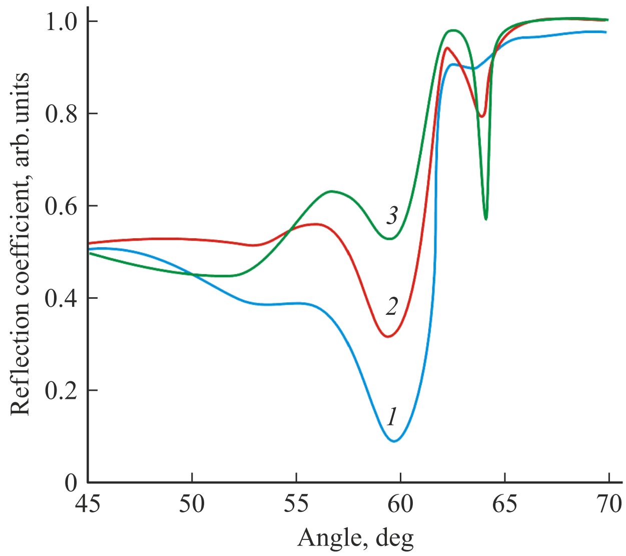

Figure 3. Calculated angular dependencies of reflection coefficient for the plasmonic waveguide structure with a silver film at the following thickness of layer I: *1* — 0.2 μm, *2* — 0.35, *3* — 0.5.

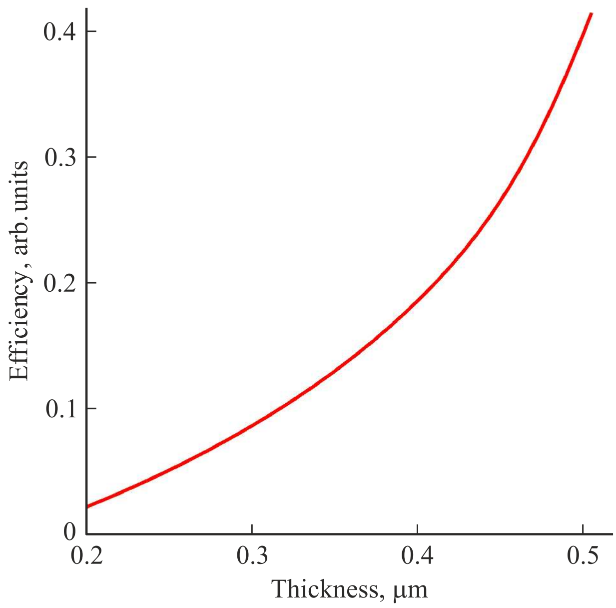

Figure 4. The effect of layer I thickness (Fig. 2) on the plasmonic waveguide mode excitation efficiency.

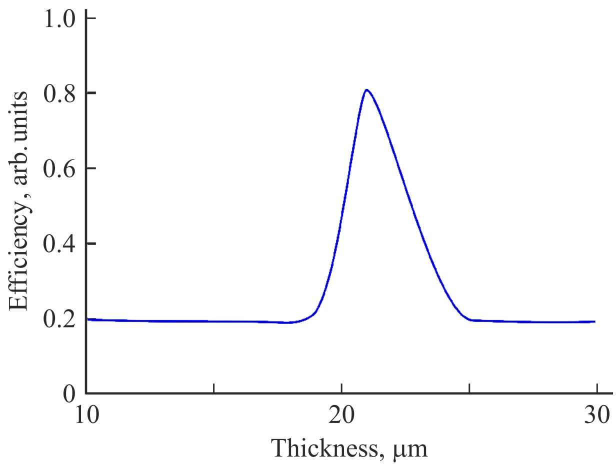

Figure 5. The effect of layer II thickness (Fig. 2) on the plasmonic waveguide mode excitation efficiency.

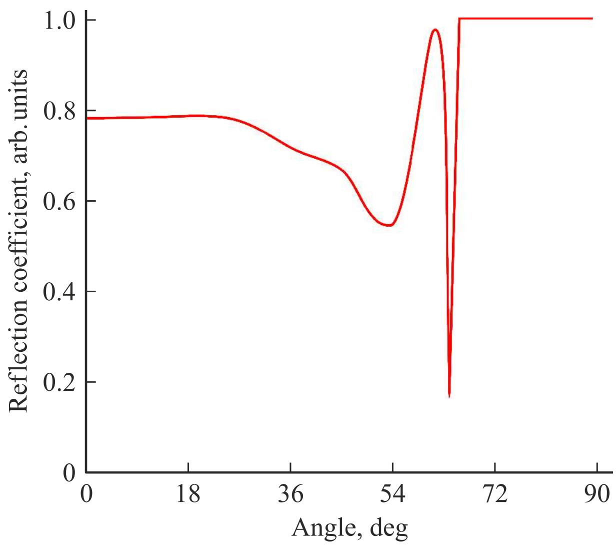

Figure 6. Calculated angular dependence of reflection coefficient for the plasmonic waveguide structure with a silver for optimum geometry. Thickness of layers: I — 0.6 μm, II — 21 nm.

wave. With a 2.5 times increase in the layer I thickness the transformation efficiency is increased 5 times (Fig. 4) and at a layer I thickness of 0.5 μm it is as high as 0.4. This is due to the fact that at low thicknesses of layer I there is a high probability of the inverse transformation of surface wave to space electromagnetic wave and output of this wave into the prism. However, it should be noted that with further increase in the layer I thickness the transformation efficiency decreases abruptly. This is caused by the fact that the intensity of the evanescent wave outgoing from the prism decreases exponentially with distance from the prism-glass interface.

Fig. 5 shows the calculated space-to-surface electromagnetic wave transformation efficiency as a function of layer II (silver film) thickness. It can be seen from the figure that at a thickness of layer II from 10 to 18 nm and over 25 nm, the transformation efficiency does not depend on the thickness and is equal to 0.2. However, the efficiency increases dramatically near 20 nm and at a layer thickness of 21 nm it is as high as 0.8. This is due to the fact that in this range of thicknesses the condition of phase synchronism is fulfilled for the electromagnetic waves that form the waveguide mode [7,12]. This results in generation of a guided waveguide mode.

Calculated angular dependence of reflection coefficient for the optimum geometry of multilayer structure is shown in Fig. 6.

Conclusion

Thus plasmonic waveguides in the form of continuous or island silver layer can be formed in silver-containing silicate glasses by electron-beam treatment. With prismatic radiation coupling only TM_0 modes are formed in such waveguides. It is shown than the transformation efficiency depends on the geometry of the layered structure and can be as high as 0.8. The obtained results can be used for electron-beam writing of plasmonic waveguides in silver-containing glasses for integral optic and nanoplasmonic devices.

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] A. Tervonen, B.R. West, S. Honkanen. Opt. Eng., **50**, 71107 (2011). DOI: 10.1117/1.3559213
[2] D. Blömer, A. Szameit, F. Dreisow, T. Schreiber, S. Nolte, A. Tünnermann. Opt. Expr., **14**, 2151–2157 (2006). DOI: 10.1364/OE.14.002151
[3] A.A. Zhiganov, O.A. Podsvirov, A.I. Ignat'ev, N.V. Nikonorov, A.I. Sidorov. J. Opt. Technol., **78**, 684–686 (2011). DOI: 10.1364/JOT.78.000684.
[4] O.A. Podsvirov, A.I. Sidorov, D.V. Churaev. Techn. Phys., **84**, 1674–1678 (2014). DOI:10.1134/S1063784214110218.
[5] A. Tervonen, S. Honkanen, M. Leppihalme. J. Appl. Phys., **62**, 759–763 (1987).
[6] M. Touzin, D. Goeriot, C. Guerret-Piécort, D. Juvé, D. Tréheux, H.-J. Fitting. J. Appl. Phys., **99**, 114110 (2006). DOI: 10.1063/1.2201851
[7] A.I. Ignat'ev, A.V. Nashchekin, V.M. Nevedomskii, O.A. Podsvirov, A.I. Sidorov, A.P. Solov'ev, O.A. Usov. Techn. Phys., **81**, 662–667 (2011). DOI: 10.1134/S1063784211050148.
[7] V.V. Klimov. *Nanoplazmonika* (Fizmatlit, M., 2009) (in Russian).
[8] S.A. Maier, P.G. Kik, H.A. Atwater. Phys. Rev. B, **67**, 205402 (2003). DOI: 10.1103/PhysRevB.67.205402
[9] V.S. Brunov, O.A. Podsvirov, A.I. Sidorov, D.V. Churaev. Techn. Phys., **84**, 1215–1219 (2014). DOI: 10.1134/S1063784214080088.

[10] E.D. Palik. *Handbook of optical constants of solids*. V. 3 (Academic press, San Diego, 1998).
[11] M. Born, E. Wolf. *Principles of optics: electromagnetic theory of propagation, interference and diffraction of light* (Cambridge University, 2000).
[12] K. Okamoto. *Fundamentals of optical waveguides*. Sec. Ed. (Elsevier, 2006).