Ge-Sb-Se AMORPHOUS CHALCOGENIDE BASED PLASMONIC PLANAR WAVEGUIDES FOR OPTICAL MEMORIES APPLICATIONS

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This paper presents a theoretical analysis of $Ge_{28.1}Sb_{6.3}Se_{65.6}$ amorphous chalcogenide glass planar waveguides for optical memories applications. Also, surface plasmon resonance in Kretschmann configuration is studied for a multilayer configuration containing an amorphous chalcogenide film of $Ge_{28.1}Sb_{6.3}Se_{65.6}$. The resonance curves of plasmonic structure containing Metal-Dielectric interface deposited on thermal oxidized silicon were investigated numerically. The reflectivity curves demonstrate sharp and very narrow plasmonic resonance with full-width half-maximum (FWHM) of 0.43÷0.85 degrees. Simulations could be used for the design of optical memory devices.

Keywords: plasmonics, surface plasmon resonance, amorphous chalcogenide materials

1. Introduction

In the last years several theoretical and experimental papers concern a multilayer configuration containing an amorphous chalcogenide film [1]-[4]. Combining plasmonics and nonlinear optics one obtained a variety of physical phenomena with great potential applications [5]-[12]. Nonlinear plasmonics has thus grown significantly in recent years. Among other nonlinear phenomena, self-trapped beams, that can lead to spatial solitons, have already been observed at very low optical power in nonstandard nonlinear media such as photorefractive materials.

The combination of a highly nonlinear medium with the tight confinement of plasmonic waves could be applied for the fabrication of several integrated devices; optical sensors, optical memories and other photonic devices.

Using a 3.6 μm thick $Ge_{28.1}Sb_{6.3}Se_{65.6}$ amorphous chalcogenide film a Kerr self-focusing was observed experimentally only for TM polarization of laser

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having 1550 nm wavelength [6]. Then, for a low input laser intensity of 0.62 GW/cm^2, the output beam was characterized by a 19 μm diameter FWHM (Full-Width Half-Maximum), while for 1.17 GW/cm^2, a 12 μm diameter FWHM was measured at the output [6].

In the present paper, a theoretical study of the transmission and reflectivity of a $Ge_{28.1}Sb_{6.3}Se_{65.6}$ amorphous chalcogenide film as a function of laser intensity at 1064 nm wavelength is presented. This amorphous chalcogenide material is characterized by large nonlinear properties and optimal crystal-glass phase transition for optical storage application. As well, in order to make calculations for SPR (surface plasmon resonance) we analyze a planar four-layer configuration (i.e. coupling prism- Au film- $Ge_{28.1}Sb_{6.3}Se_{65.6}$ film- SiO_2) with $Ge_{28.1}Sb_{6.3}Se_{65.6}$ amorphous chalcogenide film and two metal-dielectric interfaces.

The paper is organized as follows: in the second section we outline the theory used for modelling, while in the third section we report the obtained results and discuss these results. Section four is dedicated to the conclusions of this work.

2. Theoretical considerations

The transmission of $Ge_{28.1}Sb_{6.3}Se_{65.6}$ amorphous chalcogenide film was calculated using the following equation [4]:

$$I = \frac{(1-R)^2 \exp(-\alpha l)}{1 - R^2 \exp(-2\alpha l)} \tag{1}$$

where:

$$R = \left(\frac{n-1}{n+1}\right)^2, \tag{2}$$

is the optical reflection, α is the absorption coefficient, and the optical thickness of the amorphous film is:

$$l = \frac{d}{\cos\theta}\left(n_c + n_2 \frac{P}{S}\right), \tag{3}$$

where n_2 represents the Kerr nonlinearity, n_C is the ordinary refractive index of the chalcogenide film, d represents the geometric thickness, θ is the incidence angle, $I = P/S$ is the light intensity, P is the power and S represents the transversal surface of the film. The dependence of the refractive index on the intensity of the laser radiation, is given by the equation:

$$n = n_c + n_2 I = n_c + n_2 \frac{P}{S}, \tag{4}$$

The refractive index $(\lambda = 1.064\,\mu m)$ of the $Ge_{28.1}Sb_{6.3}Se_{65.6}$ chalcogenide film n_c, and n_{SiO_2}, respectively were calculated using Sellmeier equations [3], [4], [7]:

$$n_c(\lambda) = 2.609048 + 0.1113049/(\lambda^2 - 0.028) - 0.725286 \cdot 10^{-3}/(\lambda^2 - 0.028)^2 + 0.196917 \cdot 10^{-2} \cdot \lambda^2 - 0.1546277 \cdot 10^{-3} \cdot \lambda^4 \quad (5)$$

$$n_{SiO_2}^2(\lambda) = 1 + 0.6961663 \cdot \lambda^2/(\lambda^2 - 0.0684043^2) + 0.4079426 \cdot \lambda^2/(\lambda^2 - 0.1162414^2) + 0.8974794 \cdot \lambda^2/(\lambda^2 - 9.896161^2). \quad (6)$$

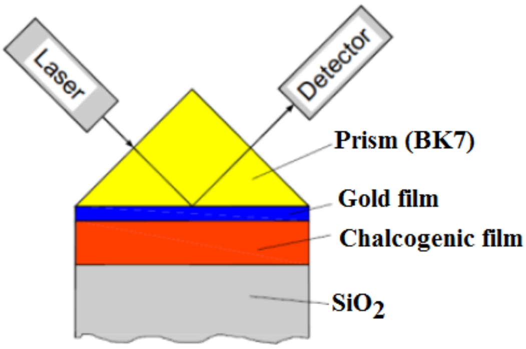


Fig. 1. Four layers-SPR configuration: prism (BK7 glass)- Au film- $Ge_{28.1}Sb_{6.3}Se_{65.6}$ film- SiO_2.

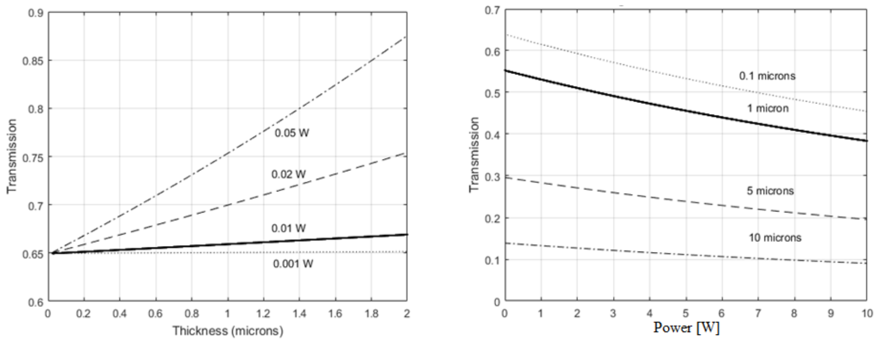
Based on the model presented in papers [3], [5], [9] in Kretschmann configuration we solved the Helmholtz type wave equation for transverse magnetic (TM) modes:

$$\frac{\partial^2 \vec{H}_y}{\partial x^2} + \left(k_0^2 \varepsilon - \beta^2\right)\vec{H}_y = 0, \quad (7)$$

where $k_o = \omega/c$ is the wave vector of the propagating wave in vacuum. The complex parameter $\beta = k_z$ is called the propagation constant of the travelling waves. The equation above is valid for each of the four layers of the plasmonic structure considered here (Fig. 1): prism (semi-infinite)-Au (of thickness *d*)-chalcogenide film (of the thickness *a*)-SiO_2 (semi-infinite). The fields continuity conditions are applied at the three interfaces and use the fact that the propagation constant β_x is the same in each layer. The system of six algebraic equations resulting from the continuity equations enable calculation of the wave's amplitudes within the four regions, considering the amplitude of the incident wave and the propagation constant as input parameters. The equations are solved numerically in MATLAB with ordinary solvers and the amplitude and power (in a.u.) of the wave reflected at the glass-metal interface is calculated relative to the power of the incident wave (for more details, see our paper [5]).

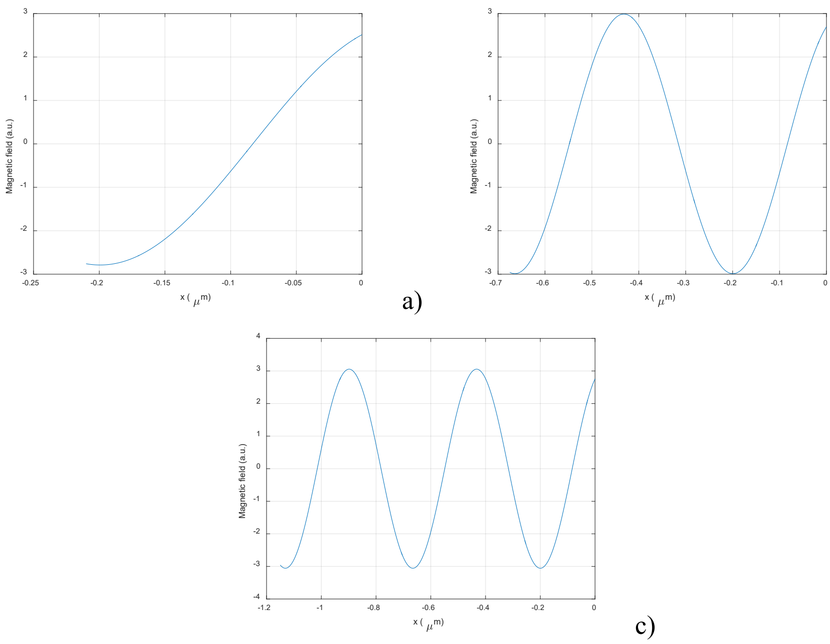
3. Simulation results and discussion

In our simulations on the transmission of the $Ge_{28.1}Sb_{6.3}Se_{65.6}$ film we used the following values of the parameters: $\alpha = 0.15\,dB/cm$, $n_c = 2.7113$, $n_2 = 0.136$ [6], $S = 4\ \mu m^2$ for the transversal surface of the film. Also, we assumed small incident angles for the irradiation of the film $\left(< 5^o\right)$.



(a) (b)

Fig. 2. (a) The transmission of the $Ge_{28.1}Sb_{6.3}Se_{65.6}$ vs the film thickness for different incident laser power. (b) The transmission of the $Ge_{28.1}Sb_{6.3}Se_{65.6}$ film vs the laser power.



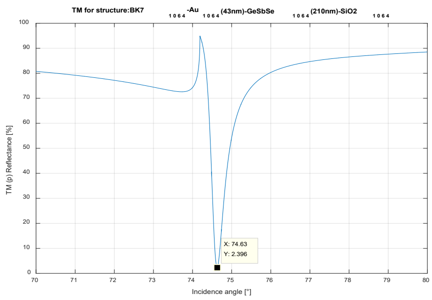
a) b) c)

Figs. 3. Magnetic field distribution across the chalcogene film at different TM modes in the chalcogene layer for a film thickness of 210 nm (a) for TM1 mode), 675 nm (b) for TM2 mode) and 1150 nm (c) for TM3 mode) at 1064 nm wavelength.

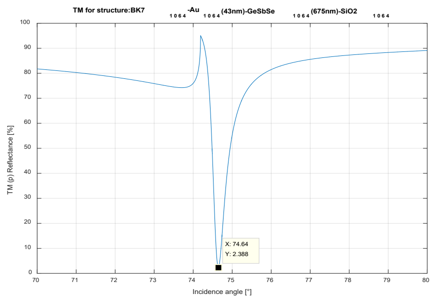
In Fig. 2(a) the transmission vs the thickness of the film for several values of the incident power of the laser, in the z direction, is presented while in Fig. 2(b) the transmission vs the laser intensity for several values of the film thickness is depicted.

As can be seen from Figs. 2(a,b), large values of the transmission of the film (~ 87% in Fig. 2(a)) are obtained for 50 mW power of the incident radiation for 2 μm thickness of the waveguide, while for 1 mW power the transmission is smaller because the nonlinear index variation is much smaller in the last case.

Next, we analysed the reflectivity of the plasmonic structure based on the $Ge_{28.1}Sb_{6.3}Se_{65.6}$ film (see Fig. 1). In the one-dimensional case, for TM modes we evaluated the magnetic field distribution. The magnetic field distribution across the $Ge_{28.1}Sb_{6.3}Se_{65.6}$ chalcogenide layer (i.e. as a function of transverse x direction) for different TM modes at λ_0 =1064 nm is given in Figs. 3 (a, b, c) for a film thickness of 210 nm (a), 675 nm (b) and 1150 nm (c), respectively.



a)



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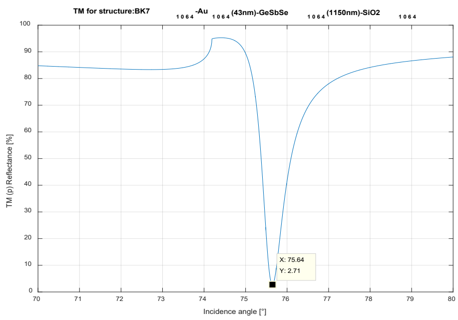
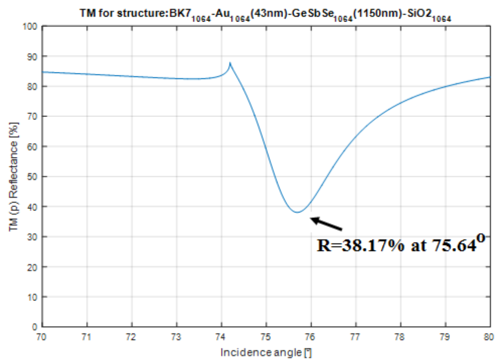


c)

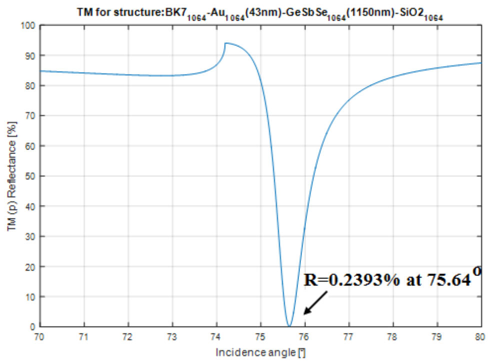
Figs. 4. SPR resonance curves for 43 nm gold film thickness and 210 nm (a), 675 nm (b) and 1150 nm (c) $Ge_{28.1}Sb_{6.3}Se_{65.6}$ thickness.

The calculation of the reflected field at the prism-metal interface allows the obtaining of resonance curves describing by the dependence of the reflectance on the angle of incidence, $R(\theta)$. The parameters used in numerical simulations are the following: incident TM modes, laser radiation having 1064 nm wavelength, 1.5066 refractive index of BK7 [14], 43nm gold thickness, $0.2585-6.9654i$ gold refractive index [13], 2.7113 $Ge_{28.1}Sb_{6.3}Se_{65.6}$ refractive index and 1.4496 silicon dioxide refractive index. The chalcogenide material and SiO_2 refractive indices were obtained using relations (5) and (6). By means of simulations we found the 210 nm (which enables resonant coupling of the TM1 mode), 675 nm (enabling resonant coupling of the TM2 mode) and 1150 nm (enabling resonant coupling of the TM3 mode) optimal thickness of the chalcogenide film for which we obtained a resonance curve (Figs. 4).

The resonance corresponds to the condition when the phase velocity of light parallel to surface equalizes the velocity of surface plasmonic wave. At the resonance a sharp dip appears in the reflected signal due to strong resonant absorption by plasmons. The minimum reflectance was obtained for the incidence angle of 74.63 degree when chalcogenide film with thickness of 210 nm were used, 74.64 degree for a thickness film of 675 nm and 75.64 degree for a thickness of 1150 nm. The width of the peak (FWHM) is 0.46° for TM1 mode, 0.43° for TM2 mode, and 0.67° for TM3 mode.



(a)

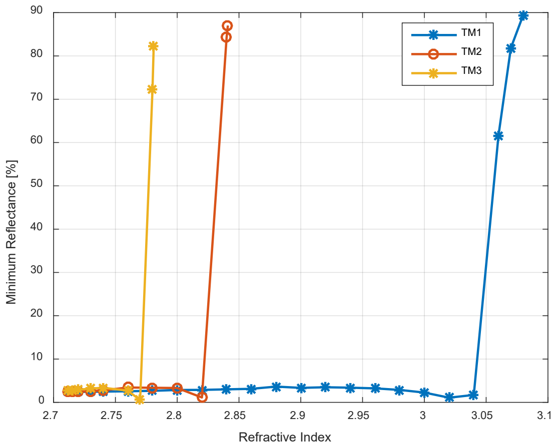


(b)

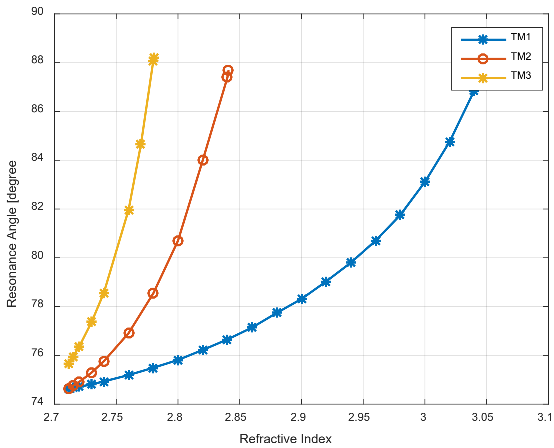
Figs. 5. Resonance curve of the plasmonic structure for two extinction coefficient values: k=0.01 (a) and k=0.001 (b). $Ge_{28.1}Sb_{6.3}Se_{65.6}$ layer thickness is 1150 nm and gold film thickness is 43 nm in both cases.

In some cases, the films have optical absorption. The influence of film absorption was put in evidence by numerical simulations. Results are presented in Figs. 5. Thus, at the 1064nm wavelength the extinction coefficient is very small. The parameters used in numerical simulations for $Ge_{28.1}Sb_{6.3}Se_{65.6}$ layer are following: TM modes $\lambda = 1064\,nm$, refractive index $n = 2.7113$, extinction coefficient k=0.01 (a) and k=0.001 (b). The absorption for k=0.01 is not much but it significantly influences the minimum reflection value. From the Figs. 4 and 5, it was observed that even a poor absorption decreases the quality of the structure with SPR and leads to an increase of the reflectance minimum up to 38.17% at an k=0.01 extinction coefficient. For films without absorption (k=0 in Fig. 4 c)), the minimum drops up to 2.71% and in the case of k=0.001 extinction coefficient the minimum drops up to 0.2393%. Moreover, this value of minimum can be even smaller by optimizing the film thickness. Also, the FWHM of the peak increases from 0.85 degrees (for k=0.001) to 2.05 degrees (for k=0.01).

The value of minimum reflectivity and the resonance angle were changed with the variation of the chalcogenide film refractive index due to Kerr efect. The variation of minimum reflectivity vs chalcogenide film refractive index is given in the Fig. 6(a) for a film thickness of 210 nm (TM1), 675 nm (TM2) and 1150 nm (TM3), respectively.



(a)



(b)

Fig. 6. (a) Minimum reflectivity vs refractive index of $Ge_{28.1}Sb_{6.3}Se_{65.6}$ film for d=210 nm (TM1 mode), d=675 nm (TM2 mode) and d=1150 nm (TM3 mode) chalcogene thickness. (b) Resonance angle vs chalcogenide film refractive index for d=210 nm (TM1 mode), d=675 nm (TM2 mode) and d=1150 nm (TM3 mode) chalcogene thickness.

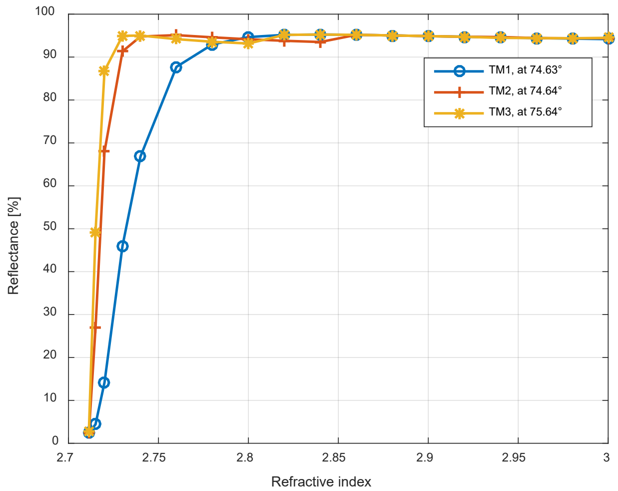


Fig. 7. Reflectance at resonance angle vs refractive index of chalcogenide $Ge_{28.1}Sb_{6.3}Se_{65.6}$ film for d=210 nm - TM1, d= 675 nm - TM2 and d=1150 nm - TM3 chalcogenide film thickness.

Also, in Fig. 6(b) we present the dependence of the resonance angle as a function of chalcogenide film refractive index. The refractive index of $Ge_{28.1}Sb_{6.3}Se_{65.6}$ was varied between 2.7 and 3.0, approximately. From the Fig. 6(b) it can be seen the shift of resonance angles vs variation of chalcogenide film refractive index.

The dependence of reflectivity corresponding to the resonance angle as a function of chalcogenide film refractive index is given in Fig. 7 for different TM modes (TM1, TM2 and TM3). In these simulations we varied the refractive index of chalcogenide film due to Kerr efect. The reflectivity was determined at the corresponding resonance angle for TM1, TM2 and TM3 modes. As can be seen in the Fig. 7, the reflectivity increases abruptly with the increase of the chalcogenide material refractive index followed by saturation in the cases of TM2 and TM3 modes. Instead, for TM1 mode the reflectivity increases more slowly before saturation.

These simulations could be used for the design of optical memories fabricated in $Ge_{28.1}Sb_{6.3}Se_{65.6}$ plasmonic structures for writing and erasing processes of the information.

4. Conclusions

Surface plasmon resonance in Kretschmann configuration was studied for a multilayer configuration containing the $Ge_{28.1}Sb_{6.3}Se_{65.6}$ amorphous chalcogenide film. The $Ge_{28.1}Sb_{6.3}Se_{65.6}$ films allow us to obtain a narrow plasma resonance curve. This indicates that the $Ge_{28.1}Sb_{6.3}Se_{65.6}$ films are promising for various photonic applications. The shape of resonance curves and resonance angles were modified at refractive index changes. The study was performed for different transverse magnetic (TM) modes (TM1, TM2 and TM3). Based on the numerical simulations presented above optical memories fabricated in $Ge_{28.1}Sb_{6.3}Se_{65.6}$ plasmonic structures could be feasible.

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