U.P.B. Sci. Bull., Series A, Vol. 78, Iss. 4, 2016 ISSN 1223-7027

OPTICAL BISTABILITY WITH A PLASMONIC CHALCOGEN-BASED WAVEGUIDE STRUCTURE

M. STAFE[1], G. C. VASILE[1], A. DUCARIU[1], M. MIHĂILESCU[1], C. NEGUŢU[1], N.N. PUŞCAŞ[1]

We analyzed theoretically and experimentally the coupling of Ar laser radiation (502 nm wavelength) as TM modes into a planar waveguide containing metallic (Au) and a chalcogenic (As_2S_3) thin layers by using Kretschmann-Raether configuration. The resonant coupling of the radiation to the waveguide is calculated to be possible when the incidence angle to the coupling prism base is 58 degrees. This is demonstrated to be in good agreement to our experiments.

Subsequent calculations indicate that, for an incidence angle slightly above the resonance coupling angle, the increase of the incident laser intensity leads to a rapid decay of the reflectivity of the waveguide structure. The decrease of the incident laser radiation leads to the increase of the reflectivity back to the original value on a slightly different path, resulting in a hysteresis like curve. This hysteresis curve is mostly due to the "memory" of the refractive index changes of the chalcogenic layer during the intensity increase phase.

Keywords: optical bistability, surface plasmon resonance, plasmonic waveguides, amorphous chalcogenide films, optical memory.

1. Introduction

The plasmons manifest as collective elementary oscillations of the electrons in a metal during the light-matter interaction [1]-[14]. When an incident *p*-polarized light beam that satisfies a certain resonance condition (angle) 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) [1]-[5]. Usually, the light coupling is carried out through a high-refractive-index substrate in the Kretschmann-Raether arrangement [1] for which the configuration is based on angular interrogation by a convergent beam in which a prism for the excitation of surface plasmons by light is used.

Because the surface plasmonic wave (electromagnetic) is propagating parallel with the metal-dielectric interface this is influenced by the border

[1] University POLITEHNICA of Bucharest, Physics Department, Splaiul Independentei, 313, 060042, Bucharest, Romania.
Corresponding authors: M. Stafe: stafe@physics.pub.ro, C. Neguțu: negutu@physics.pub.ro, G. Vasile: georgiana.vasile@physics.pub.ro.

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 coupled plasmon-waveguide resonator both *p* (transversal magnetic) and *s* (transversal electric) polarized waves may be excited, so the energy of the incident radiation is absorbed resonantly.

A current hot topic in this field is optical bistability produced by laser light reflection from non-linear thin films. When the light is incident upon a film interface at a particular angle dictated by the dielectric constants and the thicknesses of the media involved, a waveguide mode with a large field intensity can be excited in the film that, provided that the film is at least slightly absorptive, results in a significant decrease in the reflectance of the film. In this case, if one or more of the media in or around the film waveguide is nonlinear, the characteristic angle of incidence for production of the waveguide mode becomes a function of the incident intensity, and the resulting variation of the reflected signal with intensity can be exploited to create an optically bistable output.

The resonance phenomenon may be obtained for several incident angles and for several wavelengths of the incident radiation. The resonance angle may be modified by deposing a thin active amorphous chalcogenide glass (ChG) layer, for example As_2S_3 on the substrate surface, because its refractive index may be modified by the irradiation using an optical radiation with photon energy comparable with the forbidden optical band of the material.

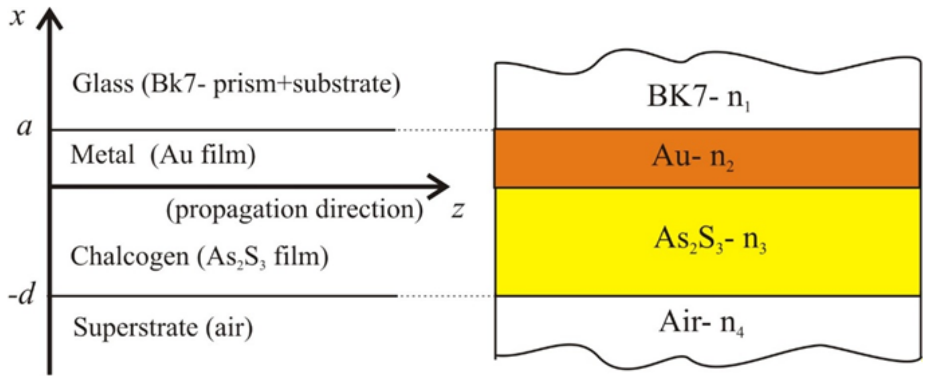
The unique optical properties of ChGs are used for a range of important applications, focusing on recent examples in mid-infrared sensing, integrated optics and ultrahigh-bandwidth signal processing. Also, using the SPR method combined with a ChG birefringent layer characterized by reversible changes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

The paper is organized as follows: in Sect. 2 we outlined some theoretical results concerning the evaluation of the reflection coefficient on the laser intensity for an incidence angle near the resonance coupling angle while in Sect. 3 the measurement of the reflection of a cw Ar laser at the prism-chalcogen interface is presented. In Sect. 4 our conclusions concerning the obtained results are emphasized.

2. Theoretical considerations

The planar waveguide consists of a structure of long and large layers in the XZ plane and have four regions in each of which the refractive index may be considered as constant. The structure scheme is shown in Fig. 1 a), b). The four constituent regions are as follows: a semi-infinite glass (BK7) medium representing the substrate and the coupling prism with refractive index n_1, a thin metallic layer with a complex refractive index n_2, a thin chalcogenic film (optical waveguide) with refractive index n_3, and a semi-infinite cover region with an index n_4. The thin optical waveguide layer has the largest index.

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.



a) b)

Fig. 1. a) The structure of the planar optical waveguide. b) Schematic of the plasmonic structure. The two finite thickness media have the thickness a (metal) and d (chalcogenide).

The waveguide structure that we analyse here consists of three layers: 620 nm thickness chalcogenic (As_2S_3) layer in direct contact to the coupling-prism base, 46 nm metallic (Au) film and a glass substrate. The chalcogenic film is deposited on the golden layer of the glass chip by thermal evaporation. First, we consider that the linearly polarized radiation at 502 nm wavelength from an Ar cw laser is sent at different incidence angles at the prism-chalcogen interface.

Based on the model presented in papers [5]-[7], the propagation equation for the electric/magnetic fields, E/H in the four regions characterized by the refractive indexes n_1-n_4 may be written in the form:

$$\frac{\partial^2 E(x,y)}{\partial x^2} + \left(k_o^2 n_i^2 - \beta^2\right)E(x,y) = 0 \quad (1)$$

$$\frac{\partial^2 H(x,y)}{\partial x^2} + \left(k_o^2 n_i^2 - \beta^2\right)H(x,y) = 0 \quad (2)$$

where i=1-4, k_0 is the vacuum wave vector and β represents the propagation constant along the z axis, being related to the incidence angle at the glass-metal interface. In the case of TM mode the electromagnetic field is characterized by H_y, E_x and E_z. The general solution of the wave equation in the four media of the waveguide structure, namely the field components H_{yi}, E_{xi} and E_{zi} of the TM mode can be written as:

$$H_{y_i}(x,z) = (A_i \cdot e^{ik_i x} + B_i \cdot e^{-ik_i x}) \tag{3}$$

$$E_{x_i}(x,z) = \frac{\beta}{\omega\varepsilon_o n_i^2} H_{y_i}(x,z) = \frac{\beta}{\omega\varepsilon_o n_i^2}\left(A_i \cdot e^{ik_i x} + B_i \cdot e^{-ik_i x}\right) \tag{4}$$

$$E_{z_i}(x) = -\frac{i}{\omega\varepsilon_o n_i^2}\frac{\partial H_{y_i}}{\partial x} = \frac{k_2}{\omega\varepsilon_o n_i^2}\left(A_i \cdot e^{ik_i x} - B_i \cdot e^{-ik_i x}\right) \tag{5}$$

where $k_i = \sqrt{k_o^2 n_i^2 - \beta^2}$ (i=1-4) is the wave number within the optical waveguide along the X direction, ω represents the pulsation, ε_o is the electric constant. The amplitudes A_i and B_i (with $A_4 = 0$ since the fourth medium is semi-infinite) are obtained from the boundary conditions of H_y, E_z and $D_x = \varepsilon E_x$ at interfaces $x = 0$, $x = a$ and $x = -d$. From eq (3-5) results that the continuity of the three measures are fulfilled if H_y and $\frac{1}{n_i^2}H_y$ are continuous.

Since the wave intensity within a medium may by directly related to the magnetic field, we can write the reflectivity at the prism-metal interface as:

$$R_{12} = \left|A_1 / B_1\right|^2 \tag{6}$$

where A_1 and B_1 are the amplitudes in the glass substrate.

The reflectivity of the waveguide structure, at the prism-metal interface, is calculated by solving numerically in MATLAB the continuity equations for H_y and $\frac{1}{n_i^2}H_y$ at the three interfaces of the waveguide structure: substrate-metal, metal-chalcogen and chalcogen-air. The refraction indexes of the materials at 502 nm laser wavelength are determined from several sources are [15-17]: $n_1 = 1.52$, $n_2 = 0.78 - 1.77i$, $n_3 = 2.76$, $n_4 = 1$.

Fig. 2 presents the dependence of the reflectivity of the structure as a function of incidence angle at the prism-metal interface. We infer from this graph a resonant coupling angle of 58 degrees for the Ar laser radiation at 502 nm wavelength.

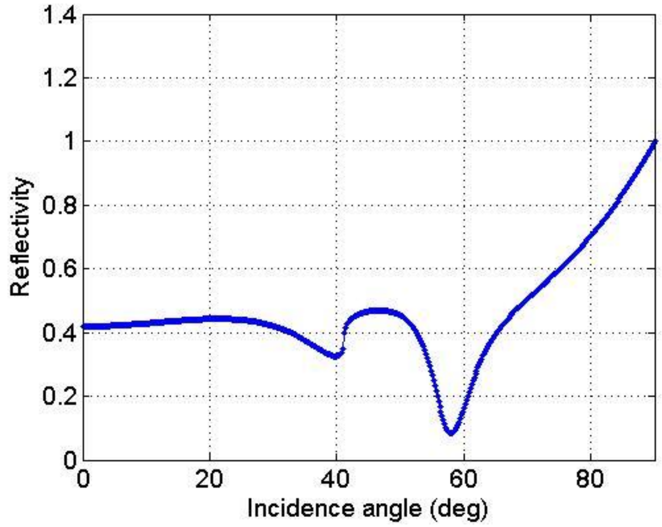


Fig. 2. The reflectivity of the structure as a function of incidence angle at the prism-chalcogen interface.

We further calculated the dependence of the reflection coefficient on the laser intensity for an incidence angle near the resonance coupling angle of 48 degrees (Fig. 3).

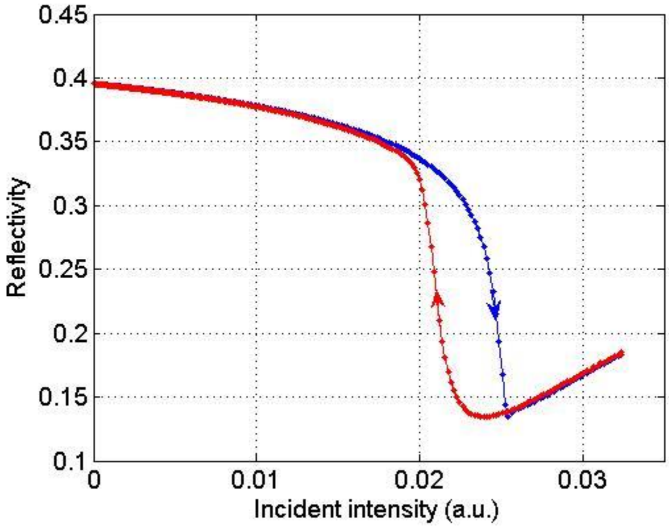


Fig. 3. The dependence of the reflection coefficient on the laser intensity for an incidence angle near the resonance coupling angle.

The calculations indicate that, for an incidence angle slightly above the resonance angle, the increase of the incident laser intensity leads to a rapid decay of the reflectivity of the waveguide structure from its original value of ~40% to

~13%. This is related to the very small increase of the intensity dependent refractive index of the chalcogenic film when the laser radiation is coupled to the waveguide. The decrease of the incident laser radiation leads to the increase of the reflectivity back to the original value on a slightly different path, resulting in a hysteresis like graph of the reflectivity vs laser intensity. This hysteresis is mostly due to the "memory" of the refractive index changes of the chalcogenic layer during the intensity increase phase.

3. Experimental

For the measurement of the reflection of a cw Ar laser (502 nm wavelength, ~0.1 W/cm^2 intensity) at the prism-chalcogen interface we use the experimental setup presented in Fig. 4. The rotation of the prism for variation of the incidence angle is realized with a Thorlabs mechanical rotation stage with a resolution of 0.04 degrees. The photodetector is a Thorlabs S310 C powermeter which is placed perpendicular to the output laser beam from the prism.

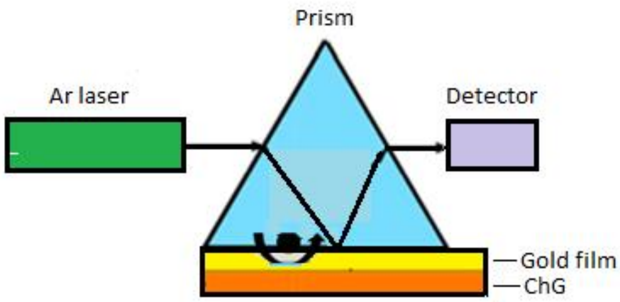


Fig. 4. The experimental setup used for the measurement of the reflection of a cw Ar laser at the prism-chalcogen interface

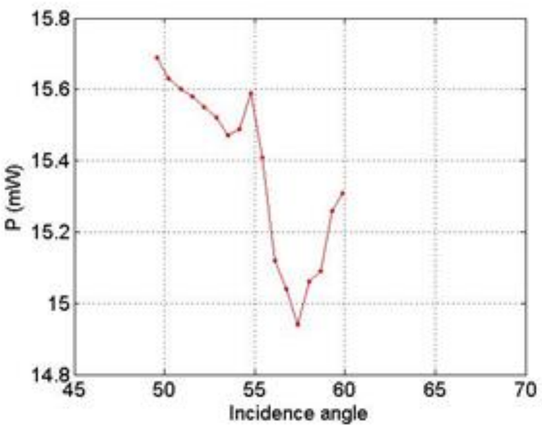


Fig. 5. The dependence of the output beam power on the incident angle.

The dependence of the output beam power on the incident angle is presented in Fig 5. The minimum of the output power is obtained for an incidence angle of ~58 degrees at the prism-metal interface. This experimental result is in very good agreement with the experimental data regarding the measurement of the reflection of a cw Ar laser (intensity of ~0.1 w/cm2) at the prism-metal interface (Fig. 2).

4. Conclusions

This paper presents some theoretical and experimental results concerning the coupling of Ar laser radiation (502 nm wavelength) as TM modes into a planar waveguide containing metallic (Au) and a chalcogenic (As_2S_3) thin layers by using Kretschmann-Raether configuration. The resonant coupling of the radiation to the waveguide is calculated to be possible when the incidence angle to the coupling prism base is 58 degrees. This result is in good agreement to our experiments.

Also, we demonstrated that, for an incidence angle slightly above the resonance coupling angle, the increase of the incident laser intensity leads to a rapid decay of the reflectivity of the waveguide structure. The decrease of the incident laser radiation leads to the increase of the reflectivity back to the original value on a slightly different path, resulting in a hysteresis like curve. This hysteresis curve is mostly due to the "memory" of the refractive index changes of the chalcogenic layer during the intensity increase phase.

Acknowledgements.
This work was supported by the Romanian National Authority for Scientific Research, CNDI – UEFISCDI, through grant PN-II-PT-PCCA-2011-25/2012.

R E F E R E N C E S

[1] *Kretschmann E., and Raether, H.,* "Radiative decay of non-radiative surface plasmons excited by light", Z. Naturforschung, 23A: (1968), pp.2135–2136.
[2] *Berini Pierre,* "Plasmon-polariton modes guided by a metal film of finite width bounded by different dielectrics", Optics Express Vol. **7**(10), (2000), pp.329-335.
[3] *Charnovych S., Szabo I.A., Toth A.L., Volk J., Trunov M.L., Kokenyesi S.,* "Plasmon assisted photoinduced surface changes in amorphous chalcogenide layer", J. Non-Cryst. Solids, Vol. **377**(SI), (2013), pp.200-204.
[4] *Sámson Zsolt L., Yen Shih-Chiang, MacDonald Kevin F., Knight Kenton, Li Shufeng, Hewak Daniel W., Tsai Din-Ping, and Zheludev Nikolay I.,* "Chalcogenide glasses in active plasmonics", Phys. Status Solidi RRL, Vol. **4**(10), (2010), pp.274–276.
[5] *Maier S. A.,* [Plasmonics: Fundamentals and Applications,] Springer, 2007.
[6] *Marcuse D.,* Book [Theory of Dielectric Optical Waveguides,] New York: Academic Press, 1974.

[7] *Vasile Georgiana C., Savastru Roxana, Popescu A. A., Stafe M., Savastru D., Dontu Simona, Baschir L., Sava V., Chiricuta B., Mihailescu M., Negutu C., and Puscas N. N.,* "Modelling the 2D plasmonic structures with active chalcogenide glass layer", Rom. Rep. Phys. Vol. **65**(3), 1012-1018 (2013).
[8] *Popescu A.A., Savastru R., Savastru D., Miclos S.,* "Application of vitreous As-S-Se chalcogenides as active layer in surface plasmon resonance configuration", Dig. J. Nanomater. Biostruct. Vol **6(**3), (2011), pp.1245-1252.
[9] *Vasile Georgiana C., Popescu Aurelian A., Stafe Mihai, Koziukhin S.A., Savastru Dan, Donţu Simona, Baschir L., Sava V., Chiricuţă B., Mihăilescu Mona, Neguţu Constantin, Puşcaş Niculae N.,* "Plasmonic waveguides features correlated with surface plasmon resonance performed with a low refractive index prism," U.P.B. Sci. Bull. Series A Vol. **75(**4), (2013), pp. 311-325.
[10] *A. Moldovan, M. Enăchescu, A. A. Popescu, M. Mihăilescu, C. Neguţu, L. Baschir, G. C. Vasile, D. Savastru, M. S. Iovu, V. I. Verlan, O. T. Bordian, I. M. Vasile, N. N. Puşcaş,* Characterization of As2S3 thin surface films using SEM and AFM methods, University "Politehnica" of Bucharest, Scientific Bulletin, Series A: Applied Mathematics and Physics, Vol. **76**, No. 2, p. 215-222, 2014.
[11] A. *A. Popescu, M. Mihăilescu, C. Neguţu, L. Baschir, M. Stafe, G. C. Vasile, D. Savastru, M. S. Iovu, V.I. Verlan, O. T. Bordian, A. Moldovan, M. Enăchescu, N. N. Puşcaş*, "Politehnica" of Bucharest, Scientific Bulletin, Series A: Applied Mathematics and Physics, Vol. **76**, No. 3, p. 211-218, 2014.
[12] *Aurelian A. Popescu, Laurenţiu Baschir, Dan Savastru, Mihai Stafe, Georgiana C. Vasile, Sorin Miclos, Constantin Neguțu, Mona Mihăilescu, Niculae N. Pușcaș,* Analytical considerations and numerical simulations for surface plasmon resonance in four layers plasmonic structures which contain high refractive index waveguide, University "Politehnica" of Bucharest, Scientific Bulletin, Series A: Applied Mathematics and Physics, Vol. **77**, No. 4, p. 233-244, 2015.
[13] *A. A. Popescu, A, L. Baschir, B, D. Savastru, M. Stafe, C. Neguțu, C, V. Savu, Georgiana Vasile, Mona Mihăilescu, Victor V. Verlan, Olga Bordian, N. N. Pușcaș,* Surface plasmon resonance and photoinduced dichroism in amorphous chalcogenide As2S3 films, Romanian Reports in Physics, Vol. **67**, No. 4, p. 1421–1430, 2015.
[14] *Mihai Stafe, Georgiana C. Vasile, Constantin Neguțu, Aurelian A. Popescu, Laurentiu Baschir, Mona Mihăilescu, Niculae N. Pușcaș,* Analysis of the optical absorption and photoinduced birefringence in As_2S_3 chalcogenide films, University "Politehnica" of Bucharest, Scientific Bulletin, Series A: Applied Mathematics and Physics, Vol. **78**, No. 1, p. 243-256, 2016.
[15] *W. S. Rodney, I. H. Malitson and T. A. King*, Refractive index of arsenic trisulfide, J. Opt. Soc. Am. 48, 633-635 (1958).
[16] *A. D. Rakić, A. B. Djurišic, J. M. Elazar and M. L. Majewski*, Optical properties of metallic films for vertical-cavity optoelectronic devices, Appl. Opt. 37, 5271-5283 (1998).
[17] SCHOTT optical glass data sheets 2015-07-22.