Design and realization of low losses chalcogenide As_xS_{1-x} planar waveguides

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Optical losses in planar waveguides are usually limited to several dB/cm that is a quite high value for practical application. In many cases the optical losses are due to light scattering on non-homogeneities rather than to material absorption. Numerical calculations for the waveguide modes show that the effective refractive index variations depend on the material and geometrical waveguide parameter and can be optimized in order to minimize the sensitivities. The optimized planar structure may be performed using a multilayer structure of As_xS_{1-x} glasses with different compositions. Experimentally symmetrical planar waveguides were realized with losses less than 0,1 dB/cm. The three prism method was used for measurement of the low optical losses.

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1. Introduction

Thin films made of optical transparent dielectric materials display, under some conditions, waveguide properties. In these structures a confined propagation of the light is achieved that allows the manufacturing of different optical elements. Their integration in the optoelectronic networks represents the concept of integrated optics [1,2,]. Nanophotonics gave a new urge to this area by the use of the photonic crystals concept [3,4] and the light propagation phenomena under the diffraction limit [5]. Besides the fact that materials such as lithium niobate, silicon (in SOI concept), Ga-Al-As are known as priority candidates, the development of the integrated optics on hybrid basis appears as imminent considering the complexity of the phenomena.

As_xS_{1-x} vitreous chalcogenide semiconductors display a series of properties favorable to this kind of applications, namely: a refractive index higher than two required for manufacturing photonic crystals [6,7]; the refractive index may vary within a large range (2.0 – 2.8) required for manufacturing the light confinement structures [8]; a considerable value of the Kerr nonlinearity constant [9,10] of about 10^2-10^3 times higher than the quartz. The modifications induced to the refractive index [9] and the change of the solubility as a result of the illumination [11] denote the capacity for application of these materials as photoresist, or waveguides and diffraction grating [12,13]. The chalcogenide planar waveguides have usually optical losses about 3-5 dB/cm. The losses as low as 0.25 dB/cm have been achieved using plasma reactive ion etching technique with CF_4-O_2 gas [14].

From several papers it follows that the main cause for the losses is not the optical absorption but the scattering of the light, caused by the poor substrate quality, the surface roughness and others. It is imperious to find out new ways of diminishing the optical losses in planar waveguides. The aim of this paper is the numerical simulation of the multilayer planar guide structure and the realization of the chalcogenide planar waveguides with optical losses diminished till 0.1 dB/cm.

2. Planar light waveguides, theoretical considerations

The confinement of the electromagnetic waves in planar light waveguide is described by Maxwell equations that must comply with the appropriate boundary conditions. It results an autocorrelated distribution of the field, which represents the waveguide mode.

It is notable that the description of the electromagnetic field in confinement structures with the film refractive index n_f greater than that of the environment is similar to the stationary Schrödinger equation for quantum mechanics particles: the refractive index profile is analogue to the potential energy while propagation constant is analogue to eigen energies. The solution for the electro-magnetic field is obtained analogically to the finding of undulatory function. Thus, the theoretical calculations arise quickly using the solutions and the mathematics of the quantum mechanics. New results can be obtained because for waveguides can be achieved technologically refractive index profiles different from the potential energy profiles existing in nature.

Let us analyze the simplest dielectric waveguide in the planar waveguide with rectangular refractive index profile. Here, the dielectric layer with the refractive index n_f is placed between the substrate with the index n_s and the protection layer with the index n_c. The typical difference of the refractive indices between the dielectric layer and substrate is from 10^{-3} till 10^{-1}.

In the planar waveguide there are a large number of wave modes. From the resonance condition, the dispersion equation [1] is deduced:

$$2\cdot k\cdot h\cdot n_f\cdot\sin(\theta_m)-\varphi_S-\varphi_C=2\cdot\pi\cdot m \qquad (1)$$

where m is an integer (mode order) and the phase differences at total reflection are calculated for the TE waves using the formulas:

$$\varphi_{SE}=\arctan\left(\frac{\sqrt{n_f^2\cdot\cos^2(\theta_m)-n_s^2}}{n_f\cdot\sin(\theta_m)}\right)$$
$$\varphi_{CE}=\arctan\left(\frac{\sqrt{n_f^2\cdot\cos^2(\theta_m)-n_c^2}}{n_f\cdot\sin(\theta_m)}\right) \qquad (2)$$

For TM waves the analogue expressions are calculated as:

$$\varphi_{SM}=\arctan\left(\frac{\sqrt{n_f^2\cdot\cos^2(\theta_m)-n_s^2}}{n_f\cdot\sin(\theta_m)}\cdot\left(\frac{n_f}{n_s}\right)^2\right)$$
$$\varphi_{CM}=\arctan\left(\frac{\sqrt{n_f^2\cdot\cos^2(\theta_m)-n_c^2}}{n_f\cdot\sin(\theta_m)}\cdot\left(\frac{n_f}{n_c}\right)^2\right) \qquad (3)$$

Transversal TE and TM modes are distinguished because the phase variation φ depends on the polarization of the electromagnetic wave. The solution of this transcendent equation can be achieved graphically or by numerical methods. As a result, a set of θ_m angles will be obtained, with different propagation constants $\gamma_m = 2\pi N_m/\lambda$, where $N_m = n_f\cdot\cos(\theta_m)$ is the effective refractive index.

The substitution of θ_m with N_m in equations (1) to (3), the N_m can be expressed as a function of the thickness h, the refractive index of the film n_f, the refractive indices of the layers adjacent to the waveguide (n_s and n_c) and the wavelength of the optical radiation λ. The change of any parameter of the waveguide will cause somewhat the change of the effective refractive index. In some cases, these changes are intentionally done in order to create, for instance, a phase modulator, planar lenses and prisms etc.

However, in many cases, the variation of the effective refractive index is undesirable. Thus, if the optical beam propagates through a waveguide with nonuniformities of the refractive index, its phase front will be distorted. If these nonuniformities are randomly distributed, then the phase front of the surface optical wave will be randomly modulated. This means a scattering of the beam in a wide range of angles, which causes losses of light.

The design of a light guide is frequently limited to the calculation of a dispersion curve. In order to study the influence of the material nonuniformity on the effective refractive index, the derivatives $\frac{\partial N_m}{\partial h}$, $\frac{\partial N_m}{\partial n_f}$ and $\frac{\partial N_m}{\partial n_s}$ were calculated.

The corresponding results are displayed in Fig. 1 and Fig. 2. Calculations were done a) for As_2S_3 thin films with a refractive index n_f = 2.45 laid on a glass substrate with a refractive index n_s = 1.5 and an air cover n_c = 1.0 (Fig. 1, left) and b) for the same As_2S_3 thin films with a refractive index n_f = 2.45 symmetrically laid between two identical As_2S_5 layers (n_s = n_c = 2.40). The derivatives of the effective refractive index N_m with respect to n_s and n_f are presented in Fig. 2, where only symmetrical layout (n_s = n_f = 2.40 and n_f = 2.45) was considered. The wavelength is considered to be 0,63 μm.

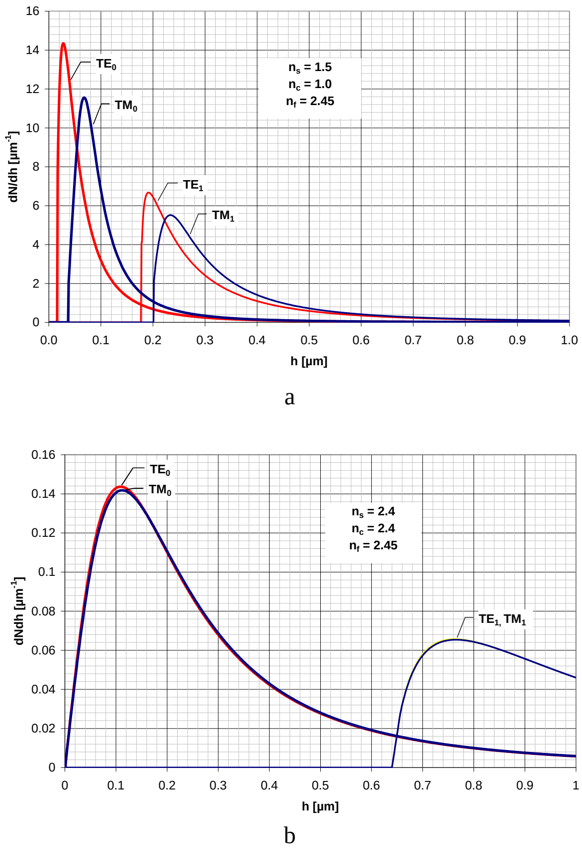

Fig. 1. The derivative of the effective refractive index with respect to the thickness h for asymmetrical (a) and symmetrical (b) layouts.

From the Fig. 1 graphs it results that: a) the waveguides propagation characterized by effective refractive index is very sensitive to the thickness fluctuations (like roughness, for example) for thicknesses a little higher than the mode cut-off. In this case, high quality technological conditions are required to prevent the light losses.

The effective refractive index variations dN/dn_f (Fig. 2) that denotes that the sensibility to the film material irregularities increases with film thickness. On the contrary, the effective refractive index variations dN/dn_s that denotes that the sensibility to the substrate material irregularities decreases with film thickness. The optimum film thickness necessary to lower the optical losses depends of what waveguide's component, film or substrate, can be realized as the best.

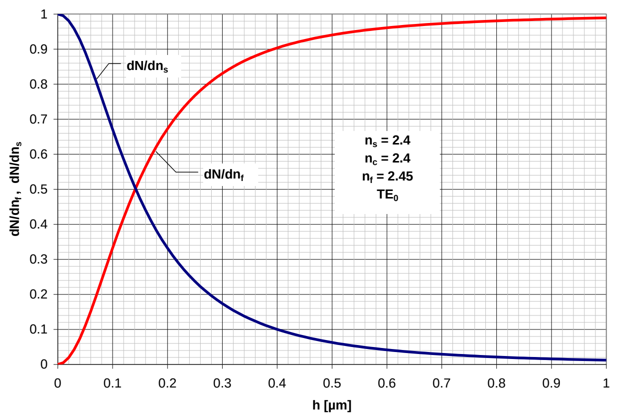

Fig. 2. Partial derivatives of the effective refractive index with respect to refractive indices of the materials as function of the film thickness. Calculation are done for TE_0 waveguide mode.

Calculations similar to those illustrated in Fig. 1 were also done for As_2S_3 waveguides laid on a substrate corresponding to chalcogenide compound with the compositions As_2S_6 (n = 2.38), As_2S_5 (n = 2.40), As_2S_4 (n = 2.43). The film acts as an optical insulator if its thickness is greater than the depth at which the evanescent field of the mode penetrates. The results of these calculations reveal that, for instance, with a As_2S_4 buffer under the As_2S_3 planar waveguide, the sensitivity of the propagation constant with respect to the thickness fluctuations decreases about 100 times. This means a possible diminution of the optical losses in such waveguide compared to the chalcogenide waveguide deposited on oxide glass like BK7, which refractive index equals 1.5.

3. Experimental investigations of the optical losses in planar waveguides

One of the main characteristics of the quality of the waveguides is the level of the optical attenuation. There are some methods for the measurement of the light attenuation.

1. Indirect methods based on the proportionality between the intensity of the scattered radiation and the intensity of the radiation, which propagates through the waveguide. In the specified case photometric measurements of the radiation intensity are done along the propagation of the light through the waveguide. The method cannot be applied for waveguides in which the losses are caused by absorption, because the measured signal, proportional to the scattered light, is zero.

2. Direct method based on light coupled into the waveguide by means of a prism and light extraction from the waveguide at a distance L. If we assume that 100 % of the intensity is extracted, the attenuation coefficient α can be calculated as:

$$\alpha(dB/cm) = \frac{10}{L}\lg\left(\frac{I_{out}}{I_0 - I_{ref}}\right) \quad (4)$$

The method suppose that the intensity of the light ($I_0 - I_{ref}$) coupled in waveguide is well known. However, in many cases is not so. The coupling efficiency measurements can be avoided if the light intensity I_1, I_2 at the waveguide output is measured twice at the distances L_1 and L_2. Then the losses can be calculated using the equation:

$$\alpha = \frac{1}{L_2 - L_1}\lg\left(\frac{I_2}{I_1}\right) \quad (5)$$

The method is widely used to characterize the losses in optical fibers, allowing the use of longer samples and offering a good repeatability of the extraction conditions.

A good precision can also be acquired applying this method for planar waveguides made from materials with low (from 1.33 to 1.69) refractive index. In this case a 100 % repeatable extraction of the light can be assured using an immersion liquid between the extraction prism and the waveguide. The immersion liquid can be obtained using, for instance, glycerin solutions in water. The refractive index of the chalcogenide glass waveguides is greater than 2.0 (lithium niobate likewise) and there is no immersion liquid with a refractive index close to this value. Because of the low repeatability for high refractive index materials, the attenuation cannot be determined with enough precision for losses values less then 1 dB/cm.

3. An effective method was proved to be the one using three prisms proposed in the paper [15]. The schematic layout is shown in Fig. 3. According to this method, the prisms 2, 3 and 4 interact independently with the waveguide. If the light enters through the prism 2, the light intensity at the output of the prisms 3 and 4 will be determined by equations:

$$P_3 = \gamma_3 \cdot I(z_3) \quad (6)$$

$$P_4 = \gamma_4\left[I(z_3) - P_3\right]\exp\left[-\alpha(z_4 - z_3)\right] \quad (7)$$

where P_3 and P_4 represent the output power of prisms 3 and 4;

γ_3 , γ_4 represent the unknown coupling constants of these prisms defining the light extraction intensity; $I(z)$ represents the light intensity in the waveguide at the distance z from the input prism 2; z_i represents the location of the prism i; α represents the attenuation coefficient of the waveguide.

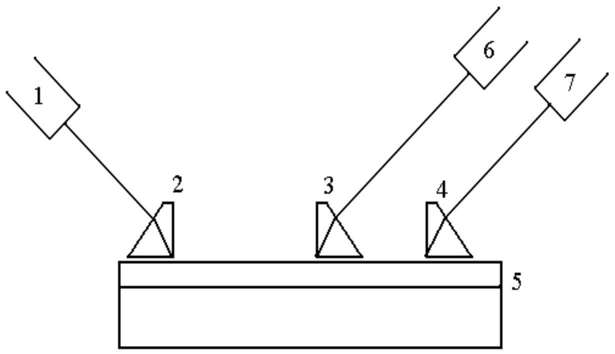

Fig. 3. Schematic layout of the three prisms methods of determining the optical losses: 1– laser, 2,3,4 – coupling prisms, 5 – waveguide, 6,7 –light intensity measuring photodiodes.

The case in which the central prism is detached from the film ($\gamma_3 = 0$) corresponds to an output intensity from prism 4 equal to P_{40}. When $\gamma_3 \neq 0$ the output intensity extracted by prism 4 diminishes till the value $P_4 = P_{40} - \Delta P$, ΔP denoting the diminished value of the output. It is noticeable that in both cases the extraction prism 4 is not reached and we can consider that the coupling constant is the same in both cases. Then, using the equations (6) and (7) for the two situations (with and without the prism 3) we will get:

$$I(z_3)\cdot(P_{40}-\Delta P)=(I(z_3)-P_3)\cdot P_{40} \tag{8}$$

from where the final equation of the light intensity in the waveguide at distance z from the input prism can be derived:

$$I(z)=\frac{P_3\cdot P_{40}}{\Delta P} \tag{9}$$

As it can be seen the result is independent of the coupling coefficients γ_2, γ_3 and γ_4. The intensity of the light inside the waveguide is calculated for two positions A and B of prism 3: z_{3A} and z_{3B}. As $I(z_{3B})=I(z_{3A})\cdot\exp(-\alpha\cdot(z_{3B}-z_{3A}))$, the attenuation coefficient is calculated as:

$$\alpha=\frac{\ln\left(\frac{P_{3A}\cdot\Delta P_B}{P_{3B}\cdot\Delta P_A}\right)}{z_{3A}-z_{3B}} \tag{10}$$

The formula is independent of any of the coupling coefficients γ. An accuracy of 0.13 dB/cm is estimated when the light intensity is measured with a precision of 3 %.

4. Manufacture of planar multilayer waveguides with low losses

The planar waveguides were achieved by vacuum thermal evaporation at (2 – 5) $\cdot 10^{-6}$ Torr. The material having the required composition was synthesized of pure As and S elements. The refractive index varies from 2.05 to 2.46 together with the decrease of the sulphur concentration from 95 % to 55 %. The ground grains of vitreous chalcogenide material, having dimensions of 2 × 2 × 2 mm^3, are placed in the evaporator that is made from tantalum as a little boat. The optimal temperatures for the evaporator lay between 220 and 270 °C. The deposition process lasts 7 – 8 minutes.

The manufactured structures are presented in Fig. 4. The measurement of optical losses are presented in Table 1. By using compounds with close refractive indices (Δn < 0.1), a diminishing of the losses was achieved in planar waveguides up to values less than the precision of the method, which is limited to 0.1 dB/cm. The layer 3 (see Fig. 4c) acts as an optical insulator for substrate, which can be of a poor optical quality.

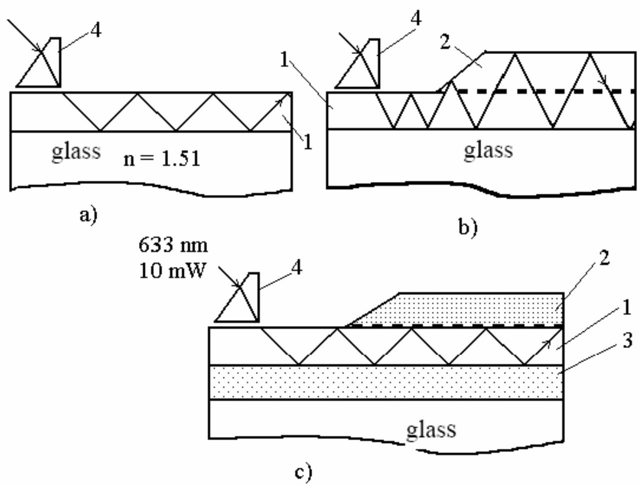

Fig. 4. Multilayer planar waveguides: 1– As_2S_3, 2– As_2S_6, 3 – As_2S_6, 4 –GaP prism.

Table 1. Optical losses in planar waveguides for different As-S structure.

Structure and composition	Sample no.	α, dB/cm λ = 0.63 μm	α, dB/cm λ = 1.15 μm
As_2S_3	1 2	3.0 2.9	1.4 1.3
As_2S_5	1 2	1.8 1.6	Less than 0.5
As_2S_6	1 2	1.6 1.2	Less than 0.5
As_2S_3+As_2S_6	1	0.9	insignificant
As_2S_6+As_2S_3+As_2S_6	1	0.5	insignificant

5. Conclusions

Numerical simulation was done for the effective refractive index variations due to material lack of homogeneities and structure irregularities. The calculations show that symmetrical waveguides with low refractive index difference are less sensitive to disorder. A multilayer planar structure was realized by thermal film deposition of chalcogenide As-S materials with a small difference of the refractive index. The planar waveguides with low, less than 0.1 dB/cm, losses were manufactured.

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References

[1] Robert G. Hunsperger. Integrated optics: Theory and technology. Second edition, Ed. Springher 1984.
[2] T. Tamir. Integrated Optics. Ed. Springer, New-York, 1979.
[3] E. Yablonovich, Phys. Rev. Lett. **58**, 2059 (1987).
[4] John D. Joannopoulos, Steven G. Johnson, Joshua N. Winn, Robert D. Meade. Photonic Crystals - Molding the Flow of Light. Book, Second edition. Princeton University Press 2008.
[5] Mark L. Brongersma, John W. Hartman, and Harry A. Atwater, Phys. Rev. B, **62**(24), 15 (2000).
[6] A. Popescu, S. Miclos, D. Savastru, R. Savastru, M. Ciobanu, M. Popescu, A. Lőrinczi, F. Sava, A. Velea, F. Jipa, M. Zamfirescu, J. Optoelectron. Adv. Mater., **11**(11), 1874 (2009).
[7] M. Popescu, A. Velea, A. Lőrinczi, M. Zamfirescu, F. Jipa, S. Miclos, A. Popescu, D. Savastru, Dig. J. Nanomater. Bios., **5**(4), 1579 (2010).
[8] B. Seddon, J. Non-Cryst Solids **184**, 44 (1995).
[9] E. M. Vogel, M. J. Weber, D. M. Krol, Physics and Chemistry of Glasses **32**, 231 (1991).
[10] Lenz, J. Zimmermann, T. Katsufuji, M. E. Lines, H. Y. Hwang, S. Spalter, R. E. Slusher, S. W. Cheong, J. S. Sanghera, I. D. Aggarwal, Opt. Lett. **25**, 254 (2000).
[11] A. Zakery, S. R. Elliott, J. Non-Cryst Solids **330**, 1-12 (2003).
[12] A. Zoubir, M. Richardson, C. Rivero, A. Schulte, C. Lopez, K. Richardson, N. Ho, R. Vallee, Opt. Lett. **29**, 748 (2004).
[13] T. V. Galstyan, J. F. Viens, A. Villeneuve, K. Richardson, and M. A. Duguay, Journal of Lightwave Technology **15**, 1343 (1997).
[14] Y. L. Ruan, W. T. Li, R. Jarvis, N. Madsen, A. Rode, B. Luther-Davies, Opt. Express, **12**, 5140 (2004).
[15] Y. H. Won, P. C. Jaussaud, G. H. Chartier, Appl. Phys. Lett., **37**, 269 (1980).
[16] H. G. Unger. Planar Optical Waveguides and Fibers. Oxford Engineering Science, 1977.

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