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The effect of interference in thin films on the optical characteristics of holograms recorded on As−Se layers

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Received April 14, 2023
Revised April 14, 2023
Accepted May 08, 2023

The effect of interference in thin films on the optical characteristics of holograms recorded on the layers of a chalcogenide glassy semiconductor of the As−Se system has been evaluated. The changes in the magnitude of reflection, transmission and optical difference in the path of the rays during the action of actinic He−Ne laser radiation on the layers are measured.

Keywords: interference in thin films, chalcogenide glassy semiconductors, refractive index, reflection, transmission, optical path difference, diffraction effectivity of holograms.

DOI: 10.61011/EOS.2023.08.57285.4859-23

Introduction

With the development of optical methods for recording, storing, and processing information, intensive creation and study of photosensitive materials continues [1]. The study of chalcogenide glassy semiconductors (CGS) as a photosensitive medium is promising due to a number of advantages discovered in CGS, such as high resolution up to $10000\,\mathrm{mm}^{-1}$ and photostimulated changes in the absorption coefficient and refraction index along with the inherent high refraction index.

The possibility of using CGS for holographic recording of information has been demonstrated quite a long time ago [2,3]. A large number of studies are devoted to the investigation of recording and reading holograms on CGS films by coherent radiation. These studies discuss the most general properties and characteristics, the mechanisms of photoinduced changes in CGS under the exposure to radiation, the possibility of creating new CGS types in terms of their composition, and the emerging prospects for new applications [4–11].

CGS materials allow multiple rewriting of information, which is convenient in operational systems for storing and processing information. Erasing information usually occurs when the CGS is heated to a temperature close to the softening point and held at this temperature for a few minutes [4]. CGSs are used to produce single-layer and multilayer optical coatings covering the visible and infrared spectral ranges as interference filters and beam splitters [5]. Also, CGSs allow recording microrelief on the surface and obtaining relief-phase and relief holographic gratings, which can be produced directly in the process of recording [6,7]. It is promising to use CGS in electronics as switches, sensors, phase memory elements, etc. [8]. The use of materials with a high refraction index to produce hologram optical elements makes it possible to reduce thickness and weight of the element, and, as a consequence, improve the transmission [9,10]. The effect of optical radiation on the CGS results in a shift of the edge of absorption band in the material, as a rule, to the long-wave region of the spectrum, as well as a change in the refraction index, which makes possible to implement amplitude-phase recording of information [11,12].

If the reading of the recorded information uses a radiation that is not absorbed by the material, then it is a pure phase recording. In this case, the recorded information will not be destroyed during reconstruction and high values of diffraction efficiency (DE) can be achieved. The investigation of the possibility of writing and reading information using radiation with one wavelength (for example, $\lambda = 0.63\,\mu\mathrm{m}$) seems no less important. In this case, when reconstructing the recorded information, no change in the geometry of the optical arrangement is required, and the reconstructed image will not contain aberrations arising from the difference in wavelengths.

The purpose of this study was to investigate the effect of interference in thin films on the optical characteristics of the material and DE of holograms recorded on AsSe layers by He-Ne laser radiation with a wavelength of $0.63\,\mu\mathrm{m}$. To assess the effectiveness of holograms recorded on CGS, it is necessary to conduct preliminary investigations that would show how such characteristics of the medium as transmission, absorption, and refraction index, which affect the DE, change during exposure to radiation.

1. Investigation of the effect of interference in thin films on the optical characteristics of holograms on AsSe layers

1.1. Setting up the experiment

To investigate the effect of interference in thin films on the optical characteristics of the material, to optimize the material parameters and conditions for recording and reconstructing holograms using the He-Ne laser radiation with a wavelength of $0.63\,\mu$m, AsSe films with a thickness of $0.5-3.5\,\mu$m were selected. The absorption coefficient and refraction index of the films at a wavelength of $0.63\,\mu$m, measured after deposition, were equal to $0.5\,\mu\text{m}^{-1}$ and 2.8, respectively.

In the first experiments, a dispersion in the resulted values of transmission, reflection, and optical path difference of beams was discovered for the same energy impact of radiation on the CGS layer already at the very beginning of the process. The cause for the instability of the response, as will be shown below, is the interference effects in the thin films under study.

If the CGS deposition resulted in a film uneven in thickness, then interference fringes of equal thickness can be observed in reflected or transmitted light. The film thickness d at the point of incidence of the beam, corresponding to the maximum or minimum of reflection, is calculated by the well-known formula: $d = \lambda m/2n\cos\beta$, where λ is wavelength in vacuum, n is refraction index of the film, β is angle of incidence of light on the film, m is integer with even m numbers corresponding to reflection maxima, and odd numbers corresponding to minima [13].

In the case of light incidence perpendicular to the sample surface at $n = 2.8$ and $\lambda = 0.63\,\mu$m, the transmission and reflection values fluctuate with a period of $0.113\,\mu$m because of the interference effects, especially noticeable due to the high refraction index of CGS. Similar fluctuations take place for the light absorption in the film. In areas with maximum transmission, there is minimal absorption and, accordingly, in areas with minimum transmission, maximum absorption takes place. As the film thickness increases due to increased absorption, the amplitude of such fluctuations decreases.

The change in the transmission and optical path difference of beams depending on the exposure time at different power densities of the affecting radiation was studied using the

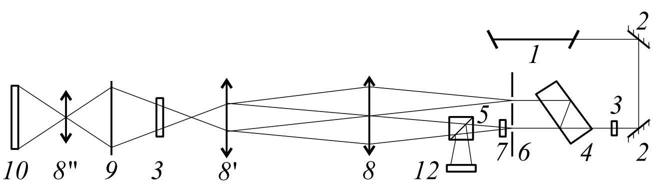

Figure 1. Scheme of the setup for studying changes in transmittance and optical path difference of the beams.

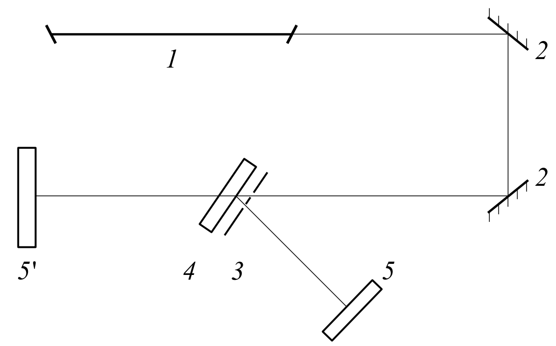

Figure 2. Scheme of the setup for studying changes in transmission and reflection.

setup shown in Fig. 1. The light beam from laser 1, reflected from mirrors 2, was divided into two parts using plane-parallel plate 4. A more intense beam, passing through diaphragm 6, was incident on CGS sample 7, causing photoinduced changes in the optical parameters in the sample. Then, this beam entered beam splitter 5, after which part of the radiation entered photodiode 12 to record the change in transmission. The second beam and part of the first beam, passing through splitter 5, create a interference pattern in the focal plane of lens 8, which was projected zoomed-in by lens 8' into the plane of slit 9. The slit was directed perpendicular to the direction of the interference fringes. The image of the slit was projected using lens 8" onto photo recorder 10.

When a CGS is exposed to radiation, an induced change in the refraction index occurs, which leads to a shift in the fringe pattern along the slit. By automatically recording the displacement of the interference fringe Δx, it is possible to obtain the dynamics of changes in the optical path difference Δl in the film under the exposure to radiation depending on the exposure time t.

To obtain a uniform distribution of radiation on the CGS film, diaphragm 6 was used that cuts out a central region with a diameter of 0.8 mm in the laser beam. To select the exposure mode, attenuating filters 3 were used.

To measure changes in the reflection and transmission of CGS films when exposed to radiation, a setup with optical scheme shown in Fig. 2 was used. The radiation of helium-neon laser 1 was directed using mirrors 2 through limiting diaphragm 3 with a diameter of 0.8 mm to sample under study 4. The intensity of reflected and transmitted light was recorded using photodiodes 5 and 5'.

All measurements were carried out on CGS films of the same thickness, which was controlled by the initial transmittance. From the dependences of transmission and reflection on exposure time, the dependence of the absorption on exposure time was calculated. Without taking into account the insignificant losses due to light scattering in the CGS layer, the intensity of absorbed light is equal to the intensity of incident light minus the intensities of reflected and transmitted light. In all experiments, the angle of incidence of the radiation on the surface of the layer did

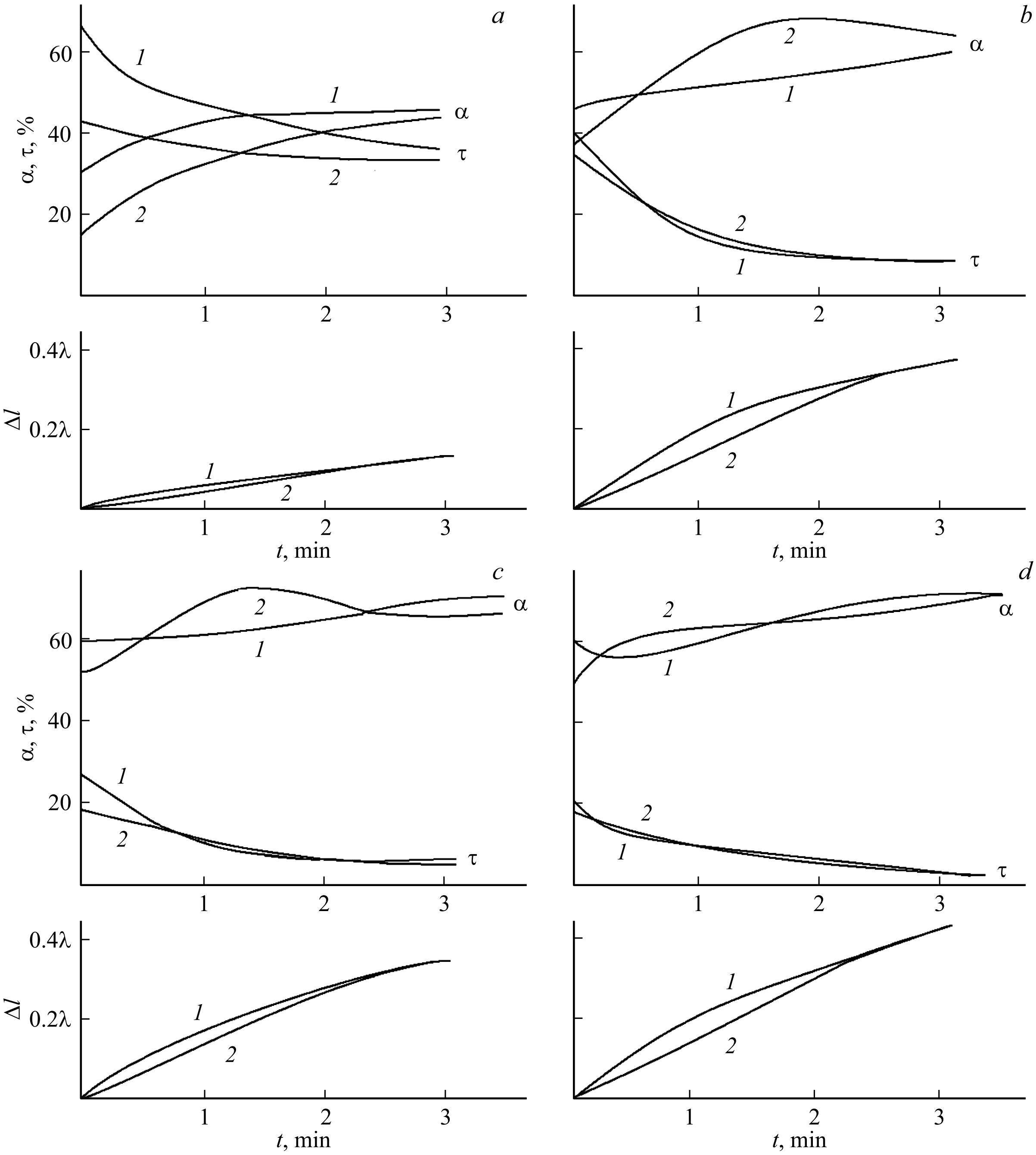

Figure 3. Dependences of absorption α, transmission τ , and optical path difference Δl of AsSe films with a thickness of $d = 0.4$ (a), 1.18 (b), 2 (c), 2.95 μm (d) as a function of exposure time t.

not change and its effect on the obtained characteristics of the sample was not taken into account.

1.2. Experimental results

Fig. 3 shows an example of the dependence of absorption α, transmission τ, and optical path difference Δl on exposure time t for films of different thicknesses d for the effective radiation power density of 0.3 W/cm^2. The optical path difference Δl was calculated from the experimentally recorded shift of the interference fringe Δx, which is caused by the phase shift $\Delta\varphi$ of the transmission wave passed through the entire thickness of the CGS layer. The interference fringe shift Δx is determined by the number of wavelengths (in this case, fractions of wavelengths) by which the interference fringe is shifted. Δl is proportional to Δx: $\Delta l = \lambda \Delta x$, where λ being wavelength.

Due to the interference effects, noticeable differences are observed in the characteristics of films for thicknesses corresponding to the maximum (curve *1*) and minimum (curve *2*) of the initial transmittance. Thus, for example, in Fig. 3, *a*, the initial values of the effective absorption of the layer α, corresponding to the minimum and maximum, differ by almost 2 times. The curves of transmittance change are determined by the superposition of photoinduced darkening, on the one hand, and changes in interference conditions, on the other hand.

The change in the optical path difference Δl is more significant at the initial stage of exposure to radiation in the region of the film with a thickness corresponding to the initial transmittance maximum, which may be associated with exposure to a higher initial light intensity. As expected, with increasing film thickness, the differences in the characteristics corresponding to maxima and minima of the initial transmittance decrease.

With an increase in the power acting radiation on the CGS, it is possible to obtain large changes in transmission and optical path difference. Thus, when exposed to radiation with a power density of the order of $1.2\,W/cm^2$, the transmittance of a film with a thickness of $1.2-1.3\,\mu m$ decreased 10 times during an exposure time of 3 min, and the change in the optical path difference Δl reached 0.55λ. For a film thickness of $2.9\,\mu m$, the transmittance of the film during the same exposure time decreased by 20 times, and Δl reached 0.72λ.

It should be noted that increasing the film thickness by more than 2 times did not result in a proportional increase in the optical path difference. This indicates the heterogeneity of photoinduced changes in the optical characteristics of CGS along the depth of the layer in the direction of propagation of the affecting radiation, the absorption of which is accompanied by more intense darkening in the near-surface layers. It follows from this that recording by radiation at $0.63\,\mu m$ occurs only in a thin layer of CGS and the use of films of the type under study with a thickness of more than $3\,\mu m$ is impractical.

2. Recording and reading holograms on AsSe films

The effect of interference is no less manifested when recording and reconstructing holograms on CGS. Fig. 4 shows optical scheme of the setup for studying the diffraction efficiency of holograms with frequency ν of about $600\,mm^{-1}$, recorded in a symmetrical scheme by helium neon laser 1 with a power of about 40 mW in single-mode with equal intensities of interfering beams. The radiation power density during recording was $1\,W/cm^2$.

To reconstruct the holograms, a significantly less powerful He-Ne laser 2 was used, the direction of radiation propagation of which was close to the direction of propagation of one of the recording beams. The power of the reading laser was selected so that the radiation did not significantly affect the films during recording of holograms. The polarization directions of the recording and reading radiation were mutually perpendicular. The use of the second laser to restore the hologram was necessary for continuous recording of the intensity of the first order of diffraction using photodetector 10 during the recording of the hologram.

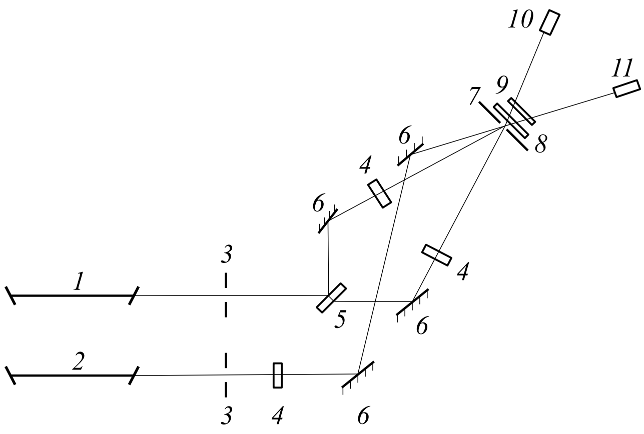

Figure 4. Scheme of the set-up for recording holograms and measuring diffraction efficiency.

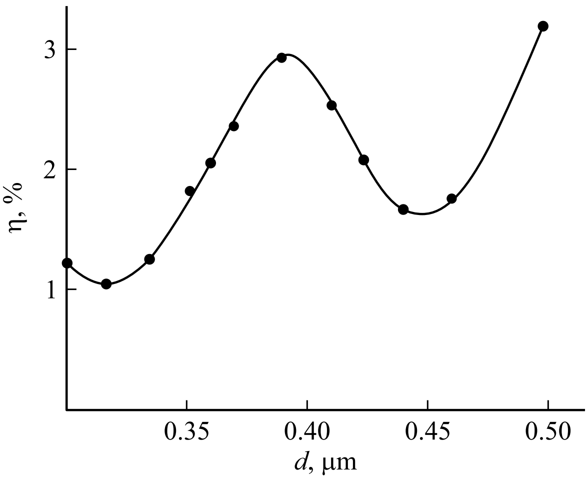

Figure 5. Dependence of the maximum achievable diffraction efficiency of holograms η on film thickness d.

With the optical scheme parameters used and thickness d of AsSe film up to $3\,\mu m$, holograms can be considered thin, according to the criterion Q introduced in [14]:

$$Q = 2\pi d\lambda\nu^2/n < 1,$$

where d is thickness of the hologram, ν is spatial frequency, n is refraction index of the film.

To study the effect of interference in thin CGS films on the DE value, samples with a wedge-shaped change in the thickness of the CGS layer from 0.2 to $3.2\,\mu m$ were used. Fig. 5 shows part of the experimental dependence of the maximum achievable DE on film thickness d. Minima of the curve are spaced at a distance close to the above value of the order of $0.11\,\mu m$ for fringes of equal thickness at $n = 2.8$ and $\lambda = 0.63\,\mu m$.

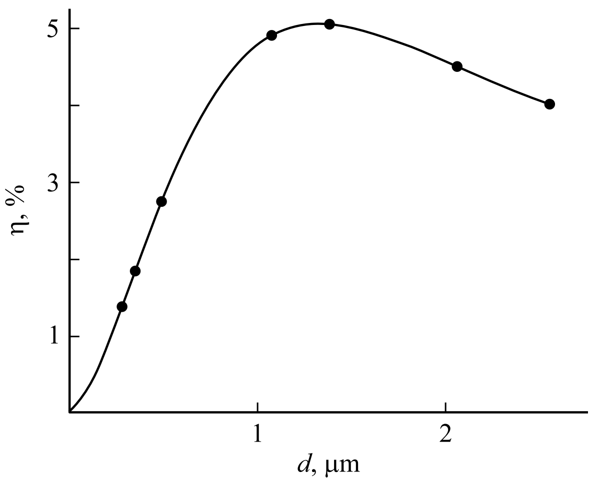

Figure 6. Dependence of the averaged maximum achievable diffraction efficiency of holograms η on film thickness d.

Changes in the geometry of the optical scheme will entail changes in the interference conditions, which will cause a shift in the maximum and minimum of fluctuations in the value of the maximum achievable DE depending on the thickness. In practice, the averaged curve (Fig. 6) with a maximum of about 5% in the thickness range of $1.5-2.0\,\mu$m is of greater interest.

To the first approximation, the DE of amplitude-phase holograms on thin films is described by the following formula [15,16]:

$$\eta = \tau_0^2 J_1^2(\Delta\varphi),$$

where τ_0 is average amplitude transmittance of the hologram, J_1 is Bessel function of the first kind of the first order, $\Delta\varphi$ is phase change calculated as $\Delta\varphi = 2\pi\Delta l/\lambda$, where Δl is optical path difference of the beams, λ is wavelength.

From the resulted values of the parameter Δl, the change in phase $\Delta\varphi$ of the wave can be calculated by the following formula: $\Delta\varphi = 2\pi\Delta l/\lambda$, where λ being wavelength. With thicknesses of $1.5-2\,\mu$m and the affecting radiation power density of the order of $1\,W/cm^2$ the parameter $\Delta\varphi$ is within the interval of $1.57-1.88$ rad. In this region, the Bessel function $J_1(\Delta\varphi)$ reaches its maximum at $\Delta\varphi = 1.86$ rad. Thus, DE, which is the product of a function τ_0^2 decreasing exponentially with thickness and a function $J_1(\Delta\varphi)$ with a maximum, will also have a maximum in the region of the above-mentioned thicknesses, which is consistent with the experimentally obtained dependence of η on d (Fig. 6).

As the power of the affecting radiation decreases, the change in the transmittance and optical path difference decreases, which leads to a decrease in the maximum value of the curve in Fig. 6.

Conclusions

The strong effect of interference in thin films on the optical characteristics of the CGS material of the As-Se system has been demonstrated. A high value of the refraction index enhances the effect of interference on the transmittance, absorption, and optical path difference in interfering beams when recording holograms, as well as on the DE value. The effect of interference in the latter case results in significant fluctuations in the maximum achievable DE depending on the thickness of the CGS layer in the thickness range up to $1.5\,\mu$m.

It should be noted that the influence of interference in thin films is significant for any photosensitive layers, especially in films of materials with a high refraction index.

It can be recommended to control the thickness of the layer during manufacturing by reflection or transmission so that the thickness corresponds to the maximum value of the initial reflection or transmission.

Conflict of interest

The author declares that he does not have conflict of interest.

References

[1] V.A. Barachevsky. Opt. Spectr, **124** (3), 373 (2018). DOI: 10.1134/S0030400X18030062.
[2] G. Brandes, F.P. Laming, A.D. Pearson. Applied Optics, **9** (7), 1712 (1970). DOI: 10.1364/AO.9.001712
[3] A.D. Pearson, B.G. Bagley. Mat. Res. Bull., **42** (12), 4908 (1971).
[4] V.E. Karnatovsriy, V.N. Naliwaiko, V.G. Zukerman. Soviet Journal of Quantum Electronics, **6** (1), 121 (1976). DOI: 10.1070/QE1976v006n01ABEH010856.
[5] A.N. Pokrovsky, M.A. Ponomaryov, O.Ya. Abel, A.N. Sosnov, *V sb.: VIII Mezhdunar. nauch. kongress Interexpo Geo-Siberia-2012*, (SGGA, Novosibirsk, 2012), v. 1, p. 121–125 (in Russian).
[6] N.A. Ivliev, A.P. Porfiryev, V.V. Podlipnov, S.N. Khonina, A.Yu. Meshalkin, *V sb.: XVIII Mezhdunarodnaya konferentsiya po golografii i prikladnym opticheskim tekhnologiyam*, pod red. A.Yu. Zherdev, (MGTU im. N.E. Baumana, M., 2021), p. 178–181 (in Russian).
[7] A.M. Nastas, M.S. Iovu, A.L. Tolstik. Opt. Spectr., **128** (2), 231 (2020). DOI: 10.1134/S0030400X20020174.
[8] N.A. Bogoslovsky, K.D. Tsendin. FTP, **46** (5), 577 (2012) (in Russian).
[9] V.N. Borisov, N.V. Muravyov, M.V. Popov, R.A. Okun, A.E. Angervaks, G.N. Vostrikov, S.A. Kozyukhin, S.A. Ivanov. *In sb.: XVIII Mezhdunarodnaya konferentsiya po golografii i prikladnym opticheskim tekhnologiyam*, pod red. A.Yu. Zherdev (MGTU im. N.E. Baumana, M., 2021), p. 276–284 (in Russian).
[10] E.N. Borisov, A.S. Tveryanovich, Sposob zapisi informatsii na khalkogenidnykh plyonkakh. RF Patent №2298839. 10.05.2007.
[11] A.M. Nastas, A.M. Andriesh, B.B. Bivol, G.M. Prisakar, G.M. Tridukh, Tech. Phys. Let, **32** (1), 45 (2006).
[12] O.V. Yasenyuk, Opticheskaya spektroskopiya khalkogenidnykh styokol $(As_4S_3Se_3)_{1-x}Sn_x$ Avtoref. dokt. dis. (Institut prikladnoy fiziki, Kishinyov, 2015), 130 p. (in Russian) http://www.cnaa.md/files/theses/2015/23259/oxana_iaseniuc_astract_ru.pd

[13] A.V. Mikhelson, T.I. Papushina, A.A. Povzner, A.G. Gofman, *Volnovaya optika: uchebnoy posobie*. pod obsch red. A.A. Povzner (Yekaterinburg: Izd-vo Ural. un-ta, 2013), p. 11–12 (in Russian).
[14] W.B. Klein, B.D. Cook, W.G. Mayer. Acustica. v. *15* (2), p. 67 (1965).
[15] Robert I. Collier, Christoph B. Burckhart, Lawrence H. Lin. *Optical Holography* (Bell Telephone Laboratories, Murray Hill, New Jersey. Academic Press, New York and London, 1971), 605 p.
[16] S.N. Koreshev, *Osnovy golografii i gologrammnoy optiki* (Universitet ITMO, Sankt-Peterburg, 2016), p. 35–38 (in Russian).

Translated by Y.Alekseev