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Total internal reflection holographic recording in chalcogenide glass films

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The results of holographic recording by the prism method are presented. The Stetson scheme is employed to obtain two slanted diffraction gratings using the 488 nm line of an Ar^{2+} laser. In this set-up, one of the recording beams suffers total internal reflection at the sample-air interface. Thus two Bragg gratings with high and low spatial frequencies are simultaneously recorded. The pitches of these gratings are 96 nm and 444.1 nm, respectively. Fresh as-deposited As_2S_3 films with 0.5, 0.87 and 2.07 μm thickness are used. This is an intermediate case between thick gratings and those recorded in a very thin layer, which represents the Nassenstein set-up. In the last scheme, the grating is situated in a layer thinner than 30 nm and the surface interactions play a major role. Upon increasing the thickness, the boundary in which the total internal reflection takes place is changed as well as the recorded diffraction pattern. This is due to the high refractive index of the recording medium. In the present work, the differences in the recording kinetics and the properties of the recorded gratings depending on the thickness are examined. The angle selectivity and polarization sensitivity are studied. A better-expressed Bragg behaviour is observed for the thicker samples. The Klein parameter is evaluated for gratings recorded in samples of different thickness.

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1. Introduction

Recently, holographic and diffractive optics is among the widest applications of total internal reflection (TIR). Employing prism methods in holographic set-ups is an approach allowing the realization of high-density optical storage [1,2], nano-scale laser lithography [3], near-field applications [4], connected to the sub-wavelength resolution problem, etc. The prism is used to ensure TIR at the desired surface. Certain advantages, from a holographic point of view, of such schemes are the possibility to use the full half-space for the object wave and to situate the object very close to the recording medium. Thus no zero diffraction order in reconstruction is present in the half-space of the object.

In 1973, Shank used a prism to increase the angle between the recording beams in order to obtain higher spatial frequency [5]. Earlier (1967) Stetson employed a prism to obtain a reference wave suffering TIR in an otherwise ordinary holographic recording set-up [6]. In his experiments, the interface where the TIR takes place is at the boundary between the recording media and air. In this case, simultaneous interference between the incident waves and between the incident object and the TIR wave takes place. Two slanted diffraction gratings – with high and low spatial frequencies - are obtained. In addition, a Lippman grating with no contribution in the reconstruction is present [7]. This is a consequence of the interference between the incident and the TIR reference wave.

If the TIR is situated at the interface between the prism and the recording medium, the interference between the evanescent waves penetrating the photosensitive layer and the object wave is recorded. Such a holographic set-up was realised first by Nassenstein [8], using a high refractive index prism.

Another way to record evanescent waves is to use a very thin photosensitive layer – some ten nanometers in the order of magnitude [9]. In this case, the refractive index of the recording material does not influence the TIR conditions. For materials with a high refractive index (like As_2S_3) the evanescent recording by the prism method is an endmost case when the thickness is very small. The grating is situated in a layer thinner than 30 nm and the surface interactions play a major role. Increasing the thickness leads to changes in the TIR boundary as well as in the recorded diffraction pattern.

The main objective of this investigation is to perform holographic recording using the Stetson scheme in As_2S_3 layers with intermediate thickness, when only several fringes of the interference pattern are recorded. Fresh as-deposited As_2S_3 films with 0.5, 0.87 and 2.07 μm thicknesses are used.

As_2S_3 is an attractive recording medium due to its high resolution, high refractive index > 2.2 and modulation reaching values ~ 0.15-0.5 [1].

We study the differences in the recording kinetics and the properties of the recorded gratings as a function of the sample thickness.

2. Experimental

The experiments are performed on as-deposited thin films of As_2S_3 having thickness between 500 and 2070 nm. The samples are prepared in the Central Laboratory of Photoprocesses at the Bulgarian Academy of Sciences. The films are obtained by vacuum deposition of high purity As_2S_3 onto linearly moving glass substrates at a residual pressure of the order of 6.10^{-4} Pa. The specially constructed evaporation source for As_2S_3 ensures a uniform thickness over the whole substrate surface. A deposition rate of 0.1 nm/s is controlled and maintained constant during the evaporation. The film thickness is measured by a Talystep profilograph, Code 112/1037 M-S, produced by Rank Taylor Hobson Ltd.

The holographic recording set-up used in the experiments is presented in Fig. 1. The interference pattern is also shown.

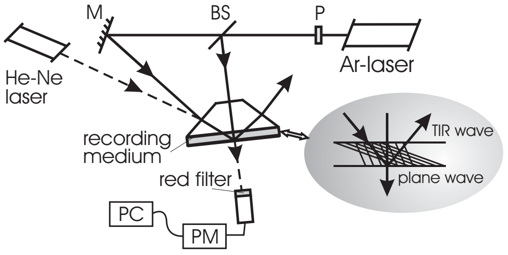

Fig. 1. Optical set-up for holographic recording: BS – beam splitter, M – mirror, P – polarizer, PM – power meter.

The emission of the Ar^{2+} laser acting at 488 nm is used to create the interference fringes (Fig. 1). The pitches of the recorded gratings are 96 nm and 444.1 nm. The He-Ne laser is applied to monitor the grating formation dynamics.

The recording kinetics for the different samples with thickness 0.5, 0.87 and 2.07 μm is shown in Fig. 2.

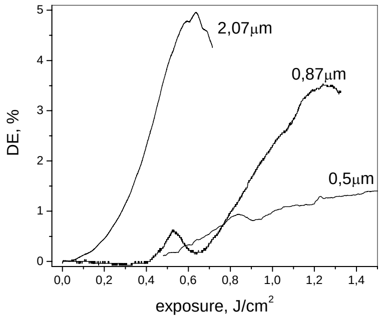

Fig. 2. Recording kinetics of samples of different thickness.

A rise in the sensitivity is observed with increasing thickness. The highest values of the diffraction efficiency (DE) ~ 5% are obtained with the 2.07 μm thick sample at 0.6 J/cm^2. The DE is calculated as the ratio of the incident and diffracted He-Ne beam intensities. Table 1 illustrates the differences in the obtained maximal DE and the necessary exposure along with the induction period depending on the As_2S_3 thickness.

Table 1. Comparison between the recording kinetics of samples of different thickness.

Sample thickness	**0.5 μm**	**0.87 μm**	**2.07 μm**
Max. DE	1.4 %	3.5 %	5.0 %
Exposure for max. DE	1.5 J/cm^2	1.25 J/cm^2	0.64 J/cm^2
Induction period	0.50 J/cm^2	0.42 J/cm^2	0.05 J/cm^2

The thicker samples exhibit higher DE values as well as lower exposure doses (for the maximal DE) and shorter induction periods. The rise in DE with increasing thickness is a consequence of a bigger number of interference fringes recorded in the material. It is accompanied by a reduction in the induction period, most probably due to a smaller degree of surface interactions.

The 0.87μm thick sample exhibits an intermediate peak of the DE growth. It is less expressed in the thinner sample recording dynamics and is not present for As_2S_3 layers with thickness of 2.07μm.

The characteristics of these gratings are presented later.

Fig. 3 shows the polarization sensitivity of the gratings recorded in As_2S_3 layers with different thickness.

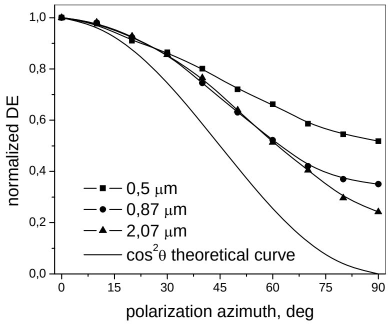

Fig. 3. Polarization sensitivity of the gratings, depending on the thickness of the recording medium.

The continuous curve (Fig. 3) represents the theoretical $\cos^2\theta$ dependence (where θ is the polarization azimuth) for thick Bragg gratings according to Kogelnik's coupled-wave theory [10]. The experimental data show a trend towards the $\cos^2\theta$ curve with increasing thickness. Nevertheless, we have a significant difference for all samples between the polarization sensitivity and the coupled-wave theory dependence. Also, the samples of 2.07 μm and 0.87 μm thickness have closer polarization behaviour compared to the 0.5 μm thick As_2S_3 layer, although its thickness differs less in comparison to the intermediate sample (0.87 μm).

It should be noted that an essential parameter for the grating properties is the sample thickness. As mentioned above, the examined layers are an intermediate case between very thin gratings recorded in almost the surface area (the case of Nassenstein set-up) and thick Stetson gratings. To evaluate the volume character of conventional Bragg gratings, Klein [11] introduces the parameter *Q* determining the lowest value of the thickness for volume holograms:

$$Q = \frac{2\pi\lambda_a d}{\bar{n}\Lambda^2} \qquad (1)$$

where λ_a is the wavelength of the reading laser in air, d is the sample thickness, $\bar{n}$ is the mean refractive index and Λ is the grating pitch.

The coupled-wave theory gives good results for $Q \geq 10$. According to our holographic set-up geometry, the pitches of our gratings are Λ_1 = 96 nm and Λ_2 = 444.1 nm, as mentioned above. In this case, the necessary thickness to obtain Q = 10 is d_1 = 56,8 nm and d_2 = 1198 nm. Thus, for one of the gratings recorded by the Stetson set-up $Q <$ 10 except in the case of the 2.07 μm thick recording medium.

The Klein parameter is determined assuming $\bar{n}$ = 2.45. Table 2 shows the obtained values of Q for samples of different thickness.

Table 2. Values of Q for the two gratings recorded in the samples of different thickness.

Sample thickness [μm]	**Grating pitch Λ**	
	96 nm	**444.1 nm**
0.5	88.05	4.17
0.87	153.20	7.26
2.07	364.51	17.27

The angular sensitivity of the gratings is presented in Fig. 3.

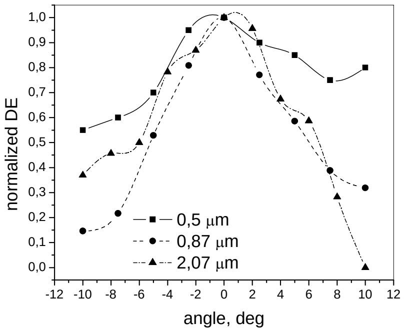

Fig. 3. Angular sensitivity of the gratings depending on the thickness of the recording medium.

The dependencies shown in the figure resemble the typical for Stetson gratings asymmetric angular behaviour [7]. The broader peak is a consequence of the thin layer in which the recorded pattern is situated. With increasing thickness, deeper shoulders of the curve are observed.

3. Conclusions

In the present work, thin samples of As_2S_3 are examined for the aim of TIR holographic recording. This is a further step in our investigations, presented in [9], aiming to increase the DE of holographic optical elements recorded in thin layers.

Conventional transmission and reflection gratings in As_2S_3 layers with similar thickness are investigated in [12]. In our case, simultaneous recording of both types of such diffraction patterns takes place. Nevertheless, some common properties are observed:

- The exposure is higher for the thinner samples (observed in [12] for both transmission and reflection gratings);
- The DE kinetics differs for samples of different thickness.

These features can be related to the reduced influence of surface interactions, experienced by the thicker samples, facilitating the photo-induced changes.

The aim of creating such thin holographic optical elements is a consequence of their main advantage – the possibility to realize complex optical systems integrating several elements with different functions in compact configurations unattainable with conventional optics.

Employing TIR holographic set-ups enlarges the possible applications of holographic optical elements. Recent areas requiring such elements range from telecommunications to security and three-dimensional displays.

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