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LINEAR PHASE SHIFT RESPONSE WITH HIGH DYNAMIC RANGE FOR HOLOGRAPHIC RECORDING IN As_2S_3

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Abstract

Amorphous As_2S_3 films are real-time photographic materials for phase holograms. This work focuses an the phase shift in As_2S_3 films as a function of the exposure. A measuring method for the phase shift response simultaneous to the exposure is presented. A relative displacement determination of interferometric patterns allows precise measurements insensitive to changes of experimental conditions. The phase shift dependence on the intensity of the writing beam is evaluated for two different films. As the result a linear phase shift response is obtained with a dynamic range of nearly [1]. It is independent of the intensity over four orders of magnitude. The results are proofed by diffraction efficiency measurements.

Keywords

Interferometric phase shift measuring, holographic recording materials, linear phase recording, As_2S_3.

Introduction

Amorphous As_2S_3 (a-As_2S_3) is a well known holographic recording material. High quality phase holograms with diffraction efficiencies up to 80% can be obtained in real-time. For that a wavelength change is necessary between recording and reconstruction of the holograms. For writing above band gap light (λ_W = 514 nm), for reading below band gap light (λ_R = 633 nm) have to be employed. This limits the use of As_2S_3 films for volume holograms, except in the case of plane wave recording. Not restricted by the wavelength change are analog or digital 2D holograms that we use in spatial multiplexed holograms for optical vector matrix multipliers.

Despite the fact that photo induced processes in As_2S_3 are widely studied [1, 2)], the holographic recording parameters of As_2S_3 films have not been investigated yet. Especially the phase shift dependence of λ_R on the exposure with λ_W is important for quantitative recording of phase holograms, we are interested in. So this work focuses on the analysis of the phase shift as a function of the exposure. Films of different thicknesses were investigated and intensities were varied over four order of magnitude.

Experimental methods

Samples

The investigated amorphous As_2S_3 films are produced by vacuum evaporation. Because of the higher light sensitivity we use temporally annealed films that show fairly constant recording parameters after annealing three month at room temperature. The same state can be achieved by annealing 10 min. at 340K- 380K.

Measuring method

The wavelength change between writing and reading of holograms allows the measuring of the phase shift simultaneously to the exposure. For that a relative interferometric measuring method was developed. This makes precise measurements possible that last several hours and are not effected from changes of the experimental conditions like room temperature and laser power. Thus, the phase shift of the reading beam can be determined as a function of the exposure with an accuracy of ± 5°.

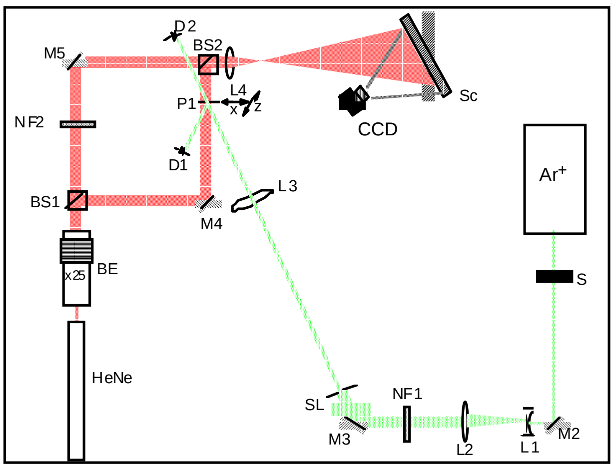

Fig. 1: Experimental setup

Experimental setup

The complete experimental setup for the phase shift measurements is shown in Fig. 1. For writing a rectangular structure an Ar^+ laser beam (single frequency mode) passes a shutter S and a beam expanding system (x 5). The intensity of the writing beam can be adjusted with a set of neutral density filters NF1. Lens L3 images a rectangular slit reduced by the factor 2.5 in the plane of the holographic film. The position of the film itself in this plan can be adjusted in x- and z-direction. The light detectors D1 and D2 measure the intensity of the reflected (I_r) and the transmitted (I_t) light of the recording beam. With this setup a rectangle of 0.4 x 2.0 mm^2 is written into the probe.

The phase shift measurement uses the technique of a Mach Zehnder interferometer. A HeNe laser beam is expanded by a factor of 25 and splitted into two beams. One part of the beam is transmitted through the a-As_2S_3 film, whereas the intensity of the other part is adjusted by the neutral density filter NF2 in order to maximize the contrast of the interference pattern. The plane of the a-As_2S_3 film is imaged onto the screen SC and detected by a CCD camera. The interferometer is adjusted such, that a magnified image of the rectangular field that is exposed with the green light builds the major part of the interference pattern. Fig. 2 shows the exposed rectangle in the interference pattern.

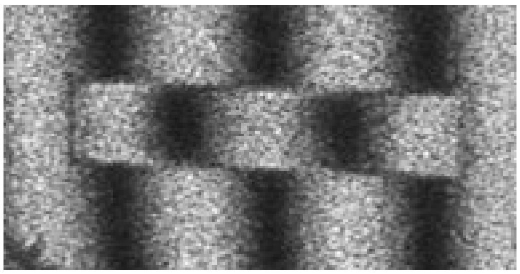

Fig. 2: Interference pattern of an exposed rectangle

Data acquisition

During the exposure of rectangles with different intensities the transmission I_t and the reflection I_r of the writing beam λ_W and the interference pattern of the reading beam λ_R is recorded simultaneously. Two PC's equipped with an ADC board and a frame grabber board resp. are used. Each measurement consists of 200 values for I_r and I_t and 11 pictures of the interference pattern.

Data processing

The measurements of I_r and I_t have to be normalized and plotted after capturing. Fig. 3 shows a typical plot.

The image processing of the interference pattern is more complex. Fig. 2 shows a typical picture of the interference pattern. The interference stripes inside the exposed rectangle are shifted against those outside. This relative displacement is determined in the following way: 1) Profiles perpendicular to the stripes inside and outside the rectangle are plotted. 2) The period of the profile is taken as the distance of the maximums outside. 3) The displacement of the maximums inside with respect to those outside is measured. 4) The phase shift is calculated from the ratio of that displacement to the period.

Finally, the 11 consecutive phase shift measurements are plotted versus the exposure.

Experiments

The following exposures were carried out:

layer thickness [µm]	intensity [W/cm^2]	repetitions	max. exposure [J/cm^2]
5.2	3.0	3	90
	1.0	3	90
	0.3	3	90
	0.1	3	90
	0.03	3	90
	0.003	1	90
	0.0003	1	45
1.3	3.0	3	90
	1.0	3	90
	0.3	3	90

Table I: Parameter settings

Exposures with lower intensities (< 0.0003 W/cm^2) are of no practical use. Exposures with higher intensities were carried out, but without measuring phase shift because of the limited speed of video grabbing.

To be able to compare the results with alternative measurements we wrote a diffraction grating (d_g = 15 µm) with two plane waves R and O (I_R = 0.25 W/cm^2, I_O = 0.18 W/cm^2). Simultaneously to writing with λ_W = 514 nm we red the grating with λ_R = 633 nm and recorded the intensities of the 0th and the first diffraction order.

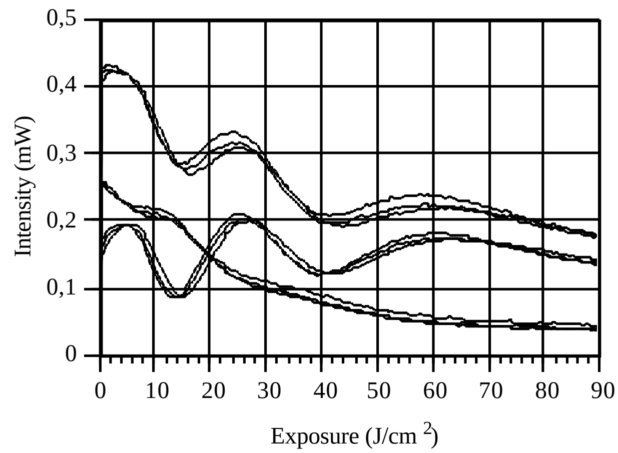

Fig. 3: Intensities of transmission and reflection and of the sum vs exposure (d = 5.2 µm, $I_{\lambda W}$ = 0.1 W/cm^2)

Results

Fig. 3 shows a typical plot of the reflection and transmission intensities I_t, I_r and I_t,+I_r of the writing beam ($I_{\lambda W}$ = 0.1 W/cm^2) as a function of the exposure. The oscillations can be explained with an optical resonator inside the thin film that changes its optical length during exposure. The maximums and minimums are given by the resonance condition. By this, the change of the refractive index for λ_W can be calculated by the number of maximums, the angle of incidence and the thickness d of the film. We obtained Δn_{514} = 0.11 for 90 J/cm^2.

Apart of the oscillations the values of I_t,+I_r are reduced to 50 % after exposure due to the photo induced increase of the absorption coefficient α, which is correlated to the band gap shift to lower energies.

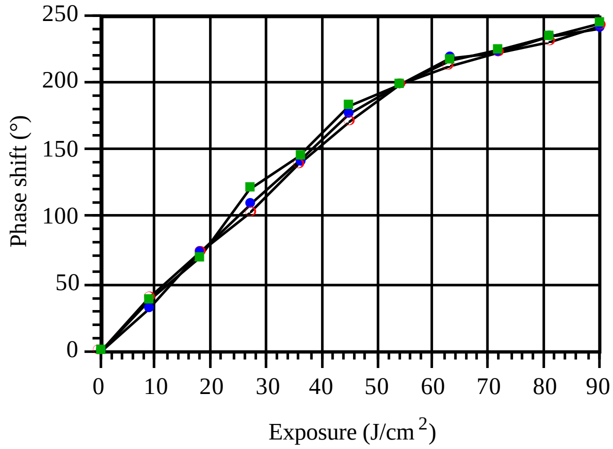

Fig. 4: Phase shift vs exposure (d = 5.2 µm, $I_{\lambda W}$ = 0.1 W/cm^2)

In Fig. 4 the phase modulation during exposure is plotted. It belongs to the same exposure as Fig. 3 (5.2 µm thick film). The maximum phase shift is 240° at 90 J/cm^2. This value corresponds to a change of the refractive index of Δn_{633} = 0.08 for the reading wavelength λ_R. Changes of the film thickness during exposure are small (1-5%) and are ignored here.

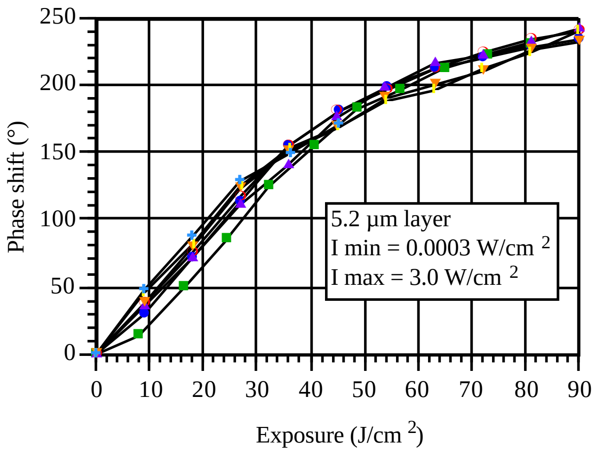

Fig. 5: Phase shift vs exposure (d = 5.2 µm, I_{min} = 0.0003 W/cm^2, I_{max} = 3.0 W/cm^2)

Fig. 5 shows all measured phase modulations for 5.2 µm thick films; for each intensity, the average of three exposures is plotted. The measurement error of 10 % takes the following error sources into account: the intensity fluctuation of the Argon laser, the mode hopping of the HeNe laser used for interference, fluctuations of the room temperature, air turbulences, and the image processing error due to the limited resolution of the interference patterns. Within this accuracy the plotted curves can be said to be equal, what is remarkable for an intensity variation of four orders of magnitudes (0.0003 W/cm^2 to 3.0 W/cm^2).

Very important for nearly all applications is the dependence of the phase shift and the index of refraction for λ_R on the density of exposure energy for λ_W. In contrast to conventional photosensitive films, e. g. silver halide films, the a-As_2S_3 films do not show a logarithmic dependence. Promising for quantitative exposures is the linear dependence between 8 J/cm^2 and 37 J/cm^2. The gradient of the curve in this region is about 4.4 °/(J/cm^2). Below 10 J/cm^2 the course of the phase modulation makes plausible a linear extrapolation down to 0 J/cm^2.

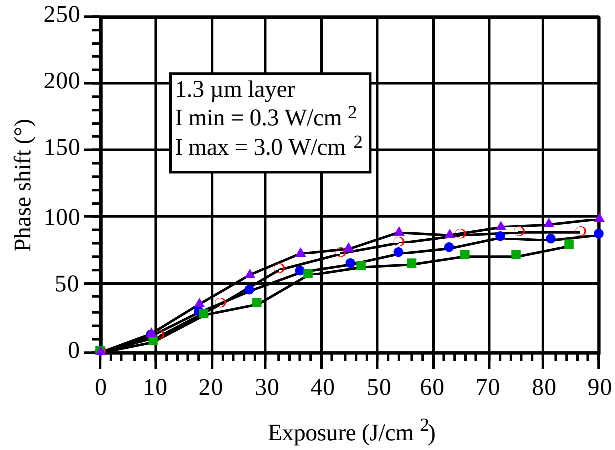

Fig. 6: Phase shift vs exposure (d = 1.3 µm, I_{min} = 0.3 W/cm^2, I_{max} = 3.0 W/cm^2)

Fig. 6 shows the phase modulation during the exposure of a 1.3 µm thick a-As_2S_3 film. The linear dependence on the density of exposure energy can be observed, too, but the maximum value of the phase shift is only 90° due to the thinner material. Because a film thickness of 5.2 µm can still be used for recording 2D-transmission holograms for most of the normal numerical apertures, and the diffraction efficiency of this holograms is much higher than that of thinner holograms, the 1.3 µm thick a-As_2S_3 films are not as suitable as 5.2 µm thick films for most applications.

The theoretical dependence of the diffraction efficiency on the amplitude of a sinusoidal phase grating is given by the square of the 1st-order Bessel function: $(J_1(\phi))^2$. This function is maximal at ϕ = 1.8 (103°) resulting in a maximum diffraction efficiency of 33.9%.

Fig. 7 shows the intensities of the 0th and 1st diffraction order that were recorded during the exposure of the sinusoidal gratings. The intensities are plotted versus the density of exposure energy. Additionally, the square of the Bessel functions J_0 and J_1 are plotted. In the linear region of the exposure the experimental and theoretical plots look identically. For higher energies the experimental plots saturate as expected.

The diffraction efficiency at W = 10 J/cm^2 was determined quantitatively. The corresponding phase shift is ϕ(10J/cm^2) = 43°, yielding a theoretical diffraction efficiency of $(J_1(43°))^2$ = 12%. From the experimental data one calculates an efficiency of 11%. Thus, the theoretical and the experimental results agree within the error limits.

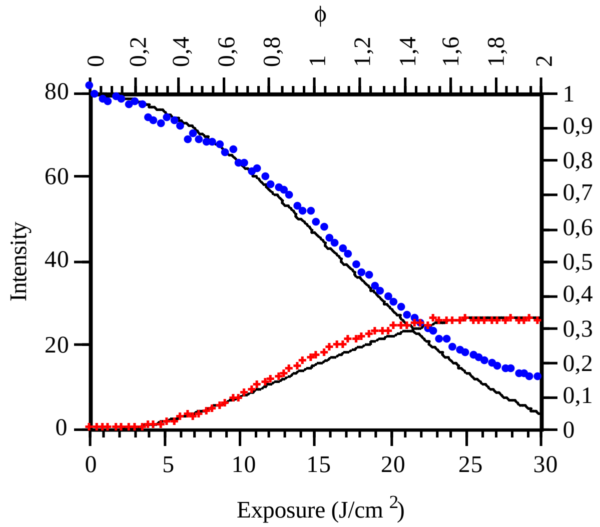

Fig. 7: Theoretical and experimental plots of the diffraction efficiency, J_0^2, J_1^2 vs ϕ; I_0, I_1 vs exposure

Summary and conclusion

In order to investigate the holographic recording parameters of amorphous As_2S_3 films the dependence of the phase shift on the exposure was examined for different intensities. It could be shown that the phase shift is independent of the intensity of the writing beam in the range of 0.0003 W/cm^2 to 3.0 W/cm^2. Further, a linear phase shift response on exposures from 0 J/cm^2 to about 40 J/cm^2 was found, corresponding to 0° – 160° phase shift in 5.2 µm thick films. These results were independently verified by diffraction efficiency measurements.

The main motivation of this work was the determination of holographic phase recording parameters appropriate to record phase holograms quantitatively. Linear dependence and high dynamic range are prerequisites for a holographic material to be well suited for high quality phase holograms — thus, our results are very promising.

References

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