

Self-diffraction effect observation and recording the holographic one-dimensional and two-dimensional gratings in thin photosensitive films

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A setup for observation of the nonlinear self-diffraction effect has been described. A semiconductor laser ($P \approx 50$ mW, $\lambda \approx 660$ nm) is used as a radiation source. The laser beam is divided into two beams by a Wollaston prism, the beams pass through a polarizer and positive lens, then they intersect and create an interference. Using a microscope, the interference may be observed in an increased scale on a remote screen. The interference is registered in a thin photosensitive As_2S_3–Ag film prepared by vacuum evaporation. We have shown an opportunity to observe the self-diffraction from recorded diffraction grating with linear grooves and from two-dimensional grating induced as a result of second exposure after turning the convergence plane of the interfering beams by 90°.

Описана схема для наблюдения нелинейного эффекта самодифракции. Источником излучения служит полупроводниковый лазер ($P \approx 50$ мВт, $\lambda \approx 660$ нм). Лазерный пучок делится на два призмой Волластона; пучки проходят через поляроид и собирающую линзу, после которой пересекаются и создают интерференцию. С помощью микроскопа интерференцию в увеличенном масштабе можно наблюдать на удаленном от микроскопа экране. Интерференция регистрируется в фоточувствительной тонкой пленке As_2S_3–Ag, приготовленной вакуумным напылением. Показана возможность наблюдения самодифракции от записываемой дифракционной решетки с линейными штрихами и от двумерной квадратной решетки, которая индуцируется в результате второй экспозиции, после поворота плоскости схождения интерферирующих пучков на 90°.

The nonlinear optical effect called self-diffraction [1, 2] occurs when intense coherent light beams create an interference field in a medium and produce a periodical modulation of dielectric permittivity of the medium, i.e. create a diffraction grating therein. It is diffraction of incident beams on the grating that is the self-diffraction phenomenon. In holography, the term "self-diffraction" is often replaced by the "dynamical holography" term implying that diffraction grating appears in the medium and is read during light action. There are cases described in literature when intense light beams and media interacting reversibly with light were used to observe the self-diffraction. In this work, the self-diffraction effect is realized using low-power continuous radiation of a semiconductor laser (SCL) and double-beam interferometer on the base of a Wollaston prism (WP). A thin photosensitive film is used as the recording medium.

The direct photosensitivity is inherent in films of chalcogenide vitriform semiconductors (CVS) and metal halogenides. Both pure CVS films and composite CVS/silver films are used in nonlinear optical experiments and in practice [3–5]. Interaction of photosensitive films with light causes changes of their optical characteristics, so it is a nonlinear effect. However, the photosensitive films show the following distinctive features as compared to other media. Nonlinear transformations are determined by product of light intensity and illumination duration, i.e. by the exposure. The threshold exposures are generally low, less than 0.1 J/cm^2. The films are characterized by large nonlinearity factors and, therefore, large response times and accumulation of the light action results are inherent therein. Finally, spontaneous relaxation of light-induced changes is absent in irradiated films. Some characteristics of the films make them similar to such media as photorefractive crystals and photochromic glasses.

We used As_2S_3–Ag films prepared by thermal vacuum evaporation on plane-parallel glass substrates of 5×2.5×0.15 cm^3 size. A 200 nm layer of CVS was deposited followed by ≈20 nm silver layer. To obtain the mentioned thicknesses, it is necessary to evaporate 50 mg of As_2S_3 and 15 mg of Ag from flat evaporator (boat) placed at 15 cm distance from the substrate. The CVS film thickness can be varied within approximately 0.1 to 0.5 μm. The deposited Ag mass should amount approximately 0.3 of As_2S_3 mass. Under red light action on As_2S_3–Ag film, the photosensitivity mechanism [4, 5] is associated with photoeffect in silver at the VCS–Ag interface, and with diffusion of photoelectrons and Ag^+ ions into VCS layer. Silver penetrating into the amorphous layer forms compounds with As and S. The As_2S_3–Ag films are used as recording media in holography for a long time [4, 5], but they were not used to observe the self-diffraction phenomenon until now.

An important feature of the described experiment is an opportunity to use low-power lasers as continuous coherent radiation sources. The diffraction pattern brightness at self-diffraction depends on the resultant grating diffraction efficiency and the intensity of laser beam used in the experiment. The results presented here were obtained with a HL6504FM laser diode from HITACHI. Such a diode is a commercial device used in DVD-RAM optical memory systems. The diode radiates a divergent linearly polarized beam with P≈50 mW and λ≈660 nm. As a power supply, a stabilized source is needed providing 2.1–3 V steady voltage on the diode and working current approximately 110–140 mA. The diode needs cooling while functioning. Therefore,

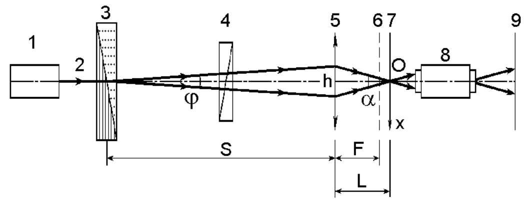


Fig. 1. The optical setup for self-diffraction observations. 1, semiconductor laser; 2, the laser beam; 3, Wollaston prism (WP); 4, polarizer; 5, positive lens; 6, the lens focal plane; 7, the plane where the film is set and interference fringes are localized; 8, microscope; 9, screen; φ, angle between beams diverging after WP; F, focal distance of the lens; h, distance between beams at lens; L, distance from the lens to the point O where beams intersect at plane (7); α, angle between meeting beams creating interference; X, coordinate on the plane (7) counted from O.

a metal frame was made to act as radiator. To create a collimated beam, a collimating lens from a semiconductor laser pointer was set into the same frame.

The optical setup for self-diffraction observation is shown in Fig. 1. The linearly polarized beam (2) passes the Wollaston prism (3) and splits into two symmetrically divergent linearly polarized beams with mutually orthogonal polarization directions. We used a standard calcite WP of 5 mm thickness and 17 mm diameter. It provides the angle between beams φ≈2°. The setup is adjusted in the following way. The WP should be set in a holder permitting the prism to be turned around the axis of normally incident laser beam. Turning the prism in such a way, one achieves equal intensities of resulting beams. In this case, the direction of incident beam polarization makes angles 45° with orthogonal directions of optical axes in two halves of prism. Then the beams pass the polarizer (4). The polarizer should be turnable. Turning the polarizer, one achieves equal again intensities of passing beams. In this case, the directions of orthogonal polarizations of incident beams are oriented at 45° to the polarization direction of the polarizer. As a result of the polarizer action, linear polarizations of passed beams are parallel, as it is required to provide interference with maximum visibility. Further, the beams pass through the positive lens (5), intersect at the vicinity of point O, and create an interference there. In the plane (7) perpendicular to the bisector of convergence angle α of the two beams, interference pattern is localized within a small area created by the intersecting beams. The pattern is a plurality of parallel alternating black and light fringes. The pattern wave vector **K** is directed perpendicularly to the interference fringes and is parallel to the plane in which the wave vectors $\mathbf{k}_{1,2}$ ($k_{1,2} = 2\pi/\lambda$) of the two intersecting beams lie. The K value is $2\pi/\Lambda$ where Λ is an interference pattern period.

A lens (5) with focal distance $F = 11$ cm is used in the setup. The lens was set at distance $S \approx 57$ cm from WP. At such installation, the distance between beams at the lens is $h \approx 1.8$ cm, and the beams cross beyond the focal plane (6) at distance $L \approx 13.6$ cm from the lens ($L = SF/(S-F)$. The SCL radiated laser beam has a nearly rectangular cross-section, approximately 1.5×3 mm^2. For the stated setup geometry, the area created by crossing beams at the plane (7) has a size of about 0.5×1 mm^2, and interference fringes are concentrated at this area.

To calculate the interference pattern period Λ in the plane (7), we assumed a strict symmetry of beams and equality of optical paths from WP to point O (path difference associated with WP action is not taken into consideration). In this case, the point O is the center of interference where the path difference is $\Delta = 0$. To calculate Λ, the interference can be supposed to be created by the beams exiting the lens. The oscillations in the beams at the lens surface are considered to be cophased, and distance between beams is h. The path difference calculations were carried out under assumptions $\Delta << L$ and $L >> h$ [1] for beams creating the pattern near the point O. The calculations give the condition of interference maxima:

$$\Delta = \frac{X \cdot h}{L} = m \cdot \lambda. \qquad (1)$$

The X axis is in the plane (7), it is parallel to **K** vector; the X coordinate is counted from the point O; $m = 0, \pm 1, \pm 2...$ is the interference order. The interference area width is approximately $2X_{max} \approx 0.5$ mm. This results in $|m_{max}| \approx 50$. From (1), we obtain the pattern period as

$$\Lambda = X_{m+1} - X_m = \frac{L \cdot \lambda}{h} = \frac{\lambda}{\alpha}. \qquad (2)$$

At the stated values of L, λ, and h the formula (2) gives $\Lambda \approx 5$ μm.

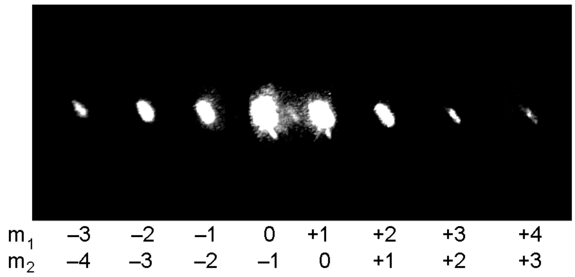
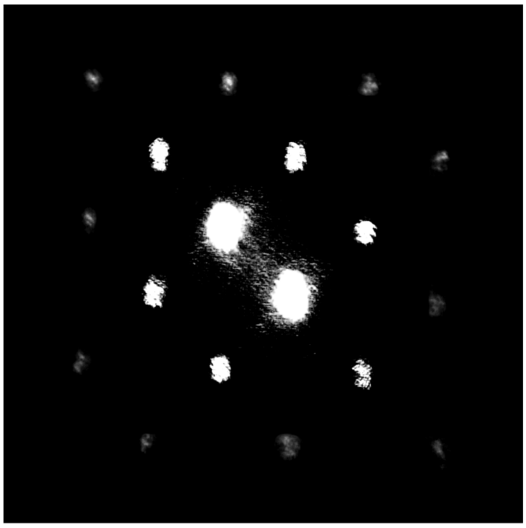


Fig. 2. Diffraction pattern developed during exposure at irradiating the photosensitive film set in plane (7) and observed on the screen (9); m_1, m_2, diffraction orders for two interacting beams.

A structure with such a period cannot be observed by naked eye. A normal eye is able to see the periodicity of structure at $\Lambda >$ 50 μm [1]. But the periodicity with $\Lambda \approx 5$ μm is easily observable under microscope (8). We have used a horizontal microscope with $8^{\times}$ objective and $10^{\times}$ ocular. The interference is observed in light exiting the microscope ocular and hitting the screen (9). The microscope is focused for pattern observation by simple shifting it along the setup optical axis until merging the two beams on the screen. The screen (9) can be set at various distances from ocular. The distance increasing, the interference pattern period on screen increases linearly due to angular magnification of the microscope. In a darkened room, an intense laser beam allows to observe interference fringes with period ≈ 1 cm on a screen positioned at approximately 6 meters from the microscope.

To observe the self-diffraction, a photosensitive As_2S_3–Ag sample is set on a substage providing the sample displacement along two orthogonal directions. The sample is situated in such a way that the film plane coincides with the plane (7). The sample size is large enough as compared to the irradiated area, thus allowing us to irradiate different parts of the film and to observe self-diffraction repeatedly. The microscope (8) is removed out of the setup, the screen (9) is situated at a distance convenient for observations. Also for convenience of observations, the screen is made of a lusterless paper allowing to carry out the observations in transmitted light. At exposure switched on, two light spots are seen on the screen situated at a specified distance from the sample; those are created by the beams exiting their crossing region at the film. The exposure increasing, new light spots appear on the screen. They correspond to diffraca)



b)

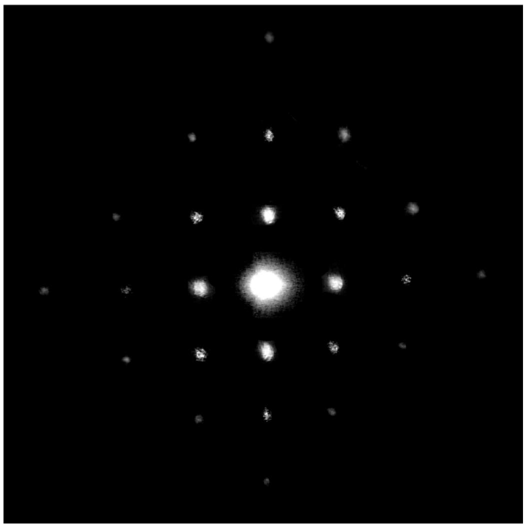


Fig. 3. (a) Diffraction pattern on screen (9) developed at formation of two-dimensional square grating in the film by two consecutive exposures at two orthogonal planes of beams meeting. (b) Diffraction pattern from the same grating at normal incidence of single laser beam.

tion at orders $m > 0$ (Fig. 2). Directions of diffracted beams met the condition

$$\mathbf{k}^{d}_{1,2} = \mathbf{k}_{1,2} + m\mathbf{K}. \qquad (3)$$

At first, the spots with orders $m = \pm 1$ appear due to diffraction of zero beams on the diffraction grating being recorded in the film. Of interest is the fact that, if the exposition is interrupted during this stage, a grating with sinusoidal profile of grooves is obtained [1]. At further increase of exposure, the sinusoidality is broken, and diffraction spots with $m > 1$ appear and are

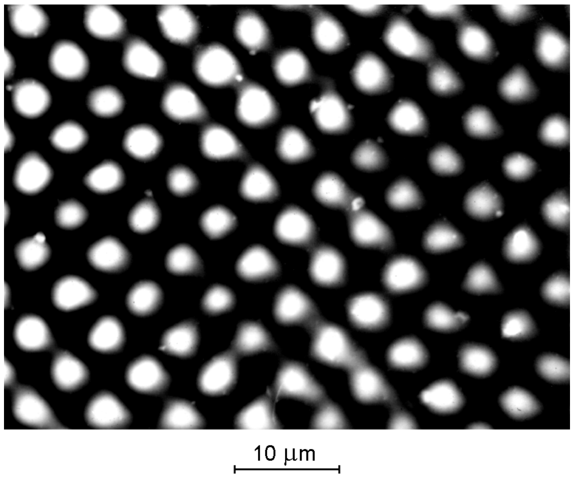


Fig. 4. Microphoto of the two-dimensional square grating ($\Lambda = 5.2$ μm) on the screen (9) observed in the scheme of Fig. 1.

developed. At self-diffraction, this is typical for thin gratings with $\Lambda >> d$ (where d is the film thickness [2]). The intensity of spots decreases as m increases. At the saturation stage which in the current experiment corresponds to exposure time of several minutes, the diffraction with $m = \pm 5$ can be observed. The diffraction angle measurements allow to calculate the period Λ using formula (3). Such measurements result in $\Lambda = 5.2$ μm being in good agreement with Λ calculation by formula (2).

An As_2S_3–Ag film retains photosensitivity not only at non-irradiated areas but also in the area where holographic diffraction grating is recorded. This allows expansion of the experiment on self-diffraction and grating recording. At WP turn by 90°, the plane of beams creating interference turns, too. In this case, the beams retain equal intensities, intersect at the same place, and form a new diffraction grating in the film with vector $\mathbf{K}_1 \perp \mathbf{K}$. As a result, one gets a two-dimensional rectangular grating diffraction from which is shown in Fig. 3a. For comparison, a diffraction pattern at normal incidence of single beam on this grating is shown in Fig. 3b. Observations with the microscope (8) allow the square grating itself to be seen on the screen (9). The two-dimensional grating recorded in the film is a two-dimensional "photonic crystal" [6] and the experiment described presents a simple way to form and research such crystals at small areas of any polished substrates. Also there may be an interest in the case of a planar waveguide on substrate surface when a grating has to be formed for radiation bringing in the waveguide.

The gratings recorded in the film are maintained for arbitrary long time if the sample is not exposed to intense light or high temperature. The recorded structures also may be fixed by means of alkali solution treatment of the sample [4, 5]. Alkali dissolves quickly the non-irradiated areas and weakly affects the irradiated ones. This results in a relief diffraction grating insensitive to intense light.

To conclude, let us denote some peculiarities of the optical scheme used in experiment. The use of a small SCL decreases considerably the overall setup size. Due to beam division into two parts by WP, the scheme has one straight direction of optical axis. This allows to assemble it on a straight optical bench (a standard 125–150 cm optical bench placed on a laboratory bench). The scheme allows turn arbitrary the plane of beams creating interference conserving their intensities along with turn of laser beam polarization plane. The latter is done by turning the laser or using a half-wave crystal plate. The intensity ratio of two beams may be easily changed by turning the WP or polarizer. This allows to extend the problem of self-diffraction to research the intensity distribution in diffraction beams [2]. One can change the interference period within certain limits either changing the distance h between beams at S distance change or using the lenses with different focal distances F. Both one-dimensional and two-dimensional gratings of micron period can be recorded in the recording medium. Finally, the self-diffraction effect observed in the scheme can be used to detect the nonlinear interaction of light with various media [7].

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Спостерігання ефекту самодифракції та запис голографічних одновимірних та двовимірних граток у тонких фоточутливих плівках

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Описано схему для спостерігання нелінійного ефекту самодифракції. Джерелом випромінювання є напівпровідниковий лазер ($P \approx 50$ мВт, $\lambda \approx 660$ нм). Лазерний пучок поділяється на два призмою Волластона, пучки проходять через поляроїд та збираючу лінзу, після якої перетинаються та створюють інтерференцію. За допомогою мікроскопа інтерференцію у збільшеному масштабі можна спостерігати на віддаленому від мікроскопа екрані. Інтерференція реєструється у фоточутливій плівці As_2S_3–Ag, яка виготовлена вакуумним напиленням. Показано можливість спостерігання самодифракції від дифракційної гратки з лінійними штрихами, що записується, та від двовимірної квадратної гратки, яка індукується у результаті другої експозиції після повороту площини сходження пучків, що інтерферують, на 90°.