Fabrication and properties of elements based on volume transmission gratings with a surface relief

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Abstract: The fabrication processes, diffraction and selective properties of volume transmitting holographic gratings with a surface relief are considered. The conditions for obtaining structures with a diffraction efficiency of the volume component up to 80% and a relief component up to 45% at angles of incidence up to 50°, as well as possible practical applications of elements based on such structures are determined.

The processes of fabrication and properties of elements based on volume transmission gratings are of great practical interest and are being widely studied at present due with the possibilities of obtaining high diffraction efficiency and high angular selectivity that determine their using in information storage devices and for obtaining light beams formation elements and selective elements. One of the perspective directions is the fabrication of elements by the holographic method in photopolymer materials. A distinctive feature of this work is the orientation on obtaining elements on the basis of volume gratings with a surface relief. Such gratings have not been previously investigated and have properties that determine new possibilities for using elements based on them. In previous works [1,2] was observed the formation of the surface relief on a volume grating with refractive index modulation, but the height of the relief was insignificant and did not significantly affect the diffraction properties of the structures.

In this paper the problems of determining the conditions for obtaining a volume grating with refractive index modulation with the greatest diffraction efficiency, the formation of a relief grating on its surface with a significant depth of the relief, and investigating the diffraction properties of such structures were solved.

The experiments were performed with holographic recording of transmission gratings at a wavelength of 442 nm at a power density of $3 \times 10^{-2}$ W/cm². As recording materials, acrylate monomer compositions based on commercial components [3] are used. The layers were formed and exposed between two surfaces - a substrate and a coating film. Surface relief was formed by removing the coating film and post-exposure processing in isopropanol. Diffraction efficiency was determined at a wavelength of 650 nm as the ratio of the intensity in the first order of diffraction to the intensity of the incident radiation.
To determine the conditions for obtaining an effective volume grating, the dependence of the diffraction efficiency on the thickness of the layer and the recording frequency was investigated. It has been found that the greatest diffraction efficiency of 80% is achieved for thicknesses of about 100 μm and recording frequencies of about 300 l/mm (figure 1) with an exposure time of 40 sec. The gratings are volume, which is confirmed by the availability of only one order of diffraction, and also by the Klein criterion [4]. For a grating with thickness of 100 μm and a period of 3 μm, Q = 29.

![Figure 1. Dependence of the diffraction efficiency on the layer thickness (a) and the recording frequency (b).](image)

It is established that when the coating is removed after exposure, on a surface grating a relief grating is formed. To determine the conditions for obtaining a grating with the greatest depth of the relief, the dependence of the diffraction efficiency of the relief grating on the duration of exposure was studied. It is established that a lattice with a significant depth of relief is formed in a very narrow range of exposure parameters (Table 1).

| №   | Exposure duration, s | Diffraction efficiency, % |
|-----|----------------------|---------------------------|
| 1   | 20 s                 | 20                        |
| 2   | 40 s                 | 45                        |
| 3   | 1 min                | 35                        |
| 4   | 2 min                | 22                        |

A relief grating with a maximum diffraction efficiency of 45% can be considered as quasi-volume, because this value exceeds the DE limit for a thin grating (33%). In addition, calculation of the diffraction efficiency using Kogelnik's theory [5] for a relief height of 0.3 μm obtained for this grating by atomic force microscopy gives a close value - of 46%.

The study of the angular selectivity of volume gratings with a surface relief - hybrid structures showed a significant broadening of the angular selectivity contour relative to the volume grating. Figure 2 shows the contour of the angular selectivity of the hybrid structure obtained at the optimal conditions in comparison with the angular selectivity of the volume grating. It can be seen that high diffraction efficiency is maintained when the deviation from the Bragg angle for the volume component of the hybrid structure is up to 50°.
Figure 2. Change in diffraction efficiency for hybrid structure by deviation from the Bragg’s angle.

In the figure 3 it can be seen that the diffraction properties of a volume grating with a surface relief are conserved at a large angle of incidence of radiation from a white light source.

Figure 3. Diffraction on hybrid structure with a change in the angle of incidence.

The established diffraction and selective properties of volume gratings with a surface relief determine possible applications of elements based on them. One of the possible applications is the fabrication of protective elements. Elements based on hybrid structures make it possible to observe the image over a wide range of incidence angles when the maximum brightness is achieved in a narrow range of angles, which is an advantage in technologies based on visual control over elements based on volume gratings. Elements based on hybrid structures can also be used as graphic design elements. Another possible application is the use in solar energy technologies to produce elements of solar concentrators that allow the use of solar radiation in a wide range of incidence angles. It is possible to use one-dimensional hybrid structures operating in one plane and as well as two-dimensional structures that can be obtained with multibeam interference. Elements based on volume gratings with a surface
relief have advantages relative to elements based on either volume or relief gratings [6-8] associated with increasing the range of incidence angles, reducing the number of elements and simplifying the fabrication process.

References
1. Naydenova I, Mihaylova E, Martin S, Toal V 2005 *Optics Express* 13, 4878-89
2. Lucchetta D E, Spegni P, Di Donato A, Simoni F, Castagna R. 2015 *Opt. Mater.* 42, 366–9.
3. Yu.E. Burunkova Yu E, S. A. Semina A, L. N. Kaporski L N, and V. V. Levichev V V 2008 *J. Opt. Technol.*, 75, 653-7.
4. Colier R J, Burckhardt C B, Lin L, 1973 *Optical Holography*, Academic Press, NY, London, 686 p.
5. Kogelnik H 1969 *Bell Syst. Tech. J.* 48, pp 2909–47
6. Jong T, Boer D, Bastiaansen C 2011 *Opt. Express* 19,15127 -15142
7. Akbari H, Naydenova I, Martin S, 2014 *Appl. Opt.* 53, 1343-63
8 J.H. Lee, H.Y. Wu, M.L.Piao, and N.Kim 2016 *IEEE Photon. J.* 8, 1-11.