Experimental study of the photon structures holographic formation by Bessel-like light beams in photopolymer materials

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Abstract. This paper presents experimental results of holographic formation of diffractive optical elements for the Gaussian light beams transformation into Bessel-like (one-dimensional and two-dimensional) in photopolymer materials using amplitude transparency (AT).

1. Introduction

Bessel laser beams have a huge number of applications in medicine, biomedical optics, pharmacology and other fields. One of them is the use in devices for nanoscale objects manipulating [1-2].

A main feature of Bessel beams is the ability to propagate along the optical axis without transverse distribution changing, that is, without the influence of diffraction effects [3]. Bessel beams are formed by conical waves traveling at equal angles to the optical axis [3]. This property is used in polarization and mode light beams conversion in anisotropic media [4-6]. In [7–9], methods for the transformation of a Gaussian light beam into a Bessel beam using a spatial light modulator (SLM) and an annular gap are presented. However, relatively large pixel size in SLM limits spatial shapes of the field. A scheme with an annular gap is not very efficient, since an insignificant part of the incident beam energy passes through a narrow annular gap. The formation of Bessel beams using axiconic lenses is energetically beneficial [10–12], but the cost of the elements used is high.

Thus, the search for cheap and high-tech methods for such beams formation is relevant. The fundamental mode transformation into an arbitrary complex distribution is effectively carried out using diffraction optics [13–15]. As it is known, one of the most effective methods of diffractive elements formation is holographic one (using photosensitive media) [16-17]. The effectiveness of this method is due to the fact that the refractive index or absorption coefficient distributions are entirely determined by the scheme of holographic recording, as well as by the physicochemical processes occurring in medium. Using the holographic method will dynamically form complex distributions of the medium characteristics, what solves the problem of creating a dynamic spatial distribution of electric field with reference to the pixel grid, which is used in the SLM [18-19]. Thus, by changing the conditions of holographic formation, arbitrarily complex diffraction (photon) structures can be created.

In this work one-dimensional and two-dimensional Bessel-like beams are formed by amplitude transparency (AT). Such beams do not have axial symmetry inherent for classical Bessel modes, and
are cosine (or sine) beams [20-22]. However, Bessel-like beams obtained using AT have diffraction-free properties [23–25].

In [23–25] it was shown that diffraction structures can be formed by one-dimensional and two-dimensional Bessel-like beams in lithium niobate crystals by the projection method. In addition, theoretical studies of holographic formation and reading of diffraction elements for converting light fields to Bessel-like ones were developed in [26–28].

This work continues the cycle of research of processes of holographic formation of diffractive optical elements (DOEs) in photopolymerizable compositions, contains experimental results and aims to explore the possibility of creating holographic DOEs using specially designed amplitude transparencies.

2. Experimental setup

In this paper, beams corresponding to Bessel function of first kind, zero order are considered. Mathematically Bessel function has the form [24-25]:

\[ J_n(x) = \frac{x^n}{\pi} \sum_{k=0}^{\infty} \frac{(-1)^k}{k!(n+k)!} \left( \frac{x}{2} \right)^{2k+n}, \]

where \( k \) – arbitrary real number called «kind», \( n \) – arbitrary real number called «order», \( x \) – coordinate.

To transform the incident light field into a Bessel-like one, setup shown in Figure 1 is used. It consists of an AT, on which a plane monochromatic wave [23-25] normally falls, a lens and a screen.

![Figure 1. Experimental setup for the formation of a Bessel-like light beam [23-25].](image)

The intensity of the light behind the AT depends on the angle \( \varphi \) between the light propagation direction and the normal to the screen [23-25]:

\[ I(\varphi) = 2 \cdot I_0 \left( \frac{\sin \left( \frac{k \cdot b \cdot \varphi \cdot \lambda}{k \cdot b \cdot \varphi \cdot \lambda/2} \right)}{k \cdot b \cdot \varphi \cdot \lambda/2} \right)^2 \left( 1 + \cos \left( k \cdot \Delta + k \cdot d \cdot \arctan \left( \frac{x}{a} \right) \right) \right), \]

where \( I_0 \) – light intensity in the center of the diffraction pattern, when only one gap is open, \( b \) – gap width, \( d \) – the distance between gaps centers, \( k = \frac{2\pi}{\lambda} \) – wave number, \( \lambda \) – wavelength, \( \Delta \) – additional path difference between the interfering rays (in the case of an oblique incidence of a plane wave on the screen).

Expression above has a dependence on the angle between the direction of light propagation and normal. In order to convert the angle to a coordinate for further comparison with the measurement results, we use the trigonometric expression for tangent of angle \( \varphi \) and then the expression will take the following form:

\[ I(x) = 2 \cdot I_0 \left( \frac{\sin \left( \frac{k \cdot b \cdot \arctan \left( \frac{x}{a} \right)}{k \cdot b \cdot \arctan \left( \frac{x}{a} \right)/2} \right)}{k \cdot b \cdot \arctan \left( \frac{x}{a} \right)/2} \right)^2 \left( 1 + \cos \left( k \cdot \Delta + k \cdot d \cdot \arctan \left( \frac{x}{a} \right) \right) \right), \]

where \( a \) – distance from amplitude transparency to the center of the screen.

The first factor in square brackets describes Fraunhofer diffraction on one gap, and the second factor – the interference from two point sources. The total energy passing through one gap is proportional to \( b \), and the width of the diffraction pattern is proportional to \( 1/b \). Therefore, the light intensity \( I_0 \) in the center of the diffraction pattern will be proportional to \( b^2 \). If it’s considered that the diffraction is on two gap, within the limits of the first diffraction maximum \( N \) interference fringes can
be observed, where \( N = \frac{2d}{b} \). When using two gaps, it is possible to transform a Gaussian light beam into a one-dimensional Bessel-like one.

Formation of a two-dimensional Bessel-like beam occurs by perpendicular imposition of two AT with parallel gaps. AT with two parallel gaps on an opaque screen were created, they are shown in Figure 2.

![AT with parallel gaps](image)

**Figure 2.** AT with parallel gaps: (a) vertical, (b) horizontal, (c) vertical and horizontal [23-25].

Figure 3 shows the experimental setup for the holographic formation of the DOE and its reading.

![Experimental setup](image)

**Figure 3.** Experimental setups: (a) for DOE formation and (b) for DOE reading.

Figure 3 shows the experimental setup for the holographic formation and reading of DOE in a sample with photopolymer materials (PPM) [29-33]. A helium-neon (He-Ne) laser with a radiation wavelength of 633 nm forms a reference light beam with a Gaussian light distribution of 2 mm in diameter and a power of 2 mW. After reflection from the mirror (M), the beam is divided into two using a beam-splitting cube (BSC). Further, the signal beam with a Gaussian intensity distribution through an AT is transformed into a one-dimensional Bessel-like. AT has a gap width of 200 microns and a distance between gaps of 900 microns. The distance from the AT to the lens (L) and from the lens to the sample corresponded to the focal length (18.4 cm). The angle of incidence of the reference and signal beam is 4 degrees. The reference beam after the mirror (M) was broadened using a collimator (C) to an aperture value of 4 mm. In the bulk of the PPM sample, the reference and signal beams interfere. Further, following to the holographic principle, a phase transmission hologram is formed in the sample.

Photopolymer films “GFPM633.5” produced by LLC Polymer Holograms-Novosibirsk with a layer thickness of 45 ± 5 μm on a glass substrate with a thickness of 1 ± 0.1 mm were used as PPM. The laser beam analyzer (A) captures the intensity distribution of the transmitted signal and reference beam. To read the obtained hologram, the signal light beam was blocked by a shutter (B). At the output of a formed structure, the analyzer recorded the intensity distribution of the diffracted light field.

### 3. Experimental results and discussion

To obtain a one-dimensional Bessel-like beam was used AT, which consisted of a metal plate with two gaps, the arrangement of the gaps corresponds to Figure 2a. The gap width is 200 microns with a
spacing of 900 microns between the gaps. Figure 4 shows images of intensity of the reference (Gaussian) and signal (one-dimensional Bessel-like) beams during the recording of a hologram.

![Figure 4](image1.png)

**Figure 4.** Intensity distributions of (a) reference and (b) signal beam when recording a hologram.

Further, for formed DOE reading, the signal beam is overlapped by a shutter (B) and beam intensity distributions are recorded using a beam analyzer (Figure 5).

![Figure 5](image2.png)

**Figure 5.** Intensity distributions of (a) reference and (b) diffracted beam when reading a hologram.

From Figure 5b, it can be seen that the diffracted beam has an intensity distribution close to the signal one (Figure 4b).

Figure 6 shows the normalized profiles of the signal and diffracted beam along the $x$-coordinate with respect to their maximum amplitude. Theoretical curves are obtained using the expression (1-3).

![Figure 6](image3.png)

**Figure 6.** Normalized profiles (a) of the signal beam during recording and (b) diffracted one along the $x$-axis.

From figure 6 it can be seen that the intensity distribution along the $x$-coordinate is Bessel-like. The difference from the square of the Bessel function is the amplitude of the side maxima, which has a
greater value. This can be explained by the geometrical parameters of the amplitude transparency, on which the type of the Bessel-like beam depends.

The experiment was carried out in a similar way to obtain two-dimensional Bessel-like beams. For this, two metal plates with two gaps superimposed on each other (Figure 2) were used as AT. The gap width was 200 microns, with a distance between gaps of 700 and 900 microns. Figure 7 shows the intensity distributions of signal (two-dimensional, Bessel-like beam) and diffracted beams.

![Figure 7. Intensity distributions of (a) signal beam during recording and (b) diffracted beam when reading the DOE.](image)

From Figure 7 it can be seen that the diffracted beam has intensity distribution close to the signal one – a two-dimensional Bessel-like beam.

Figures 8 and 9 show the normalized profiles of the signal and diffracted beams along the $x$ and $y$ coordinates relative to their maximum amplitude. Theoretical curves are obtained using expressions (1-3).

![Figure 8. Profiles of signal beam during recording (a) along the $x$ and (b) along the $y$ axes.](image)

From Figure 8 and 9, the central and lateral maxima can be seen. In Figure 8 and 9, the profiles are similar to the distribution of the Bessel function. The width and number of maxima for the $x$ and $y$ axes turned out to be different, since plates with different parameters were used. As in the previous experiment, the difference in the amplitudes of the side maxima is explained by the geometric parameters of the AT.

An important parameter of DOE is diffraction efficiency (DE). This parameter characterizes the ratio of the power of a diffracted beam to the power of the incident beam. The expression for the DE is shown below:

$$\eta = \frac{I_d}{I_d + I_p},$$

where $I_d$ – diffracted beam intensity, $I_p$ – transmitted beam intensity.

The relative power of the transmitted beam during diffraction for two-dimensional and one-dimensional cases was 257 and 265 units respectively. The relative power for the diffracted beam for two-dimensional and one-dimensional cases was 1.27 and 1.7. DE in this case will be equal to:
\[ \eta_{\text{two-dimensional}} = 0.492\% , \eta_{\text{one-dimensional}} = 0.637\% . \]

Figure 9. Profiles of diffracted and signal beams (a) along the x and (b) along the y axes.

4. Conclusion
As a result of the work, diffraction optical element, which allows transforming Gaussian light fields into one-dimensional and two-dimensional Bessel-like ones, was formed with the help of amplitude transparency. Diffraction efficiency up to 0.637% was achieved.

5. References
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