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Laser beams mixing using a single volume grating

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An approach to combining beams with different wavelengths using a single volume holographic grating is proposed and experimentally validated. This approach is based on its diffraction properties for radiation incidence over a wide angular range in three-dimensional space.

Keywords: volume holographic grating, laser beam mixing with different wavelength.

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Introduction

The relevance of the problem of mixing laser beams for tackling various practical issues is emphasized in a whole number of publications. One of these problems is aligning several beams having the same wavelength in one direction in order to increase the output power of laser systems [1–6]. The principles of coherent and spectral mixing are being developed. Spectral beams unification has an advantage in some cases, since it has no any requirements on mutual coherence, phase synchronization of beams and polarization, which simplifies technical solutions. Another important practical issue is to ensure the required directivity of beams with different wavelengths. RGB-mixers occupy a special place, including in relation to augmented reality systems [7–21].

Various methods and materials are used to implement the principles of mixing. The traditional method is to use dichroic mirrors [7] in optical circuits, but they require precise positioning and a large amount of space when combined in a plane. Among the non-conventional methods, mixing in waveguides can be mentioned [8]. Methods using diffraction gratings of various types — reflective, transmissive, and their combinations are considered more widely [1–5,9–12,15,16,18,20,21]. However, a number of proposed methods for obtaining lattices, in particular, lithography methods [4,9–12], are technically difficult. Holographic methods are easier to implement.

There is great interest in volume Bragg grating [1–5,9,12,15,18–21]. Since high diffraction efficiency is required for efficient operation of mixers, materials based on bichrominated gelatin [15] and photo-thermo-refractive (FTR) materials are considered [1–3,16,17]. FTR glasses in relation to augmented reality systems have the advantage of combining input and output arrays and a waveguide in one element, but the materials and elements are difficult to fabricate. Recently, there has been a steadily growing interest in photopolymer materials [18–21], which provide high diffraction efficiency while simplifying the process of holographic gratings registering.

In most studies, the principles of beams combination are based on the use of multiple arrays and multiplex recording [1–6,9–12,15,16,18,19]. However, such approaches are somewhat troublesome in terms of accounting and eliminating the impact of the gratings' components and interference, especially when the combined beams fall on the grating in the same plane. These problems are tackled through providing high selective properties of the gratings' components.

In this paper, we consider another approach that eliminates the need for multiple gratings, based on the use of a single three-dimensional holographic grating in a photopolymer material and the combination of beams incident on the grating in 3D space.

1. Properties of 3D grating

The principle of alignment is based on the diffraction properties of a volume grating when radiation is incident over a wide angular range in three-dimensional space, which were partially reviewed in [22,23]. Let us consider these properties in relation to the problem of combining laser beams with different wavelengths.

Non-inclined transmission holographic gratings were registered in Bayfol HX material with a $16\,\mu$m thick layer by radiation with a wavelength of 633 nm in optimal conditions [22]. Grating period $1.6\,\mu$m. The Klein parameter [24] for such a grating at an incident radiation wavelength of 650 nm $Q = 17$.

Figure 1 shows the dependences of diffraction efficiency on the angles of incidence when they vary over a wide angular range. Measurements scheme is presented in Fig. 1, *a*. During measurements, the grating in its initial position rotated by 90° relative to the position corresponding to its recording. The angle α of the grating rotation around vertical axis Z and the angle β of rotation around the horizontal axis X, which sets the spatial orientation of the plane of incidence, were changed. The dependences of diffraction efficiency on α were determined for the given β.

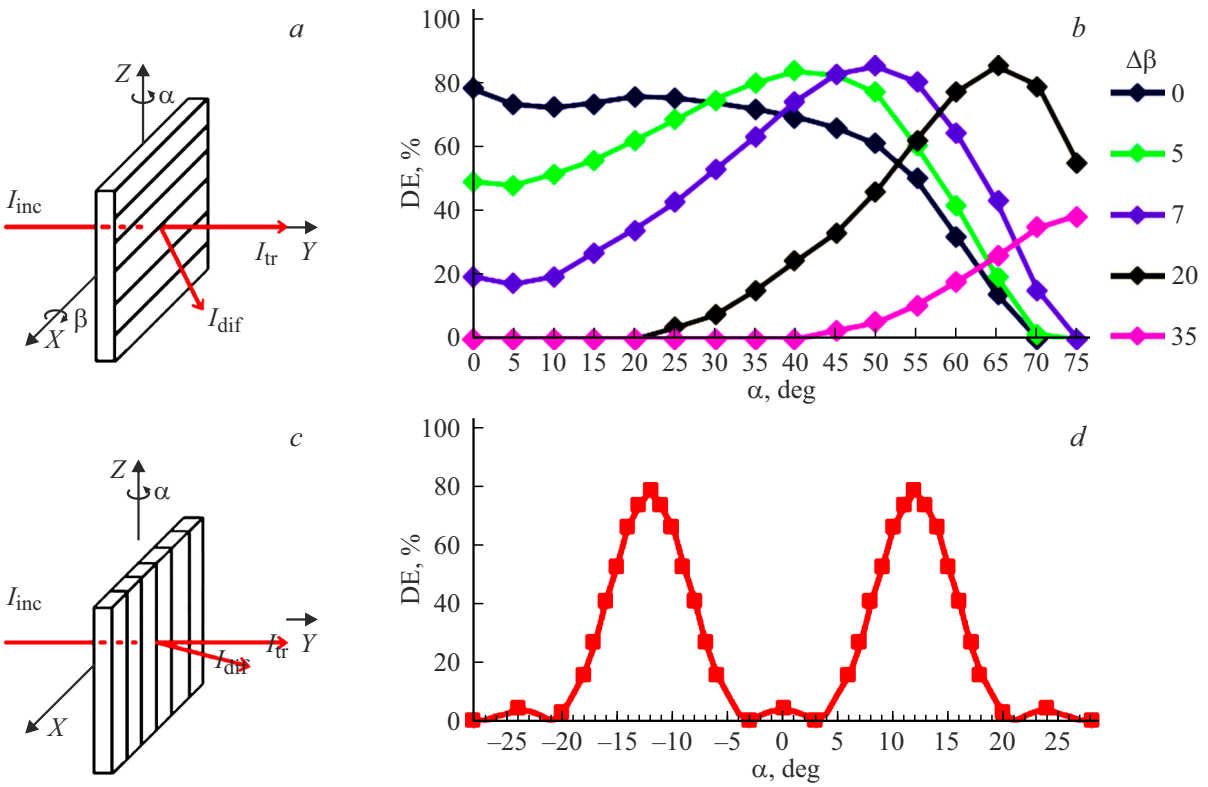

Figure 1. Diffraction properties of a 3D grating. Measurement scheme (*a*) and diffraction efficiency versus spatial orientation of the grating (*b*). Conventional scheme (*c*) and contour of angular selectivity (*d*).

It's worth mentioning that this scheme is equivalent to the scheme when the grating is set to the registration position, and the variable angles are reversed.

The following relationships are of interest. If the angle β is equal to Bragg angle Θ_{Br}, and the angle α changes, i.e., the radiation is incident on the grating in the „Bragg plane" — a plane forming the Bragg angle with the dielectric planes, then, diffraction efficiency is maximal (about 80 %) over a wide angular range α — up to 40°. For the studied grating $\Theta_{Br} = 12°$.

At $\beta = \Theta_{Br} + \Delta\beta$, i.e. growth of angle β (up to 30°) the maxima of diffraction efficiency are moved towards higher values α (up to 70°). The shift, according to the available ideas [25], may be related to the fact that in „oblique passage" directions the increase in the grating period is compensated by a longer optical path.

The maximum diffraction efficiency (Bragg diffraction) is provided for a variety of directions in space, determined by a combination of angles α and β. It is essential to notice that when radiation passes through the grating in „oblique" ways the contours of angular selectivity are wide, and their width exceeds the width obtained according to the traditional scheme (Fig. 1, *c, d*), i.e. in the incidence plane during the grating registering.

These results were obtained in the red region of the spectrum for the wavelength $\lambda_1 = 650$ nm. For the wavelengths in green and blue regions ($\lambda_2 = 530$ nm, $\lambda_3 = 405$ nm), similar trends in diffraction efficiency are observed. The quantitative differences are found by values of β related to the differences in Bragg angles, which are defined as

$$\beta_{2,3} = \Theta_{Br\,2,3} + \Delta\beta, \quad (1)$$

$$\Theta_{Br\,2,3} = \arcsin[(\lambda_{2,3}/\lambda_1)\sin\Theta_{Br\,1}]. \quad (2)$$

Absorption by the 3D gratings used in the experiment

№	Wavelength, nm	Optical density
1	650	0.05
2	530	0.12
3	405	0.15

The examined grating samples have low absorption that slightly rises in the short-wavelength region. Results from spectrophotometer UV-3600i Plus (Shimadzu, Japan) are given in the table.

Thus, the outlined properties indicate that maximum diffraction efficiency is achieved in a wide angular range of radiation incident on the grating in three-dimensional space, which leads to a higher degree of freedom to manipulate the directions of incident beams when combining diffracted beams.

In relation to the considered problem along with diffraction efficiency, the direction of the diffracted beams for different angles of incidence and wavelengths is critical. When experimentally estimating the position of a diffracted

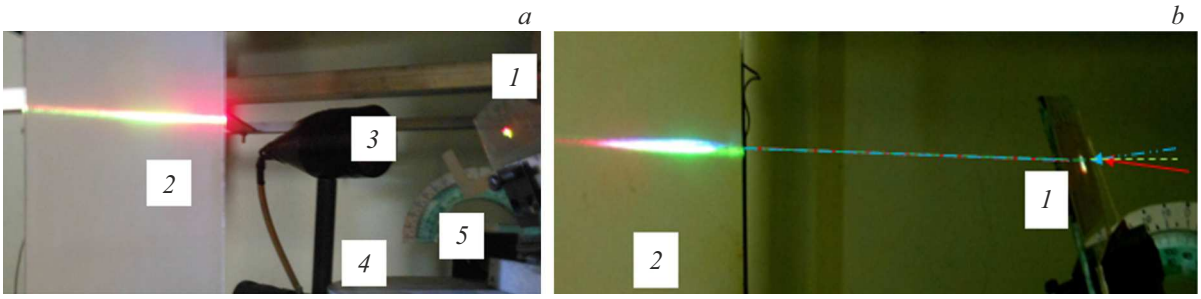

Figure 2. Examples of combining two diffracted beams with wavelengths of 650 and 530 nm (*a*) and three beams with wavelengths of 650, 530, 405 nm (*b*): *1* — 3D grating, *2* — screen, *3* — photodetector, *4* — limb of the grating rotation around vertical axis, *5* — limb of the grating rotation around horizontal axis.

beam on a screen 0.7 m away from the point of the beam entry into the grating with a change in the grating's spatial orientation (rotation) it was demonstrated that at $\beta = \Theta_{\mathrm{Br}}$, i.e., incidence in the Bragg plane and angles α variation in the range up to 40° the diffracted beam has practically the same angular position — the range of angular deviation is less than 1°, while for the largest values α and β and different wavelengths the angular deviation is 2–5°.

2. Studying the option of beams combination with different wavelengths

During the experiments, laser diodes with wavelengths of 650, 530, and 405 nm were used as radiation sources. It was possible to shift and rotate the sources in three dimensions.

The procedure for combining the diffracted beams started with the installation of a grating and a beam with a wavelength of λ_1 in positions corresponding to the maximum diffraction efficiency under required direction of the diffracted beam (e.g., in horizontal plane). When adding beams with other wavelengths, the directions of incidence of radiation with wavelengths λ_2 and λ_3 were set by the angles α and β corresponding to the maximum diffraction efficiency, which were determined from Fig. 1, *b* and expressions (1). The diffracted beams were combined at two points — the point of the beams entry into the grating and a point on the screen at a distance of 0.7 m from the grating. The mismatch of the diffracted beams directions was compensated by a change in the incident beams directions. At the same time, due to the wide contours of angular selectivity with „oblique passage" radiation through the grating, the diffraction efficiency decreased slightly — around 10 %.

Figure 2 shows a fragment of the experimental setup and examples of aligning the diffracted beams. Tracks are shown on the scattering screen of two aligned diffracted beams with wavelengths of 650 and 530 nm (Fig. 2, *a*) and three beams with wavelengths of 650, 530, 405 nm (Fig. 2, *b*). The beams alignment accuracy is at least 0.5° and diffraction efficiency is up to 70–80 %. It should be noted that it is possible to combine the beams at angular distances of tens of degrees between the beams incident on the grating.

Conclusion

An approach to aligning the beams with different wavelengths using a single volume grating is proposed and experimentally confirmed, based on diffraction and selective properties when radiation passes obliquely through the grating and falls in a wide angular range.

The spatial alignment of diffracted beams with two and three wavelengths with an accuracy and diffraction efficiency sufficient for practical application is obtained. The advantages are the ease of obtaining elements, convenience and the possibility of downsizing the optical circuits.

The results can be useful in the development of individual elements — RGB mixers for mixing laser beams, as well as components of systems requiring spatial alignment of beams with different wavelengths.

Conflict of interest

The authors declare that they have no conflict of interest.

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