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Features of color reproduction in images reconstructed by pulse holograms

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The color characteristics of images reconstructed by transmission pulse holograms in monochromatic light were estimated with changes in wavelengths and the intensity ratio of the reconstructing radiation. The method of calculating the chromaticity coordinates taking into account the reflectivity of colored objects was used, and the calculation results were compared with experimental results. The conditions for obtaining color images that meet the requirements of practical problems were determined..

Keywords: pulse holography, color holographic images, color reproduction.

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Introduction

Holographic methods, as the most promising for solving problems of three-dimensional visualization and obtaining three-dimensional color images, are used in digital and analog holography technologies. Digital holography methods are based on calculation of the amplitudes and phases of the wave field and their reproduction on a display using spatial light modulators [1–3], as well as optical printing on photosensitive materials [4–6]. Despite numerous advantages, digital technologies face multiple challenges related to simultaneously achieving the required parallax, image depth, and color reproduction. These demands necessitate complex computational algorithms [7–9] and substantial computing power. Moreover, there are problems related to the characteristics of technical devices, in particular spatial light modulators, as well as achieving image characteristics that display the properties of real objects [10–12]. These problems are resolved by analog methods.

The analog color holography has achieved the greatest by using continuous-action lasers for recording on various materials [13–17]. Reflective holograms have been obtained on silver halide materials that reproduce „ultra-realistic“ color images in white light [13,14]. However, continuous radiation recording does not allow recording non-stationary objects, and restoration by white color sources does not provide a large depth of images.

Advantages for recording non-stationary and extended objects are provided by the use of pulsed lasers and recording of transmission holograms. Transmission pulse holograms are used to implement the two-stage method [18] of obtaining reflective copies that are reconstructed in white light. However, the technologies for obtaining transmission pulse holograms [19–21] are of independent interest. Recording transmission holograms by reducing the requirements for the resolution of recording media makes it possible to use materials with high sensitivity to pulsed radiation, and when restored with modern monochromatic radiation sources, to obtain images with a large length in depth. The features of obtaining images of extended objects reconstructed by monochrome and color transmission holograms were considered in previous studies [22,23]. In this paper, we will consider the features of color reproduction in the restored images.

With regard to pulse recording, ensuring the number of recording wavelengths necessary for full color reproduction is associated with problems in obtaining high energy parameters and coherence of laser radiation at various wavelengths [24], which increase the cost of pulsed lasers. Nevertheless, recording at two wavelengths significantly improves the visual perception of images compared to monochrome images. Let's consider the features of color reproduction when recording at two wavelengths.

1. Theoretical results

The color characteristics were evaluated by using a method of calculation of the chromaticity coordinates in the reconstructed images, taking into account the reflectivity of colored objects. Chromaticity coordinates according to the rule of addition of two colors [25] are defined by the expression

$$\frac{X_2 - X_c}{X_c - X_1} = \frac{Y_c - Y_2}{Y_1 - Y_c} = \frac{I_1}{I_2}, \tag{1}$$

where X_c, Y_c are the chromaticity coordinates of the restored image, X_1, X_2, Y_1, Y_2 — chromaticity coordinates of the reducing radiation, I_1, I_2 — the intensity of diffracted beams.

The ratio of the intensities of the diffracted beams can be expressed in terms of the intensities of the restoring

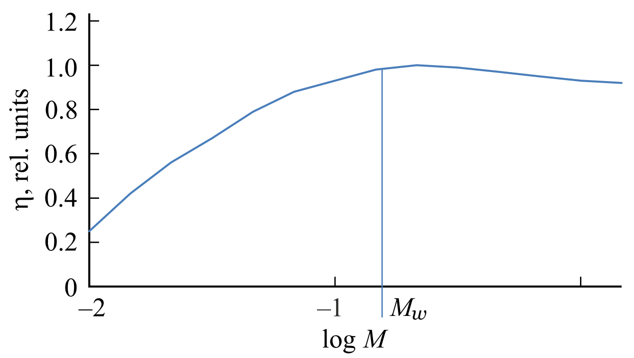

Figure 1. The dependence of the diffraction efficiency on the ratio of the intensities of the object and reference beams.

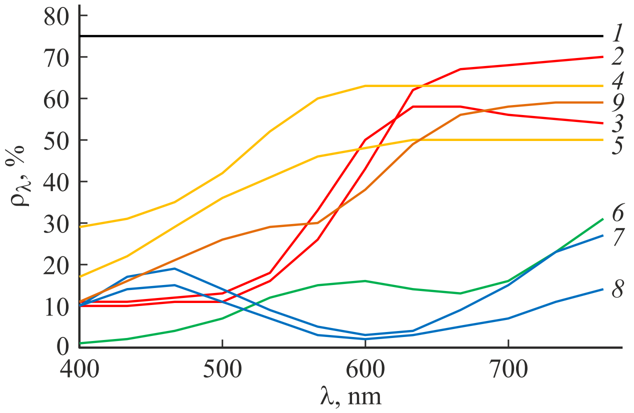

Figure 2. Reflection spectra of colored objects. Object color: *1* — white (paper), *2, 3* — red (paper, fabric), *4, 5* — yellow (paper, flower), *6* — green (leaf), *7, 8* — blue (flower, plastic), *9* — human skin.

beams and the diffraction efficiency of the monochrome components of color images as:

$$\frac{I_1}{I_2} = \frac{I_{r1}\eta_1}{I_{r2}\eta_2}, \quad (2)$$

where I_{r1}, I_{r2} are the intensities of the restoring beams, η_1, η_2 are the diffraction efficiencies of monochrome components of color images.

The experimental dependence of the diffraction efficiency on the ratio of the object and reference beam intensities was used to determine the values of η_1 and η_2 (Fig. 1).

The ratio of the intensities of the object and reference beams for objects with a given color tone was determined by the ratio

$$M = M_w \frac{\rho_\lambda}{\rho_w}, \quad (3)$$

where M_w is the optimal ratio of the object and reference beam intensities for a white object, ρ_w, ρ_λ is the spectral reflection coefficients for a white object and an object with a given color tone.

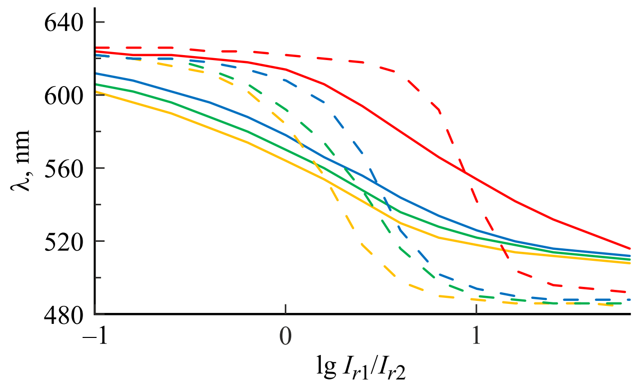

Figure 3. The dependence of the color tones of images of colored objects reconstructed at wavelengths 633 and 514 nm (solid curves) and 633 and 496 nm (dashed lines) on the ratio of the intensities of the restoring beams.

Fig. 2 shows the curves of the spectral reflection coefficients of various colored objects obtained using SF18 spectrophotometer.

Using the found diffraction efficiency values for colored objects, determined by their reflectivity for each of the two recording wavelengths, as well as the ratios(1) and (2), the chromaticity coordinates in the reconstructed image were calculated for the specified intensity ratios of the restoring beams. The color tones of the reconstructed images were determined by the intersection of a straight line connecting the white point and the point corresponding to the calculated chromaticity coordinates with the locus line on the color diagram. The calculation was performed for recording wavelengths of 678 and 530 nm. For reconstruction, pairs of lines in the red and green spectral regions (633 and 514 nm), as well as the red and blue regions (633 and 496 nm) were considered. The choice of these wavelengths is related to the conditions of subsequent experimental verification.

Fig. 3 shows the dependences of the color tones of the restored images of various colored objects (with color tones of 600, 575, 555, and 460 nm) on the intensity ratios of the restoring beams.

These dependencies make it possible to trace the change of color tones in the restored images when the restoration conditions change. It can be seen that red is the most stable color, which is reproduced in a wide range of intensity ratios of the reconstruction beams, especially for wavelengths of 633 and 496 nm. A pair of wavelengths in the red and green regions (633 and 514 nm) are characterized by a smoother change in color tones with a change in the intensity ratio. Color shades are reproduced in a wide range of reconstruction beam intensity ratios. For another set of spectral lines in the red and blue regions (633 nm and 496 nm), grayscale reproduction can only be achieved within a limited range of reconstruction beam intensity ratios, and is dependent on the predefined red hue

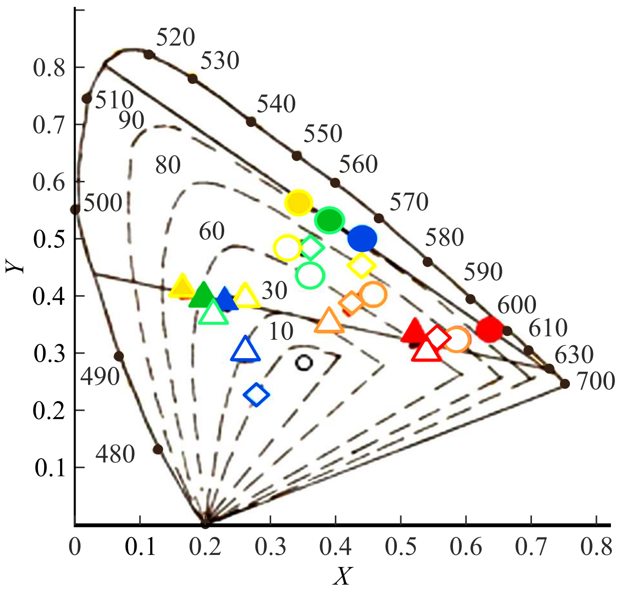

Figure 4. Color characteristics of objects and their images. Reconstruction wavelengths: (◯) — 633 and 514 nm, (△) — 633 and 496 nm, (◇) — properties of objects. The calculation results are shown by filled dots, the experimental results are shown by blank dots.

calibration. The other tones shift to the blue area when the red color tone is set to about 600 nm.

2. Experimental results

Transmission holograms recorded by pulsed radiation with a pulse duration of 10–30 ns and wavelengths of 678 and 530 nm were used during the experiments — holographic portraits, holograms of colors and other non-stationary colored objects. A single-layer material based on a water-soluble polymer emulsion was used to record holograms with a size of 30×40 cm, with the introduction of optical sensitizers that provide spectral sensitivity to radiation from the green and red regions of the spectrum simultaneously. The material also ensured the equality of maximum diffraction efficiency values in the same exposure ranges. The images were reconstructed using radiation from a helium neon laser with a wavelength of 633 nm and an argon laser with wavelengths of 514 and 496 nm. The color characteristics of the objects and the reconstructed images were determined using the color tables [26]. The calculation results and experimental results are plotted on the color chart shown in Fig. 4.

One can see a close agreement in color tones between the calculated and experimental data. When restoring images with radiation with wavelengths of 633 and 514 nm, the color tones of „red“ and „green“ objects are reconstructed with an accuracy of 5 nm, and „yellow“ objects are about 20 nm. The red color is well reproduced in case of reconstruction at wavelengths of 633 and 496 nm, but other tones are shifted to the short-wavelength region. At the same time, the color purity is lower compared to the restoration at wavelengths of 633 and 514 nm. It is important to note a fairly good transfer of a person's complexion, as well as its details and shades. The color is close to its natural color and can be adjusted. From the point of view of visual perception, reconstruction in red and green light is preferable due to the predominance of a combination of these colors in objects of visual technology. It should be noted that the wavelengths used for reconstruction are available in modern sources of monochromatic radiation based on LED and laser diodes.

Fig. 5 shows an image reconstructed by a transmission hologram recorded by pulsed radiation at two wavelengths. It is possible to see a fairly good display of red and white, shades of green, and skin color.

Conclusion

The results of theoretical evaluations and experiments have shown that a fairly good quality of color images is achieved for pulsed holograms recorded at two wavelengths, significantly exceeding the quality achieved with monochrome recording. The primary colors characteristic of the objects used in visual holography are reproduced. This eliminates the need to use expensive multicolor pulsed lasers for recording. Reproduction of images of extended objects is possible using modern cheap sources of monochromatic radiation. Recording of color transmission holograms in combination with restoration in monochromatic light is of independent interest for obtaining images of extended objects, in addition, holograms can be used for subsequent copying using the technique of obtaining color reflective holograms by continuous radiation.

Figure 5. Example of an image reconstructed by a transmission hologram.

Conflict of interest

The authors declare that they have no conflict of interest.

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