RECORDING CONDITIONS AND PROCESSING OPTIMIZATION FOR HOLOGRAMS USING BAYFOL HX200 PHOTOPOLYMER FILM

CONDICIONES DE GRABACIÓN Y OPTIMIZACIÓN DEL PROCESADO DE HOLOGRAMAS CON PELÍCULA FOTOPOLÍMERA BAYFOL HX200

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Abstract

This work aims to analyze the process of recording and reconstructing holograms based on Denisyuk's method, as well as calculating the power of the reference ZZZyclops camera laser beam required to record a hologram on the photopolymer film Bayfol HX200. We have studied how ultraviolet light and intense light affect the quality of holograms immediately after recording. Our experimental findings demonstrate that curing a hologram with ultraviolet light improves brightness and enhances color transfer, with better results achieved through longer exposure times. Additionally, our experiment reveals that strong illumination of a newly recorded hologram can severely damage the image and distort the object's information. We have estimated the dosage of emission absorbed by the film and compared our results with the dosages recommended by the manufacturer.

Keywords: Denisyuk's method, Bayfol HX200 photopolymer film, ZZZyclops, UV light influence, strong illumination influence.

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Resumen

El objetivo de este trabajo es analizar el proceso de grabación y reconstrucción de hologramas basado en el método de Denisyuk, así como calcular la potencia del haz láser de la cámara ZZZyclops de referencia necesaria para grabar un holograma en la película de fotopolímero Bayfol HX200. Hemos estudiado cómo afectan la luz ultravioleta y la luz intensa a la calidad de los hologramas inmediatamente después de su grabación. Nuestros resultados experimentales demuestran que el curado de un holograma con luz ultravioleta mejora el brillo y potencia la transferencia de color, obteniéndose mejores resultados con tiempos de exposición más largos. Además, nuestro experimento revela que una iluminación intensa de un holograma recién grabado puede dañar gravemente la imagen y distorsionar la información del objeto. Hemos estimado la dosis de emisión absorbida por la película y comparado nuestros resultados con las dosis recomendadas por el fabricante.

Palabras clave: método de Denisyuk, película de fotopolímero Bayfol HX200, ZZZyclops, influencia de la luz ultravioleta, fuerte influencia de la iluminación.

Introduction

Holography is an optical way of storing information that implies recording an object on a 2D medium and later reproducing it as a 3D image. In 1948, Dennis Gabor invented a technique of recording the information on the phase of a wave using a background wave [1], which transforms phase difference into intensity difference. In 1962 Yu. N. Denisyuk [2] combined holography and the works of the Nobel laureate Gabriel Lippmann in the field of natural color photography [3], creating the first reflection holograms. These holograms could be reconstructed with a usual incandescent lamp.

A Denisyuk's hologram can be recorded using one laser. With three or more lasers, an Optoclone, i.e. a color hologram, can be created.

Holograms have several advantages over photographs. First, a hologram contains information about the amplitude and phase of the electromagnetic field, which allows obtaining a 3D image of an object. It is also possible to observe such an image from several slightly different angles. The second advantage is its reliability, i.e. an image can be restored from a single piece of a fractured photographic plate (although for holograms made using Denisyuk's method, this effect is subtle, because during recording, the distance between the plate and the object is small). However, the angular resolution of such an image will be low. This is due to Huygens' principle, i.e. light scattered from an object hits every point of the recording plate. Finally, several images can be recorded on a single photoplate and then reconstructed separately (for example, by changing the angle of incidence of the reference wave) without spoiling other images. Currently, holography is widely used in storage devices, diffraction gratings, lenses, and other optical elements. It is also employed in exhibitions, particularly in the field of artistic holography [4].

The goal of this study is to find optimal parameters of the setup for recording full-color artistic Denisyuk's holograms and conditions for post-processing.

To achieve this goal, we set the following objectives:

1. Adjust the setup for holography recording so that the three beams are collimated.

2. Estimate the power output of the reference beams for each of the three wavelengths.

3. Study the influence of UV light on the quality of the hologram.

4. Study the effect of strong illumination on the quality of the hologram.

1. Theory

1.1. General Concept of Hologram Recording and Reconstruction

The main idea of holography is recording the interference pattern produced by two waves with the same frequency ω. One of these waves comes from the object and contains the information (phases and amplitudes) about the object itself: it is called the *subject* or *secondary* wave. The other wave, which is a coherent background wave, is called *reference* wave. Usually, these two coherent waves are obtained by splitting the wave front of a single wave. See Fig. 1(a).

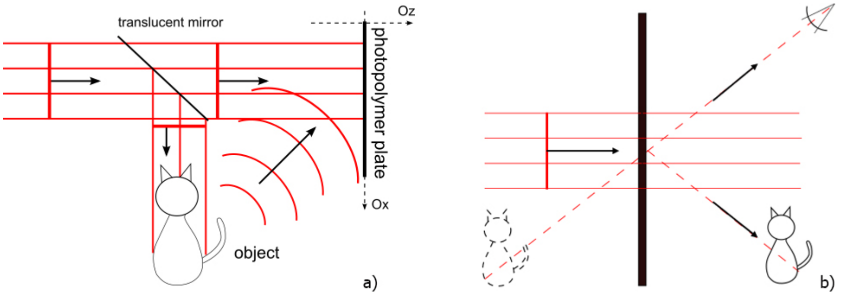


FIGURE 1. *a) Hologram recording; b) Hologram reconstruction.*

The interference pattern is usually recorded on a photoplate, a photopolymer film, or another layer of photographic medium. To "reconstruct" a 3D image of an object, the hologram is illuminated by a wave with the same frequency as that of the reference wave, illustrated in Fig. 1(b). Due to the diffraction, two images are formed. One of them is real and pseudoscopic, the second one is virtual, and its shape is a copy of the object shape. Usually, the virtual image is used for observation, and in that case, the real image is an obstacle. Therefore, it is common to illuminate a hologram in such a way that the real image does not appear. For a more detailed mathematical description of those processes, see [5] (8.10. Gabor's method of imaging by reconstructed wave fronts).

1.2. Denisyuk's Method

In our work, we recorded thick-layer holograms using Denisyuk's method [6]. The main feature of this method is that the reference and the secondary waves are directed towards each other (Fig. 2(a)). To record the hologram, a coherent beam, specifically a plane monochromatic wave, is used. This incident beam reaches the object at an arbitrary angle, with the angle only affecting the position of the light source during image reconstruction. Another advantage of Denisyuk's method is its ability to record a color hologram.

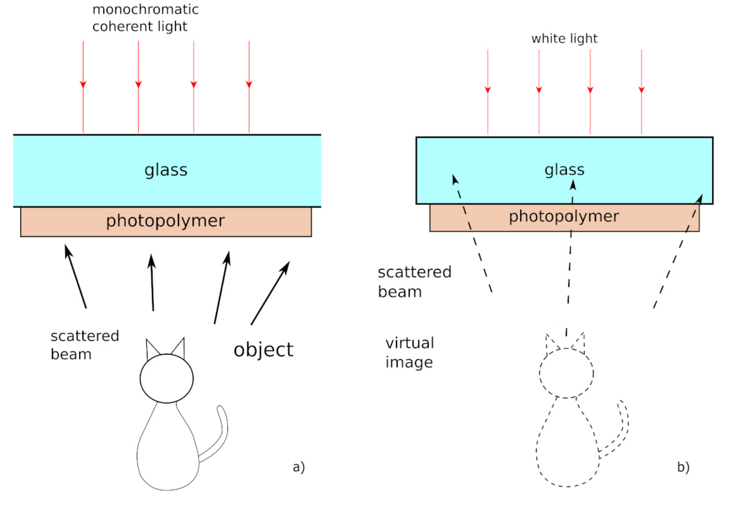


FIGURE 2. *Denisyuk's method a) Recording b) Reconstruction.*

Let us now consider what happens during the recording of a thick-layer hologram with a plane monochromatic wave (see Fig. 2(a)). Let the amplitude of the reference wave be E_0 and its wave vector be k_0. Similarly, let the amplitude of the secondary wave be E_1 and its wave vector be k. The two waves are propagating towards each other. The distribution of the intensity I(r) on one of the layers of the hologram during the interference of these waves will be:

$$I \sim E_0^2 + E_1^2 + 2E_0E_1 \cos\left[(k_0 - k) \cdot r\right]$$

The maximums of light intensity induce a chemical reaction on the photopolymer film, forming areas of maximum photographic response (reflective surfaces). In this case, the condition of intensity maximum is:

$$(k_0 - k) \cdot r = 2\pi m, \quad m \in \mathbb{Z} \tag{1}$$

If we use a plane wave front, then (1) sets a system of parallel planes, where the distance between the adjacent surfaces is given by $h = 2\pi/|k_0 - k|$. These surfaces form the maximum reflection areas.

The reference and the secondary waves have the same module of the wave vector $|k_0| = |k| = 2\pi/\lambda$ (where λ is the wavelength) and propagate in opposite directions, then $|k_0 - k| = 4\pi/\lambda$. The difference between the surfaces with maximum reflection will be:

$$h = \lambda/2 \tag{2}$$

To reconstruct a clear wave front, the falling reconstruction beam should follow Bragg's law (3) in the multi-layer film (thick-layer hologram).

$$2h \cos\beta = m\lambda, \quad m \in \mathbb{N} \tag{3}$$

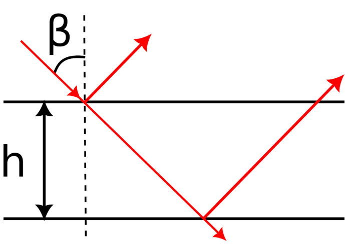


FIGURE 3. *Bragg's law.*

For the hologram recording, the reflected beams should interfere with the reference beam. (Fig. 3). We can note that the plate intended for hologram of a plane wave considered above, with the distance between the reflective surfaces defined by 2, follows Bragg's law when the reconstruction wave falls normally. Thus, monochromatization of the reflected light can be achieved. That means that to reconstruct a hologram recorded with counter-directed beams (i. e. Denisyuk's hologram), white light can be used, instead of a laser with the same wavelength as the reference wave.

When recording the hologram of an arbitrary object that reflects the wave with a complex wavefront, reflective surfaces with a complex shape appear in a thick-layer hologram. However, these surfaces act in the same way as plane surfaces since each differential area follows Bragg's law. Therefore, a reconstruction with a white lamp is possible, as such a structure will achieve monochromatization automatically. Moreover, the hologram can be recorded by lasers of different wavelengths. If several different interference patterns are recorded, they will not impede each other. This feature allows recording a colored hologram by illuminating the object with green, blue and red lasers.

To observe the image from a Denisyuk's hologram with a naked eye, we have to look at it from the side from which the plate is illuminated. In this case, we see only the virtual image in the reflected light, and the real image does not appear at all: this is an advantage, as it does not impede the reconstruction of the image from the hologram.

2. Equipment and Materials

2.1. ZZZyclops (Experimental Setup)

In this experiment, we used a ZZZyclops camera (see Fig. 4). This camera is designed for recording color holograms using Denisyuk's method. The camera works with three lasers with different wavelengths: 457 nm (1), 532 nm (2) and 640 nm (3), with power outputs of 200 mW, 500 mW and 500 mW, respectively.

Each laser is placed on a separate thermoelectric Peltier cooler (TEC)(4-6), which is used for temperature control of lasers, and a common metal plate. TEC dissipates heat without any vibration.

Three laser beams exit the camera as a single combined "white" beam. Before leaving the camera, the beam goes through a microscope lens (7) and the pinhole of a spatial filter (8), which

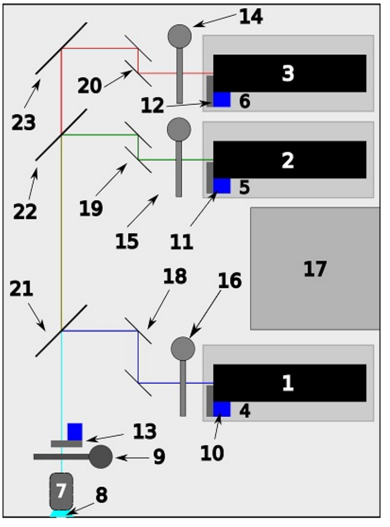


FIGURE 4. *ZZZyclops camera layout.*

expands the beam to the illumination area. There is a polarization rotator installed before the spatial filter (9), which rotates the polarizations of the three beams to the same angle at the same time.

The camera has four electromechanical shutters that can shut each beam individually (10-12) or shut the combined beam (13). The shutters independently control the exposure time for each beam.

The camera has three neutral-density (ND) filters (14-16) with inhomogeneous angle distribution of shading, placed on electric rotors. This allows regulation of the radiation intensity, if necessary.

There are four thermal sensors inside the camera. Three of them regulate the TECs' surface temperature. The fourth one regulates the temperature inside the camera in general. It also monitors the temperature and the air humidity in the laboratory. The main control unit (MCU) (17) is placed inside the camera. It runs the software that controls temperature monitoring, exposure time, ND rotation and other functions.

The lasers are adjusted using usual mirrors (18-20) and dichroic mirrors (21-23).

2.2. Bayfol (Photopolymer Film)

In the experiment, we used a photosensitive self-developing photopolymer film, Bayfol HX200, suitable for 3D holography. The main advantage of this film is that recording does not require any post-processing. The film is made of a three-layer substrate, a photosensitive photopolymer and a protective film. The substrate is made of cellulose acetate, and the protective film of polyethylene.

The hologram should be recorded in the dark to protect the film from excessive light, although it is not convenient. Figure 5 shows the dependence of the energy transmittance coefficient T(λ) on the incident radiation wavelength for this film. There is a local maximum of transmittance, which corresponds to the wavelength of amber light ($\sim$565 nm).

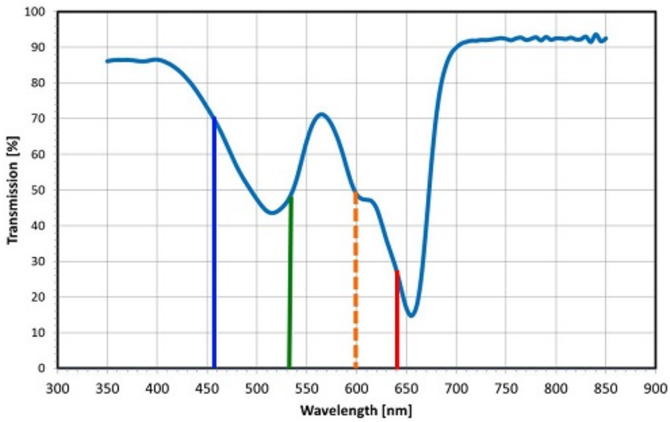


FIGURE 5. *Light absorbance spectrum for Bayfol HX200 film.*

For this reason, to work with this sensitive photopolymer film, we chose an amber LED lamp with a wavelength of $\lambda = 600$ nm (half-width of the spectral line $\Delta = 20$ nm. The spectrum is shown in Fig. 7b). This lamp allows working under dim light conditions without overexposing the film. The probability of chemical reactions (i.e. radiation absorbance by the film) at this lamp wavelength is minimal. Moreover, the wavelengths used in lasers are close to the minimum of absorbance. The film characteristics are provided by Bayfol [7] [8] in related documents.

The layers'composition is given in Table 1.

Layer	Thickness (μm)
Substrate	60 ± 2
Photopolymer	16 ± 2
Protective layer	40

TABLE 1. *Bayfol photopolymer film structure.*

3. Methodology

3.1. Calculation of the Reference Laser Beam Power

A portable laser power and energy meter Ophir Nova II was used to measure the power of the laser beam. It was later used to adjust the setup to the calculated parameters. The square photodetector has an edge length d and area $S_{mes} = d^2$.

Optimal energy dosages (energy per unit area) for three laser beams'wavelengths (457 nm, 532 nm and 640 nm) are indicated in the Bayfol HX200 photopolymer film manual. This data was used to calculate the required power of the reference laser beam $W_{las}(\lambda, \theta)$ for the three wavelengths in the recording area of the hologram, depending on the wavelength λ and the incidence angle θ of the beam.

Let the total power absorbed by the film per unit area (J/m^2) be $\zeta_{dos}(\lambda)$. From the manual:

$$\begin{cases} \zeta_{dos}(\lambda = 457\ nm) = 150\ \mathrm{J/m^2} \\ \zeta_{dos}(\lambda = 532\ nm) = 200\ \mathrm{J/m^2} \\ \zeta_{dos}(\lambda = 633\ nm) = 250\ \mathrm{J/m^2} \end{cases}$$

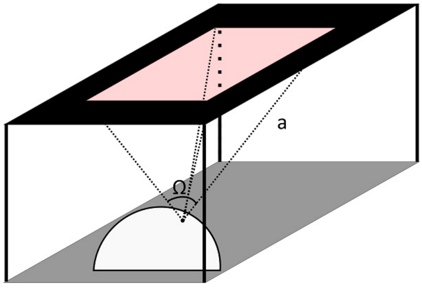


FIGURE 6. *Calculation of the reflected beam intensity via body angle.*

To obtain the required formula, we applied the Fresnel equations to calculate the fraction of laser beam intensity reflected from the holographic object and determined the total power absorbed by the film (the full results are presented in Section 11.2). We then applied this result to all subsequent setup tuning procedures:

$$W_{las}(\lambda,\theta) = \frac{S_{mes}\cdot\zeta_{dos}}{\tau\cdot(1-T(\lambda))}\cdot\left[1+\frac{n_{gl}\cdot|t_{gl}(\theta)|^2\cdot\cos\left(\arcsin\left(\frac{\sin\theta}{n_{gl}}\right)\right)\cdot\alpha\cdot T(\lambda)\cdot\frac{S_{bayf}}{\pi a^2}}{\cos\theta}\right]^{-1}, \tag{4}$$

where $T(\lambda)$ is the Bayfol HX200 transmittance, τ is the exposure time, n_{gl} is the glass refraction index, $t_{gl}(\theta)$ is the glass transmittance amplitude, α is the scattering factor, S_{bayf} is the film area, and a is the average distance between the object and the film.

We used the following setup parameters in our work:

$$\begin{cases} \alpha = 0.85 \\ d = 10^{-2}\ \mathrm{m} \\ S_{bayf} = 25\cdot 10^{-4}\ \mathrm{m}^2 \\ \theta = \dfrac{14\cdot\pi}{45} \\ a = 1.4\cdot 10^{-2}\ \mathrm{m} \\ n_{gl} = 1.5 \\ T(\lambda = 457\ \mathrm{nm}) = 0.69 \\ T(\lambda = 532\ \mathrm{nm}) = 0.46 \\ T(\lambda = 640\ \mathrm{nm}) = 0.27 \end{cases}$$

Calculation of the power required for $\tau = 30$ s for each of the three wavelengths:

$$\begin{cases} W_{las}(\lambda = 457\text{nm}) = 0,77 \text{ mW} \\ W_{las}(\lambda = 532\text{nm}) = 1,04 \text{ mW} \\ W_{las}(\lambda = 640\text{nm}) = 1,70 \text{ mW} \end{cases} \quad (5)$$

Calculation of the power required for $\tau = 20$ s for each of three the wavelengths:

$$\begin{cases} W_{las}(\lambda = 457\text{nm}) = 0,92 \text{ mW} \\ W_{las}(\lambda = 532\text{nm}) = 1,29 \text{ mW} \\ W_{las}(\lambda = 640\text{nm}) = 2,19 \text{ mW} \end{cases} \quad (6)$$

In ZZZyclops setup we used a spatial filter, which consists of a 20x micro lens and a pinhole (20 μm in diameter), to arrange a uniform flare in the zone of hologram recording. We also conducted the experiment on measuring the power of a falling laser beam with a portable laser power and energy meter Ophir Nova II. Using those experimental data, we adjusted the power falling on the photopolymer to the required level, according to (5) and (6). Using this equipment we also checked that the flare of the photopolymer was uniform - the difference of the power in the center and on the edges was not higher than 10-15 %.

3.2. Criteria for Hologram Quality Comparison

To objectively compare the quality of the holograms, we examined and compared the hologram spectrum with the object spectrum to draw conclusions about the appropriate recording conditions. For spectrum measurement, we employed a spectrometer operating within the range of Δ = 350-900 nm, with a spectral resolution of ξ = 1 nm. To ensure measurement accuracy, we captured the spectra of all objects from the same angle and under identical illumination levels. The spectra were subsequently compared using their respective graphs.

4. Measurements

4.1. Choice of the Test Object

To study the properties of holograms that were exposed to ultraviolet light or were kept under intense light for different time periods, we needed to choose an experimental object. Such an object should be monochrome, homogeneous, solid, and stable; it should also have a simple shape and should not create extra shadow or glares during the hologram recording. These qualities are essential to avoid the problems of shadows, glares, and complex spectra (i.e. spectra depending on the viewing angle) during the measurements.

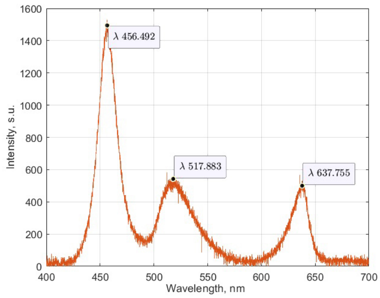
We chose a *white* experimental object to reveal whether the alignment of the optical scheme was adequate. It could also verify the accuracy of the lasers'power calculations. The spectra of a white object hologram would show which lasers underexposed the hologram and which ones overexposed it (the image of the object in the hologram would predominantly consist of the colors corresponding to the lasers that overexposed the photopolymer during the recording). As an experimental object, we chose a half of a white ping-pong ball. It was mechanically stable, matt and homogeneous.

For further analysis, we measured the spectrum of the selected object using a digital spectrometer *3B Scientific* (Fig. 8a). Subsequently, this spectrum was utilized to assess the quality of the recorded holograms by comparing their spectra with that of the object.

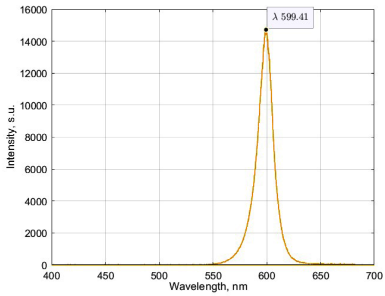
We also recorded the spectra of an RGB-lamp (Fig. 7a) used to view all of the holograms and of the amber-colored lamp (Fig. 7b).

4.2. Effect of Ultraviolet Light on the Hologram Quality

Using the calculated parameter values and the exposure time τ = 30 s, three holograms were recorded: the first one was immediately exposed to an RGB-lamp, the other two were illuminated only by amber LED and cut in halves. Then, each

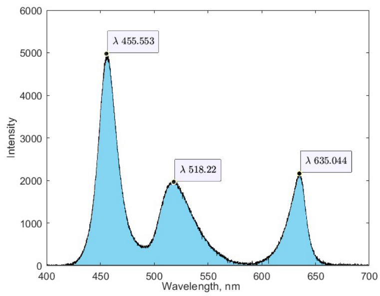


(a) RGB lamp, t_m *= 1,3 ms*

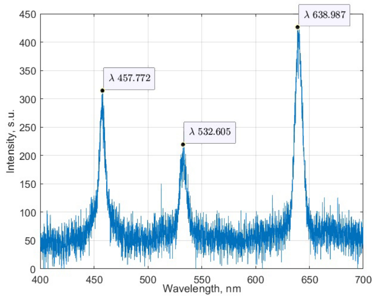


(b) Amber light, t_m *= 3 ms*

FIGURE 7. *Spectrum of the sources in relative units.* t_m *is the spectrometer exposure time.*



a) Test object illuminated by RGB lamp, t_m *= 400 ms*

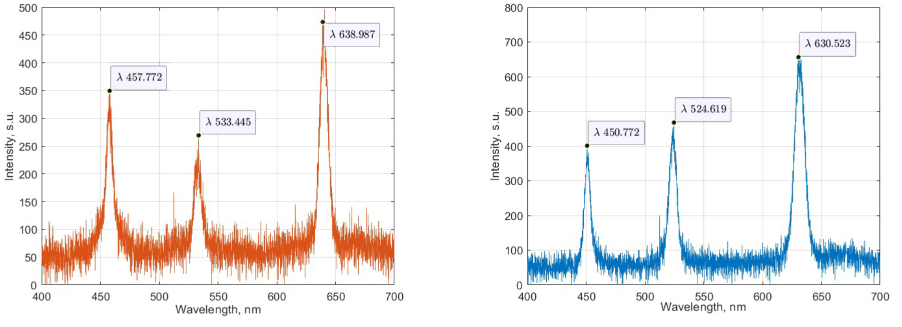


(b) τ *= 30 s;* τ_{UV} *= 0 min,* t_m *= 400 ms*

FIGURE 8. *Spectrum of the test object and spectrum of its hologram not affected by UV lamp with* τ *= 30 s in relative units.*

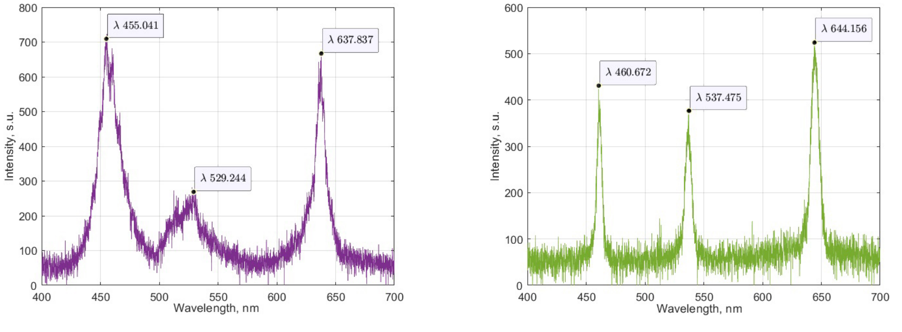
of the four holograms was held under an ultraviolet lamp with the wavelength $\lambda = 365$ nm and the output power P = 26 W for $\tau_{UV} = 5, 15, 30, 60$ minutes, where τ_{UV} is the ultraviolet exposure time. The exposure times were chosen randomly.

After the holograms were exposed to the RGB-lamp and external light, the spectral composition of the reflected light from the test object and from the hologram of the test object was locally investigated. The spectra are presented in the following figures: for $\tau_{UV} = 5$ min, in Fig. 9a; $\tau_{UV} = 15$ min, in Fig. 9b; $\tau_{UV} = 30$ min, in Fig. 10a; and for $\tau_{UV} = 60$ min, in Fig. 10b.



(a) $\tau = 30$ s; $\tau_{UV} = 5$ min, $t_m = 400$ ms *(b) $\tau = 30$ s; $\tau_{UV} = 15$ min, $t_m = 400$ ms*

FIGURE 9. *Holograms'spectra with $\tau = 30$ s in relative units for different times of UV illumination.*



a) $\tau = 30$ s; $\tau_{UV} = 30$ min, $t_m = 400$ ms *(b) $\tau = 30$ s; $\tau_{UV} = 60$ min, $t_m = 400$ ms*

FIGURE 10. *Holograms'spectra with $\tau = 30$ s in relative units for different times of UV illumination.*

From Fig. 9a - 10b, we can conclude that the brightest holograms with the right color transmission were obtained by exposure to ultraviolet light for 15 and 30 minutes. Let the dosage of ultraviolet light absorbed by an already recorded film be ζ_{UV}. We estimated it and compared the results with the following recommendations from the technical specification: ζ_{UV} should be equal to 50 - - 10 kJ/m^2 at an intensity of 400 W/m^2.

To calculate ζ_{UV}, the absorption factor should be taken into account, but the photopolymer manufacturer has provided only the dependence of transmission factor T on the wavelength λ. Thus, we used the fact that 1 - T is the sum of the absorbed and reflected light fractions.
Within this model, the ultraviolet lamp can be considered as a light source that produces waves with a spherical front. The distance between the holograms and the lamp was r = 0,6 m. Therefore, the intensity of the light falling on the holograms is $I_0 = \dfrac{P}{4\pi r^2} = 5,75$ W/m^2 and the intensity of the light passing through the film is $I' = I_0 \cdot T(\lambda)$.

We have also assumed that the scattering factor of the floor under the hologram is $\beta = \dfrac{1}{2}$. Because of the thin glass, we assumed that all the scattered light returns to the film, then the intensity of light reflected from the floor is equal to $I_1 = I_0 \cdot T(\lambda) \cdot \beta$.

The resulting intensity of the light absorbed by the film is

$$I \leq I_0 \cdot (1 + T(\lambda) \cdot \beta) \cdot (1 - T).$$

We estimated the dosage of an ultraviolet absorbed by the already recorded film to be $\zeta_{UV} = I \cdot \tau_{UV}$, and therefore

1. $\tau_{UV} = 15$ min

   $\zeta_{UV} \leq \tau_{UV} I_0 \cdot (1 + T(\lambda) \cdot \beta) \cdot (1 - T(\lambda)) = 1036$ J/m^2

2. $\tau_{UV} = 30$ min

   $\zeta_{UV} \leq 2072$ J/m^2

3. $\tau_{UV} = 40$ min

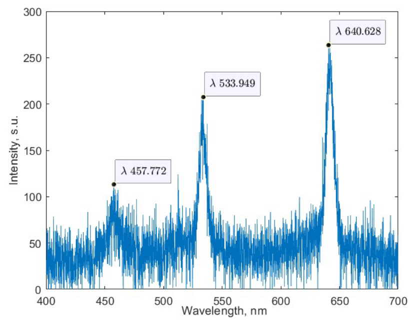
   $\zeta_{UV} \leq 2763$ J/m^2

4. $\tau_{UV} = 60$ min

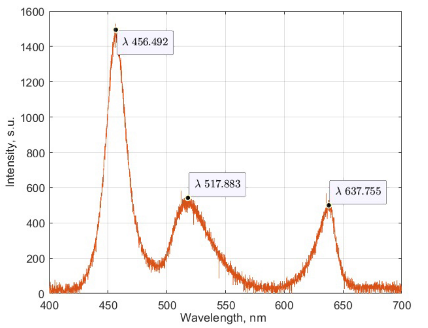
   $\zeta_{UV} \leq 4144$ J/m^2

4.3. Effect of Intense Light Illuminating the Hologram Immediately after the Recording

We recorded one hologram of the test object with an exposure time of $\tau = 20$ s. Then, we cut the hologram in half: the first one was held under ultraviolet light for 40 minutes (fig. 11b), and the second one was held under a powerful LED lamp light with a luminous flux of $\Phi \upsilon = 500$ lm.



a) $\tau = 20$ *s;* $\tau_{LED} = 40$ *min,* $t_m = 400$ *ms*



(b) $\tau = 20$ *s;* $\tau_{UV} = 40$ *min,* $t_m = 400$ *ms*

FIGURE 11. *Holograms'spectra with* $\tau = 20$ *s in relative units for different times of UV illumination.*

From Fig. 11a - 11b, we see that the illumination of a hologram by intense light immediately after the recording has an extremely negative effect on the hologram, both on its visual and spectral characteristics. We estimated the dosage of the LED lamp light absorbed by the already recorded film ζ_{LED}, assuming that all the light emitted by the LED lamp is absorbed by the film due to the small distance between them: $\zeta_{LED} = \dfrac{\Phi_\nu \cdot \tau_{LED}}{S_{bayf}}$, where τ_{LED} is the intense light exposure time. Therefore, for $\tau_{LED} = 40$ min: $\zeta_{LED} = \dfrac{\Phi_\nu \cdot \tau_{LED}}{S_{bayf}} = 480$ MJ/m^2, which is three orders of magnitude larger than the value allowed by the technical specification.

Note that the hologram with $\tau_{UV} = 40$ min and $\tau = 20$ s was the best in the series of experiments: the intensity peaks and maximum values correctly describe the spectral shape of the test object. The image was very bright and had a correct color transmission (fig. 12).

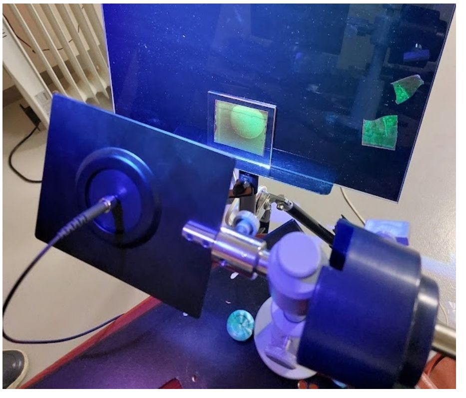


FIGURE 12. *Photograph of the object's hologram with $\tau = 20$ s; $\tau_{UV} = 40$ min, and $t_m = 400$ ms.*

Conclusions

We chose the reference wave parameters following the calculations of the optimal power values and adjustment of the ZZZyclops camera. The proper reconstruction of white object in the hologram proved the importance of system calibration. In case the power values were changed arbitrarily, the spectrum of the hologram image differed from the spectrum of an object in real life more (because of overexposure, some colors would dominate in the spectrum).

During the experiment, we confirmed that exposing a newly made hologram to ultraviolet light improves its quality and color rendering. According to the experimental data, as the time of ultraviolet exposure increases, the intensity of the light reflected from a hologram increases. It is easy to notice that the wavelengths, on which the object spectrum has maximums, can be defined from any spectrum of a hologram that had been exposed to ultraviolet light. The best experimental hologram (from the set with $\tau = 30$ sec) was illuminated with ultraviolet light for $\tau_{UV} = 30$ min. The spectrum of that hologram best matches the spectrum of a real object. That hologram was the most clear and precise among all the fabricated holograms, because the maxima of the spectra are the highest for the main wavelength.

In almost all the holograms exposed to a laser for $\tau = 30$ sec, red color is dominating in their spectra. The possible explanation is the following: photopolymer films are rectangular, with dimensions of 2.5×5 cm. After these holograms are cut into two parts, in one of the parts the image is reconstructed with a different angle, which causes the change of a measurement angle of the spectrum by means of a spectrometer light guide. What is more important, the photopolymer film itself is slightly red, and during the measurement of the hologram spectrum, we also measured the spectra of the film.

The dosage of ultraviolet absorbed by the film has been estimated, and we compared it to the dosages recommended by the manufacturer. In the experiment, the dosage of the ultraviolet is significantly less than that recommended by those manufacturer.

The influence of strong illumination on the quality of an already recorded hologram has been studied. It has been found that intense illumination almost completely destroys the image, greatly distorting the color transfer and the transmission of information about the shape, volume of the object, as the dose of radiation exceeds the allowed one by several orders of magnitude. The photopolymer was irradiated with a LED lamp, and the image of the test object became blurry and indistinguishable.

A hologram with $\tau = 20$ seconds and $\tau_{UV} = 40$ minutes had the highest quality. Note that the hologram's spectrum is very close to the test object's spectrum. Moreover, the intensity of the radiation carrying information about the object is greater than the same intensity of any of the holograms exposed to ultraviolet light for $\tau = 30$ s. It can be concluded that the quality of the hologram depends not only on the correct ratio of the powers of the three lasers, but also on the absolute magnitude of the intensity of the incident radiation.

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Used software

1. Calculations were made in Wolfram Mathematica.
2. Plots were made in MATLAB.
3. Figures were made in Inkscape.
4. Embedded software was used to operate the ZZZyclops.

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Appendix

Adjusting of the Experimental Setup

The goal of the adjustment is to align three laser beams parallel to the floor. The adjustment process is described below.

1. We pointed the red beam at the target on a wall. Then we installed a microscope lens and used a pair of adjusting mirrors to aim the expanded beam right at the target.
2. The same procedure was repeated for the green and blue lasers.
3. Then, we installed a pinhole as a spatial filter. We used dichroic and adjusting mirrors to align all three beams. The accuracy of the alignment depended on the pinhole diameter.

Reference Laser Beam Power Calculation

1. The beam with the wavelength λ comes out of the camera, a mirror reflects it, and the beam with the intensity I_0 hits the glass plate with the photopolymer at the angle θ (close to the Brewster's angle $\sim \theta_{\text{br}}$, as it decreases the reflections from the plate). The plate is placed on the object table. The plate is parallel to the floor. Note that
$$I_0 = \frac{W_{las}}{S_{mes}}$$
2. After the refraction at the air-glass boundary, the beam intensity becomes:
$$I_f = I_0 \cdot \frac{n_{gl} \cdot \cos\varphi}{\cos\theta} \cdot |t_{gl}(\theta)|^2,$$
where t_{glass} is the glass amplitude transmittance, and n_{gl} is the glass index of refraction. From the Snell's law:
$$\sin\theta = n_{gl}\sin\varphi \quad \Rightarrow \quad \varphi = \arcsin\left(\frac{\sin\theta}{n_{gl}}\right)$$
The incident radiation's polarization is horizontal, then:
$$t_{gl}(\theta) = \frac{2\cos\theta}{n_{gl}\ \cos\theta + \cos\varphi}$$
Beam with the intensity I_f falls on the film above.
3. The film is much thinner than the glass plate; therefore, the glass-film and film-air boundaries can be considered as a single boundary with the transmittance T(λ). The transmittance T is estimated from the plot 5 showing the dependence of transmittance on wavelength λ. Consequently, the intensity of the light that passed through the boundary is:
$$I_t = I_f \cdot T(\lambda)$$
4. The object is illuminated by a wave with the intensity I_t. On average, each point of the object dissipates energy into solid angle π because of the object placement. A part of the energy is absorbed by the object. Let α be the coefficient of dissipation. Then the scattered beam intensity is αI_t. Note that we are considering only the part of the radiation that

reaches the film. We determine the solid angle of the direction from the object to the film for each point of the object:

$$\Omega = \frac{S_{bayf}}{a^2},$$

where S_{bayf} is the film's surface area, a is the mean distance from object to the film.

Then the intensity of the beam reaching the film from below:

$$I' = \alpha I_t \frac{S_{bayf}}{\pi a^2}$$

5. Total intensity of all the beams absorbed by the film:

$$I_\Sigma = (I_0 + I') \cdot (1 - T)$$

6. On the other hand,

$$I_\Sigma = \frac{\zeta_{dos}(\lambda)}{\tau}$$

7. The final power of the reference beam:

$$W_{las}(\lambda, \theta) = \frac{S_{mes} \cdot \zeta_{dos}}{\tau \cdot (1 - T(\lambda))} \cdot \left[1 + \frac{n_{gl} \cdot |t_{gl}(\theta)|^2 \cdot \cos\left(\arcsin\left(\frac{\sin\theta}{n_{gl}}\right)\right) \cdot \alpha \cdot T(\lambda) \cdot \frac{S_{bayf}}{\pi a^2}}{\cos\theta} \right]^{-1}$$