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Reconstruction of silver halide volume reflection holograms at the wavelengths of recording

BRANIMIR IVANOV, MARIANA SHOPOVA, ELENA STOYKOVA*, VENTSESLAV SAINOV

Institute of Optical Materials and Technologies, Bulgarian Academy of Sciences, Acad. G. Bonchev Str., Bl. 101, 1113 Sofia, Bulgaria

*Corresponding author: elena@optics.bas.bg

Reconstruction at the wavelengths of recording is obligatory in color holography. If recording is made on silver halide light sensitive materials, a shrinkage of the layers causes different shifts of diffraction peaks towards lower wavelengths. The shrinkage is compensated by suitable swelling before final drying of the holograms. The report presents recent results obtained for swelling of holograms recorded at wavelengths in the red, green and blue spectral regions for an ultra-fine grain panchromatic silver halide emulsion with 10 nm average size of initial silver halide grains. The cases of successive and simultaneous irradiation of a single silver halide plate with the three wavelengths used are compared. Experiments on repeatability of the swelling procedure are also provided. Diffraction efficiency of bleached single exposure volume reflection holograms in red, green and blue has values higher than 50% for exposure energy of 2.0 mW/cm^2 both for the CW and pulse lasers.

Keywords: color holographic recording, panchromatic emulsion.

1. Introduction

Production of effective and reliable holographic recording materials is nowadays a mandatory task in view of the potential mass-markets for holographic applications. A lot of research work has been done for development of an ideal panchromatic medium with high sensitivity, resolution and signal-to-noise ratio across the visible region and excellent performance in creation of stable images [1, 2]. High reliability and reproducibility are also obligatory requirements. The dichromated gelatine, photopolymers, and silver halide emulsions are among the candidates for such a medium [1–9]. Very low losses and high diffraction efficiency make the dichromated gelatine an excellent choice for holography; however, its spectral response and sensitivity (>20 mJcm^{-2}) [2, 5] are far from those expected for holographic applications. Different types of photopolymers are efficient media for high resolution recording and permit simple rapid processing. Their shortcomings are low sensitivity (~30 mJcm^{-2}) and a very poor spectral response in the red end of the spectrum. Currently, the most suitable for RGB holographic recording are the silver halide emulsions which offer high sensitivity in a broad spectral range, recording of thin and thick holograms on rigid and flexible substrates, and long-term storage. Recently, a new panchromatic emulsion with 10 nm average grain size and laboratory production of holographic plates HP-P for recording of multicolor reflection holograms have been reported [9, 10].

The specific chemical development of silver halide materials reduces the volume of the light sensitive layer due to the lesser volume of the silver grains developed in comparison with that of the initial silver halide crystals [11]. As a result, the Bragg diffraction condition for volume reflection holograms is fulfilled at shorter wavelengths than the wavelengths of recording. To achieve the obligatory in color holography reconstruction at wavelengths of recording [12], one should compensate the shrinkage by suitable swelling before final drying of the holograms. This crucial task is rather complicated due to various factors which affect the process such as initial dubbing of the layer, aging of the materials, developing procedures, *etc*. Obviously, this variety of effects is also the reason for very few systematic data having been published as far as the swelling procedure is concerned [13]. In the present work, we report the results obtained for the swelling of holograms recorded at wavelengths in the red, green and blue spectral regions on a single plate. The cases of successive and simultaneous irradiation of the holographic plate with the three lasers used are compared. Experiments on repeatability of the swelling procedure are also provided.

2. Multicolor recording

Preparation of our ultra-fine grain panchromatic silver halide emulsion is based on the “double jet” technique well-known since Lippmann’s time, without using “freezing and thawing” like for Slavich materials PFG-01-PFG-03C. The average grain size, polydispersity and temporal stability of the emulsion are regularly measured before coating using preliminary calibrated with a TEM data nephelometric and refractometric measurements. The small average size of initial silver halide grains (10 nm) ensures high resolution, diffraction efficiency and signal-to-noise ratio of holographic recording. The sensitizers used for the red and green spectral regions are selected to achieve maximal absorption and maximal hologram’s recording sensitivity respectively at 632.8 and 532 nm [14]. Natural emulsion sensitivity is used for recording in the blue spectral region (400–442 nm). The thickness of the light sensitive layer in the HP-P plates is about 8 μm [9]. We apply a two-stage processing of the recorded plates to create only phase modulation characterized by high diffraction efficiency. The first stage includes amplitude developing with the SM-6 developer of the following composition: ascorbic acid – 18 g, sodium hydroxide – 12 g, phenidone – 6 g, sodium phosphate dibasic – 28.4 g, water – 1 dm^3. The resulting modulation in the interference pattern is due to strongly absorbing silver grains. The second stage

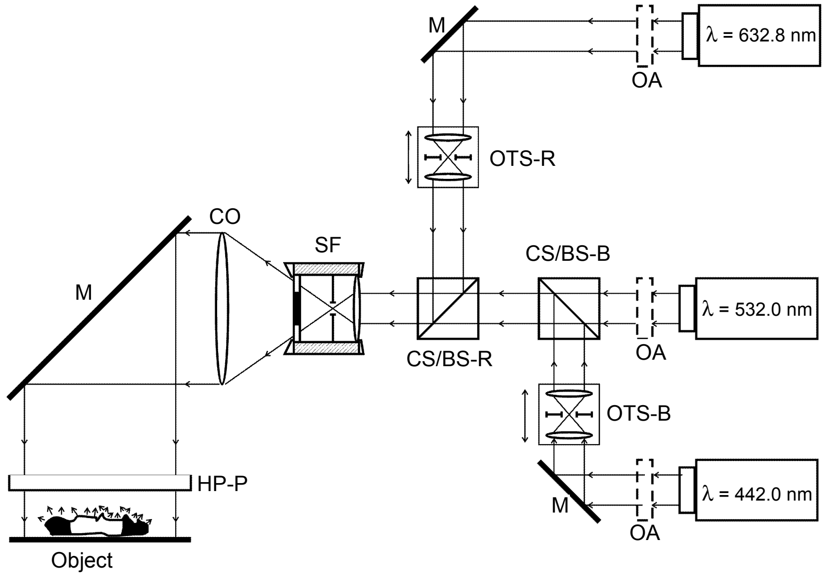

Fig. 1. Optical set-up for multicolor holographic recording: M – mirror, CO – collimating objective, SF – spatial filter, CS/BS – controllable switch and beam splitter, OTS-R – optical transfer system for the red laser, OTS-B – optical transfer system for the blue laser, OA – optical attenuator.

transforms the amplitude recording into phase one by bleaching the developed holograms with a Slavich PBU-Amidol bleacher of the following composition: potassium persulphate – 10.0 g, citric acid – 50.0 g, cupric bromide – 1.0 g, potassium bromide – 20.0 g, amidol – 1.0 g, water – up to 1.0 dm^3.

To perform simultaneous recording at different wavelengths we built the optical set-up shown in Fig. 1. It permits single recording at each of the wavelengths or mixing the radiations from all three lasers. The main advantage of the scheme is that their beams pass through a single spatial filter. Thus a condition for a point light source for RGB recording can be satisfied. To this ends, we designed a special beam combiner which allows any one or combination of any two or three lasers to be chosen. The beam combiner for mixing the red and green radiations was implemented as an interference mirror inclined at 45° with respect to the falling light beam. The mirror had about 80% reflection in the red and 80% transmittance in the green spectral regions. The combiner for mixing blue and green radiations was constructed in the same way with 80% reflection in the blue and 80% transmittance in the green. Since the focal distances of the spherical micro-objectives of the spatial filter depend on the wavelength, we introduced two optical transfer systems which controlled the divergence of the beams and made the necessary compensation of the focal distance for the blue and the red lasers. We also introduced optical attenuators to change the intensity of each laser beam. As a rule, the photosensitive layer is facing the object.

To estimate the exposure and spectral dependence of diffraction efficiency of the obtained bleached reflection holograms we measured the transmission spectra of

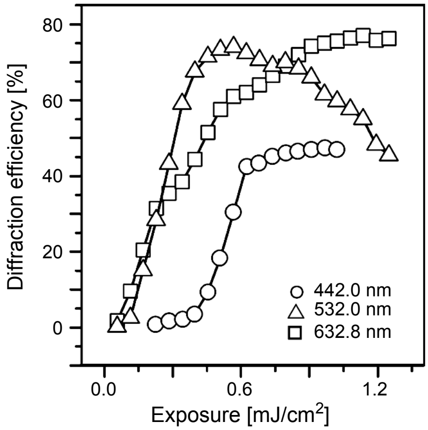

Fig. 2. Exposure characteristics of reflection RGB holograms.

the samples at reconstruction with a normally impinging collimated white light using an Ocean Optics HR-4000 spectrometer. From the spectra we determined the spectral dependence of the diffracted intensity taking into account absorption and Fresnel losses. The maximal values of diffracted intensity at different exposures gives the exposure characteristic for the red, green and blue spectral regions (Fig. 2). The maximal values of diffraction efficiency in single recording reach almost 80% upon exposure of 1 mJ/cm^2 for recording with 632.8 nm, 75% at 0.6 mJ/cm^2 for recording at 532 nm and about 50% at 0.75 mJ/cm^2 for recording at 442 nm.

3. Swelling procedure

Developing in SM-6 without fixing offers the advantage of less shrinkage in comparison with the other fixing developers. The observed shrinkage is different for the wavelengths used as can be seen in Fig. 3, which depicts the spectral dependence of diffraction efficiency for recording at 442 nm, 532 nm and 632.8 nm. Figure 3**a** combines the spectra corresponding to independent single recordings on three holographic plates at each of the wavelengths. Figure 3**b** presents the result of successive recordings on a single holographic plate at the three wavelengths. The recordings were made in succession from the longer wavelength to the shorter one. We see that in both cases the shrinkage shifts position of diffraction peaks approximately at 16 nm in the blue, 51–54 nm in the green and 65 nm in the red spectral regions towards lower wavelengths of reconstruction.

As should be expected, diffraction efficiency for successive recordings is lower. A possible explanation for different shifts on the wavelength axis is the different mechanism of formation of interference patterns at 442 nm, 532 nm and 632.8 nm within the bulk of the layer. Strong scattering in the blue region makes it possible to

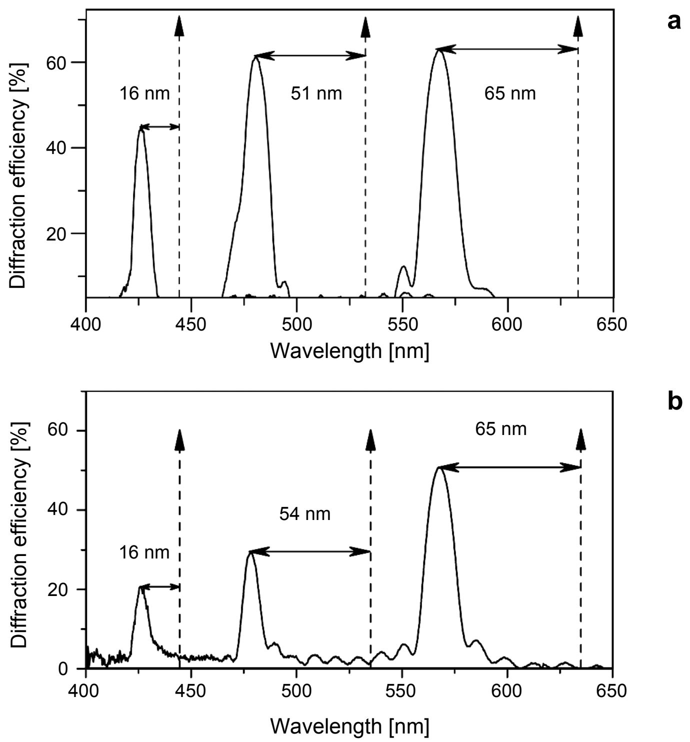

Fig. 3. Spectral dependence of diffraction efficiency for recording at 442 nm, 532 nm and 632.8 nm; independent recordings on three different holographic plates at each of the wavelengths (**a**), successive recordings on a single holographic plate at the three wavelengths (**b**).

form in-phase fringes only near the boundary layer in the coated emulsion just below the impact area of the falling laser beam, thus decreasing the effective depth of the light-sensitive layer. Scattering in the red and green regions is more or less comparable leading to close values of the wavelength shifts. Different shifts may render correct Bragg's reconstruction difficult when the swelling procedure is applied to a RGB reflection hologram on a single holographic layer.

To study the kinetics of swelling for reconstruction of RGB reflection holograms we used the set-up in Fig. 1 to perform successive and simultaneous delivery of radiations from the three lasers on a single holographic plate. To compensate the shrinkage the holograms were put in a bath of water solution of collagen hydrolizate at different concentrations for 5 minutes at 20 °C (the same temperature was maintained for developing, bleaching and washing of the plates). After the swelling, the diffraction peaks were determined using an Ocean Optics HR 4000 spectrometer. Figure 4 presents the results obtained for two plates with successive delivery (Fig. 4**a**) and two plates with simultaneous delivery (Fig. 4**b**). The results for the two plates at a given

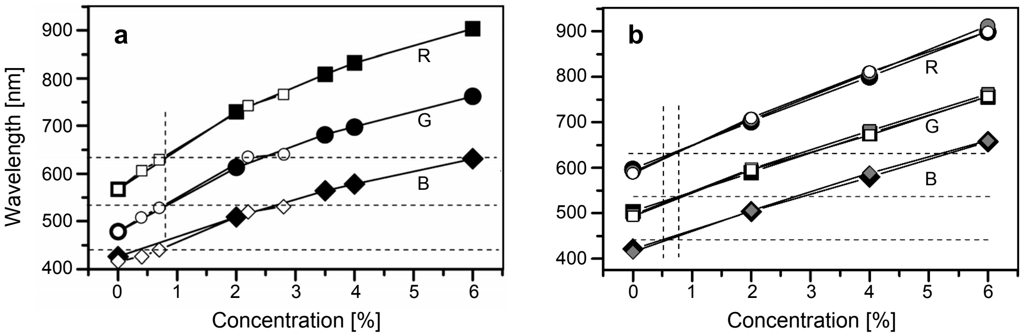

Fig. 4. Kinetics of swelling for reconstruction of RGB reflection holograms at successive (**a**) and simultaneous (**b**) delivery of radiations at 442 nm, 532 nm and 632.8 nm (the horizontal dashed lines correspond to the wavelengths of recording; the open and solid symbols present the results from two different measurements).

type of delivery are depicted with open and solid symbols, respectively. Each recorded holographic plate was cut into several patches which underwent swelling under increasing concentrations. We see a very good coincidence between the results for the two plates in Figs. 4**a** and 4**b**.

There is a slight difference in the slopes of the curves for simultaneous and successive recordings. The shifts of the diffraction peaks from their true positions due to the shrinkage of the light-sensitive layer in simultaneous recording are smaller compared to the shifts in successive recordings. As a whole, the differences between the positions of the peaks obtained for recordings at 442 nm, 532 nm and 632.8 nm increase with the concentration of the swelling agent. We see that practically correct compensation for the red and green recordings can be achieved with a single swelling bath both for successive and simultaneous delivery of radiations. For the blue recording the concentration of the swelling agent needed to shift the peak to its true position is more or less the same in Fig. 4**a** and slightly lower in Fig. 4**b** in comparison to the corresponding values for the red and green recordings. One should have in mind that a difference of a few nanometers can destroy the color balance required [12].

An effective way to avoid possible complications which may arise from the swelling procedure and to keep high diffraction efficiency is to apply a "sandwich" structure with red and green recordings on one of the plates and a single blue recording onto the other. In this experiment, for the blue recording only, the substrate of the plate is facing the object.

The results after the swelling procedure in this case are shown in Figure 5. The recording at 442 nm was performed at irradiance of 106 $\mu W/cm^2$ with exposure times of 3, 5 and 7 s and at 119 $\mu W/cm^2$ with exposure times of 6, 8 and 10 s. In the blue spectral region the correct value of the reconstruction wavelength is reached at concentrations of the water solution of the collagen hydrolizate between 1 and 1.8%. As a preliminary result a conclusion could be drawn that the higher the delivered exposure is, the higher the required concentration for reaching the proper wavelength,

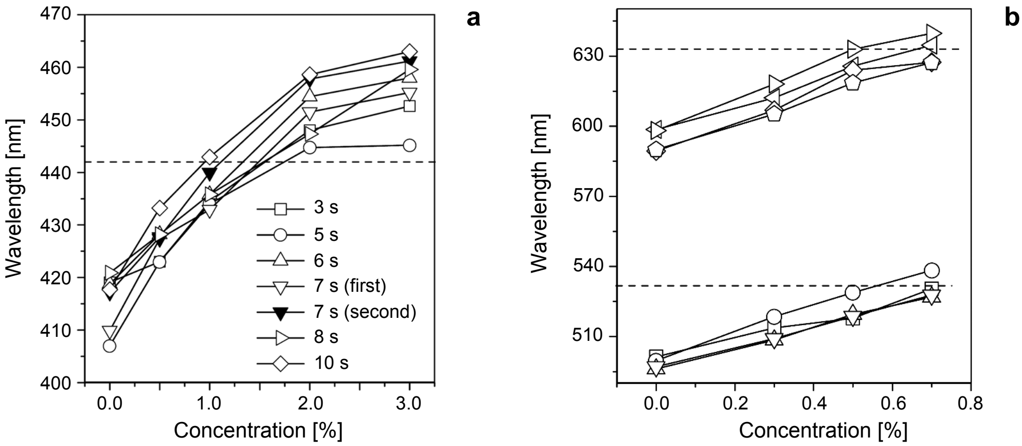

Fig. 5. Kinetics of swelling for reconstruction at the wavelengths of recording for holograms recorded at 442 nm (**a**) and for holograms recorded simultaneously with 532 nm and 632.8 nm (**b**).

but additional experiments have to be done to confirm this statement. In the case of swelling of holograms with combined recording in the red and green spectral regions, we made firstly rough estimation for concentration values of 0.5, 1, 2, 3, 4 and 5%. As in the case of the blue recording, the saturation effect was clearly observed at concentrations above 2%. On the basis of these rough results we made a second set of experiments varying the concentration from 0 to 0.8%. We found out that the same kinetics characterized the swelling process for both recordings. Contrary to the results obtained for recording on a single plate, the correct reconstruction at wavelengths 532 nm and 632.8 nm was achieved at twice lower concentration of the swelling agent in comparison with the single blue recording. We see good reproducibility of the curves obtained.

4. Conclusions

We have presented experimental data for the swelling procedure of multicolor reflection holograms, recorded on light sensitive plates with ultra-fine grain panchromatic silver halide emulsion (10 nm average size of initial silver halide grains). The diffraction efficiencies achieved in red, green and blue spectral regions proved that the light sensitive material is a suitable medium for multicolor holographic recording. We found the optimal concentrations of the swelling agent to shift the wavelengths of the diffraction peaks at reconstruction to the wavelengths used for recording. We obtained close values of these concentrations for recordings on a single plate. Thus, using this type of recording the chromatic and geometric distortions of reconstructed images are minimized but at the expense of decreased diffraction efficiencies. The results obtained for a sandwich structure with recordings on two plates indicated that the concentration of the swelling agent required for the correct wavelength shift at single blue recording is twice as large as the corresponding concentration for the simultaneous red and green recording on a single plate. The observed empirical result shows the need for gathering more raw data to clarify the complicated nature of the swelling process and to create a reliable swelling procedure.

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