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Multi colour holographic recording♣

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Basic holographic characteristics are presented of a newly developed panchromatic ultra-fine grain silver halide light-sensitive material, for RGB recording of reflective holograms. The average size of initial silver halide grains is less than 10 nm. This ensures a large dynamic range, high resolution, diffraction efficiency and signal-to-noise ratio (exceeding 100:1) in RGB reflective holographic recording. The decrease in the diffraction efficiency in the recording of scattering objects is less than 30% from the maximal values, obtained for specular reflection. The analysis of the colour characteristics of reflection holograms is presented for consecutive holographic recording in the blue, green and red spectral regions.

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1. Introduction

Ultra fine grain panchromatic silver halide light sensitive emulsions were first created more than 100 years ago, by Gabriel Lippmann [1]. He used the developed emulsion for his famous colour photography (Nobel prize in physics for 1908), which was based on the recording of interference patterns and the reconstruction by diffraction of the white light from the recorded structures. Silver halides are still the most suitable light sensitive materials for the recording of colour (RGB) reflection holograms [2-11], mainly due to the complex of features such as appropriate sensitivity which enables the use of new generation low-power diode and diode pumped solid state lasers, a high diffraction efficiency and signal-to-noise ratio, and very stable parameters after developing. These characteristics make silver halide materials suitable for art holography and holographic 3D displays. Bulgarian ultra fine grain silver halide light sensitive emulsions for the recording of reflection (Denisyuk) holograms are well known. Their average grain size is about 10 nm, which is important for holographic recording in the blue spectral region. Recently, on the basis of long term experience and modified technology, new panchromatic (400 – 675 nm) ultra fine grain silver halide light sensitive materials HP-P have been developed. An average grain size less than 10 nm and an improved homogeneity of the emulsion have been achieved. Thus, the problem of the limited lifetime (several days for maximum diffraction efficiency), due to the thermodynamic instability of the matrix silver halide nano-sized grains dispersed into the gelatine has been solved. The main goal of the work is to present recently obtained results for multicolour holographic recording onto the newly developed nano-sized grain panchromatic silver halide emulsion (HP-P).

2. Preparation, processing and basic characteristics of the HP-P plates

Preparation of the ultra-fine grain silver halide emulsions for panchromatic HP-P plates is based on the well known, from Lippmann's time, "double jet" technique, without using "freezing and thawing", as for the Slavich materials PFG-01- PFG-03C proposed by Kirillov [2].

Basic parameters of emulsions, such as the average grain size, polydispersity and temporal stability, were measured under laboratory conditions, using preliminary calibrated nephelometric and refractometric techniques which were applied to the diluted (1.2:24 in distilled water) emulsion, at 35°C. The average grain size and polydispersity, presented in Fig. 1, were determined by precise light scattering measurement, using a Multiangle BI-200SM. As has been already pointed out, the average size of silver halide grains of emulsion for panchromatic

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HP-P material is less than 10 nm with improved homogeneity as shown in Fig.1 (Sample 6).

To determine precisely the submicrometer grain size distribution, accurate information about the viscosity of the samples is required, at the temperature of measurement (35°C).

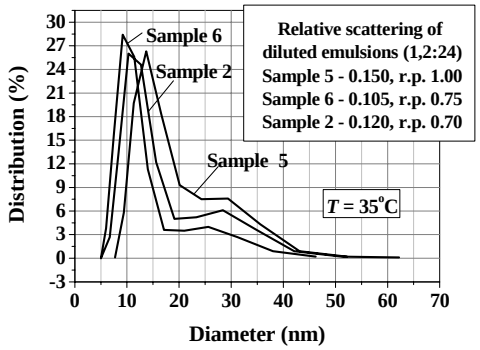

Fig.1 Average grain size and polydispersity of different emulsions.

We used the same preliminary evaluated viscosity value for all studied samples. This induced a positive bias (1-2 nm) in the estimates of the average grain size. However, it should be noted that not only the average grain size but the spread of the size distribution curve is an essential parameter for emulsion's thermostability. To compare the samples, we characterized their polydispersity with a relative polydispersity value (r.p.) calculated as a ratio of the measured polydispersity and the value which corresponds to the curve with the maximal spread (sample 5). The thickness of the light sensitive layer, coated onto the glass substrate, was about eight micrometers. The transmission spectrum of HP-P plates, measured precisely by a Carry-Varian 5E spectrophotometer, is shown in Fig. 2.

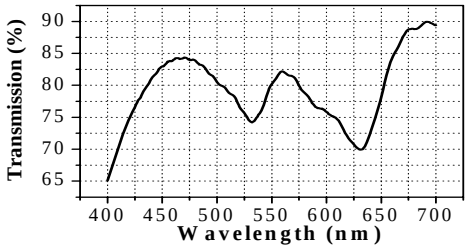

Fig. 2. Transmission spectrum of HP-P plates.

To measure the exposure dependence of the diffraction efficiency, we recorded reflection holograms of two collimated beams of CW laser irradiation at different wavelengths – 442 nm (He-Cd laser), 532 nm (diode pumped solid state laser) and 632.8 nm (He-Ne laser). For testing of the plates, small samples sized 2×7 cm were used. The reflection holographic recording was made with collimated beams. The illuminating beam impinged normally onto the sample, after passing through an optical wedge parallel to the sample optical wedge, with longitudinally varying absorption. The beam interfered with the "reference" beam, which was reflected from a flat mirror positioned parallel to the wedge and inclined at 173 deg with respect to the illuminating beam. The developer SM-6, with a composition: ascorbic acid – 18 g, sodium hydroxide – 12 g, phenidone – 6 g, sodium phosphate dibasic – 28.4 g, water – 1 *l* was used for bleached reflection holograms. The bleaching was performed with a Slavich PBU-Amidol 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 – to 1.0 *l.* To compensate for the shrinkage of the layers after chemical processing, and to ensure reconstruction of the Bragg reflection holograms at the wavelengths of recording, suitable swelling was performed before drying the developed holograms in a bath of a 10% water solution of collagen hydrolizate (C_H = 10%) for τ=5-10 min at 20^0C (the same temperature as for developing, bleaching and washing of the plates). The time dependence of the swelling process is illustrated in Fig. 3 which, shows the shift of the peak of the diffraction efficiency as a function of time in the swelling bath, for holograms sensitized in the red spectral region.

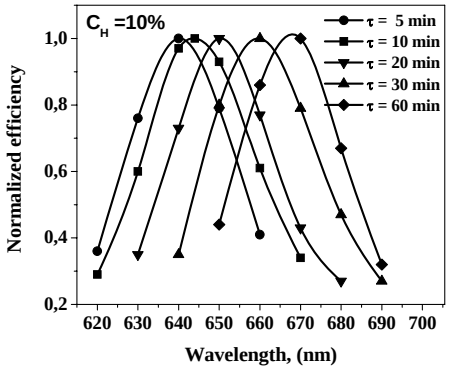

Fig.3. Diffraction efficiency after swelling in a 10% water solution of collagen hydrolizate (C_H) for different times, τ, in the swelling bath.

The exposure characteristics measured at the recording wavelengths are shown in Fig. 4. As can be seen, the dynamic range (linear part of the exposure characteristic) is 0.05 – 0.6 mJ/cm^2 for recording in the blue (442 nm), 0.05 – 0.5 mJ/cm^2 for recording in the green (532 nm), and 0.05 – 0.75 mJ/cm^2 for recording in the red (632.8 nm) spectral regions.

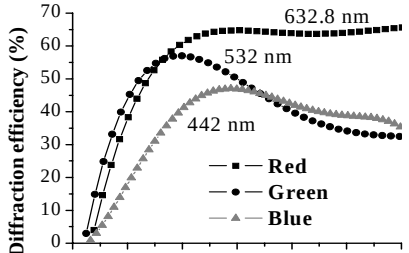

Fig 4. Exposure characteristics.

The spectral dependences of the diffraction efficiency, η, in the case of a single exposure made at each recording wavelength, are given in Fig. 5.

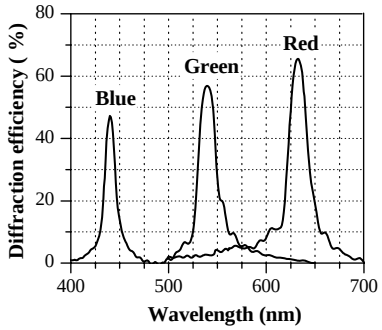

Fig. 5. Diffraction efficiency of bleached reflection holograms of two collimated beams for a single exposure in the blue (442 nm), green (532 nm) and red (632.8 nm) spectral regions.

We see that we can expect values above 40% in the blue, 50% in the green and 60% in the red for reconstruction with the used recording wavelengths. As the dynamic range of the refractive index modulation for all bleached silver halide materials is limited, being typically less than 0.08 for BBVPan plates [10,11] and less than 0.05 for the HP-P, in the case of multiplexing RGB holographic recording onto a single plate the diffraction efficiency of the individual holograms diminishes by a factor equal to the number of recordings to a power of 1.5-2. The decrease of the efficiency in the recording of light scattering objects is not more than 20% for the all used wavelengths. The FWHM (full width at half maximum) of the curves for diffuse reflection is practically the same as for specular reflection, which is due to the high signal to noise ratio of recording (exceeding 100:1). The obtained result is especially important for recording in the blue spectral region. As a whole, the measured characteristics of the HP-P are promising for RGB recording of reflection holograms, and for correct colour balance in the reconstruction with incoherent "point source" white light.

3. Colour balance of reconstructed images

Successful RGB reconstruction depends on a correct energy balance of light exposures within the dynamic range of the recording material, for different wavelengths. The total diffraction efficiency, η_Σ, is determined from:

$$\eta_\Sigma = \frac{I_{dB}}{I_{0B}} + \frac{I_{dG}}{I_{0G}} + \frac{I_{dR}}{I_{0R}} = \eta_B + \eta_G + \eta_R \quad (1)$$

where I_{dB}, I_{dG}, I_{dR} and I_{0B}, I_{0G}, I_{0R} are the intensities of the diffracted and reconstructing light in the blue, green and red spectral regions respectively. If, for simplicity, we accept that $I_{0B} = I_{0G} = I_{0R} = I_0$, the total diffraction efficiency becomes

$$\eta_\Sigma = \frac{I_{dB} + I_{dG} + I_{dR}}{I_0} \quad (2)$$

The diffraction efficiency of a bleached HP-P hologram diminishes approximately by a factor of $\frac{1}{2}K^2$ under multi-exposure recording, where K is the number of exposures. In accordance with the colour diagram in Fig. 6, reconstruction of a white colour for the used wavelengths is achieved if the ratio between the intensities of the reconstructed waves are $I_{dB} : I_{dG} : I_{dR} = 1 : 0.68 : 0.95$. Having in mind the experimentally obtained (Fig.3) maximum values of the diffraction efficiency, $\eta_{B\max} = 0.48; \eta_{G\max} = 0.57; \eta_{R\max} = 0.66$, we obtain from (1) that the ratio between the intensities of the light waves for reconstruction of the primary colours should be:

$$I_{0B} : I_{0G} : I_{0R} = 1 : 0.57 : 0.69 . \quad (3)$$

In general, the total exposure E_T delivered to a single layer can be described as:

$$E_T = \sum_{i=1}^{K} \left[(E_{\max}^{C_i} - E_{\min}^{C_i}) \times (\alpha_i) \right] + E_{\min}^{C_i} , \quad (4)$$

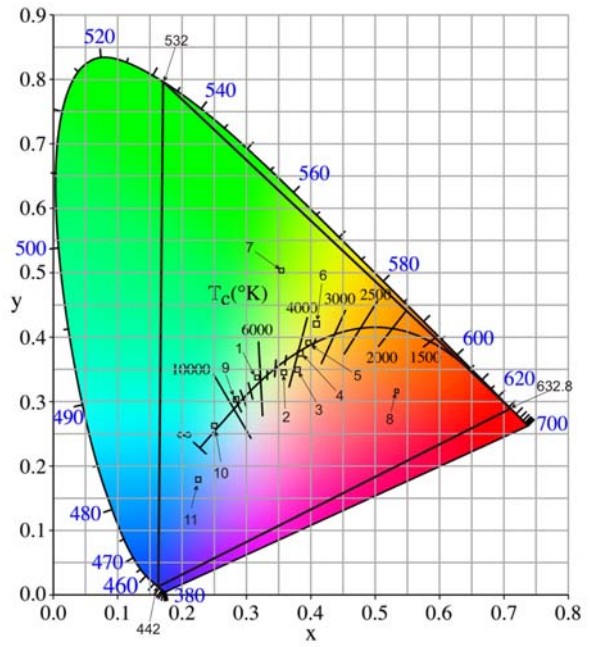

Fig. 6. Diagram of colour coordinates and colour temperatures of real objects:1 – white surface; 2 – snow; 3 –white skin; 4 – grey stone; 5 – sand; 6 – yellow flower; 7 – green grass; 8 – red flower; 9 – blue sky; 10 – lake on a sunny day; 11 – blue flower.

where K is the number of recordings onto the light sensitive material, $E_{min}^{C_i}$ and $E_{max}^{C_i}$ are the minimal and maximal exposures respectively, in the linear part of the exposure characteristic for the monochrome recording at the corresponding wavelength, which is indicated with a special colour pointer C_i. The colour filling coefficient $0 < \alpha_i \leq 1$ is introduced to ensure optimal use of the dynamic range of the light sensitive material, and to avoid its saturation. A proper choice of the colour filling coefficient is essential for additive correct colour mixing in reconstruction. The second term in (4) gives the necessary offset which is accumulated during the first exposure.

4. Conclusions

In summary, the basic holographic characteristics of bleached colour reflection holograms, recorded onto panchromatic silver halide light sensitive plates HP-P, as the exposure and spectral dependences of the diffraction efficiency in the red, green and blue spectral regions, were investigated. The dynamic range was 0.05–0.6 mJ/cm^2 for recording in the blue (442 nm), 0.05 – 0.5 mJ/cm^2 for recording in the green (532 nm) and 0.05 – 0.75 mJ/cm^2 for recording in the red (632.8 nm) spectral region. The signal to noise ratio was more than 100:1, with a maximal value of the efficiency of above 40% in the blue, 50% in the green and 60% in the red spectral region. The developed panchromatic ultra fine grain silver halide material HP-P has been successfully used for recording of Denisyuk's colour reflection holograms by CW and pulse (30-40 ns) generating lasers, in the spectral range 440 nm – 660 nm, as well as for recording of monochrome holograms by temperature stabilized diode lasers at 636 nm, 658 nm and 672 nm.

Acknowledgements

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