Progress in colour reflection holography

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Abstract

A simplified method for recording Denisyuk colour reflection holograms using pseudowhite laser light is described. The three wavelengths used were 633, 531 and 476 nm, and the emulsion was the Slavich ultrafine-grain panchromatic material. The beams were combined using dichroic filters for a single RGB exposure, which simplified the recording procedure and facilitated exposure and colour balance control. A test object consisting of the 1931 CIE chromaticity diagram along with a rainbow ribbon cable, pure yellow dots and a cloisonné elephant was used for colour recording experiments, as well as the Macbeth ColorChecker® chart. Both colorimetric evaluation and scattering noise measurements were performed.

1. Introduction

Currently, the possibility of producing true colour volume holograms in large quantities is very limited. Although various special techniques of today allow for the production of holograms exhibiting several different colours, in most cases the colours displayed in these holograms are not the true, original colours of the holographed object. These holograms are often referred to as *pseudo-* or *multicolour* holograms. There exist methods of creating colours that give an impression of a true colour in the finished image; e.g., multiple recorded stereograms or rainbow holograms; although the recordings could have well been made from objects with completely different colours, or from multiple sets of colour-separated photographs or movie recordings. By using the rainbow technique, it has actually been possible to mass-produce embossed holograms with either "natural" or artificial colours. It is also very common among artists to make multiple-exposed colour reflection holograms using a single-wavelength laser, where the emulsion thickness has been changed between the recordings of special objects. In this paper we present the technique for recording *colour* holograms, based on a holographic panchromatic, ultra-high resolution, single-layer silver-halide emulsion.

To be able to record high-quality colour reflection holograms, it is necessary to use extremely low scattering recording materials, which means, for example, the use of ultrahigh resolution silver-halide emulsions.[1] This type of material has the advantage of higher sensitivity compared to photopolymer or dichromated gelatin (DCG) materials which are alternative materials for colour holography. Ultra-high resolution silver-halide emulsions for monochrome holography have been manufactured in Russia for many years, and recently these emulsions have been panchromatically sensitised. In this paper we refer to the ultrahigh-resolution holographic emulsions (grain size 10 to 20 nm) as "Russian" emulsions, since they were first made in Russia (by both Protas and Kirillov). Protas was able to slow down grain growth during emulsification by increasing the number of growth centers and introducing special growth inhibitors.

The best Russian emulsion ever made is probably the one achieved by Kirillov. In this case, grain growth was hampered by the fact that, in the emulsification process, a highly diluted solution was used and the emulsion concentration was increased by applying the method of gradual freezing and thawing.

The highest resolution commercial holographic materials from Agfa, Ilford, and Kodak have a grain size of 35 nm to 50 nm and are not suitable for colour holograms. Blue scattering during recording will make the holograms rather milky looking with low signal-to-noise ratio. In addition, with the exception of the Kodak 649-F plate, the holographic materials are not panchromatic.

The holographic colour plates (PFG-03c) are produced by the SLAVICH photographic company outside Moscow.[2] The sizes used in our laboratory range from 5"x 4" format up to 12"x 16". SLAVICH can coat 60 cm x 80 cm size glass plates, which currently represents the largest format. Since there are great variations from batch to batch of this material, it is rather difficult to make a detailed characterisation of the emulsion itself. However, the silver-halide grain size is the most important parameter of this material and is the main reason for the obtained quality of the holographic images. Some characteristics of the SLAVICH material are presented in Table 1.

Silver halide material	PFG-03c
Emulsion thickness	7 µm
Grain size	12 - 20 nm
Resolution	~10000 lp/mm
Blue sensitivity	~1.0- 1.5.10^{-3}J/cm2
Green sensitivity	~1.2 - 1.6 .10^{-3}J/cm2
Red sensitivity	~0.8 - 1.2.10^{-3}J/cm2
Colour sensitivity peaked at:	633 nm, and 530 nm

Table 1. Characteristics of the SLAVICH colour emulsion.

Ultra-high-resolution holographic emulsions are normally processed in solution-physical development, creating colloidal silver. In this way, high image resolution can be obtained.[3] Such processing also requires emulsions with ultra-fine silver-halide grains (about 20 nm). The most common procedure used for holograms of the Russian type is based on diluted emulsions processed in solution- or semi-physical developers; e.g., the Russian GP-2 developer, in such a way that silver particles of an appropriate size are formed (colloidal silver). However, although this processing technique works extremely well for monochrome recordings, it is less suitable for colour holograms. The colloidal silver accreted in the emulsion introduces a light red or brownish colour to the processed emulsion. This affects, in turn, colour rendition and must therefore be avoided in holographic colour recordings. By composing special processing chemistry and processing baths, it has been possible to obtain high-quality colour holograms, first reported by Bjelkhagen and Vukicevic[4] and further developed by Bjelkhagen and Jeong[5]. Bjelkhagen *et al.* published a paper on the development of colour holography and, in particular, the new volume reflection holograms in a single-layer silver-halide emulsion, including a bibliography on colour holography.[6] Characterization of the SLAVICH colour emulsion has been presented by Markov.[7] A theoretical analysis with some experimental results on the selective properties of thick reflective gratings, intended for colour holography, was made by Markov and Khizhnyak.[8] Applications of colour holography have been reported by Jeong *et a1*[9]. Bjelkhagen and Huang described large-format colour hologram recording.[10, 11] Jeong *et al.* introduced the application of colour holograms in holographic interferometry[12].

Colour reflection holography presents no problems as regards the geometry of the recording setup, but the final result is highly dependent on the recording material used and the processing techniques applied. The single-beam Denisyuk recording scheme has produced the best results so far.

Following are some problems associated with the recording of colour reflection holograms in silver-halide emulsions:

- Scattering occurring in the blue part of the spectrum found in Western silver-halide emulsions makes them rather unsuitable for the recording of colour holograms.
- Multiple storage of interference patterns in a single emulsion reduces the diffraction efficiency of each individual recording. The diffraction efficiency of a three-colour recording in a single-layer emulsion is lower than a single wavelength recording in the same emulsion.
- During processing, emulsion shrinkage frequently occurs, causing a wavelength shift. White-light-illuminated reflection holograms normally show an increased bandwidth upon reconstruction, thus affecting the colour rendition.
- The fourth problem, related to some extent to the recording material itself, is the selection of appropriate laser wavelengths and their combination in order to obtain the best possible colour rendition of the object.

The problem of choosing optimal primary laser wavelengths for colour holograms has been treated in a paper by Bjelkhagen and Jeong.[13] A factor that influenced the choice of the recording wavelengths is the availability of wavelengths in different cw lasers currently in use in holographic recordings: argon ion, krypton ion, diode-pumped frequency-doubled Nd:YAG, helium neon, and helium cadmium lasers. In particular, the selection of the wavelength in the blue part of the spectrum is critical. Initially, the 488 nm wavelength was used when recording colour holograms in a silver-halide emulsion.[4] This was based on a desire to obtain highest possible signal-to-noise ratio, considering scattering during blue recording. However, for blue, there are several possible wavelengths: 458, 476, and 488 nm obtained from the argon-ion laser. The green wavelength, 532 nm, from a cw frequency-doubled diode-pumped Nd:YAG laser, is most suitable for the green primary wavelength. The 531 nm wavelength from an argon-krypton ion laser is an alternative. In regard to the red wavelength, the 647 nm of the krypton-ion laser offers high output power, important for large-format colour holograms.

2. Colour Hologram Recording

2.1 Recording setup

The Lake Forest College colour hologram recording setup is illustrated in Fig. 1. Three laser wavelengths are employed for the recording: 476 nm, provided by an argon ion laser; 531 nm, provided by a mixed argon-krypton ion laser; and 633 nm, provided by a helium-neon laser. Two dichroic filters are used in combining three colour-laser beams. The “white” laser beam goes through a spatial filter, and a colour reflection hologram is recorded with a Denisyuk geometry.

The hologram recording setup is arranged on an optical table. The lasers are installed on an independent vibration-isolation system isolated from the table surface with the Denisyuk hologram recording setup.

Using the dichroic filters in combining laser beams demonstrated multiple advantages compared to the previous beam-combining mechanism with movable mirrors. Without changing mirror positions between exposures, the dichroic filter approach shortens and simplifies the exposure procedure tremendously. The light intensity and RGB ratio on the recording plane remain undisturbed after the setting. Therefore, the check-up and calibration between hologram recordings are not absolutely necessary. The improvement manifests more significantly when producing large quantity colour holograms. Besides the simplification and convenience, the most important novelty of using the dichroic filter beam combination is to perform *simultaneous* exposure recording. In contrast to the *sequential* exposure method used before, the simultaneous exposure approach makes it possible to independently control the light RGB ratio and overall exposure energy in the emulsion. The light RGB ratio can be varied by changing the power outputs of the lasers, while the overall exposure energy is controlled solely by the exposure time. A specially designed test object consisting of the 1931 CIE chromaticity diagram, a rainbow ribbon cable, pure yellow dots, and a cloisonné elephant, was used for the colour balance adjustments and exposure tests.

To record holograms with deep scenes, long coherence is absolutely required from all wavelengths. The usual method of ascertaining single mode operation of a laser is to monitor its output with a scanning Fabry-Perot interferometer. Although this instrument is available in our laboratory, it has a specified set of mirrors for one specific wavelength (488 nm). Due to its small, free spectral range, this instrument cannot be used for other wavelengths that we actually used. Furthermore, severe problems in mode hopping were experienced, early in our experiment, in the HeNe laser due to the lack of temperature control in its etalon.

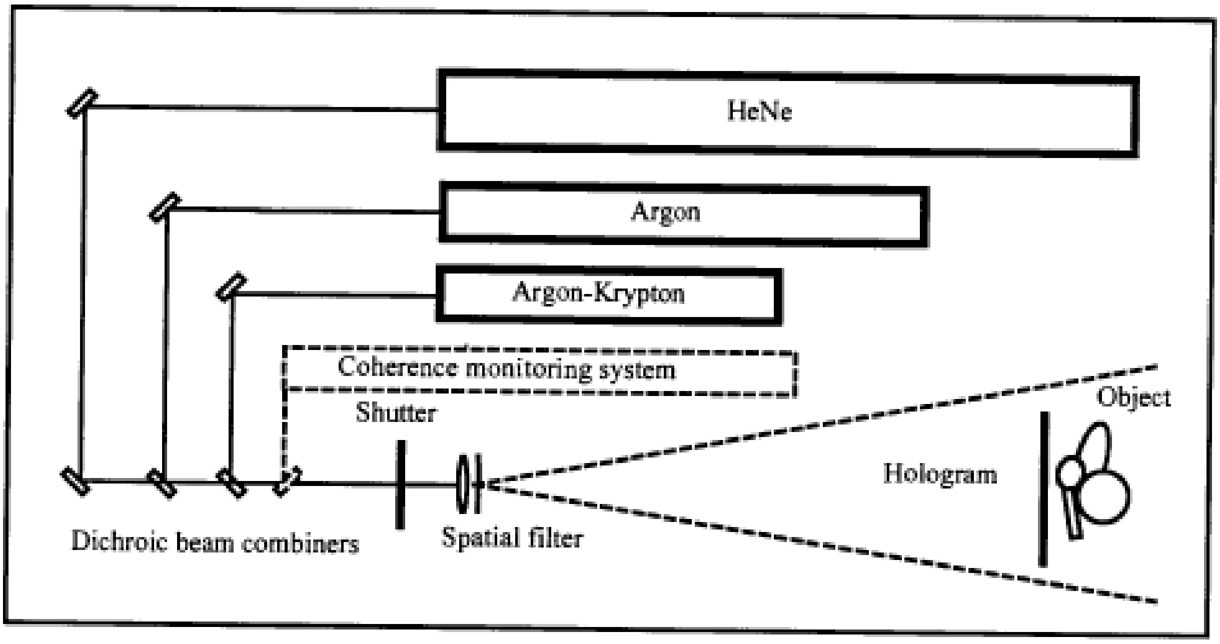

Fig. 1. The setup for recording colour holograms at Lake Forest College.

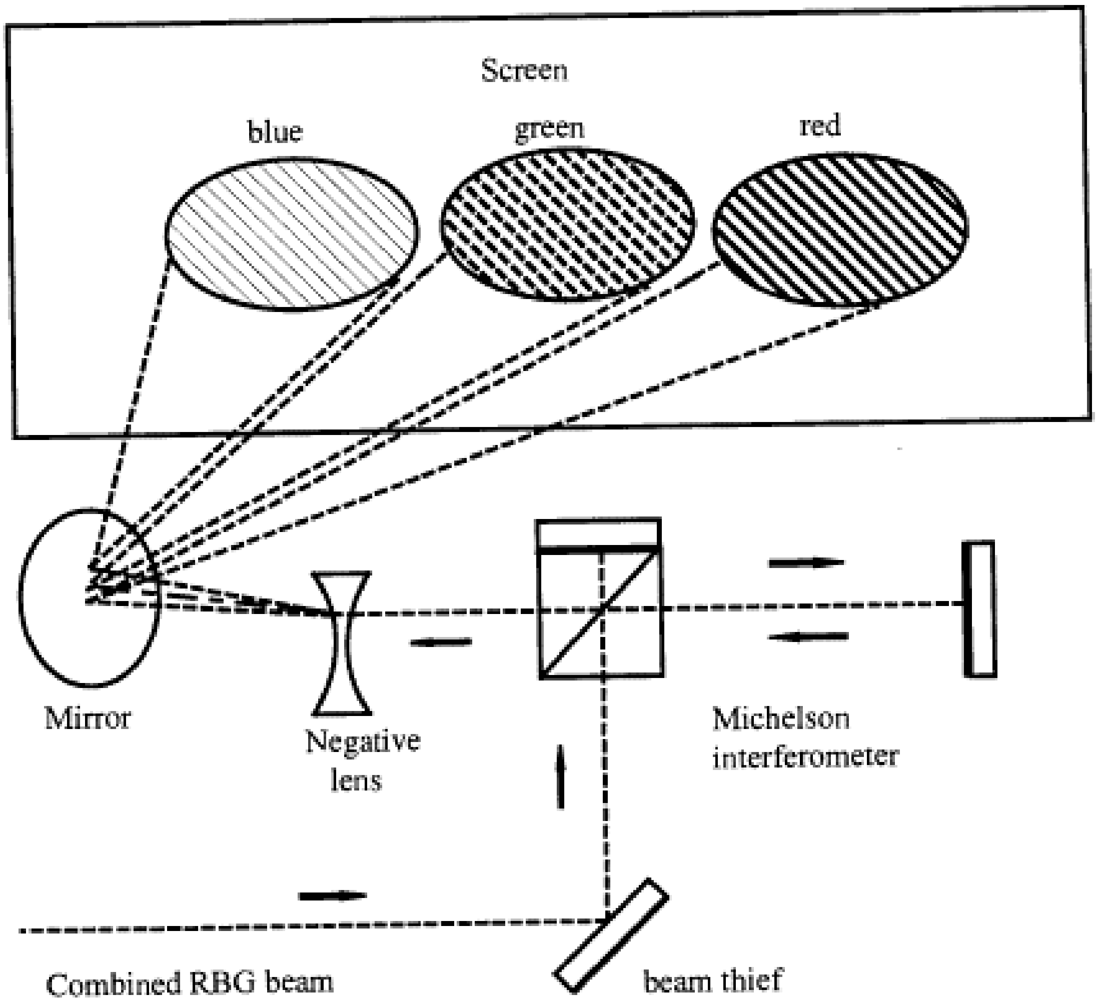

Fig. 2. Coherence monitoring system.

In order to be certain that each wavelength is operating in a single axial mode at a constant power output, a novel scheme was devised, as shown in Figure 2. To constantly monitor both the output and the temporal coherence of all the light, a glass wedge is placed before the shutter, at a small angle of incidence. Thus, each of the two surfaces on the wedge reflects about 5-6% of the incident light. One of these reflected beams is used by power monitoring; the other is reflected by a mirror into a classical Michelson interferometer. The two mirrors of the interferometer are adjusted to have an optical path difference of approximately one meter. The recombined beam at the beamsplitter is directed to a first-surfaced concave mirror, which directed the spread-out interference pattern onto a screen. This system makes it possible to observe the contrast of the interference pattern as well as the power output of the laser wavelengths.

Russian PFG-03c silver halide emulsion is selected for recording colour holograms. It has been demonstrated that this colour-sensitised, ultra-high resolution, single-layer emulsion coated on glass plate is one of the most successful recording materials for colour holography. The RGB sensitivity values of the recording plate are determined experimentally. Using the simultaneous exposure approach, the overall energy density for exposure is about 4 mJ/cm^2.

This system makes it possible to observe the contrast of the interference pattern as well as the power output of the laser wavelengths.

2.2 Processing of colour holograms

The processing of the plates is critical. The emulsion is rather soft, and it is important to harden the emulsion *before* the development and bleaching takes place. Emulsion shrinkage and other emulsion distortions caused by the active solutions used for the processing must be avoided. In particular, recording master colour holograms intended to be used for photopolymer replication, shrinkage control is extremely important. The general processing of SLAVICH colour holograms has been reported previously.[6] The processing steps are summarised in Table 2.

1.	Tanning in a Formaldehyde solution	6 min
2.	Short rinse	5 sec
3.	Develop in the CWC2 developer	3 min
4.	Wash	5 min
5.	Bleach in the PBU-amidol bleach	~5 min
6.	Wash	10 min
7.	Soak in acetic acid bath	1 min
8.	Short rinse	1 min
9.	Wash in distilled water with wetting agent added	1 min
10.	Air dry the holograms	

Table 2. Colour holography processing steps.

Some modifications have been introduced in order to produce holograms without any shrinkage. Such colour holograms can be suitable as masters for mass production of colour holograms on photopolymer material. The photopolymer materials from DuPont have a shrinkage of about 5% after processing making these materials less suitable for colour hologram mastering.

3. RESULTS

The new as well as previously recorded colour holograms of the two test targets have been evaluated using the PR-650 Photo Research SpectraScan SpectraCalorimeter. The illuminating spotlight to reconstruct the colour holograms was a 12-Volt 50-Watt Phillips halogen type 6438 GBJ lamp. This type of spotlight is normally used for the display of colour holograms. The particular lamp used to reconstruct a colour hologram is much more critical than lamps for monochrome hologram display. The colour balance during the recording of a colour hologram is determined by the type of spotlight that is going to be used for the display of the finished hologram. Figure 3 shows the spectrum from such a lamp.

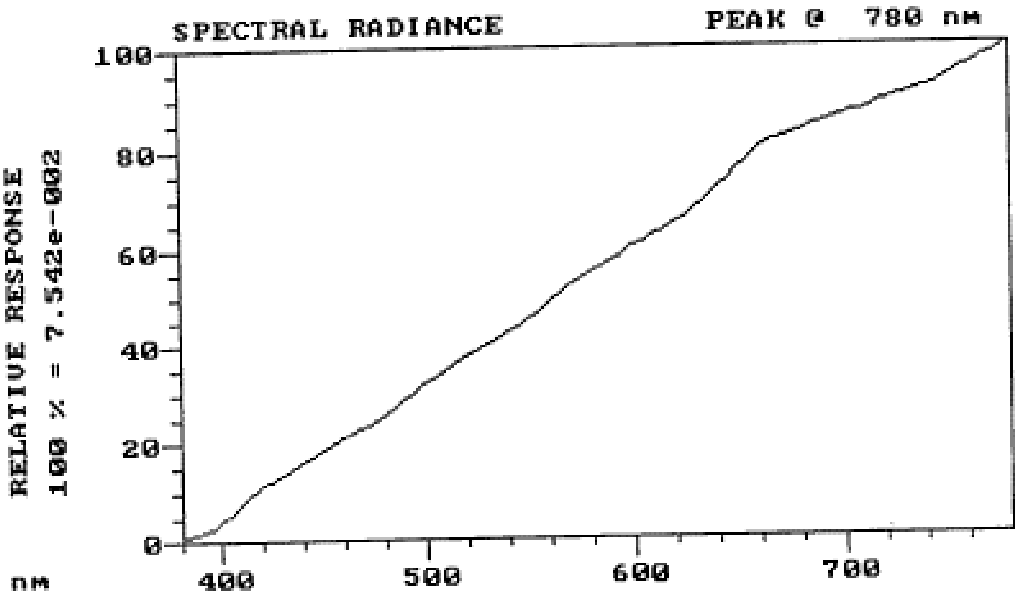

Fig. 3. Spectrum from a Phillips halogen type 6438 GBJ lamp

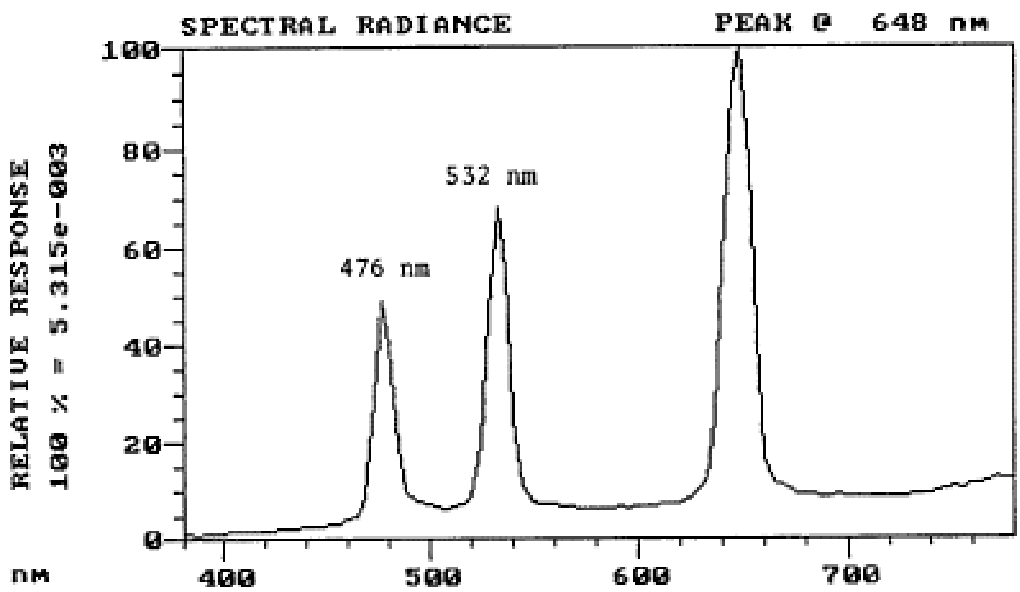

Fig. 4. Spectrum from a white area of a colour hologram without normalising the illuminating source spectrum.

Figure 4 is a typical spectrum from a white area of the colour test target colour hologram without normalising the illuminating source spectrum. Figure 5 shows the normalized spectrum, which means that the diffraction efficiency for each colour component is obtained assuming a flat spectrum of the illuminating source. The noise level, mainly in the blue part of the spectrum, is visible and low. The measured hologram is processed in such a way that no shrinkage has occurred. The three peaks are exactly at the recording wavelengths; i.e., 647 nm, 532 nm, and 476 nm.

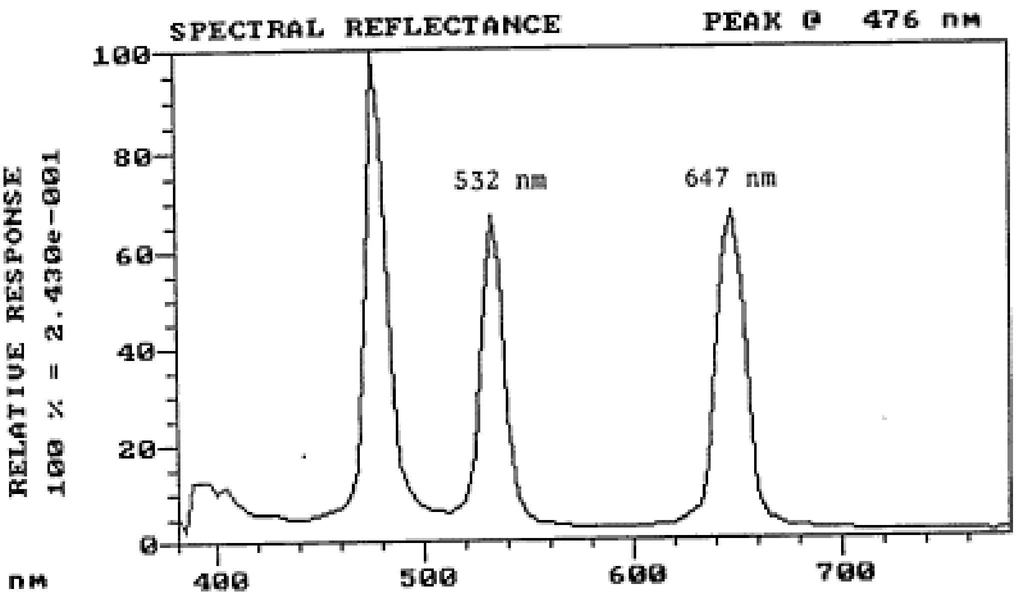

Fig. *5.* Normalised spectrum from a white area of a colour test target hologram.

In Table 3 some results of the Macbeth ColorChecker® investigation are presented. The 1931 C.I.E. x and y coordinates are measured at both the actual target and the holographic image of the target. The measured fields are indicated in the table by colour and the corresponding field number.

Object	White #19	Blue #13	Green #14	Red #15	Yellow #16	Magenta #17	Cyan #18
CIE x y	x/y	x/y	x/y	x/y	x/y	x/y	x/y
Target	.435/.405	.295/.260	.389/.514	.615/.335	.517/.450	.524/.322	.285/.380
Image	.354/.419	.335/.362	.337/.449	.476/.357	.416/.437	.448/.338	.295/.366

Table 3. Chromaticity coordinates from colour hologram recording tests using the Macbeth ColorChecker®

Colour prints of colour holograms are presented in Figures 6 and 7. The photographs of the reconstructed colour holograms were recorded using the above-mentioned halogen spotlight, positioned at the correct distance from the hologram and illuminating the hologram at the correct angle according to the recording geometry.

In Fig. 6a a photographic print of the Macbeth ColorChecker® is shown, and Fig. 6b shows the colour hologram of it. Both photographs were recorded using the same negative colour film and the same illuminating spotlight. In addition, a recent 4" x 5" colour hologram is featured in Fig. 7: a fish brooch.

PAGE FOR COLOUR PLATES IF INCLUDED

4. DISCUSSION AND CONCLUSION

The problem of emulsion shrinkage and the resulting wavelength shift, as well as the colour desaturation problems, make holographic colour reproduction difficult. The white-light reconstruction of a colour hologram shows a decreased signal-to-noise ratio and an increased bandwidth, compared to the wavelengths used at the recordings. Desaturation is caused primarily by noise, but partly by the increased bandwidth. Although good colour rendition can be obtained, problems connected with colour desaturation still remain to be solved. In a recent paper, Phillips has treated the colour saturation issue[14].

The development process has been further improved in order to avoid emulsion shrinkage and non-uniform development. Other limitations concerning the recording of colours in a hologram include the fact that some of the colours we see are the result of fluorescence which cannot be recorded in a hologram. There are some differences in the recorded colours of the Macbeth colour test chart. However, colour rendition is a very subjective matter. Different renditions may be preferred for different applications, and different people may have varied colour preferences.

At the present time, the research on processing colour reflection holograms recorded on ultra-high-resolution materials is still in progress. We are working on techniques to increase diffraction efficiency by SHSG processing. SHSG means silver-halide sensitized gelatin and represents a method for converting the silver-halide hologram into a dichromated gelatin-type hologram.

An alternative to silver-halide material for colour holograms is the new colour holographic photopolymer from E.I. du Pont de Nemours & Co.[15-18] The monochrome materials (OmniDex®) are commercially available, but the panchromatic materials are still in the development phase. Photopolymer film can become a very suitable recording material for mass replication by contact-copying colour holograms and colour HOEs from silver-halide masters.

The virtual colour image behind a Denisyuk holographic plate represents the most advanced image of an object that can be obtained today. The large field of view adds to the realistic illusion of viewing an image which will really not differ from viewing the actual object. The wavefront reconstruction process recreates accurately the three-wavelength light scattered from the object during the recording of the colour hologram. Such an imaging technique will have many obvious applications; in particular, for displaying unique and expensive artifacts. There are also many potential commercial applications of this new feature of holography. Finally, holography may well become the next century's new and highly recognized imaging technology that is much more than a gimmick or security product. Computer-generated images of this type would make it possible to display extremely realistic full parallax 3D images of non-existing objects, which would have its unique applications; e.g., product prototyping, as well as other applications in 3D visualisation and for three-dimensional art.

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