Super-realistic-looking images based on colour holography and Lippmann photography

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Abstract

Two imaging techniques will be presented which can create remarkable images. The first technique is colour holography, which provides full parallax 3D colour images with a large field of view. The virtual colour image recorded in a holographic plate represents the most realistic-looking image of an object that can be obtained today. The extensive field of view adds to the illusion of beholding a real object rather than an image of it. In connection with the presentation, colour holograms will be shown, including the artist Anaït's Flag colour hologram.

The other technique is interferential colour photography or Lippmann photography. This almost forgotten one-hundred-year-old photographic technique is also remarkable. It is the only colour recording imaging technique which can record the entire visible colour spectrum. It is not based on Maxwell's tri-colour principle, the dominating principle behind most current colour imaging techniques. The natural colour rendition makes this 2D photographic technique very interesting. For example, the reproduction of human skin and metallic reflections are very natural looking, not possible to record in ordinary photography. Examples of Lippmann photographs will be on display during the presentation.

Introduction

There is an interest in high-fidelity image recording techniques with perfect colour rendition, which can also accurately capture the three-dimensional shape of an object. As regards colour rendition, Lippmann photography is the only imaging technique that directly can record the entire colour spectrum of an object or a scene. Holography can record and store laser light scattered off an object. The scattered light can be reconstructed by illuminating the holographic plate with the reference light which creates a full parallax 3D image, visible behind the plate. The technique of recording holograms using three (red, green, and blue) laser wavelengths provides extremely realistic-looking 3D images.

After the invention of black-and-white photography in the 19th century, there was a lot of interest in finding ways of recording natural colour photographs. The somewhat difficult but very interesting interferential photographic technique provided such images in 1891. Lippmann photography shows similarities to holography. In both cases an interference structure is recorded in a fine-grain emulsion. The fundamental difference is that, in the Lippmann case, there is *no phase recording* involved; the recorded interference structure is a result of *phase-locking* the light by the reflecting mirror. In holography, the *phase information is actually recorded*, being encoded as an interference pattern created between the light reflected from the object and a coherent reference beam. The recording of monochromatic light in a Lippmann photograph is easy to understand, and it is very similar to recording a reflection volume hologram. A broadband polychromatic spectrum, such as a landscape image, is very different. In this case, the recorded interference structure in the emulsion is located only very close to the surface of the emulsion in contact with the reflecting mirror. A colour reflection hologram, on the other hand, is a result of the three-colour RGB process involving three monochrome recordings superimposed in the same emulsion. In the following both imaging techniques will be described and how to obtain the most realistic-looking 3D and 2D images.

Colour Holography

After 40 years since the appearance of the first laser-recorded monochromatic holograms the possibilities of recording full-colour high-quality holograms have now become a reality. What is referred to here, is the technique to obtain a colour 3D image of an object where the colour rendition is as close as possible to the colour of the real object. In theory, the first methods for recording colour holograms were established in the early 1960s. Already in 1964 Leith and Upatnieks proposed multicolour wavefront reconstruction in one of their first papers on holography.[1] The early methods concerned mainly *transmission* holograms recorded with three different wavelengths from a laser or lasers, combined with different reference directions to avoid cross-talk. The color hologram was then reconstructed by using the original laser wavelengths from the corresponding reference directions. However, the complicated and expensive reconstruction setup prevented this technique from becoming popular. More suitable for holographic colour recording is *reflection* holography. A reflection hologram can be reconstructed and viewed in ordinary white light from a spotlight. Over the last few years many high-quality colour holograms have been recorded mainly due to the introduction of new and improved panchromatic recording materials. On the market are the Slavich[2] ultrafine-grain silver halide emulsions as well as photopolymer materials, manufactured by E.I. du Pont de Nemours & Co.[3]

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. Before panchromatic emulsions existed the sandwich technique was used to make colour reflection holograms. Two plates were sandwiched together, in which, e.g., two different types of recording materials were used. The most successful demonstration of the sandwich recording technique was made by Kubota[4] in Japan. He used a dichromated gelatin plate for the green (515 nm) and the blue (488 nm) components, and an Agfa 8E75 silver halide plate for the red (633 nm) component of the image. Not until panchromatic ultrafine-grain silver halide emulsions were introduced in Russia in the early nineties it was possible to record high-quality colour holograms in a single emulsion layer as demonstrated by Bjelkhagen *et al*.[5]

Recording Materials

Silver halide materials

To be able to record high-quality colour reflection holograms it is necessary to use extremely low light-scattering recording materials. This means, for example, the use of ultrafine-grain silver halide emulsions (grain size about 10 nm). Currently the main commercial producer of such a material is the Slavich company. Some characteristics of the Slavich material are presented in Table 1.

Table 1. Characteristics of the Slavich emulsion**.**

Silver halide material	PFG-03c
Emulsion thickness	7 µm
Grain size	12 - 20 nm
Resolution	~10000 lp/mm[1]
Blue sensitivity	~1.0 - $1.5 \cdot 10^{-3}$ J/cm^2
Green sensitivity	~1.2 - $1.6 \cdot 10^{-3}$ J/cm^2
Red sensitivity	~0.8 - $1.2 \cdot 10^{-3}$ J/cm^2
Colour sensitivity peaked at:	633 nm, and 530 nm

In France, Gentet is manufacturing a new panchromatic silver halide emulsion with extremely fine grains. It is called the *Ultimate* emulsion.[6] Although impressive colour holograms have been recorded by Gentet, there is a question whether it is possible to accurately record blue colour in the Ultimate plates. Gentet's displayed holograms have, so far, shown red and green objects with a hint of blue only. Blue is the most difficult colour to record in a silver halide emulsion. By avoiding blue it is easy to record holograms with very low light scattering, which means that a very high signal-to-noise ratio can be obtained. Nevertheless Gentet has shown that it is possible to improve silver halide emulsions for holographic recordings. Slavich plates are by no means at the limit of silver halide emulsion technology. Unfortunately the highest-quality Ultimate colour emulsion is not for sale, it is reserved for Gentet's own holograms.

Photopolymer materials

The panchromatic photopolymer material from DuPont is an alternative recording material for colour holograms. Although, being less sensitive than the ultrafine-grain silver halide emulsions, it has its special advantages of easy handling and *dry* processing (only UV-curing and baking.) The colour photopolymer material needs an overall exposure of about 10 mJ/cm^2. After the exposure is finished, the film has to be exposed to strong white or UV light; about 100 mJ/cm^2 exposure at 350-380 nm. After that, the hologram is put in an oven at a temperature of 120^{o}C for two hours in order to increase the brightness of the image. Recently DuPont announced that their materials will no longer be on the market. DuPont will be using the materials for their own production of holograms and HOEs. Only special customers working in the field of optical security may still be able to obtain DuPont photopolymer materials.

Laser Wavelengths for Colour Holograms

Choosing the correct recording wavelengths and the exact laser wavelengths is the key issue where accurate colour reproduction is concerned. So far most colour holograms have been recorded using three primary laser wavelengths, resulting in rather good colour rendition. However, some colours are not identical with the original colours and also *colour desaturation* (colour shifting towards white) is a problem.

Hubel and Solymar[7] provided a definition of colour recording in holography: "A holographic technique is said to reproduce 'true' colours if the average vector length of a standard set of coloured surfaces is less than 0.015 chromaticity coordinate units, and the gamut area obtained by these surfaces is within 40% of the reference gamut. Average vector length and gamut area should both be computed using a suitable white light standard reference illuminant."

One important consideration is the question of whether *three* laser wavelengths are really sufficient for accurate colour reproduction in holography. The wavelength selection problem has been discussed in several papers, for example, by Peercy and Hesselink.[8] They discussed the wavelength selection by investigating the sampling nature of the holographic process. During the recording of a colour hologram, the chosen wavelengths point-sample the surface-reflectance functions of the object. This sampling of colour perception can be investigated by the tristimulus value of points in the reconstructed hologram, which is mathematically equivalent to the integral approximations for the tristimulus integrals. Peercy and Hesselink used both Gaussian quadrature and Riemann summation for the approximation of the tristimulus integrals. In the first case they found the wavelengths to be 437, 547, and 665 nm and in the second case the wavelengths were 475, 550, and 625 nm. According to the above mentioned authors, the sampling approach indicates that three monochromatic sources will almost always be *insufficient* for the accurate preservation of all of the object's spectral information. The authors claim that four or even five laser wavelengths may be required. When using the relative weights from Gaussian quadrature, they obtained the following four wavelengths:

ë_1 = 424 nm, ë_2 = 497 nm, ë_3 = 598 nm, and ë_4 = 678 nm.

When the relative weights from Riemann summation were used, they obtained the following four wavelengths:

ë_1 = 460 nm, ë_2 = 520 nm, ë_3 = 580 nm, and ë_4 = 640 nm.

Peercy and Hesselink found that for a particular test scene and with four sampling wavelengths, Riemann summation performed significantly better than Gaussian quadrature.

Recently, Kubota *et al.*[9] presented a theoretical analysis of colour holography based on four recording wavelengths. Using the 1976 CIE chromaticity diagram, and by minimizing the distance between the selected object points in the diagram and the corresponding reconstructed image points, they were able to obtain four optimal laser wavelengths. The calculation was based on the nonlinear least square method. For the reproduction of nineteen selected colour patches of the Macbeth ColorChecker the following four wavelengths were obtained:

ë_1 = 459.1 nm, ë_2 = 515.2 nm, ë_3 = 585.0 nm, and ë_4 = 663.2 nm.

Using these wavelengths, the average distance between the actual points and the recorded image points was 0.0087 CIE 1976 chromaticity units. If the same calculation was performed using only three recording wavelengths the following wavelengths were obtained:

ë_1 = 462.7 nm, ë_2 = 528.0 nm, and ë_3 = 599.6 nm.

In this case the average distance between the actual points and the recorded image points was 0.015 CIE 1976 chromaticity units, which is twice larger than when four wavelengths are used. The four optimal wavelengths quoted in the paper by Kubota *et al.*[9] show good correlation with Peercy and Hesselink's wavelengths obtained when using Riemann summation.

Since it is difficult to find lasers which can provide the optimal four wavelengths in practice, Kubota *et al.*[9] suggested the following laser wavelengths to be employed:

ë_1 = 457.9 nm (Ar-ion), ë_2 = 514.5 nm (Ar-ion), ë_3 = 580.0 nm (dye laser), and ë_4 = 647.2 nm (Kr-ion).

It is obvious that by selecting the optimum four or even more laser recording wavelengths it is possible to record colour holograms with extremely good colour rendition. Hopefully, tuneable lasers may provide the desired wavelengths in the future. Only further experiments will show how accurately holographic colour reproduction can be performed in practice. Colour rendition is the most important issue here and the question is, whether colour holography can really provide an absolutely identical copy of the recorded object.

RGB laser wavelengths for colour holograms

Up until now most colour holograms have been recorded using only three laser wavelengths. Primary laser wavelengths are found in the 1976 CIE chromaticity diagram in Fig. 1.

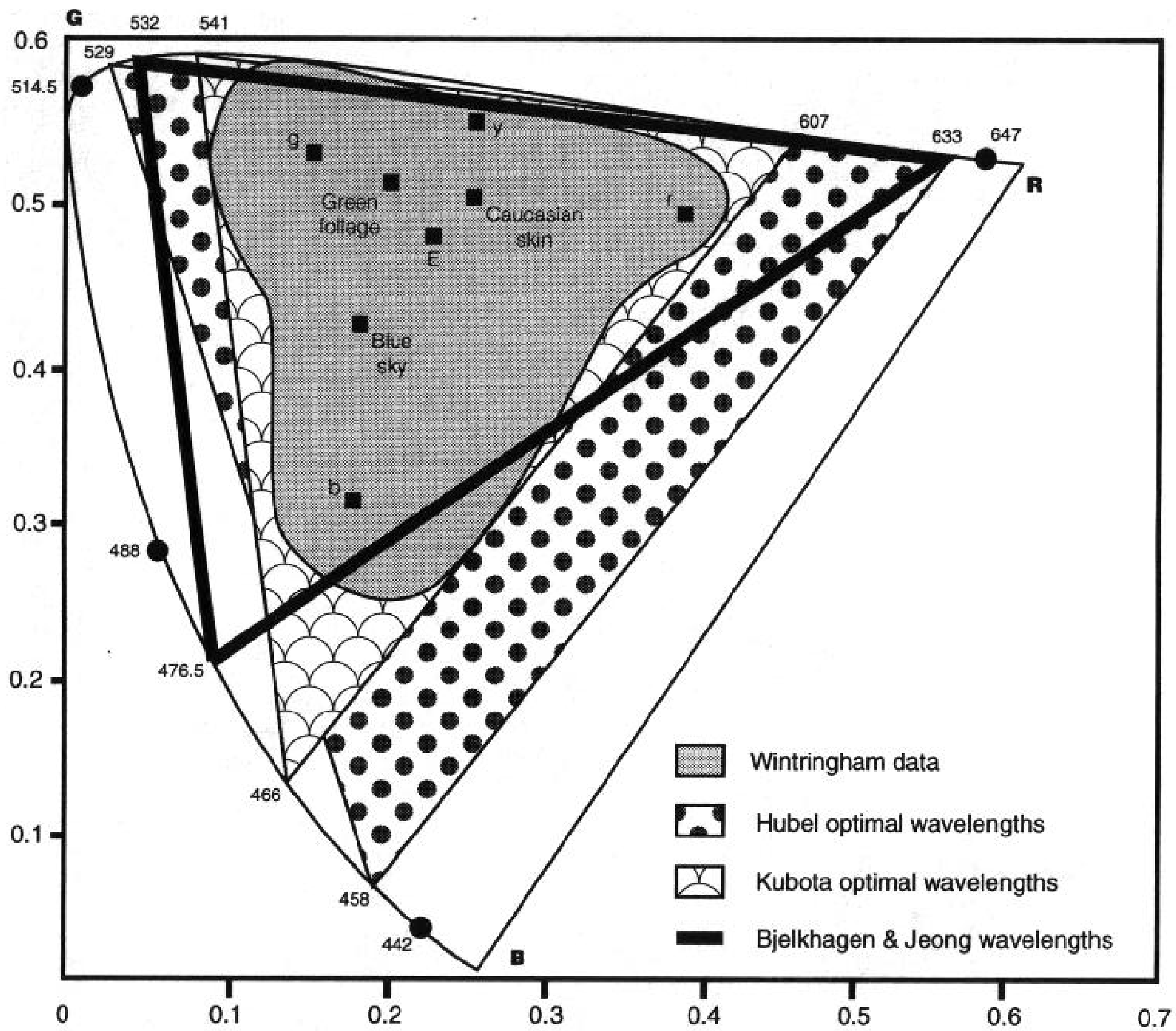

Figure 1. The 1976 CIE uniform scales chromaticity diagram shows the gamut of surface colours and positions of common laser wavelengths. Optimal colour-recording laser wavelengths are also indicated

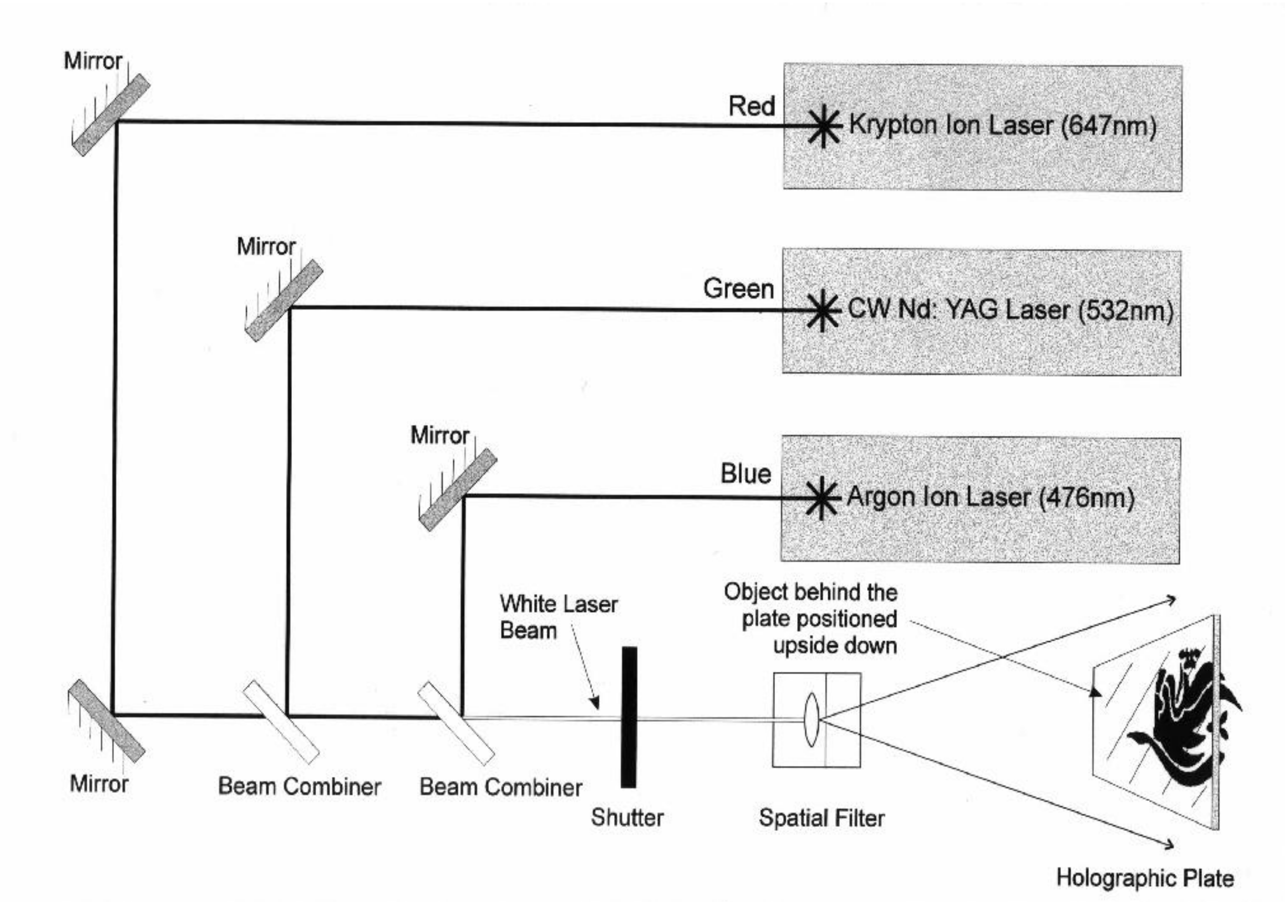

Figure 2. Setup for recording colour holograms

Recording Colour Holograms

Denisyuk setup for recording colour holograms

A typical reflection hologram recording setup is illustrated in Fig. 2. For most display purposes, the very large field of view obtainable in a single-beam Denisyuk hologram is very attractive. Therefore such a recording scheme is selected. The different laser beams necessary for the exposure of the object pass through the same beam expander and spatial filter. The light reflected from the object constitutes the object beam of the hologram. The reference beam is formed by the three expanded laser beams. This "white" laser beam illuminates both the holographic plate and the object itself through the plate. Each of the three primary laser wavelengths forms its individual interference pattern in the emulsion, all the patterns being recorded simultaneously during the exposure. In this way, three holographic images (a red, a green, and a blue image) are superimposed on one another in the emulsion. The three laser wavelengths used by the author are: 476 nm, provided by an argon ion laser, 532 nm, provided by a cw frequency-doubled Nd:YAG laser, and 647 nm, provided by a krypton ion laser. Two dichroic filters are used for combining the three laser beams. By using the dichroic filter beam combination technique it is possible to perform simultaneous exposure recording, which makes it possible to control independently the RGB ratio and the overall exposure energy in the emulsion. The RGB ratio can be varied by individually changing the output power of the lasers, while the overall exposure energy is controlled solely by the exposure time. The overall energy density for exposure is about 3 mJ/cm^2 for Slavich material.

Processing of colour holograms

The processing of holograms recorded in silver halide emulsions is of critical importance. The Slavich emulsion is rather soft, and it is important to harden the emulsion *before* development and bleaching take place. Emulsion shrinkage and other emulsion distortions caused by active solutions used for the processing of holograms must be avoided. The processing steps are summarized in Table 2. It is very important to employ a suitable bleach bath to convert the developed amplitude hologram into a phase hologram. The bleach must create an almost stain-free clear emulsion so as not to affect the colour image. In addition, *no emulsion shrinkage* can be permitted, as it would change the colours of the image. Washing and drying must also be done so that no shrinkage occurs. Finally, to prevent any potential emulsion thickness changes caused by variations in humidity, the emulsion needs to be protected by a glass plate being sealed onto the holographic plate.

Table 2: Colour holography processing steps.

1. Tanning in a Formaldehyde solution	6 min
2. Short rinse	5 sec
3. Development in the CWC2 developer	3 min
4. Wash	5 min
5. Bleaching in the PBU-amidol bleach	~5 min
6. Wash	10 min
7. Soaking in acetic acid bath (printout prevention)	1 min
8. Short rinse	1 min
9. Washing in distilled water with wetting agent added	1 min
10. Air drying	

Recorded Colour Holograms

A specially designed test object consisting of the 1931 CIE chromaticity diagram is used for the colour balance adjustments and exposure tests. The Macbeth ColorChecker chart is also often used for colour rendering tests. A recorded colour hologram of the CIE targets is presented in following. The spotlight used to reconstruct that hologram as well as all the other recorded holographic images was a 12-V 50-W halogen lamp. The colour balance for the recording of a colour hologram must be adjusted with what type of spotlight that is going to be used for the display of the finished hologram in mind. Figure 3 shows a typical normalized spectrum obtained from a white area of the colour test target hologram. One should note the high diffraction efficiency in blue, needed to compensate for the rather low blue light emission of the halogen spotlight. The noise level, mainly in the blue part of the spectrum, is visible and low. The three peaks are exactly at the recording wavelengths; i.e., 647, 532, and 476 nm. A reproduction of the CIE hologram is presented in Fig. 4.

A few examples of colour display holograms are shown in Figs. 5 – 7. In Fig. 5 a large Chinese Vase was recorded in a 30 cm x 40 cm glass plate. Figure 6 depicts a hologram of a little French house in a 4” x 5” plate and in Fig. 7, six Peking masks were recorded in another 4”x 5” Slavich plate.

In 1995 Anaït produced two interesting 8” by 10” colour holograms at Lake Forest College with assistance of the author. Two pseudoscopic objects were made by Anaït with the intention to have the reconstructed holographic images of the recorded objects to appear in front of the plate. One of her holograms is illustrated here: the *Flag* hologram, in Fig. 8. The other hologram recorded at Lake Forest College was the *Cave* hologram.

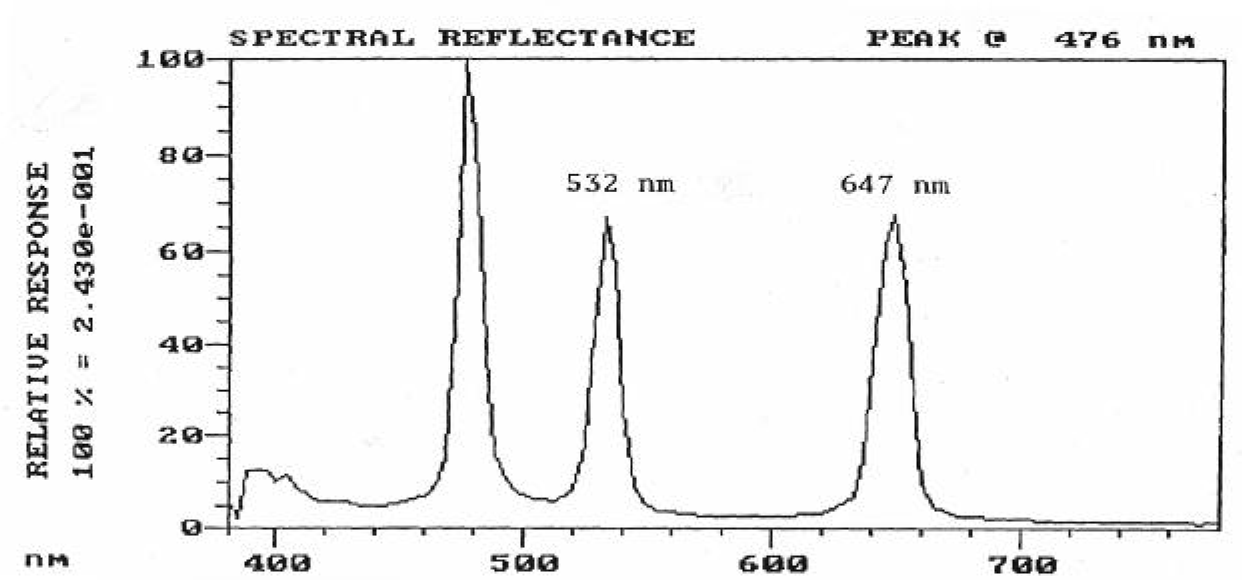

Figure 3. Normalized spectrum from a white area of a colour test target hologram

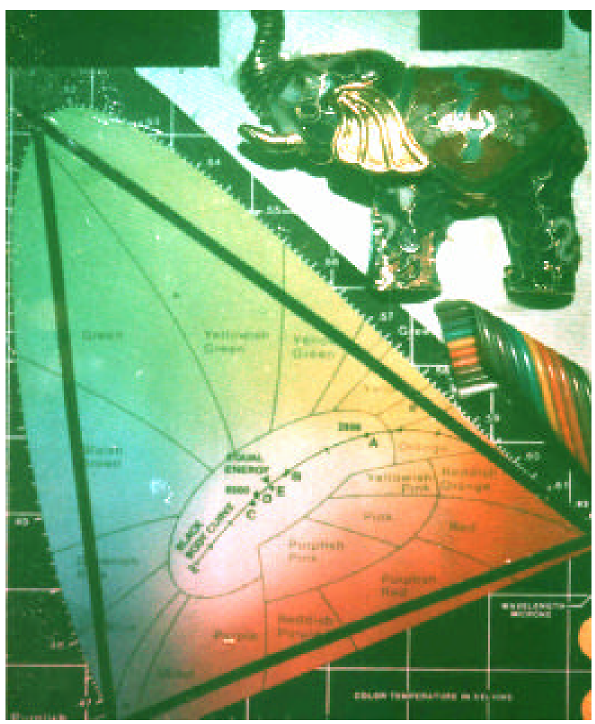

Figure 4. Hologram of the CIE test object recorded
with 476, 532, and 647 nm laser wavelengths

Figure 5. Chinese Vase, 30 cm x 40 cm plate

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Figure 6 . French House, 4" x 5" plate

Figure 8. The Flag colour hologram by Anaït, an 8”x 10” plate

Lippmann Photography

History and principle of interferential photography

Gabriel Lippmann (1845 - 1921) was able to record the first colour photographs for more than one hundred years ago. His technique has become known as *interferential photography* or *interference colour photography*. In 1891 Lippmann announced that he had succeeded in recording a true-colour spectrum.[10] A little more than one year later Lippmann displayed four colour photographs of different objects.[11] Although the new photographic colour recording technique, also known as Lippmann photography, was extremely interesting from a scientific point of view, it was not very effective for colour photography since the technique was complicated and the exposure times were too long for practical use. The difficulty in viewing the photographs was another contributing factor, in addition to the copying problem, which prevented Lippmann photography from becoming a practical photographic colour-recording method. However, one-hundred-year-old Lippmann photographs are very beautiful and the fact that the colours are so well preserved indicates something about their archival properties. Lippmann was awarded the Nobel Prize in physics for his invention in 1908.

The principle of Lippmann photography is shown in Fig. 9. Because of the demand for high resolving power in making Lippmann photographs, the material had to be a very fine-grain emulsion and thus of very low sensitivity. The coating of emulsion on Lippmann plates was brought in contact with a highly reflective surface, mercury, reflecting the light into the emulsion and then interfering with the light coming from the other side of the emulsion. The standing waves of the interfering light produced a very fine fringe pattern throughout the emulsion with a periodic spacing of ë/(2n) that had to be recorded (ë is the wavelength of light in air and n is the refractive index of the emulsion). The colour information was stored locally in this way.

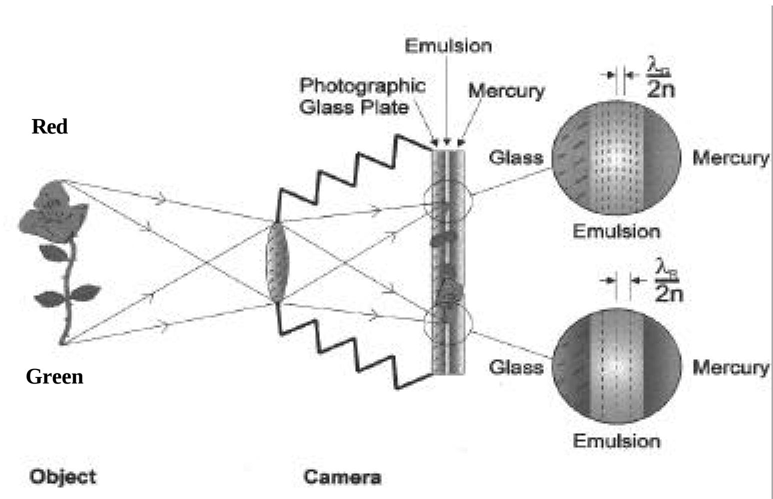

Figure 9. The principle of Lippmann photography

The larger the separation between the fringes, the longer was the wavelength of the recorded part of image information. This is only correct when rather monochromatic colours are recorded. A polychrome recording is more complex, and was first mathematically treated by Lippmann.[12]

When the developed photograph was viewed in white light, different parts of the recorded image produced different colours. This was due to the separation of the recorded fringes in the emulsion. The light was reflected from the fringes, creating different colours corresponding to the original ones that had produced them during the recording. In order to observe the correct colours, the illumination and observation have to be at normal incidence. If the angle changes, the colours of the image will change. This change of colour with angle, known as iridescence, is of the same type as found in peacock feathers and mother of pearl. The image is recorded as a Bragg structure.

There was very little interest in making silver-halide plates of the Lippmann type after this type of photography disappeared. However, the need for such plates came back when holography started to become popular in the early 1960s. Recent progress in development of colour holography has opened up new possibilities to investigate Lippmann photography again. Using new and improved panchromatic recording materials (silver-halide and photopolymer) combined with special processing techniques for colour holograms have made it possible to record interference colour photographs.

Modern Lippmann photography

Lippmann photography shows similarities to holography. In both cases an interference structure is recorded in a fine-grain emulsion as a b/w pattern. To some extent, a Lippmann photograph can be regarded as a reflection image-plane hologram recorded with light of very short temporal coherence. The reference wave is a diffuse complex wavefront (the mirror image of the exit pupil of the recording lens.)

The recording of monochromatic light in a Lippmann emulsion is easy to understand, and it is very similar to recording a reflection volume hologram. A broadband polychromatic spectrum, such as a landscape image, is very different. In this case, the recorded interference structure in the emulsion is located only very close to the surface of the emulsion in contact with the reflecting mirror. Bjelkhagen *et al.*[13] and Bjelkhagen[14-16] demonstrated the possibility to record Lippmann photographs in Slavich PFG-03c panchromatic holographic emulsion. To record Lippmann photographs, it is not necessary to use mercury as the light reflector. The gelatin-air interface can act as a reflector of light. The plate is inserted in a conventional dark slide with the *emulsion side facing away* from camera lens. Inside the adapter, black velvet is attached in order to reduce scattered light. When the plate is exposed without mercury, the exposure time is slightly increased compared to a recording with a mercury reflector.

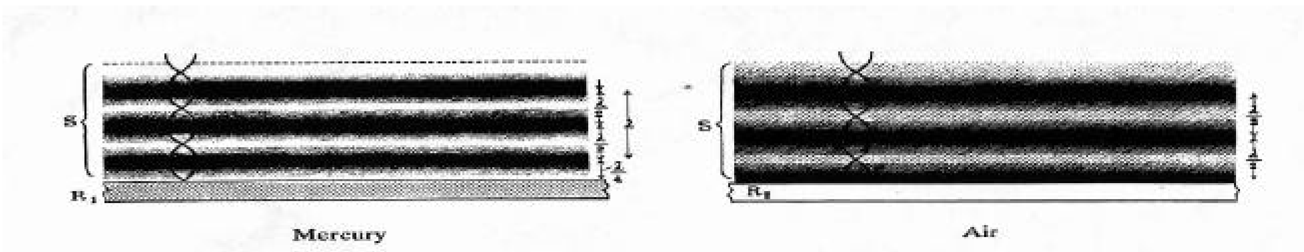

Figure 10. Light reflected at an optically thicker medium (mercury, R_1) and at an optically thinner medium (air, R_2). S is the gelatin emulsion.

The reason why it is possible to obtain a Lippmann photograph without mercury can be explained in the following way. One must study the difference between a reflection at the mercury surface or obtained at the gelatin-air interface, illustrated in Fig. 10. A node is located at the mercury reflector (an optically thicker medium than gelatin), which means at the gelatin surface. The phase shift there is . On the contrary, a crest is located at the surface when the reflection is obtained from the gelatin-air interface (an optically thinner medium than gelatin), which means, since no phase shift occurs in this case, a silver layer will be created at the emulsion surface after development. In the mercury case the first silver layer is located at a distance of ë/4 inside the gelatin emulsion. When using air reflection, the exposure must be slightly increased to bring the recording up on the linear part of the Hurter-Driffield curve. The weaker fringe modulation caused by the Fresnel reflection at the air-gelatin interface is amplified in the developing process. The problem, pointed out by Wiener, about the surface reflection being out of phase with the image when viewing a Lippmann photograph only exists in the mercury case. When using the air reflector, the surface reflection is in phase with the image.

The processing of the Lippmann photographs is critical. The interference pattern is recorded only in a very thin volume at the top of the emulsion. This area has to be maintained intact after processing. Emulsion shrinkage and other emulsion distortions caused by the developer must be avoided. Among the old Lippmann developers, the Lumière pyrogallol-ammonia developer give good results. To avoid shrinkage the plates are not fixed, only washed after development.

A recorded Lippmann photograph is a portrait of the author reproduced in Fig.11. The exposure time was two minutes at aperture F:4 using an Auto Graflex 4" by 5" camera equipped with a Kodak Aero Ektar F:2.5, 178 mm lens. After being processed, the back of the plate was painted black. For better viewing of the image, a wedged glass plate (Wiener prism) was cemented to the emulsion side, as for old Lippmann photographs. The reproduction of human skin is remarkable realistic in a Lippmann photograph. Also metallic reflections are accurately recorded.

Conclusions

Large-format colour reflection holograms can be recorded with rather good colour rendition. However, further improvements are needed, e.g., as regards colour saturation, image resolution, signal-to-noise ratio, dynamic range. Employing emulsions with a grain size less than 10 nm and four recording laser wavelengths will soon make it possible to make a holographic image that would not be possible to distinguish from the object itself. The virtual colour image behind a holographic plate represents the most realistic-looking image of an object that can be recorded today. This perfect 3D imaging technique has many obvious applications, e.g., for displaying unique and expensive artefacts as well as in advertising.

Modern Lippmann photography may have limited applications in photography and colour imaging, but may very well appeal to artists and art photographers. The Lippmann photograph is virtually impossible to copy, which makes it a unique, one of its kind, photographic recording combined with extremely high archival stability. Since the quality of a Lippmann photograph mainly depends on the recording material, special isochromatic ultrafine-grain emulsions are absolutely necessary in order to record absolute correct colour photographs. The holographic plates used here are not really designed for Lippmann photography and thus it is not possible to demonstrate the perfect quality that theoretically can be obtained with interferential colour imaging.

Figure 11. Lippmann portrait of the author

References

1. E. N. Leith and J. Upatnieks, "Wavefront reconstruction with diffused illumination and three-dimensional objects," *J. Opt. Soc. Am.* **54**, pp. 1295-1301, 1964.
2. S. J. Zacharovas, D. B. Ratcliffe, G. R. Skokov, S. P. Vorobiov, P. I. Kumonko, and Yu. A. Sazonov, "Recent advances in holographic materials from Slavich," in *HOLOGRAPHY 2000*, T. H. Jeong, and W. K. Sobotka, eds., Proc. SPIE **4149**, pp. 73-80, 2000.
3. M. Watanabe, T. Matsuyama, D. Kodama, and T. Hotta, "Mass-produced color graphic arts holograms," in *Practical Holography XII*, S. A. Benton, ed. Proc. SPIE **3637**, pp. 204-212, 1999.
4. T. Kubota, "Recording of high quality color holograms," *Appl. Opt.* **25**, pp. 4141-4145, 1986.
5. H. I. Bjelkhagen, T. H. Jeong, and D. Vukièeviæ, "Color reflection holograms recorded in a ultrahigh-resolution single-layer silver halide emulsion," *J. Imaging Sci. Technol.* **40**, pp. 134-146, 1996.
6. Y. Gentet and P. Gentet,""Ultimate" emulsion and its applications: a laboratory-made silver halide emulsion of optimized quality for monochromatic pulsed and full color holography," in *HOLOGRAPHY 2000*, T. H. Jeong and W. K. Sobotka, eds., Proc. SPIE **4149**, pp. 56-62, 2000.
7. P. M. Hubel and L. Solymar, "Color reflection holography: Theory and experiment," *Appl. Opt.* **30**, pp. 4190-4203, 1991.
8. M. S. Peercy and L. Hesselink, "Wavelength selection for true-color holography," *Appl. Opt.* **33**, pp. 6811-6817, 1994.
9. T. Kubota, E. Takabayashi, T. Kashiwagi, M. Watanabe, and K. Ueda, "Color reflection holography using four recording wavelengths," in *Practical Holography XV and Holographic Materials VII*, S. A. Benton, S. H. Stevenson, and T. J. Trout, eds., Proc. SPIE **4296**, pp. 126-133, 2001.
10. G. Lippmann, "La photographie des couleurs," *C. R. Hebd. Séances Acad. Sci.* **112**, pp. 274-275, 1891.
11. G. Lippmann, "La photographie des couleurs [deuxième note]," *C. R. Hebd. Séances Acad. Sci.* **114**, pp. 961-962, 1892.
12. G. Lippmann, "Sur la théorie de la photographie des couleurs simples et composées par la méthode interférentielle," *J. Physique* **3** (3), pp. 97-107, 1894.
13. H. I. Bjelkhagen, T. H. Jeong, and R. J. Ro, "Old and modern Lippmann photography," in *Sixth Int'l Symposium on Display Holography*, T. H. Jeong, ed., Proc. SPIE **3358**, pp. 72-83, 1998.
14. H. I. Bjelkhagen, "Lippmann photographs recorded in DuPont color photopolymer material," in *Practical Holography XI and Holographic Materials III*, S. A. Benton and T. J. Trout, eds., Proc. SPIE **3011**, pp. 358-366, 1997.
15. H. I. Bjelkhagen, "New optical security device based on one-hundred-year-old photographic technique," *Opt. Eng.* **38**, pp. 55-61, 1999.
16. H. I. Bjelkhagen, "Lippmann photography: reviving an early colour process," *History of Photography* **23**, pp. 274-280, 1999.