Lippmann Photography and Color Holography: 2-D and 3-D Color Imaging Techniques

Hans I. Bjelkhagen
De Montfort University
Leicester, England, United Kingdom

Abstract

At the end of the 19th century, Gabriel Lippmann was experimenting with color photography. His photographic color recording technique, Lippmann photography, produced very beautiful photographs and the fact that the colors are preserved in the early Lippmann photographs indicates something about their archival properties. Recent progress in color reflection holography has made it possible to take a new look at this one-hundred-year-old photographic technique. Today, high-resolution panchromatic recording materials suitable for Lippmann photography are on the market. Both silver halide and photopolymer materials can be used.

Reflection color holography provides full parallax 3-D color images with a large field of view. By the introduction of extremely high-resolution panchromatic silver halide emulsions it has become possible to obtain high-quality, large-format color holograms. The use of three laser wavelengths on a single-layer emulsion and a Denisyuk setup in the recording process makes the holographic recording technique similar to the early Lippmann photography technique. Due to the fact that no dyes or pigments are used in the emulsion of the final hologram, high archival color stability of the holographic image can be predicted.

Introduction

There is an interest in image recording techniques with perfect color rendition and that can capture the three-dimensional shape of objects. As regards color rendition, Lippmann photography is the only imaging technique that directly can record the entire color spectrum of an object or 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 3-D image, visible behind the plate. So far, the majority of holograms have been mono-chromatic, i.e., recorded with a single-wavelength laser only. However, for most 3-D imaging purposes, a monochromatic image is not sufficient. Therefore, the technique of recording holograms using red, green, and blue laser wavelengths provides extremely realistic 3-D images. After the invention of black-and-white photo-graphy in the 19th century, there was a lot of interest in finding ways of recording natural color photographs. The somewhat difficult but very interesting interferential photo-graphic technique provided such images in 1891.

Lippmann Photography

Gabriel Lippmann (1845 - 1921) was able to record colors as standing light waves in an emulsion. His technique has become known as *interferential photography* or *interference color photography*. In 1891 Lippmann announced that he had succeeded in recording a true-color spectrum.[1] A little more than one year later Lippmann displayed four color photographs of different objects.[2]

Lippmann developed the first theory of recording monochromatic and polychromatic spectra.3 He applied Fourier mathematics to optics, which was a new approach at that time. Although the new photographic color recording technique, also known as Lippmann photography, was extremely interesting from a scientific point of view, it was not very effective for color 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 color-recording method. However, one-hundred-year-old Lippmann photographs are very beautiful and the fact that the colors 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 Figure 1. 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 $\lambda/(2n)$ that had to be recorded (λ is the wavelength of light in air and n is the refractive index of the emulsion). The color information was stored locally in this way. 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 mono-chromatic colors are recorded. A polychrome recording is more complex, and was first mathematically treated by Lippmann.[3]

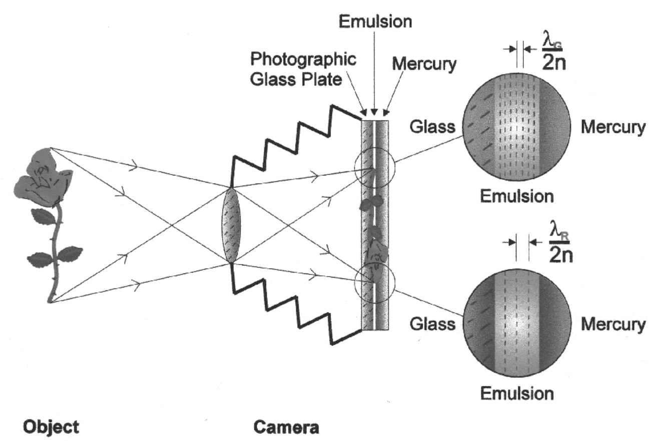

Figure 1. The principle of Lippmann photography

When the developed photograph was viewed in white light, different parts of the recorded image produced different colors. This was due to the separation of the recorded fringes in the emulsion. The light was reflected from the fringes, creating different colors corresponding to the original ones that had produced them during the recording. In order to observe the correct colors, the illumination and observation have to be at normal incidence. If the angle changes, the colors of the image will change. This change of color 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 color 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 color holograms have made it possible to record interference color photographs. The new interest in Lippmann's technology has been manifested by many recent publications.[4-12]

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. 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. 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. A color reflection hologram, on the other hand, is a result of the three-color RGB process involving three monochrome recordings superimposed in the same emulsion. Bjelkhagen *et al.*[10] and Bjelkhagen[11,12] demonstrated the possibility to record Lippmann photographs in Slavich[13] PFG-03c panchromatic holographic emulsion. In order 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.

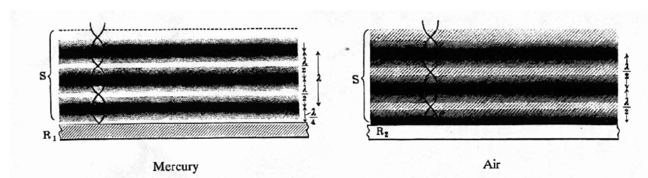

Figure 2. Light reflected at an optically thicker medium (mercury, R1) and at an optically thinner medium (air, R2). S is the gelatin emulsion.

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. Figure 2. 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 $\forall\pi$. 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 $\lambda/4$ 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 newly recorded Lippmann photograph is a portrait of the author. Figure 3. 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.

Color Holography

After 40 years since the appearance of the first laser-recorded monochromatic holograms the possibilities of recording full-color high-quality holograms have now become a reality. What is referred to here is the technique to obtain a color 3-D image of an object where the color rendition is as close as possible to the color of the real object. In theory, the first methods for recording color holograms were established in the early 1960s. Already in 1964 Leith and Upatnieks proposed multicolor wavefront reconstruction in one of their first papers on holography.[14] 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. Such a color hologram was then reconstructed (displayed) 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 color 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 color holograms have been recorded mainly due to the introduction of new and improved panchromatic recording materials. On the market are the already mentioned Slavich ultra-fine-grain silver halide emulsions as well as photopolymer materials, manufactured by E.I. du Pont de Nemours & Co.

Figure 3. Lippmann portrait of the author

Color 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 the new Russian panchromatic emulsions existed the sandwich technique was used to make color 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[15] 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 ultra-fine-grain silver halide emulsions were introduced in Russia in the early nineties it was possible to record high-quality color holograms in a single emulsion layer as demonstrated by Bjelkhagen *et al.*[16]

Recording Materials

To be able to record high-quality color reflection holograms it is necessary to use extremely low light-scattering recording materials. This means, for example, the use of ultra-fine-grain silver halide emulsions (grain size about 10 nm). Currently, the only commercial producer of such a material is the Slavich company.[13] 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 - $1.2{\cdot}10^{-3}$ $J(cm)^{-2}$
Color sensitivity peaked at:	633 nm, and 530 nm

The panchromatic photopolymer material from DuPont is an alternative recording material for color holograms. Although, being less sensitive than the ultra-fine-grain silver halide emulsion, it has its special advantages of easy handling and dry processing (only UV-curing and baking.) The color 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°C for two hours in order to increase the brightness of the image.

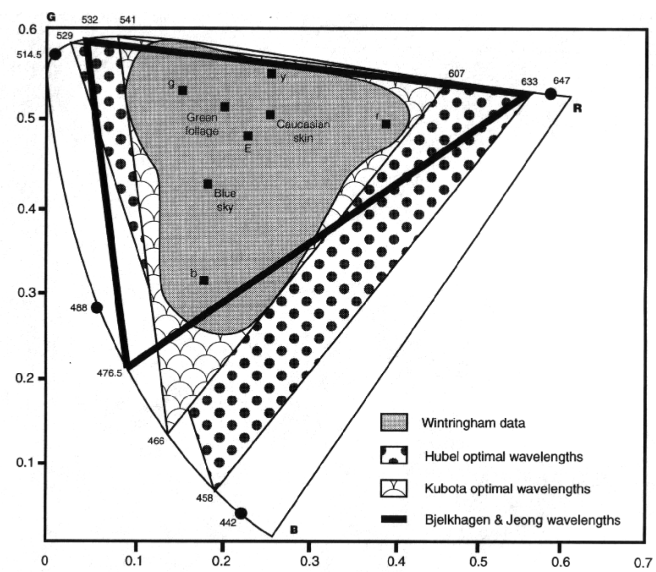

Figure 4. The 1976 CIE uniform scales chromaticity diagram shows the gamut of surface colors and positions of common laser wavelengths. Optimal color-recording laser wavelengths are also indicated

Laser Wavelengths for Color Holograms

Optimal primary laser wavelengths for color holography is illustrated in the 1976 CIE chromaticity diagram. Figure 4.

It may seem that the main aim of choosing the recording wavelengths for color holograms would be to cover as large an area of the chromaticity diagram as possible. However, there are many other considerations that must be taken into account when choosing the wavelengths for color holograms. One of these important considerations is the question of whether *three* wavelengths are really sufficient for color holography. The wavelength selection problem for color holography has been treated in several papers, for example, by Peercy and Hesselink[17] and by Kubota.[18]

Hubel and Solymar[19] provided a definition of color recording in holography: "A holographic technique is said to reproduce 'true' colors if the average vector length of a standard set of colored 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." According to Hubel's color rendering analysis, to maximize the gamut area the following set of wavelengths is obtained: 456, 532, and 624 nm. However, when approached from a different viewpoint, the optimal trio of wavelengths based on the reconstructing light source of 3400°K, a 6 Φm thick emulsion with a refractive index of 1.63 and an angle of 30° between the object and the reference beam Kubota obtained the following wavelengths: 466.0, 540.9, and 606.6 nm. Peercy and Hesselink[17] discussed wavelength selection by investigating the sampling nature of the holographic process. They 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. In the second case the wavelengths were 475, 550, and 625 nm. According to Peercy and Hesselink, the sampling approach indicates that three monochromatic sources are almost always insufficient to preserve all of the object's spectral information accurately. They claim that four or five laser wavelengths are required. In the recent paper by Kubota[18] four wavelengths were used. Only further experiments will show how many wavelengths are really necessary and which combination is the best for practical purposes.

Setup for Recording Color Holograms

A typical reflection hologram recording setup is illustrated in Figure 5. 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.

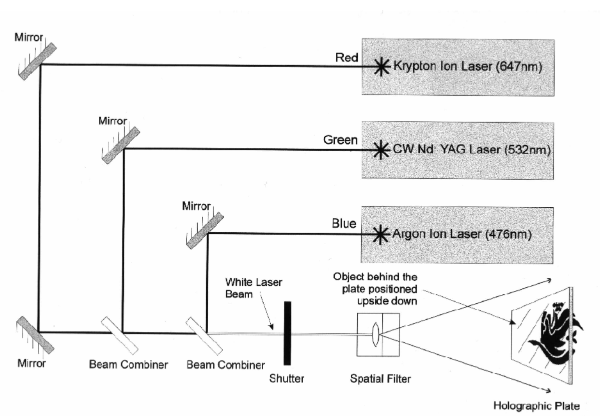

Figure 5. Setup for recording color holograms

In the Denisyuk arrangement, the object is illuminated through the recording holographic plate. 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 of which are recorded simultaneously during the exposure. In this way, three holographic images (a red, a green, and a blue image) are superimposed upon one another in the emulsion.

Three primary laser wavelengths are employed for the recording: 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 laser. Two dichroic filters are used for the combining of the three laser beams. The "white" laser beam goes through a spatial filter, illuminating the object through the holographic plate. By using dichroic filter beam combiners, simultaneous exposure recording can be performed. This 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 $mJ(cm)^{-2}$.

A specially designed test object consisting of the 1931 CIE chromaticity diagram is used for the color balance adjustments and exposure tests. The Macbeth Color-Checker chart is used for color rendering tests.

The processing of silver halide emulsions is more difficult and critical than the dry processing of photopolymer materials. Emulsion shrinkage and other emulsion distortions caused by the active solutions used for the processing must be avoided.

Recorded color holograms of the two test targets are presented in following. The spotlight used to reconstruct the recorded holographic images was a 12-Volt 50-Watt halogen lamp.

The color balance for the recording of a color 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 6 shows a typical normalized spectrum obtained from a white area of the color 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 Figure 7.

In Table 2 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 color and the corresponding field number.

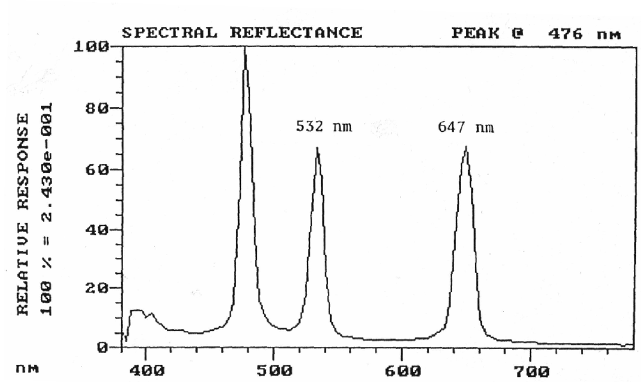

Figure 6. Normalized spectrum from a white area of a color test target hologram

Figure 7. Hologram of the CIE test object recorded with 476, 532, and 647 nm laser wavelengths.

Table 2. Chromaticity coordinates from color hologram recording tests using the Macbeth ColorChecker

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

Conclusion

Modern Lippmann photography may have limited applications in photography and color 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 ultra-fine-grain emulsions are absolutely necessary in order to record absolute correct color 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 color imaging.

Large-format color reflection holograms can be recorded with rather good color rendition. However, further improvements are needed, e.g., as regards color saturation, image resolution, signal-to-noise ratio, dynamic range. Other limitations concerning holographic color recording include the fact that some colors we see are the result of fluorescence, which cannot be recorded in a hologram. The virtual color image behind a color holographic plate represents the most realistic image of an object that can be recorded today. This 3-D imaging technique has many obvious applications, e.g., for displaying unique and expensive artifacts.

References

1. G. Lippmann, *Comptes Rendus* **112**, 274-275 (1891).
2. G. Lippmann, *Comptes Rendus* **114**, 961-962 (1892).
3. G. Lippmann, *J. Physique* **3**:3, 97-107 (1894).
4. N.J. Phillips, H. Heyworth, T. Hare, *J. Photogr. Sci.* **32**, 158-169 (1984).
5. P. Connes, *J. Optics (Paris)* **18**, 147-166 (1987).
6. H. Nareid, *J. Photogr. Sci.* **36**, 140-147 (1988).
7. H. Nareid, H. M. Pedersen, *J. Opt. Soc. Am. A* **8**, 257-265 (1991).
8. J.-M. Fournier, *J. Optics (Paris)* **22**, 259-266 (1991).
9. J.-M. Fournier, P. L. Burnett, *J. Imaging Sci. Technol.* **38**, 507-512 (1994).
10. H. I. Bjelkhagen, T. H. Jeong, R. J. Ro, Old and modern Lippmann photography, *Proc. SPIE* **3358**, 72-83 (1998).
11. H. I. Bjelkhagen, *Opt. Eng.* **38**, 55-61 (1999).
12. H. I. Bjelkhagen, *History of Photography* **23**, 274-280 (1999).
13. SLAVICH Joint Stock Co., Micron Branch Co., 2 pl. Mendeleeva, 152140 Pereslavl-Zalessky, Russia.
14. E. N. Leith, J. Upatnieks, *J. Opt. Soc. Am.* **54**, 1295-1301 (1964).
15. T. Kubota, *Appl. Opt.* **25**, 4141-4145 (1986).
16. H. I. Bjelkhagen, T. H. Jeong, D. Vuki evi , *J. Imaging Sci. Technol.* **40**, 134-146 (1996).
17. M. S. Peercy, L. Hesselink, *Appl. Opt.* **33**, 6811-6817 (1994).
18. T. Kubota, E. Takabayashi, T. Kashiwagi, M. Wantanabe, K. Ueda, Color reflection holography using four recording wavelengths, *Proc. SPIE* **4296**, 126-133 (2001).
19. P. M. Hubel, L. Solymar, *Appl. Opt.* **30**, 4190-4203 (1991).

Biography

Hans Bjelkhagen received his Ph.D. degree in 1978 from the Royal Institute of Technology in Stockholm, Sweden, where he was working on holography until 1982. In 1983, he joined CERN, Geneva, Switzerland, where he was involved bubble chamber holography. That work continued in 1984 at Fermilab, Batavia, IL, where he participated in holographic recording of neutrino events. Between 1985-1991 he was with the BME department at Northwestern University, Evanston, IL, working on medical holography. Since 1992 he has been involved in color holography and Lippmann photography. In 1997 he joined De Montfort University, Leicester, UK. He is the author of *Silver Halide Recording Materials for Holography*, Springer-Verlag. He is a member of IS&T and OSA and a fellow of SPIE.