Lippmann photography: its history and recent development

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Abstract

More than one hundred years ago Gabriel Lippmann recorded the first permanent colour photographs in France. His technique based on recorded light interference structures in an emulsion produced unique colour photographs. It is known as *interferential photography* or *interference colour photography*, as well as *Lippmann photography*. This type of direct colour photography was rather complicated, which is why only very few people recorded such photographs after Lippmann revealed his technique in 1891. When correctly performed, very beautiful colour photographs could be obtained. The fact that the colours of the early Lippmann photographs are well preserved indicates that their archival properties are very good. The principle of Lippmann photography is presented, and a review of its early history is provided. Important early contributions were made by Eduard Valenta, the Lumière brothers, Richard Neuhauss and Hans Lehmann. They improved, in particular, the recording emulsions and recorded many beautiful colour photographs.

Over the last few years there has been increasing interest in Lippmann's unique photographic technique. Recent progress in panchromatic ultrafine-grain recording materials for holography has made it possible to record Lippmann photographs again. Since a Lippmann photograph can record the entire colour spectrum, it can provide the best possible photographic colour rendition. In particular, human skin and reflections from metallic objects look extremely realistic. Because of ultrahigh resolution, image detail quality is also remarkable.

Today, high-resolution panchromatic recording materials, suitable for Lippmann photography, are on the market. Improved and simplified techniques to record modern Lippmann photographs are described. Photographs of some recent Lippmann colour images are included. Due to the fact that no dyes or pigments are used in the emulsion of the final colour photograph, high archival stability of the colour image can be predicted.

Introduction

Today there is an interest in image recording techniques with perfect colour rendition. As regards colour rendition, Lippmann photography is the only imaging technique that directly can record the entire colour spectrum of an object or scene. 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, invented by Lippmann, provided such images in 1891.

Lippmann Photography

Gabriel Lippmann (1845 - 1921) was able to record colours as standing light waves in an emulsion. 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.[1] A little more than one year later Lippmann displayed four colour 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 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 in 1908 - the only Nobel Prize awarded in the field of photography.

The principle of Lippmann photography is shown in Fig. 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 emulsion side of the Lippmann plate 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 colour 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 monochromatic colours are recorded. A polychrome recording is more complex, and was first mathematically treated by Lippmann.[3]

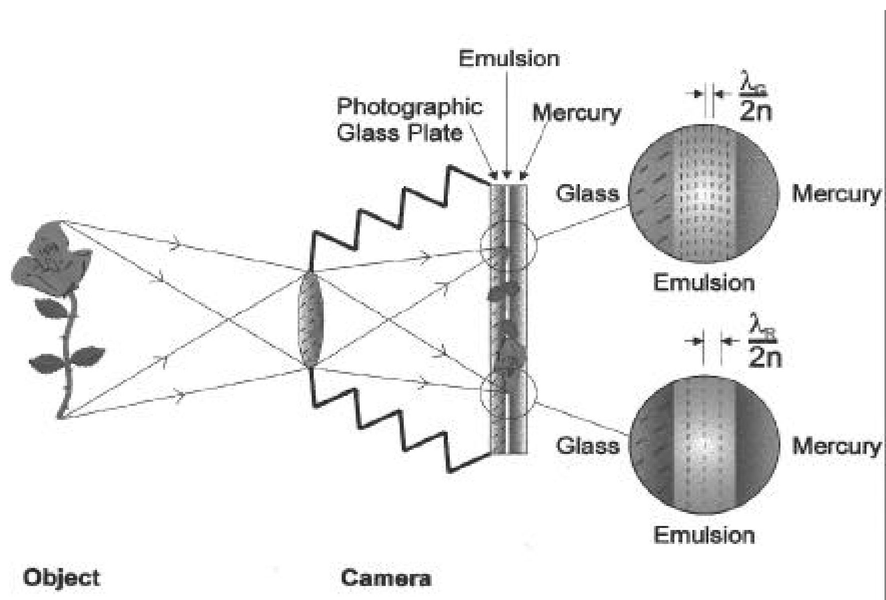

Figure 1. The principle of Lippmann photography

When the developed photograph was viewed in white light, different parts of the recorded image produced different 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.

Several scientists and researchers began to explore and further develop this new colour photography technique. Among them, Auguste and Louis Lumière,[4,5] Hermann Krone,[6,7] Eduard Valenta,[8,9] Otto Wiener,[10] Richard Neuhauss,[11] Herbert Ives,[12] Hans Lehmann,[13,14] and Ramón y Cajal[15] contributed extensively to the progress in this field. There are also several books published on Lippmann photography.[16-23] The most important contributions were made by Neuhauss and Lehmann, both active in Germany. They devoted a lot of time to the perfection of the Lippmann process. Many beautiful photographs were recorded by them, some of which have been preserved and are part of photographic collections in different museums.

Many of the professional photographic cameras used at the end of the 19th century were cameras for glass plates. The use of mercury as the light-reflecting and phase-locking technique was generally used by Lippmann photographers. It worked rather well, but involved both practical problems and safety concerns. Fog and streaks caused by mercury in contact with the silver halide emulsion were a big problem The main required additional piece of equipment for the Lippmann photographer was the mercury dark slide. At first, the slide had to be made up by the person who wanted to record a colour photograph. However, after some time it was possible to obtain the equipment from camera manufacturers. Carl Zeiss Kamerawerke in Jena manufactured mercury plate holders, filters, viewing and projection apparatus. Equipment was also made by other German companies: Stegemann, Braun, and the plate manufacturer Kranseder & Cie. In England dark slides were manufactured by Watson & Sons and Penrose & Co.

Neuhauss was a physician and one of the most experienced experimenters. Between 1894 and 1908, he produced about 2500 plates and performed experiments in his home in Gross-Lichterfelde located outside Berlin. His test object was most often a stuffed parrot installed on his balcony, but also landscapes and several portraits were recorded by him. His book[11] contains important information on emulsion making. The early Lippmann photographers had to mix their own Lippmann emulsion and coat the glass plates. This was a very difficult task and the emulsion had to be of the highest quality to be able to record perfect Lippmann photographs. Neuhauss stresses the importance of gelatin quality for making successful emulsions. One example of his Lippmann photographs, shown in Fig. 2, is an image of the parrot, which belongs to the collection of the National Museum of Photography, Film and Television in Bradford, England, where the APIS 2002 symposium took place.

The processing of the colour photographs was done in more or less the same way by most of the photographers. They used developers based on *pyrogallol* and *ammonia*, which were formulated to suit the particular emulsion. A surface developer will perform well since no image information is located deep inside the emulsion. In addition, the hardening effect on gelatin that pyrogallol provides is important. The Lumièr developer was frequently recommended and can also be used for modern Lippmann photographs. Development time was one to three minutes. Most often the image was fixed. However, it was sometimes recommended not to fix the developed image, since that would change the thickness of the emulsion and, thus, change the colour of the image. Many Lippmann photographers used image intensification by a bleaching and redeveloping process, which compensated for the shrinkage introduced by the fixing step.

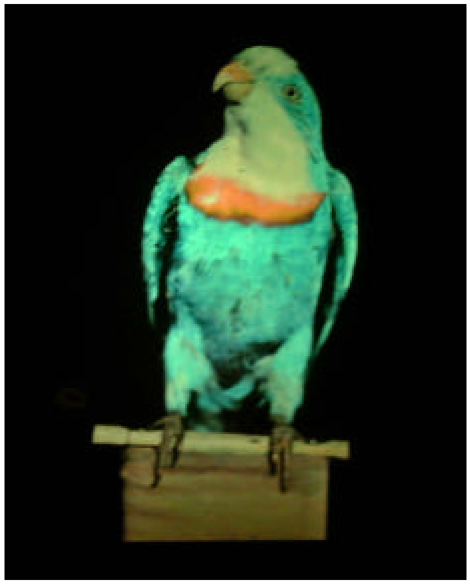

Figure 2. Lippmann photograph by Neuhauss from 1899

Viewing Lippmann Photographs

There is one particular problem in viewing Lippmann photographs. The reflection from the gelatin surface of the emulsion can cause colour distortion as a result of the phase shift in the gelatin/mercury interface during recording. In addition, the specular surface reflection has to be separated from the image in order to see it clearly. This can be accomplished by attaching a wedged (angle about 10^o) glass plate on top of the emulsion using an index-matching glue, most often Canada balsam (n = 1.52 - 1.54). The old Lippmann photographs were painted black (e.g. flowing on asphaltum varnish mixed with machine oil) covered with black paper and the edges were sealed.

The images have to be observed in parallel diffuse light and shielded from all side light. A good condition for viewing is by a small opening in a wall facing a brilliant white sky. If the observer stands with his back to the opening and holds the picture at arm's length reflecting the sky the image appears at its best. In the Lippmann times there were special viewing devices, such as *dioptric* and *catoptric* viewing apparatus, which facilitated the display of these beautiful colour photographs. The photographs could also be viewed enlarged, by projecting the reflected image using a special projector. The image could not be projected like a modern slide. The *reflected* image had to be projected which required a projector of the *aphengescope*-type. Carl Zeiss in Jena in Germany produced the viewing and projecting equipment for Lippmann photographs.

There was very little interest in making silver halide plates of the Lippmann type after this type of photography disappeared in the early 1900s. However, the need for such plates came back when holography started to become popular in the late 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 high-quality interference colour photographs.

Modern Lippmann Photography

The new interest in Lippmann's technology has been manifested by many recent publications.[24-36] 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 colour reflection hologram, on the other hand, is a result of the three-colour red-green-blue process involving three monochrome recordings superimposed in the same emulsion. Bjelkhagen *et al*[32] demonstrated the possibility to record Lippmann photographs in Slavich 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.

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 a reflection obtained at the gelatin-air interface as shown in Fig. 3. 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 $\pm\pi$. 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.

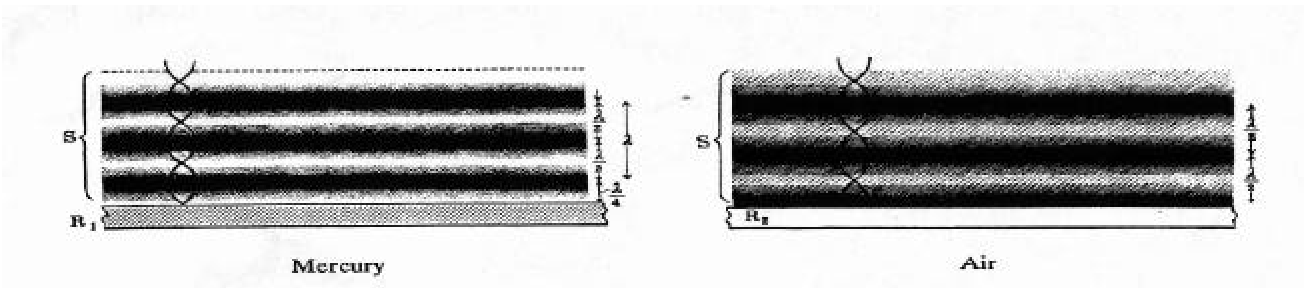

Figure 3. Light reflected at an optically thicker medium (mercury, R_1) and at an optically thinner medium (air, R_2). S is the gelatin emulsion.

Recording Lippmann Photographs without Mercury

To be able to record Lippmann photographs it is necessary to use extremely low light-scattering panchromatic recording materials. It is very difficult to make ultrafine-grain silver halide emulsions and only a few people have been able to do that since the time Lippmann photography was practiced. However, there is a commercial panchromatic holographic emulsion for recording colour holograms. This emulsion has very fine silver halide grains (grain size about 10 nm) and it is possible to use it for recording Lippmann photographs as well. It is the Russian Slavich PFG-03c emulsion coated on glass plates, which the author has employed for all Lippmann photographs presented here. 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
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 new Lippmann photographs by the author were all recorded without using mercury. The camera used was an Eastman Kodak Co. (Folmer & Schwing Div.) Auto Graflex 4" by 5" camera equipped with a Kodak Aero Ektar f/2.5, 178 mm lens. The unexposed Lippmann plate is inserted in a dark slide with the *emulsion side* facing away from the camera lens. A modified Graphic Film Pack Adapter was used as the dark slide. Inside the adapter, black velvet was attached in order to reduce scattered light. The light reflected at the interface between the emulsion and air is the only light allowed to hit the emulsion, all other light reflected inside the dark slide has to be absorbed. The principle of recording Lippmann photographs without the need for mercury is shown in Fig. 4.

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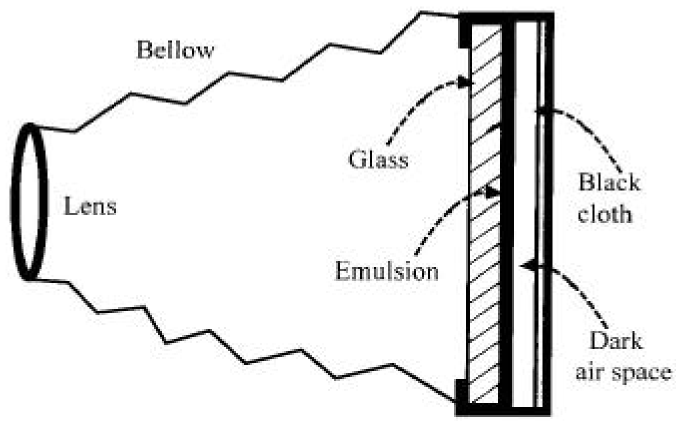

Figure 4. Modern Lippmann photography recording principle

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 gives good results. To avoid shrinkage the plates are not fixed, only washed after development. The Slavich emulsion requires pre-development hardening in a formaldehyde solution.

Lumière developer:

Solution A:

Pyrogallol	1 g
Alcohol (propanol)	100 ml

Solution B:

Potassium bromide	10 g
Water (distilled)	100 ml

Working solution: Mix 20 ml solution A + 30 ml solution B + 140 ml water.
Add 10 ml ammonia (s.w. 0.960 at 18 degree C) just before using.
Use only once. Use at 15 degree C. (Both important)

Figure 5 demonstrates what a processed Lippmann photographic plate looks like when illuminated and observed in different ways. When the plate is viewed in reflected light, where illumination or observation is not performed perpendicularly to the plate, a negative image is seen (*a*). When the plate is studied in transmitted light, a red positive image can be seen (*b*). Caused by the absorption of light by minute colloidal silver particles in the emulsion, the image appears red. When illumination and observation is perpendicular in relation to the plate, the correct colour image is seen (*c*). The illumination has to be emitted from a large diffuse area above the plate.

a *b* *c*

Figure 5. Lippmann photographic plate illuminated and observed in different ways

a. *Negative reflected image seen when illumination and observation is not perpendicular*
b. *Positive red image seen in transmitted illumination caused by colloidal silver particles*
c. *Colour reflected image seen when illumination and observation is perpendicular*

A beautiful example of a modern Lippmann photograph is shown in Fig. 6. Blue is the most demanding colour to record caused by the fact that blue light creates the finest interference structure in the emulsion, which has to be resolved during recording. A decorative plate, *Princess of the Iris* (by M. Noble), was recorded in diffuse light from an overcast sky requiring a six-minute exposure at aperture f/4 on a Slavich PFG-03c panchromatic holographic plate, size 4" by 5."

Figure 6. Lippmann photograph of "Princess of the Iris" decorative plate

Figure 7. Lippmann photograph of an elephant with metallic gold reflections

Metallic reflections are accurately recorded in Lippmann photographs. An example of this is a 4” by 5” recording of a white porcelain elephant, illustrated in Fig. 7. The photograph was recorded outside in daylight illumination on a Slavich plate.

Another modern Lippmann photograph is a portrait of the author reproduced in Fig. 8. The plate size is 4” by 5”. The exposure time was two minutes at aperture f/4. The reproduction of human skin is remarkably realistic in a Lippmann photograph. It was recorded in bright sunlight softened with diffuser on a Slavich plate.

After being processed, the back of the Lippmann plates was painted black. For better viewing of the image, a wedged glass plate (Wiener prism) was cemented to the emulsion side of each plate. The photographs of the Lippmann plates have been recorded with a digital camera.

Since conventional photography, conventional or digital, cannot record the colours recorded in a Lippmann photograph, only by viewing real Lippmann photographs, one can appreciate the quality of them. It is also difficult to obtain the very high image resolution of the Lippmann images when reproducing them by digital photography.

Figure 8. Lippmann portrait of the author

Conclusion

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 photographs with the correct colour rendition. 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.

A potential application of Lippmann photography is a new type of Optical Variable Device (OVD) currently under development.[35] A Lippmann OVD can be applied as a unique security device on security documents, such as, e.g., identification cards, passports, credit cards, and other documents where a high degree of security is needed. A Lippmann photograph is almost impossible to copy, which makes it a unique colour photographic recording. The iridescence of the Lippmann photograph is another important security feature as well as the switch between a negative and positive colour image, easily seen when tilting the document.

References

1. G. Lippmann: La photographie des couleurs. *Comptes Rendus Hebdomadaires des Séances de l'Académie des Sciences* **112**, 274-275 (1891)
2. G. Lippmann: La photographie des couleurs [deuxième note]. *Comptes Rendus Hebdomadaires des Séances de l'Académie des Sciences* **114**, 961-962 (1892)
3. G. Lippmann: Sur la théorie de la photographie des couleurs simples et composées par la méthode interférentielle. *J. Physique* **3** (No.3), 97-107 (1894)
4. A. and L. Lumière: Sur les procédés pour la photographie des couleurs d'après la méthode de M. Lippmann. *Bull. Soc. franç. Phot.* (2[o] série) **9**, 249-251 (1893)
5. A. and L. Luimère: Untersuchungen über die Herstellung einer lichtempfindlichen kornlosen Schict. *Eder's Jahrb. f. Photogr. u. Reproductionstechn*. **11**, 27-30 (1897)
6. H. Krone: Über Farbenphotogramme von Spectren. *Annalen der Physik und Chemie* **46**, 426-430 (1892)

7. H. Krone: *Die Darstellung der natürlichen Farben durch Photographie. Deutsche Photographen-Bibliotek.* Band **III** (Verlag der Deutschen Photographen-Zeitung, Weimar 1894) pp.50-78
8. E. Valenta: *Die Photographie in natürlichen Farben* (W. Knapp Verlag, Halle a.S. 1894)
9. E. Valenta: *Die Photographie in natürlichen Farben mit besonderer Berücksichtigung des Lippmannschen Verfahrens sowie jener Methoden, welche bei einmaliger Belichtung ein Bild in Farben liefern*. Zweite vermehrte und erweiterte Auflage. Encyklopädie der Photographie. Heft 2 (W. Knapp Verlag, Halle a.S. 1912)
10. O. Wiener: Ursache und Beseitigungen eines Fehlers bei der Lippmann'schen Farbenphotographie, zugleich ein Beitrag zu ihrer Theorie. *Annalen der Physik und Chemie* **69**, 488-530 (1899)
11. R. Neuhauss: *Die Farbenphotographie nach Lippmann's Verfahren. Neue Untersuchungen und Ergebnisse*. Encyklopädie der Photographie. Heft 33 (W. Knapp Verlag, Halle a.S. 1898)
12. H.E. Ives: An experimental study of the Lippmann color photograph. *Astrophysical J.* **27**, 325-352 (1908)
13. H. Lehmann: *Beiträge zur Theorie und Praxis Direkten Farbenphotographie mittels Stehender Lichtwellen nach Lippmanns Methode* (Trömer, Freiburg i.Br. 1906)
14. H. Lehmann: Die Praxis der Interferenzfarbenphotographie, unter besonderer Berücksichtigung der in den Optischen Werkstätten von C. Zeiss in Jena konstruierten Specialapparaten. *Phot. Rundschau* **23**, 125-134 (1909) [English transl.: H. Lehmann: Practical application of interference colour photography. *Brit. J. Phot.* (Col. Suppl.) (4 Nov. 1910) pp.83-86, Practical application of interference colour photography. II. *Brit. J. Phot.* (Col. Suppl.) (2 Dec. 1910) pp.92-95]
15. S.R. y Cajal: Estructura de las imágenes fotocrómicas de G. Lippmann. *Revista de la real Academia de Ciencias Exactas, Físicas y Naturales de Madrid* **4**, No.4 (1906) [German transl.] Die Structur der Lippmannschen Photochromien. *Zeitschr. f. wiss. Phot.* Band **V**, 213-245 (1907), [English transl.] The structure of Lippmann heliochromes. *Brit. J. Phot.* Aug. 27, 59-79 (1907)
16. A. Berthier: *Manuel de Photochromie Interférentielle. Procédés de Reproduction directe des Couleurs.* (Gauthier-Villars et Fils, Paris 1895)
17. F. Drouin: *La photographie des couleurs* (C. Mendel, Paris 1896)
18. R. Child Bayley: *Photography in colours* (Iliffe, Sons & Sturmey Ltd., London 1900)
19. E. Senior: Lippmann's process of interference heliochromy, in *A Handbook of Photography in Colours*, Section III (Marion & Co., London 1900) pp.316-343
20. A. Berget: *Photographie directe des couleurs par la méthode interférentielle de M. Lippmann* (Gauthier-Villars, Paris 1901)
21. L. Tranchant: *La photographie des couleurs simplifiée* (H. Desforges, Paris 1903)
22. E. König: *Die Farben-Photographie* (Gustav Schmidt Verlag, Berlin 1904) [English translation by: E.J Wall: *Natural-color photography* (Dawbarn & Ward, Ltd., London 1906)]
23. B. Donath: *Die Grundlagen der Farbenphotographie* (Verlag Freidrich Vieweg und Sohn, Braunschweig 1906)
24. P. Connes: Silver salts and standing waves: the history of interference color photography. *J. Optics (Paris)* **18**, 147-166 (1987)
25. H. Nareid: A review of the Lippmann color process. *J. Photogr. Sci.* **36**, 140-147 (1988)
26. H. Nareid, H.M. Pedersen: Modeling of the Lippmann color process. *J. Opt. Soc. Am. A* **8**, 257-265 (1991)
27. J.-M. Fournier: Le photographie en couleur de type Lippmann: cent ans de physique et de technologie. *J. Optics (Paris)* **22**, 259-266 (1991)
28. J.-M. Fournier, P.L. Burnett: Color rendition and archival properties of Lippmann photographs. *J. Imaging Sci. Technol.* **38**, 507-512 (1994)
29. K. Bernhardt: *Die Interferenzfarbphotographie nach Gabriel Lippmann.* Diplomatarbeit Mat. Nr. 827176, (Fachhochschule Köln, 1993)
30. C.C. Rich, L. Dickerson: Lippmann photographic process put to practice with available materials, in *Holographic Materials II*, ed. by T.J. Trout. Proc. SPIE **2688**, 88-95 (1996)
31. H.I. Bjelkhagen: Lippmann photographs recorded in DuPont color photopolymer material, in *Practical Holography XI and Holographic Materials III*, ed. by S.A. Benton, T.J. Trout. Proc. SPIE **3011**, 358-366 (1997)
32. H.I. Bjelkhagen, T.H.Jeong, R.J. Ro: Old and modern Lippmann photography, in *Sixth Int'l Symposium on Display Holography*, ed. by T.H. Jeong, H.I. Bjelkhagen. Proc. SPIE **3358**, 72-83 (1998)
33. W.R. Alschuler: On the physical and visual state of 100 year old Lippmann color photographs, in *Sixth Int'l Symposium on Display Holography*, ed. by T.H. Jeong, H.I. Bjelkhagen. Proc. SPIE **3358**, 84-94 (1998)
34. P. Hariharan: Lippmann photography or Lippmann holography? *J. Mod. Optics* **45**, 1759-1762 (1998)
35. H.I. Bjelkhagen: A new optical security device based on one-hundred-year-old photographic technique. *Opt. Eng.* **38**, 55-61 (1999)
36. H.I. Bjelkhagen: Lippmann photography: reviving an early colour process. *History of Photography* **23**, (No.3), 274-280, (1999)