The True Colour of Photography

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"*We, the progeny of James Clerk Maxwell are beginning to recognize the need to return to the genius of Newton, to resurrect the startling beauty of Lippmann and to step outside the constraints of a system which throws away a universe of information as soon as original spectra are converted to three channels of data"*. Rosen & Jiang (1999)

Introduction

Few photographers today are familiar with the name Gabriel Lippmann (1845-1921), even fewer have seen a Lippmann colour photograph, but 100 years ago, Lippmann was awarded the 1908 Nobel Prize in Physics for his invention of ***Interference Photography***, an early colour technique exploiting the phenomenon of optical standing waves. Lippmann's prize represents the only time this prestigious award has been given for a photographic invention. However, the process proved difficult and impractical, exposures ran into minutes, the colours were difficult to view and almost impossible to copy. Only a minority of photographers recorded successful Lippmann photographs. Those who did were skilled in making and coating their own emulsions and dedicated many years to the cultivation of the technique. Original examples of this extremely rare, exotic and arcane medium number around 500 specimens world-wide. Attempts at commercialization floundered and by the time Lippmann was awarded his prize the more practical Autochrome plates had become available. Despite the difficulties, Lippmann's photography remains, to this day, the only direct process of true colour photography known. It is a technique of exquisite beauty, both technically and aesthetically. The ultra-fine grain plates, essential to the medium, display the highest photographic resolution ever achieved. The encoding of colour, as a periodic volume diffraction grating of pure silver offers excellent and unrivaled archival longevity.

Even today the technology of Lippmann photography appears sublime and remarkably sophisticated. It has directly contributed to the modern development of holography which has kept the memory of Lippmann's name alive.

In the 1980s & 90s there was a renewal of interest in the technique and several interesting papers were published. Recent developments in colour holography have made it possible to record new Lippmann photographs.

On the 100th anniversary of Lippmann's Nobel Prize Award the authors, H. Bjelkhagen (HB) and D. Green (DG), present the history, theory and practice of Lippmann's photography, illustrated with modern examples of the medium. Their research represents over a decade of work in celebration of a phenomenon - arguably the most beautiful and pure form of photography ever conceived.

Philosophy

Photography appears to possess a mythical power in its ability to realistically record information with seamless optical clarity. Photographs don't simply copy reality; they actively create it in the image of our perceptions.

Just as manual techniques of picture making are praised for being hand-made, photographs are admired precisely for the absence of 'touch', they are to be as much as possible 'acheiropoietai' literally 'things made without hands'.

For a medium celebrated for its optical truth, it may be a surprise to read, that colour in photographs, has been viewed with suspicion and distrust by photographers and literary critics.

Colour has been described as the 'ultimate distraction' Griffiths (2008) 'modifying that which exists...robbing photography of its most valuable attribute'. The idea that colour is a modification that diminishes the pure formality of the monochrome image is also found in 'Camera Lucida' Barthes (2000). Barthes felt that colour, whether added by hand or chemistry was a cosmetic afterthought superfluous to 'the original truth of the black-and-white photograph'.

In 'Towards a Philosophy of Photography' Flusser (2000) describes colour in photographs as a chemical artifact, which operate on a higher level of abstraction than black-and-white. Colour is less true, because it conceals its theoretical origins in chemistry and lacks the theoretical purity of the original photographic concept of black-and-white.

Quite why colour should be such anathema to some photographers and writers, when it is such an integral part of visual experience appears to reside in the question of truth. No commercial colour material is capable of anything more than an approximation, a subjective interpretation and appears, therefore untrue to the original purity of the photographic program.

There is no photography without light, and there is no light without colour. What is black-and-white but the total absorption and reflection of the whole spectrum? Therefore there can be no photography without colour, only photographs with more or less colour definition.

There is one arcane technique - Lippmann photography, in which the true colour of the photograph is black-and-white even when the image displays full colour! The surprising ability to record full colour images in a black-and-white emulsion, simultaneously confers excellent archival longevity, as there are no dye-stuffs or pigments to fade in time.

The colour in Lippmann photography is not a cosmetic artifice, nor is it a deceptive chemical abstraction. Rather, it is a physical code, like a thumb print, inseparable from the structure of lights spectral signature, and of such delicate subtlety, it is impossible to retouch, which insures the authenticity of the colours. Its theoretical origin, resides in the wave theory of light, and is identical in principle to the original photographic concept of recording light and shadow. The only difference between conventional black-and-white images and Lippmann “colour” photographs is one of relative scale or resolution. The Lippmann plate records black-and-white details smaller than a wavelength of light, exceeding the resolution of the sharpest lens.

History of Lippmann Photography

Gabriel Lippmann, professor of mathematical physics at the Sorbonne invented, demonstrated and mathematically formulated the process of ***interference colour photography***, also known as ***interferential photography***, or ***Lippmann photography,*** in the years 1891-1894 (Lippmann 1891, 1892, 1894). Lippmann's process was the first exploitation of optical standing waves for the direct recording of permanent colour realized after some twelve years of experimentation. Lippmann photography is the only imaging technique (theoretically) that can directly record the entire colour spectrum of an object or scene. It is based on Newtonian optics, in contrast to the Maxwellian tri-chromatic method of colour synthesis prevalent in modern colour techniques. In optics, Lippmann's colours are related to the class of colour phenomenon known as 'thin films' and the effect is explained using the wave theory of light and in particular interference and diffraction. Such thin film colours are familiar to everyone, and can be seen in the swirling colours of soap bubbles and films of oil dispersed on water, or the transparent wings of insects. When a stack of thin films are packed in layers, like a sandwich, they form a volume diffraction grating which enhances colour resolution and brilliance. Many insects, crustaceans, fish and birds exhibit exotic and brilliant colours using organic but colourless structures and Lippmann plates behave in much the same way.

The process exploits the formation of standing light waves, by means of a mirror, and records these in a single-layer, panchromatic, ultra-fine grain, but ***black-and-white*** photographic emulsion. The developed plate consists of an array of volume gratings containing a coding of the actual spectral distribution of the light for each discrete region of the optical image. When illuminated by white light, the gratings select and reflect the original spectra registered in the image, and these construct, by Bragg diffraction, the colours of the original scene.

The principle of Lippmann photography is illustrated in Fig. 1. An ordinary plate camera is used to form an image on the photographic plate. But the plate is loaded backwards with the emulsion side placed away from the lens and in optical contact with a mirror of mercury. The incident light waves interfere with their own reflections forming a standing wave pattern within the volume of the emulsion, with a periodic spacing of $\lambda/(2n)$ that has to be resolved and recorded (λ is the wavelength of light in air and n is the refractive index of the emulsion). The colour information is stored locally in this way. The larger the separation between the fringes, the longer is the wavelength of the recorded light. When the developed photograph is viewed in white light, different parts of the recorded image produce different colours. This is due to the separation of the recorded fringes.

In this way Lippmann's photographs reproduce all the monochromatic components registered on them. Since wavelength is relative to colour the spectra corresponding to the original scene can be reproduced with formidable accuracy, unlike any other colour photograph. It may seem reasonable that pure spectral colours could be recorded this way, but what about most natural colours with complex and mixed spectra? Lippmann (1894) explained the polychromatic case using Fourier mathematics. Put simply, any distribution of simple waves may be added up to produce a singular wave modulation of more complex profile.

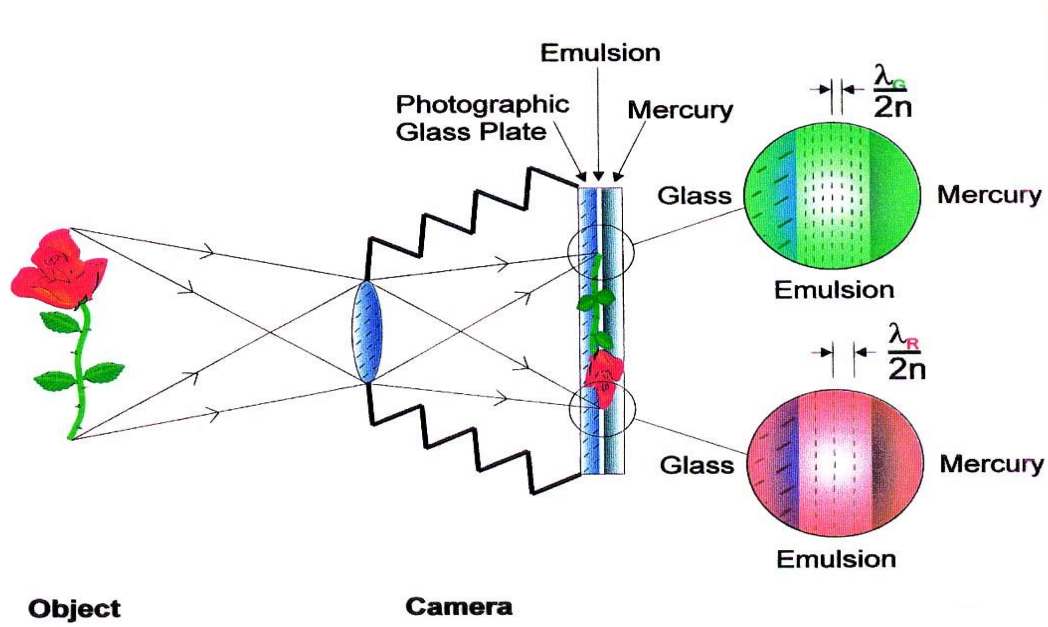


Figure 1. The principle of Lippmann photography

The Lippmann process was first met with circumspection, and in some cases ridicule in the photographic press. However, a few dedicated and persistent workers, fascinated by the lure of the iridescent and true colour, took up the process and started producing their own images.

Among them, August and Louis Lumière (1893, 1897), Eduard Valenta (1912), Richard Neuhauss (1898), Herbert Ives (1908), and Hans Lehmann (1908) contributed extensively to progress in this field. In some cases they dedicated years to the perfection of the Lippmann process. Many of the photographers - scientists involved in Lippmann photography are listed in Table 1. Extremely rare & beautiful colour photographs, among the first ever recorded, were made by them, some of which have been preserved and are part of photographic collections in various museums. See Table 2.

The Lumière brothers made the first silver-gelatin emulsions for the process and produced the first ever colour portrait. However they were eventually forced to abandon the technique as exposures couldn't be reduced below one minute, and even working with the same batch of plates, exposed and processed the same way, they found it impossible to produce identical results.

One very dedicated worker, Richard Neuhauss, was a physician and one of the most experienced experimenters. Between 1894 and 1905, he made about 2500 Lippmann recordings at his home in Gross-Lichterfelde outside Berlin, and also examined the images microscopically which vindicated Lippmann's theory. His test object was an unfortunate stuffed parrot installed on his balcony, but he also recorded several portraits and landscapes. His book (Neuhauss 1898) contains important information specific to making Lippmann emulsions. One example of a Lippmann image by Neuhauss is of his parrot, shown in Fig. 2 and held in the RPS collection at the National Museum of Photography, Film and Television in Bradford, England.

Table 1:

People Involved in Early Lippmann Photography

Santiago Ramón y **Cajal** (1852-1934) Spain
Herbert **Ives** (1882 - 1953) USA
Richard **Jahr** (1861 - 1938) Germany
Hermann **Krone** (1827 - 1916) Germany
Hans **Lehmann** (1875 - 1917) Germany
Raphael Eduard **Liesegang** (1869 - 1947) Germany
Gabriel Jonas **Lippmann** (1845 - 1921) France
Auguste **Lumière** (1862 - 1954) France
Louis **Lumière** (1864 - 1948) France
Henricus **Lüppo-Cramer** (1871 - 1943)
Richard **Neuhauss** (1855 - 1915) Germany
Adolf **Miethe** (1862 - 1927) Germany
Edmond **Rothé** (1873 - 1942) France
Edgar **Senior** (1862 - 1937) England
Eduard **Valenta** (1857 - 1937)
Otto **Wiener** (1862 - 1927)
Wilhelm **Zenker** (1816 - 1899) Germany

Table 2:

Collections of old Lippmann photographs

Musée de l'Elysée Lausanne, 18 avenue de l'Elysée, CH-1014 Lausanne, Switzerland
Université Pierre et Marie Curie, L.D.M.C., Tour 22, 4 place Jussieu, F-75252 Paris, France
Musée français de la Photographie, 78 rue de Paris, F-91570 Bièvres, France
Société française de Photographie, 2 - 4 rue Vivienne, F-75002 Paris, France
Musée Nicéphore Niepce, 28 quai des Messageries, F-71100 Chalon-sur-Saône, France
Preus Fotomuseum - Norsk Museum for Fotografi, Nedrevej 8, N-3192 Horten, Norway
Graphic Art College, VFG-GLV, Leyserstrasse 6, A-1140 Vienna, Austria
The Royal Photographic Society, Nat'l Museum of Photography, Film and Television, Bradford BD1 1NQ, UK
International Museum of Photography, George Eastman House, 900 East Avenue, Rochester, NY 14607, USA

Figure 2. Lippmann photograph by Neuhauss, recorded in 1899
(*Collection: Royal Photographic Society*)

The first Lippmann photographers had to make and coat their own emulsions. This was a very skilled craft, as the crystals in the emulsion had to be extremely fine-grain if any colours were to be recorded. Emulsions were not permitted to ripen, or subjected to temperatures higher than 40^{o}C. Emulsions were washed on the plate and this can easily spoil the delicate coating.

While eventually some plate manufacturers produced Lippmann plates, e.g. Richard Jahr's Dry Plate Factory in Dresden, there is very little evidence of much public interest. The difficulty of recording and processing Lippmann photographs may have disappointed many photographers, and discouraged others from buying plates.

Standard plate cameras of the time were suitable for recording Lippmann photographs. It was only the dark-slides which had to be adapted to flow mercury behind the emulsion. 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.

The processing of the colour photographs was done in a similar way by most of the photographers. They used a developer based on pyrogallol and ammonia, which was formulated to suit the particular emulsion. However, the use of mercury during the recording presented problems with fog and streaks formed on the images caused by mercury contact with the silver halide emulsion.

There was very little interest in making emulsions for Lippmann photography after this type of colour photography was succeeded by the Autochrome process introduced in 1907. Only with the development of holography has there been renewed interest in the manufacture of Lippmann emulsions.

Viewing Lippmann Photographs

There is one particular problem in viewing Lippmann photographs. The images have to be observed in parallel diffuse light and shielded from all side light. A good condition for viewing is a small window facing a brilliant white sky. To view, hold the plate at arms length, emulsion side facing you, and stand with your back to the window. Tilt the plate until it reflects a broad region of feature-less sky and you will see the colours "switch-on". The photographs can also be viewed enlarged by projection of the reflected image using an *aphengescope*. Carl Zeiss in Jena, Germany, produced such a projector for Lippmann photographs.

Un-protected images are particularly sensitive to humidity variations. On humid days the colours can look noticeably red-shifted. Also, since it is the gelatin side of the plate which has to be viewed for the colours to be reconstructed it is especially vulnerable to damage from scratching and finger prints etc. In addition, the specular surface reflection from the gelatin has to be separated from the image in order to improve image contrast. Further, in the case of mercury reflection, there is the problem of the so-called 1/4 wave shift which can falsify the colours as a result of the phaseshift at the gelatin/mercury interface. The Weiner prism (a 10-degree glass wedge prism) is therefore the ideal solution to improve viewing conditions, to protect the emulsion from damage, and finally to hermetically seal it to protect it from environmental pollutants and humidity variations. The prism is mounted on the emulsion side using an index-matching glue, most often Canada balsam. The photographs are painted black on the glass side black tape is used to seal the edges.

Modern Lippmann Photography

The recent history of Lippmann's photography has become almost inextricably woven into the modern development of holography. The analysis of Lippmann's technique in relation to holography is comprehensible to holographers but must seem highly esoteric to photographers. It is in the recording of an interference pattern and the replay of colour by diffraction from that pattern that holography resembles Lippmann's photography. The Lippmann image is a distinctly photographic one devoid of the whole-in-the-part property that confers depth and full parallax on the hologram. In fact, the spectral signature (intensity distribution pattern) at each pixel of a Lippmann plate is even more complex than a colour hologram as it represents a continuous spectrum, while colour holograms usually sample only three RGB wavelengths.

Recent progress in the development of colour holography has opened up the possibility to reinvestigate Lippmann's photography. Modern examples of interference colour photography have been made using improved panchromatic ultra-fine grain recording materials combined with special processing techniques. The revival of interest in Lippmann's technique began in the mid 1980s, and manifested in several interesting publications: Phillips and colleagues (1984), Phillips (1985), Connes (1987), Naried (1988), Nareid & Pederson (1991), Fournier (1991), Fournier & Burnett (1994), Rich & Dickerson (1996), Bjelkhagen and colleagues (1998), Alschuler (1998), Hariharan (1998), Bjelkhagen (1999a), Bjelkhagen (1999b), Alschuler (2002). Most interest was displayed by scientists working in holography because of the close technical proximity of the techniques.

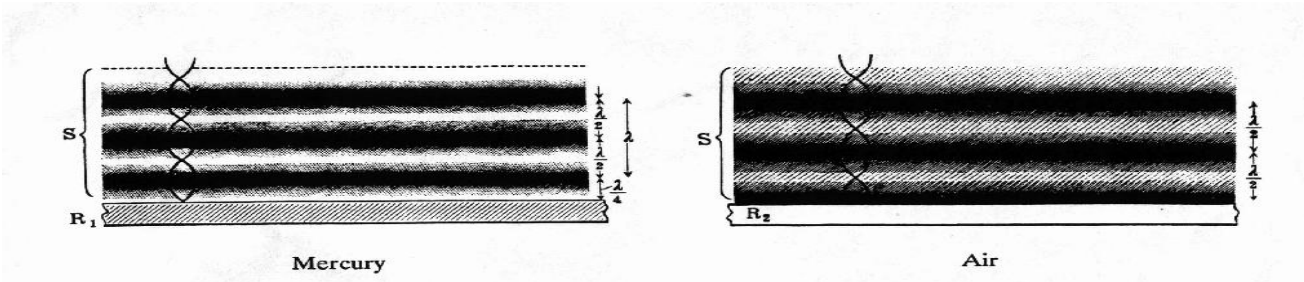


Figure 3. Light reflected at an optically thicker medium (mercury, R_1) and at an optically thinner medium (air, R_2). S is the gelatin emulsion.

The Recording Material

Ultra-fine grain (extreme resolution) and panchromatic materials are essential for recording Lippmann photographs. These must exhibit extremely low light scattering, be practically transparent, and be able to resolve upwards of 10,000 lines/mm. It is very difficult to make ultra-fine grain emulsions and only a few people have been able to do that since the time Lippmann's photography was practiced.

However, the Russian colour holographic plates - Slavich PFG-03c, a panchromatic ultra-fine grain silver-halide emulsion (grain size about 10 nm), can also be used to record Lippmann photographs. HB recorded his first Lippmann photographs using Slavich PFG-03c in 1995. His recordings were made without mercury using only the gelatin/air interface as a reflector as described in Bjelkhagen (1998). Later, the authors employed the same material for some of the images presented here. However the Slavich emulsion is not really designed for Lippmann's technique and DG has been working on his own emulsions.

Recording Lippmann Photographs without Mercury

An old Eastman Kodak Co. (Folmer & Schwing Div.) Auto Graflex 4"x5" camera equipped with a Kodak Aero Ektar f/2.5, 178 mm lens was used by HB for Figs. 7 and 8. A modified Graphic Film Pack Adapter was used as a dark slide. The unexposed plates were loaded with emulsion side facing away from the lens, with black velvet behind to reduce scattering. The light reflected at the interface between the emulsion and air is the only light allowed to hit the emulsion, all other light in the dark slide has to be absorbed using flat black material.

Figure 3 shows the standing-wave pattern for the mercury reflector compared with the gelatin/air reflection. A node is located at the mercury reflector, an optically thicker medium than air, and coincides with the gelatin surface. The phase shift there is $\lambda/2$. On the contrary, an anti-node (wave crest) is located at the emulsion surface in 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 $\lambda/4$ inside the emulsion.

When using air reflection, the exposure must be 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 gelatin/air 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 applies to the mercury case. When using the air reflector, the first fringe is in phase with the emulsion surface.

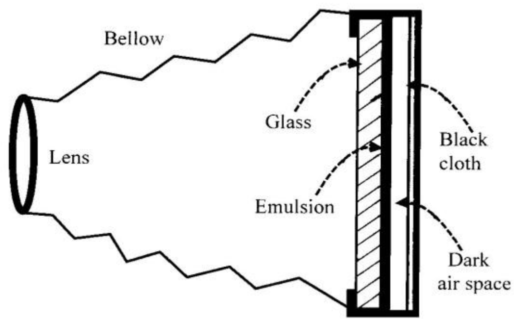


Figure 4. Modern Lippmann photography recording principle

Figure 5. Graflex Camera and dark slide for modern Lippmann photography

The principal of recording Lippmann photographs without mercury is shown in Fig 4. Figure 5 depicts photos of the Graflex camera and the modified dark-slide.

The processing of the Lippmann photographs is critical. 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. This is not a problem since the developed colloidal silver is not light sensitive.

Figure 6 demonstrates what a processed Lippmann photographic plate looks like when illuminated and observed in different ways. (***a***): When the plate is viewed in reflected light, where illumination or observation is not performed perpendicularly to the plate, a negative image is seen. (***b***): When the plate is studied in transmitted light, a red positive image can be seen caused by the absorption of light by minute colloidal silver particles in the emulsion. (***c***): When illumination and observation is perpendicular in relation to the plate, the correct colour image is seen. The illumination has to come from a large diffuse area above the plate. Figure 6 was recorded by HB and DG at Hengrave Hall near Bury St Edmunds on 17 June 2000. Exposure time: 4 min 45 sec at aperture f/11.

a *b* *c*

Figure 6. Lippmann photographic plate iluminated and observed in different ways:

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

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

Metallic reflections are accurately reproduced in Lippmann photographs. An example of this is a 4" x 5" plate of a white porcelain elephant recorded by HB and illustrated in Fig. 7. The plate was recorded outside in daylight illumination on a Slavich plate.

Another modern Lippmann photograph is a portrait of the author HB reproduced in Fig. 8. The plate size is 4" x 5" and recorded on Slavich material in bright sunlight softened with diffuser. The exposure time was two minutes at aperture f/4. Skin tones are remarkably realistic in a Lippmann photograph.

Figure 8. Lippmann portrait of HB and the recording of it

After being processed, the back of the Lippmann plate is painted black. For better viewing of the image, a wedged glass plate (Wiener prism, Fig. 9) is cemented to the emulsion side of each plate. Figure 10 shows an 8" x 10" plate with the Wiener prism mounted on it.

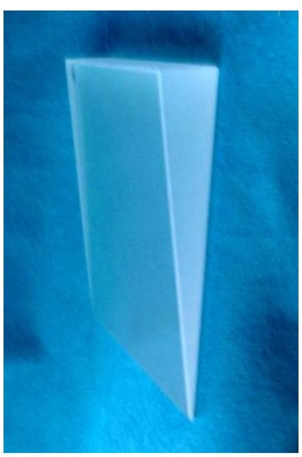


Figure 9. Wiener prism

Figure 10. 8" x 10" plate with Wiener prism attached

Lippmann Emulsions, Old and New

The silver halides are the only "practical" recording material for Lippmann photography. They can offer extreme-resolution, and the highest sensitivity due to the development-amplification factor. In the period silver bromide was used in Lippmann emulsions.

There were two basic ways Lippmann plates were prepared. The first technique was by diffusion precipitation of silver bromide in a pre-coated albumen or gelatin film by successive bathing in potassium bromide and silver nitrate solutions followed by optical sensitizing. This was soon succeeded by precipitation of silver bromide in molten gelatin, with both salts in gelatin or halide only in gelatin with the silver added either in aqueous solution or dry and powdered. Optical sensitizers were added before the emulsion was filtered and coated. Emulsions had to be coated rapidly after mixing to avoid crystal growth. The coatings were left to gel before washing to remove unwanted potassium nitrate. In all the old formulae except that formulated by Hans Lehmann, the silver was added to the halide at 35^{o}C with gentle stirring over 1-2 minutes.

While the old formulae just about work (on a good day!) they are not ideally suited to the technique. The use of bromide excess during precipitation incurs more crystal growth than silver excess. The reason is that the silver bromide is more soluble under bromide excess. This means that initial crystals nucleated continue to grow during mixing and only the last crystals formed are the finest. Thus a wide distribution of crystal sizes result, the largest of which adversely affect the recording of high quality interference colours.

DG's emulsions, even after a decade of research, are still experimental as the limits of resolution and efficiency are still being explored. However, good Lippmann images can be made on single-jet emulsions precipitated under silver excess, as performed by Lehmann, who kept his method secret as it was for a commercial product but was published later by Jahr (1925). The more complicated holographic double-jet emulsions, mixed under high dilution with freeze-thawing also perform well, and also benefit from silver excess during mixing. DG’s emulsions are typically iodo-bromide. The introduction of potassium iodide in the emulsion improves general and optical sensitivity. Since pure silver iodo-bromide is sensitive to only blue/green an optical sensitizer is added to make emulsion red sensitive. DG’s most successful single-jet emulsion and recording/processing technique are presented in Table 3.

Table 3:

Green's Lippmann Emulsion

Emulsion:

1. Soak 4g gelatin in 100 ml deionised water for 20 min. Heat to dissolve using hot water bath, and cool to 40 ^{o}C.
2. Add 1g silver nitrate to 80 ml of the gelatin solution over 1min with stirring.
3. Add 0.68 g potassium bromide & 0.048 g potassium iodide to the remainder of the gelatin solution. (Remaining steps under green or red safelight)
4. Add the halide/gelatin to the silver/gelatin over one min at 35 ^{o}C with stirring. Stir for a further min.
5. Pour emulsion into a light-proof plastic box and leave to set in a freezer for 30 min.
6. Cut up emulsion into 1/4" cubes and return to freezer for 12 hours.
7. Wash in three changes of chilled deionised water over 20-30 min.
8. Drain emulsion and melt using hot water bath and maintain at 35 ^{o}C for the following procedures:
9. Add optical sensitizers:

    A: Pinacyanol chloride 1-2 ml of 1:1000 in methanol

    B: Pinacyanol chloride 1ml of 1:1000 in methanol
    3,3'-Diethyl-9-methylthiacarbocyanine iodide 1ml 1:1000 in methanol
    3,3'-Diethyloxacarbocyanine iodide 1 ml of 1:1000 in methanol

Use either A or set B. Add each dye drop by drop over 10-20 sec with stirring.

10. Add 2 ml 1% chrome alum (hardener), filter and coat.
11. Apply 8 ml emulsion to centre of plate and tilt gently to cover each corner in succession.
12. Leave level to set and dry 18-24 hours.

Before recording:

1. On day of use hypersensitize plates in bath of 0.5% ascorbic acid + 2 drops Kodak Photoflo for 1-2 min with agitiation.
2. Stand plates vertical to dry.

Recording:

Expose in camera with emulsion-side away from the lens with a flat black light well behind the emulsion. Try 3-5 min at f/5.6 at EV 15.

Processing:

Develop in GP2 diluted 15+100 for 3 min at 18 ^{o}C.

GP2:

• Deionised water at 50 ^{o}C	750 ml
• Methyl phenidone	0.2 g
• Hydroquinone	5 g
• Sodium sulphite (anhydrous)	100 g
• Potassium hydroxide	5 g
• Ammonium thiocyanate	12 g
• Deionised water to make	1 l

Wash plate for 10 min and dip in 2% glycerin solution + 2 drops of Kodak Photoflo to compensate for processing induced shrinkage. Leave to dry naturally. For protection mount image under 10-degree prism using Canada balsam.

The finished plates must be transparent with no or very low light scatter. The ideal crystal size for Lippmann emulsions is assumed to be 10-20 nm. To get an idea just how small this is, there are one million nanometers (nm) to the millimeter! Inevitably Lippmann emulsions are spectacularly light insensitive, and are rated at around 0.001 ASA. However, the resolution is a formidable 10,000 lp/mm outstripping the sharpest lens and is able to resolve half-wavelengths of violet light (200 nm).

Exposure times are very long, even by the standards of traditional black-and-white plates in Lippmann's time. It takes around 2-5 minutes at f/5.6 to capture an image under blazing sunshine! Several shots (4-6) will be required to deliver one good result for colour and efficiency. Sometimes results are frustrated by chasing the colours with varying concentrations of solvent, and the problem of getting consistent exposures with variations in light due to passing clouds! Processing is an extremely sensitive procedure. Pure chemical developers give very dim colours indeed. Solution-physical developers are the only type of developers that give satisfactory results. In the period, pyrogallol-ammonnia was a favourite. Today developers used in holography, such as GP2 also perform very well for Lippmann photography. The solvent content of the developer has to be balanced for every emulsion, and very small changes in solvent concentration give drastic changes in visual efficiency. Lower levels give "pure" but dim colours, and higher levels result in impressive efficiency but muddy colours. There is always a trade-off between colour resolution and efficiency.

Perhaps the most serious problem during processing is differential changes in thickness of maxima and minima due to solution of unexposed crystals in minima which shrink, and migration of silver to the maxima which swell. This unavoidably results in loss of integrity in the profile of the original spectral distribution pattern. However it is only this amplification of the fringes by solution-physical development that gives acceptable efficiency and makes Lippmanns worth seeing at all.

Figure 11. Rose Garden, 4" x 5" plate by DG

In Fig. 11, a 4" by 5" Lippmann plate of the Rose Garden in Bury St Edmunds is reproduced. It was recorded without mercury by DG on 25 June 2003 using a Kodak Aero-Ektar f/2.5 178 mm lens. The recording material was a single-jet emulsion made by DG. Exposure time 10 minutes with aperture f/8 and developed in GP2.

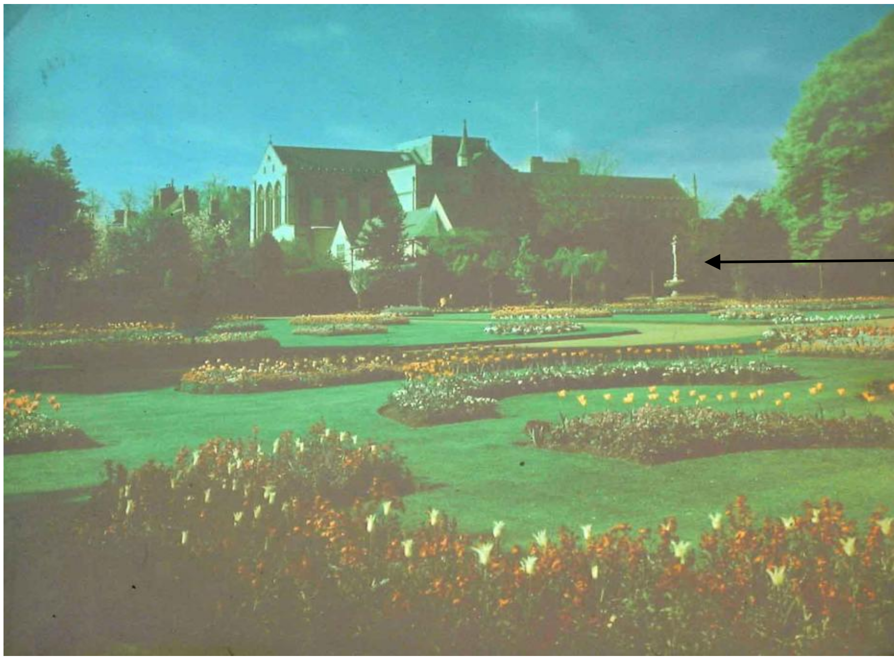
Figure 12. Newton's "Opticks", 4"x 5" plate by DG

Fig 12 shows a 4" x 5" still life Lippmann plate: ***Newton's "Opticks"*** by DG. It was recorded without mercury outside in sunlight on 2 May 2007 using a Schneider Apo-Symmar f/5.6 150 mm lens. Exposure details: 5 minutes 45 seconds, f/8 -1/3 stop.

Figure 13. HB with the 4" x 5" Graflex camera

Figure 14. DG with the 8" x 10" Iston view camera

The authors have recorded several large Lippmann photographs together. When not using mercury it is much easier to record large Lippmann photographs, provided one has access to large photographic plates. Here is an example of an 8" x 10" plate recorded on 1 May 2000 in the Abbey Gardens, Bury St



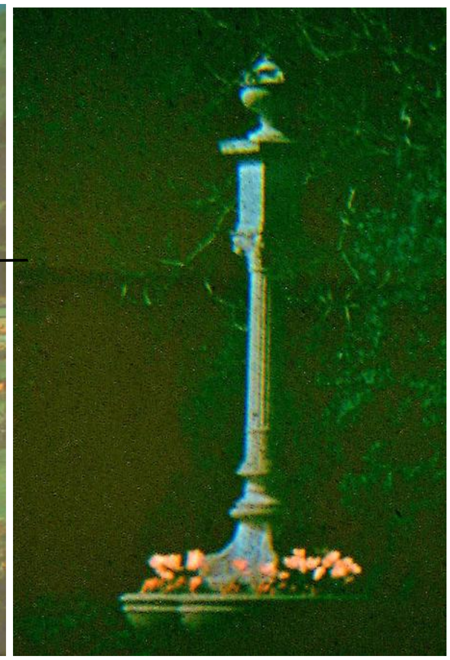


Figure 15. Abbey Gardens, Bury St Edmunds, 8" x 10" plate *Figure 16. Detail from Fig. 15*

Edmunds. Recording data: aperture f/11, exposure time 3 minutes on a Slavich PFG-03c glass plate. The plate was developed in the holographic GP8 developer. The very high image resolution of the recorded Lippmann plate in Fig. 15 is demonstrated in Fig. 16, showing a detail of the recorded scene. The resolution is actually limited by the quality of the camera lens and not by the resolving power of the recording material.

In the USA the art photographer Jesús López (2003) has built a large Lippmann plate camera named "***Gabriela***" for the recording of glass plates up to 60 cm x 60 cm. This camera is equipped with a 1940s Bausch & Lomb Aero Tessar lens, f/6.0, focal length 610 mm. He is using the recording materials from Slavich (PFG 03c, most often 30 cm x 40 cm glass plates). The exposure time varies between 5 to 20 minutes in his Michigan studio equipped with a very strong lighting system. He got exited about Lippmann's technique when he saw some of HB's first Lippmann photographs in the mid 1990s. In particular he was impressed how the colour of skin could be reproduced in such a photograph. López' interest in art has always been the beauty of the female figure and he found that Lippmann photography would be the most suitable media for this. Since he wanted to create large format Lippmann photographs he needed an equally large camera. When mercury is no longer needed; making large-format Lippmanns is no longer an impossible task, but still a lot a work went into the fabrication of the ***Gabriela*** camera.

According to López: "*The large-format Lippmann is a grand art and science. Conquering it brings satisfaction, pleasure, and the ability to begin a more selective form of photography. It is the finest in performance, where each image can be handcrafted and every image you dream of can become a reality. A large format camera takes more thought and preconception to operate. It leads you down to the point where fundamentals are used as steps to build an image. The end result is a clearer method of approaching an image and accomplishing what after all is a complement to our vision."*

Figure 17. Jesús López and HB next to the "Gabriela" camera.

*Figure 18. Jesús López next to "**The Beautiful Mathilda**," a 30 cm x 40 cm Lippmann plate, recorded in 2001*
(Note the display installation with the large diffuse light above the plate needed to display the image)

Cultural Impact

The momentous disclosure of photography in 1839 has been described as a turning point in human culture, comparable to the invention of linear writing (Flusser 2000). The new art presented a medium of unprecedented realism that captivated spectators. The inimitable rendering of apparently endless detail, and seamless chiaroscuro struck the most scientific of observers as miraculous. But the lack of colour didn't go un-noticed, and the quest for true colour photography was initiated at the very dawn of the medium. Traces of colour appeared spontaneously on papers and plates well within the first decade of photography, but the exact nature of their formation remains obscure, and since the exposures took hours by print-out and the colours couldn't be fixed, the effect was of no use to photographers.

The photographic landscape had been predominantly monochrome for fifty years before Lippmann finally presented his definitive solution to the problem. His disclosure in February 1891 is reported to have caused 'considerable commotion' and was highly acclaimed. In a time when the only permanent colour was applied by hand, the idea of direct/natural colour photography had seemed as far away as ever, and a few writers found Lippmann's theory absurd and his results marginal.

The first Lippmann colour images made by the Lumière brothers were inspected by members of the Royal Photographic Society in 1893, and settled any lingering doubts over the veracity of the reports - true colour photography had been realized. In 1897, Lippmann himself addressed the same society, demonstrating his process, apparently speaking in 'faultless English'.

For a period spanning two decades, photographic journals carried numerous reports on progress in Lippmann photography. Whole books were devoted to the technique detailing every aspect of the process, from emulsion making and coating, to processing and display. The final effort to commercialize came from Zeiss in 1910.

The minority of skilled experimenters who succeeded with the process, generously and openly reported their findings, disseminating their research to a wider public. It is not known how extensive was its practice among photographers generally, but there is little doubt that technical difficulties inhibited its wide-spread use. At a time when commercial developments such as hand-cameras, roll-film and factory processing were making photography more user-friendly, the introduction of a technique that offered the photographer yet more difficulties must have seemed to some like a step backwards. However, the impression Lippmann's images made on photographers of the day is clearly expressed by at least one master of monochrome - Edward Steichen who wrote to Stieglitz in 1908: [Newhall (1982)] “*Professor Lippmann has shown me slides of still-life subjects by projection, that were as perfect in color as in an ordinary glass positive in the rendering of the image in monochrome. The rendering of white tones was astonishing, and a slide made by one of the Lumière brothers, at a time when they were trying to make the process commercially possible, a slide of a girl in a plaid dress on a brilliant sunlit lawn, was simply dazzling, and one would have to go to a good Renoir to find its equal in color luminosity*.”

The impact of Lippmann's process on the scientific community is evidenced by his nomination for the Nobel Prize, which began as early as 1903. His process had vindicated Maxwell's electro-magnetic wave theory of light, and his mathematical analysis, using Fourier transforms, was considered to be of extraordinary elegance.

An interesting aside to this is that Max Planck, father of quantum physics, was also a favourite candidate for the 1908 Prize. There may be more than irony to why the Prize went to Lippmann. Lippmann's process neatly vindicated the wave theory of light. The return to what looked like a particle theory of light was found absurd and objectionable even to those who advocated the quantum theory. Trying to explain interference colours using a particle theory would have been conceptually impossible in 1908. Today Lippmann's interference patterns might be explained by that favourite trick of quantum mechanics: self-interference of photons.

Lippmann photography also stimulated the search for improved optical sensitizers, particularly for red sensitization, and this contributed to more practical colour processes, such as Trichrome c1900 and Autochrome c1907 when they appeared.

Finally the concept of the spectral registration of colours in a volume interference pattern and replay by diffraction combined with the extreme resolution plates necessary to realize this, contributed directly to the development of holography.

Conclusion

Today Lippmann's photography has limited applications in photography and colour imaging, but may well appeal to artists and art photographers. The Lippmann photograph is virtually impossible to copy, which makes each image a unique, one-of-a-kind photographic recording, combined with extreme archival longevity.

Perhaps in the future, some of the technical obstacles which have prevented its wide-spread practice will be overcome. Already, the authors have shown that mercury is not essential to record the colours. A recent development for a "new" kind of optical display (Waldrop 2007) is the 'interferometric modulator' (IMOD) which reflects brilliant colours by changing the gap between a pair of micro-mirrors, and shows iridescent colours similar to Lippmann's.

The renovation and realization of the true colour of Lippmann photography is surely long overdue. There is no doubt that Lippmann has left us an exquisite and truly enduring legacy. Perhaps the real impact of Lippmann's contribution lies in the future of photography, not simply its forgotten past. It may be that the best Lippmann photographs are yet to be made...

Note: (Since conventional photography, analog 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.)

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