Lippmann Color Reproduction

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Abstract

Lippmann color photography is the only process known to record physically the spectral composition of any light distribution. It can be regarded as a precursor of Fourier spectroscopy or simply as a physical process for the memorization of colors. The method is described and revisited to explore its scientific impact, and the technical challenges that infer with its realization. The implication of its cultural vigor and the formidable longevity of Lippmann photographs are also described.

Introduction

Color reproduction by the interferential method invented by G. Lippmann relies on a geometrical distribution of scattering elements.[1] Lippmann photography mimics some color production mechanisms encountered in nature with some insects and shellfish displaying so-called structural colors. Encoding and reconstruction of Lippmann "colors" is based on a very simple theory. It holds the unique characteristic to be capable of an exact memorization of spectral components as well as an almost rigorous reconstitution of spectra. However, any implementation of the system turns out to be a monumental challenge.

This paper first describes the method to underline its enormous potential. It also stresses the difficult technical solutions needed to carry out the process. Then, the Lippmann method is compared to some processes used in holography, mainly to point out how more complex a broadband Lippmann photograph is compared to a Lippmann hologram. The impact of Lippmann color reproduction is described and recent proposals and potential future uses are analyzed.

Memorizing Colors through Interference

The imaging theory underlying Lippmann color photography is very simple: incident light forming the image in a camera interferes with its own reflection on a mirror attached to the photosensitive layer. This redistributes the wave energy to generate an interference pattern into the thickness of the photosensitive film. For any spatial element of the image, such pattern is a light intensity distribution laying perpendicular to the image plane and represents the temporal Fourier transform of the spectral composition of incident light, as demonstrated by Lippmann.[2] Imprinting this motif constitutes the record that corresponds to a full memory of the spectral distribution. After recording has been performed, the mirror is removed. One can retrieve the spectral distribution by illuminating the record with a broadband white light source: reflection on the imprinted motif performs an inverse Fourier transform, thus regenerating the original spectrum. Two examples of spectral encoding in Lippmann photography are represented in Figure 1. The upper part is a cross section of the recording of a monochromatic collimated light beam, having a 3-nm wide bandwidth at half-maximum The lower part shows the geometrical distribution of scatterers in the recording of a broadband area of a scene. The pattern corresponds to an area on a Lippmann color photograph that contains snow on a mountain and therefore to a "white" spectrum. Both parts of the figure correspond to the light amplitude along a direction normal to the photograph plane.

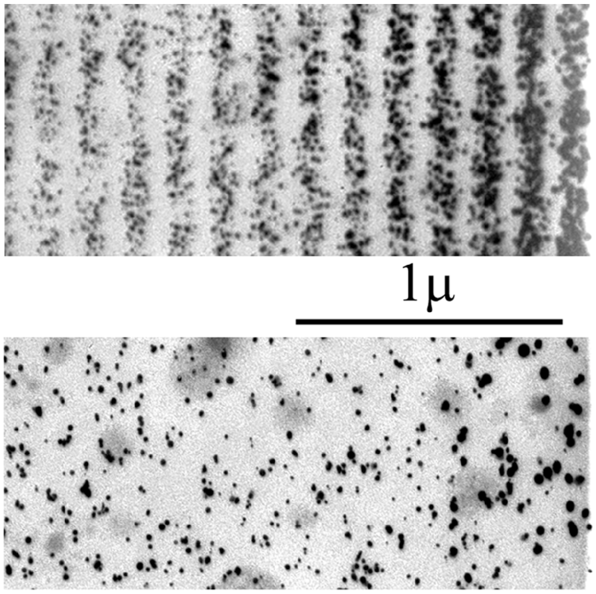

Figure 1. Color encoding by amplitude modulation in the thickness of a black and white film. A mirror in contact with the emulsion (here at the right side) produced the standing waves. Top: quasi-sinusoidal distribution for a 3 nm narrow-bandwidth filter at 633 nm; Bottom: part of Fourier Transform intensity distribution for a 250 nm bandwidth spectrum.

From Monochromatic to Broadband Light

As trivial as the interposition of a mirror in a light beam seems to be, one must notice the optical physics function it performs: any reflection on a medium of higher optical index is associated with a 180-degree phase shift. This feature induces another remarkable property, that is the standing wave generated by interference between an incident wave and its reflection presents always a node at the mirror surface. Thus, any mirror hit by a light wave acts as a phase locker for that wave. This very characteristic interaction constitutes the basis for the Lippmann interferential method. Coding a spectral line becomes extremely simple, at least in principle, since the interference pattern associated with two counter-propagating plane waves is a standing wave made of sinusoidal fringes separated by a distance $d = \lambda/2$ where λ is the wavelength of light in the photosensitive medium. All standing waves have a node at the surface of the mirror, which is also the external surface of the photosensitive medium. Since this phenomenon is wavelength independent, one can easily foresee the mechanism involved for a broadband case: there, each individual component of the light spectral distribution generates it's own standing wave, holding its own particular $\lambda/2$ pitch. The linear combination of all standing waves is an amplitude distribution of light, fading away very quickly when it departs the mirror plane. This shortening of the contrast and of the amplitude of the total standing wave is the result of the addition of many individual sinusoids of slightly different pitches. Indeed, it characterizes the coherence length of the light, and it constitutes the Fournier transform of the spectral distribution.

Let's now consider color reconstruction. Any periodic structure can act as a resonant filter and select some wavelength component out of a broadband illumination. This is how an interference filter works. If a periodic structure with period $\delta = \lambda/2$ is illuminated with a broadband collimated beam of light, whith direction parallel to the period of the structure, a retro-reflected beam is generated by constructive interference at precisely the wavelength λ, twice the spacing of the structure. This provides the scheme for reconstructing narrow-band spectra. In the case of more complex broadband spectra, each single component of the recorded Fourier transform distribution scatters the impinging light. One can demonstrate that the collective back-scattering performs an inverse temporal Fourier transform, then reconstructing a light beam having a spectral composition of light identical to the one previously encoded.

Practical Aspects of Interference Recording

Lippmann photographs can be recorded in many different materials, as long as the necessary spatial resolution can be achieved. Indeed, what has been called scatterers above can be made indifferently from metallic or from dielectric material.

The intensity distribution which constitutes the interference pattern is generated by the constructive and destructive addition of wave amplitudes. This later phenomenon takes place only within the coherence length of the light used. To give an order of magnitude, a 250-nm bandwidth spectrum affiliated to some pixel of a scene will be coded by the shape of the interference pattern, that has a thickness less than 0.3 microns long. The record needs only to keep the shape of the interference pattern, It can be done in either an material that, after processing, can act as a dielectric or as a metallic material. There are many examples using either case. At the reading stage, the amplitude and the phase of the illuminating beam will be reshaped to reproduce the original spectra.

Perfect color reconstruction would, in theory, call for genuine phase materials, since pure transparency would not affect diffracted colors. Any stain or any other source of coloring into the recording material would be a source for noise. In practice, very good spectra reconstruction have been obtained despite stained emulsion layers, particularly in the case of broadband reconstruction where encoding is done over a thickness of the order of magnitude of the wavelength of light.

The process requires ultra-high resolution recording materials, that should handle the possibility to at least separate "fringes" with a pitch of $\lambda/2$. This corresponds to about 8, 000 lines/mm at the blue end of the visible spectra for a medium of optical index equal to 1.6. Moreover, the mechanical stability of the recording material must be excellent. It has been stated that most of the information corresponding to a broadband spectrum can lay within a thickness of less than 0.3 micron at the top surface of the recorded layer. Indeed the relative position of scatterers must be maintained within this tiny depth.

Features of Lippmann Color Reproduction

Lippmann color results from the interaction of a broadband illumination light with a geometric structure. Such spectral selectivity does not depend on pigments or dyes to filter light, and therefore holds the potential for an extreme longevity. Here, there is no dye to fade over time, and therefore no tarnishing of colors, as long as the structure is kept rigid. This is similar to structural colors seen on some insects and on some bird feathers, which keep their vivid and brilliant hues for ages, regardless of light exposure. Some Lippmann photographs display intense colors and shining tints more than 100 years after having been recorded. The accuracy of spectral reconstruction has been measured on several Lippmann photographs 80 to 100 year old.[3] In a particular case for an 19th century photograph of a spectrum, some spectral lines are still reconstructed with a shift as small as 1 nm.

To appreciate this achievement, one must realize that it is extremely difficult to attain such values in modern holographic materials where some of the best colors are produced also by constructive interference generated by illuminating sets of Bragg diffraction gratings.[4]

A Lippmann structure diffracts color in a reflection mode. In the simple case of the registering of monochromatic spectra, the sets of fringes can be recorded on a high resolution photographic film, which is developed in a conventional way. However, the colors appear in reflection. The photograph acts as a negative when viewed in transparency: each color is represented by its complement; By reflection, however, the system acts as a positive: it reconstructs the proper color.

From History to Modern Applications

The memorization of colors through three-dimensional recording on a photosensitive layer coated on a mirror dates back probably to the invention of photography, especially to the work of Niépce in the 1820s.[5] Convincing records have been shown and published by Becquerel, who wrongly attributed the result to a chemical artifact. The work of Lippmann had a considerable impact on color photography and on Science. Lippmann showed his first pictures, displaying brightly colored spectra, in early 1891. Several concepts to realize color photographs had been proposed before. However, the photographs Lippmann showed were the first color photographs an educated public saw; they had been recorded in black and white emulsions and they were convincing proof that high quality color photography was feasible. This stimulated an intense research to improve the process, which became supplanted within a few years by more user-friendly methods, such as trichrome and autochrome photography. Nevertheless, interferential color photography found some applications in the use of very-fine tunable interference filters, first as a source for monochromatic light in photometry, later in spectroscopy.

Lippmann's model to explain color reproduction was highly criticized long before receiving total acceptance by the scientific community. It helped to answer one of the major questions not resolved then in optical physics, that is the direction of what is now called the electric vector in an electromagnetic wave. Lippmann's work was aimed as an experimental proof of Maxwell electromagnetic theory.[6] Many years later, photographic materials manufacturing and chemical processing - refined in the development of Lippmann photography - had a huge impact in volume holography. In return, Lippmann photography happens to be an extremely simple and efficient tool to characterize holographic materials.

In more recent times, several applications have been suggested, such as the use of the Lippmann technique for optical storage.[7] New materials have been applied or developed to record interferential colors.[8] Lippmann photographs cannot be reproduced easily: this feature has been a constant drawback for photographic uses, but could work advantageously as a security feature.[9] An innovative scheme called diffractive printing allows to produce color reproduction of broadband scenes through a set of monochromatic records.[10] Rejection filters manufactured by techniques very similar to Lippmann's method - as it is described in textbook presentations - are currently used in Raman spectroscopy in operating rooms, and in fluorescence microscopy.[11]

Conclusion

Lippmann color reproduction gets its quality from a very powerful coding method that is based on a simple reflection to produce light interference. This extremely stable pigment-less system is capable of a remarkable longevity and of an accurate memorization of the spectral composition of light.

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