Color holography to produce highly realistic three-dimensional images

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The 1964 publication by Emmett Leith and Juris Upatnieks [J. Opt. Soc. Am. 54, 1295 (1964)] introduced the possibility of using holograms to record three-dimensional (3D) objects. Since then, there has been an interest in creating display holograms, i.e., holograms primarily produced to show objects in 3D. More recently, full color holography has become a reality, which was predicted in the 1964 paper. To record a hologram in which both the 3D shape and the color of the object are accurately reproduced, at least three laser wavelengths are needed. By computer simulation of the holographic color rendering process, the required amount of laser wavelengths and their distribution within the visible electromagnetic spectrum have been investigated. The quality of a color hologram also depends on the properties of the recording material. The demand on a panchromatic material for color holography is described. Recording techniques for color holograms are presented as well as the future of color holography as the perfect 3D imaging technique. © 2008 Optical Society of America

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1. Introduction

The 1964 publication by Emmett Leith and Juris Upatnieks [1] presented the possibility of recording transmission holograms of 3D objects by introducing the off-axis reference-beam technique. A hologram of a model railroad engine was on display at the OSA spring meeting in Washington, D.C., which was held in April 1964 [2]. The hologram, illuminated with a laser, displayed a realistic-looking 3D image, which had a huge impact on the scientists at the meeting. In principle, when illuminated with the same laser wavelength as was used for the recording, it is not possible to see any difference between the holographic image recorded and the object itself. The displayed hologram and the publication started a tremendous interest in holography. Because only one laser wavelength was used to record and display the hologram, the 3D image was, of course, monochromatic. However, multicolor wavefront reconstruction was described in the Leith–Upatnieks paper; the authors mentioned that it should be possible to illuminate a scene with coherent light in each of the three primary [red, green, blue (RGB)] colors. Transmission holograms were the main topic of the paper and therefore the three reference beams proposed for recording a color hologram had to come from three different directions to avoid cross talk when viewing the recorded hologram. The hologram would comprise three incoherently superimposed RGB holograms, showing a full color 3D scene upon reconstruction. In a note, pointed out by a reviewer, it was stated, “An object illuminated by monochromatic light in three primary colors may not produce the same color rendition as would the object if illuminated by ordinary white light. This could happen if the wavelength variation of object transmittance or reflectance were not a smooth, slowly varying function of wavelength” [3]. This statement is important since it highlights the problem of recording color holograms that can be viewed under ordinary white-light illumination. Leith and Upatnieks pointed out that holography is related to the Lippmann color process [4]. Interferential color photography, invented by Lippmann in 1891 [5], is capable of perfect color rendition since it

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is actually recording the entire visible spectrum. However, in practice, Lippmann's technique is complicated and requires a perfect isochromatic and panchromatic recording material that has ultrahigh resolving power as well [6].

Attempts to record full-color holograms, transmission or reflection, were reported a few years after the Leith–Upatnieks publication [7–12]. The most logical name for a hologram in which the recorded object's color is accurately reproduced is a color hologram. Other terms such as full-color, natural-color, or true-color holograms have been used for lifelike holographic images. In an analogy with color photography, color movies, and color television, the term color holography should now become the norm. However, this term is sometimes objected to on the grounds that some colors of the objects we normally see around are sometimes impossible to record holographically since holograms can only reproduce colors of objects created by laser light scattered off objects. Colors we see are often the result of fluorescence, which cannot be recorded in a hologram. For example, some dyed and plastic objects achieve their bright, saturated colors by fluorescence. However, this potential limitation in color holography should not be much of a concern.

Since the 1960s, there has been progress in color holography [13–24]; however, to be able to record high-quality color holograms, many problems still remain to be solved.

The important issues here are

- how many and which laser wavelengths to employ,
- what material to select for the recording of the hologram,
- how to reconstruct the wavefronts in the hologram so that the recorded image can be correctly viewed (i.e., what type of light source to use to illuminate the holographic plate).

The color reflection hologram technique is most often used because ordinary white-light sources can be used to illuminate the hologram for display. Earlier, when no suitable panchromatic materials existed, a sandwich technique was used to record color reflection holograms. A successful demonstration of a sandwich recording technique was made by Kubota who used a dichromated gelatin plate for the green and blue components, and a silver halide plate for the red component of the image [17]. Kubota's sandwich color hologram of a Japanese doll recorded in 1986 clearly demonstrated the potential of high-quality color holography. Subsequently when panchromatic silver halide materials for holography became available, Bjelkhagen et al. [22] demonstrated the possibility of recording color holograms in a single-layer emulsion.

2. Selection of Laser Wavelengths

Choosing the correct recording laser wavelengths is a key issue where accurate color rendition is the concern. So far, most color holograms have been recorded using three primary laser wavelengths, resulting in rather good color rendition. However, the colors recorded are not identical to the original colors and also color desaturation (color shifting toward white) may be a problem.

As suggested by Leith and Upatnieks [1] and as a starting point, three RGB laser wavelengths can be employed for recording color holograms; this follows the tristimulus theory of color vision, which implies that any color can be matched as a linear superposition of three primaries. The tristimulus values define the color appearance of an object illuminated by a certain light source for an average observer. The tristimulus values of an object are given by

\[
X = \int_\lambda \tilde{x}(\lambda)S(\lambda)E(\lambda)d(\lambda),
\]

\[
Y = \int_\lambda \tilde{y}(\lambda)S(\lambda)E(\lambda)d(\lambda),
\]

\[
Z = \int_\lambda \tilde{z}(\lambda)S(\lambda)E(\lambda)d(\lambda).
\]

In the above equations \(\tilde{x}\), \(\tilde{y}\), and \(\tilde{z}\) represent the color-matching functions of the average observer, \(E(\lambda)\) represents the power output of the illuminant over the visible spectrum, and \(S(\lambda)\) is the spectral reflectance curve of the object. Each color has a different spectral curve. The nature of the illuminant in color holography plays the most important role regarding color reproduction. The reason is the difference between white light produced by narrowband monochromatic laser wavelengths and broadband light of a common illuminant such as daylight. In Figs. 1 and 2 there is a demonstration of the difference between broadband and monochromatic illuminants. Because of the narrowband response of the laser illumination sources, the tristimulus values of a hologram are given by

![Fig. 1. Spectral radiance of white light produced by a tungsten lamp.](image-url)
where \(i\) is the number of laser wavelengths that are used during the recording of the hologram. There is a fundamental difference between the tristimulus values of the object [Eqs. (1), (2), (3)] and the tristimulus values of the hologram [Eqs. (4), (5), (6)]. For the calculations of the tristimulus values of the object all the components of the spectral curve are taken into account. On the other hand, regarding the hologram the only information about the spectral curves that is preserved is that located at the points that correspond to the recording wavelengths. Figures 3 and 4 illustrate the difference between the spectral response of an object illuminated by a broadband light source (Fig. 3) and three monochromatic laser wavelengths (Fig. 4). It is apparent from Eqs. (4), (5), (6) that the monochromatic laser light introduces the sampling of the spectral properties of the object. Undersampling can lead to significant differences between the tristimulus values of the hologram and the tristimulus values of the object and hence an overall difference in color. To demonstrate the effect of undersampling in color holography, an example given by Peercy and Hesselink [21] is employed. Figure 5 plots the spectral reflectance curves of objects A and B. Object A has a gray color and B has a bluish-purple color. At wavelengths of 477, 514, and 633 nm, both objects have the same value for spectral reflectance. Assuming a holographic recording of objects A and B with these laser wavelengths, the holographic images of both objects will appear to have the same color, since the hologram of the scene preserves only the surface-reflectance sampling wavelength information. The color reproduction problem in this example is caused by undersampling in the wavelength domain, which leads to aliasing.

It is important to ensure that a sufficient number of laser wavelengths are employed to avoid undersampling; it is also critical to define the minimum number of laser wavelengths to produce a hologram that demonstrates a visibly acceptable error in color rendering. Increasing the amount of recording laser wavelengths will improve color rendition, but, at the same time, it will considerably increase the complexity and cost of the recording setup.

There have been theoretical investigations carried out that studied the minimum number of laser wavelengths needed to give an error in color rendition that is small enough to be undetectable by an observer. Peercy and Hesselink [21], as well as Kubota et al. [23], obtained results that indicate that more than three laser wavelengths are needed to reduce the color error. Since the previous investigations obtained different results, Mirlis et al. [24] performed a computer simulation based on Eqs. (1) to (6), in order...
to define the error values for different numbers of laser wavelengths, taking into account all possible combinations of wavelengths between 400 and 700 nm. The authors found that, once above seven laser wavelengths, further improvement in color rendition is minimal and four or five should be considered the optimum number for high-quality color holography. The results are plotted in Fig. 6. In Table 1 the average color rendering error for three to seven optimal laser wavelengths is listed. The Macbeth Color-Checker target was used to illustrate the improved color rendering. Figures 7–10 illustrate the error for each Macbeth color, as calculated by computer simulations. Figure 7 presents the error for a hologram recorded with the laser wavelengths that are available to the authors (476, 532, and 647 nm). Figures 8–10 present the error of the optimal sets of wavelengths that are listed in Table 1. By comparing the error graphs with each other, it is apparent that color reproduction will be enhanced dramatically by employing one of the optimal sets. The problem that arises is that the optimal wavelengths are a product of simulation and they perhaps do not correspond to existing or commercially available lasers suitable to holography. Recently, the authors obtained access to new lasers that will introduce more wavelengths in the recording. Also the new lasers have the ability to be tuned to different wavelengths to allow several different combinations.

It should be pointed out that when compared with a monochrome hologram, a color hologram is less affected by laser speckles, which have an influence on image resolution. There is an averaging of the speckle effect between different wavelengths when recording a color hologram, this averaging effect is more pronounced when the number of recording laser wavelengths is increased [25]. Another improvement is that often a moiré pattern may appear on the surface of the glass plate when recording a monochrome reflection hologram. This is caused by interference between the two surfaces of the glass substrate. By employing multiple wavelengths during the recording of a color hologram, the individual moiré patterns are superimposed, resulting in a moiré-free plate.

3. Recording Materials

The choice of recording material is of equal importance to the choice of laser wavelengths for the recording of a color hologram. To be able to record high-quality color reflection holograms, it is necessary to use extremely low light-scattering panchromatic recording materials. Currently the main materials in use are certain photopolymers and a special emulsion based on silver halide. There are several problems associated with the recording of color reflection holograms. First, severe light scattering from the blue part of the spectrum excludes many materials from being used, e.g., many common holographic silver halide emulsions that in the past worked well for green and red monochrome holography. Second, mul-

### Table 1. Total Average Error for Three to Seven Optimal Wavelengths

<table>
<thead>
<tr>
<th>Number of Wavelengths</th>
<th>Optimal Laser Wavelengths (nm)</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>466, 545, 610</td>
<td>0.0137</td>
</tr>
<tr>
<td>4</td>
<td>459, 518, 571, 620</td>
<td>0.0064</td>
</tr>
<tr>
<td>5</td>
<td>452, 504, 549, 595, 643</td>
<td>0.0059</td>
</tr>
<tr>
<td>6</td>
<td>451, 496, 544, 590, 645, 655</td>
<td>0.0040</td>
</tr>
<tr>
<td>7</td>
<td>445, 482, 522, 560, 599, 645, 655</td>
<td>0.0026</td>
</tr>
</tbody>
</table>
multiple exposures in a single emulsion may reduce the diffraction efficiency of each individual recording [26]. Third, the shrinkage of the material, which often takes place during or after processing, causes a wavelength shift in the reconstructed image. Finally, white-light-illuminated reflection holograms normally show an increased bandwidth upon reconstruction, thus affecting the color rendition.

A. Photopolymer Materials

Certain panchromatic photopolymer materials are suitable for recording color holograms. Currently, the only commercial manufacturer of such a material is DuPont [27,28]. It has the advantages of easy handling and dry processing (only UV curing and baking.) However, DuPont announced recently that their materials will no longer be on the general market, with the exception of their in-house hologram production and a few select customers such as those working in the field of optical document and product security.

B. Silver Halide Materials

There are very few materials of the silver halide type on the market suitable for color holography. What is needed here is a panchromatic ultrafine-grain silver halide emulsion (grain size of approximately 10 nm or less). Currently, the only commercial producer of such a material is the Slavich Company [29] in Russia. However, the quality and performance of the Slavich products can vary considerably. Poor reproducibility and problems in supply have not been conducive to market or application development. There are a few experimental panchromatic silver halide materials that have been described but not commercialized [30–34]. As there are no truly suitable materials for recording high-quality color holograms and holographic optical elements (HOEs), the development of new materials is needed.

The European SilverCross Project [35] was created to design and develop for mass production a recording material for color holography. The chosen technical route for this project was to continue the use of materials based on photographic silver halide technology because over the years this has proved to produce the results of the highest recording quality and image fidelity. The key to achieving the SilverCross Project aims was the design of a suitably sensitive silver halide emulsion. In essence the important specification criteria for the emulsion were identified as follows:

- a new nanoparticle, panchromatic, silver halide gelatin emulsion;
- target particle size of 5–10 nm;
- high sensitivity of \(<2 \text{ mJ (cm}^{-2}\); low image noise, i.e., low light scattering;
- isochromatic, i.e., a reasonable equality between the red, green, and blue sensitivity of the emulsion;
- reproducible characteristics, batch to batch and plate to plate;
- stable performance characteristics with time as well as storage conditions.

It was also essential to use and develop techniques that could be used for manufacture on an industrial scale by

- identifying a process of coating these emulsions in quantity onto glass plates (and eventually film),
- developing a prototype emulsion manufacturing apparatus and process.

At the close of the project in February 2007 most of these key aims had either been met in full or had reached a practical and acceptable point.

In spite of the volumes written about photographic science, little is specifically known about the making of very small photosensitive particles, i.e., in the 5–10 nm size region, that has been investigated. Silver halide crystals in photographic film emulsions are typically between 350 and 2000 nm, depending on the film’s sensitivity. In printing paper emulsions, the crystals are between 200 and 300 nm. It was only with the development of monochrome holographic materials that considerably smaller crystals were first produced, but even then these were still typically 30–100 nm. In essence, the development of photo-

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Fig. 9. Computer simulation bar graph that displays the error for each Macbeth color of a hologram that is recorded with four laser wavelengths at 459, 518, 571, and 620 nm.

Fig. 10. Computer simulation bar graph that displays the error for each Macbeth color of a hologram that is recorded with five laser wavelengths at 452, 504, 549, 595, and 643 nm.
graphic silver halide designs has been all about the controlled growth of crystals to meet the specified sensitivities and other characteristics. The crystals required by the SilverCross emulsion are little more than the nucleation particles seen at the start of making a conventional photographic material; therefore the problem has not been about crystal growth, but rather it has primarily been about growth prevention or restriction and then about how to achieve sensitivity from the very small particles thus formed without also inducing further growth.

The most information about producing very small or ultrafine-grain silver halide crystals comes from the very early work of Lippmann [5] in color photographic reproduction. Therefore the Lippmann emulsions [6] have become a good starting point for making ultrafine-grain holographic recording materials, which was first adopted by Denisyuk and Protas [35] when recording their single-beam reflection holograms.

One of the many difficulties to solve for the emulsion design was growth restriction, and to this end a technique based on one used by Kirillov et al. [37,38] was developed. In essence this is the removal of the precipitation by-products by freezing and thawing the emulsion. The technique Kirillov et al. used involved a number of freeze–thaw cycles plus showering the emulsion with very cold water as well as additions of gelatin and other chemicals; for the SilverCross Project this was simplified to one freeze–thaw cycle.

In essence the SilverCross holographic emulsion is an iodobromide, one that is spectrally sensitized by use of sensitizing dyes to be panchromatic and then chemically sensitized with a cocktail of compounds to give the required sensitivity.

Figure 11 shows a sensitometric Hurter and Driffield (H&D) curve for a typical emulsion; it plots relative log exposure against the measure density achieved. The exposure to produce this is 2 min at 1200 lux to a full spectrum white light, and in practice this equates to a sensitivity of approximately 2 mJ/cm² when making exposures using lasers of three RGB wavelengths. A TEM electron micrograph of a typical SilverCross emulsion showing the size and size distribution of the silver halide crystals, determined as 8–15 nm, is shown in Fig. 12.

4. Recording and Displaying Color Holograms

It is difficult to produce high-quality color holograms because a minimum of three laser wavelengths
(RGB) are needed, all with a stable balanced output power. To obtain white is difficult because variation in the output powers of the lasers will result in a color shift and thus a color cast in the recorded image. If one wants to record the most realistic-looking images, both vertical and horizontal parallax are essential. This combined with a viewing field of 180 deg in both dimensions means that the most suitable recording setup is the single-beam Denisyuk technique for recording reflection holograms.

The light source used to replay recorded holograms is also important. The selection of a suitable spotlight for displaying color holograms is more critical than choosing one for monochrome holograms because the color temperature of the source has an influence on the color rendering of the holographic image. In addition, the display source size determines the blur in the parts of the image that appear either in front of or behind the plane of the holographic plate. Arranging the correct illuminating angle (i.e., the same reference angle that was used for recording the hologram) between the holographic plate and the spotlight ensures that the correct color of the displayed image is seen. To avoid any image aberrations, the distance from the display light source to the holographic plate should be the same as the distance from the divergent point of the reference beam to the plate used during the recording.

The rapid progress in solid-state lasers, LEDs, and organic LEDs (OLEDs) has opened new possibilities for the display of color holograms. The ideal situation would be if the wavelengths of the LED or OLED light source could match the recording laser wavelengths used. This would guarantee that only the light from the source (mixture of the wavelengths) to illuminate the hologram is the same as the one used to create the holographic image. Using a halogen spotlight, which is the common practice today, a large part of the light spectrum emitted is illuminating the surface of the plate without having any effect on the intensity of the image. Instead it creates light scattering, lowering the image contrast. LED light sources have considerable advantages over halogen and other traditional lighting sources, such as

- long life (20,000 to 100,000+ hours),
- small size for improved design and sharper holographic images,
- high durability and robustness to thermal and vibration shocks,
- low energy usage and high energy efficiency,
- no IR or UV in the beam output,
- directional light output for increased system efficiency,
- digital dynamic color control—white point tunable.

Solid-state RGB lasers could also become potential light sources for holograms in the future, and this will make it possible to display deep-scene, off-axis transmission color holograms of the Leith–Upatnieks type.

5. Setup for Recording Color Holograms

A. Color Transmission Holograms

As mentioned above, an off-axis transmission color hologram may eventually be possible to record, but even if suitable small solid-state lasers existed today, the complex arrangement to display such a hologram to avoid cross talk makes it not very practical. The laser safety aspect of such a display system must be considered as well; i.e., it is essential that the observer avoid looking directly into the reconstructing laser reference beams. However, the quality of a deep-scene hologram illuminated with the required amount of laser wavelengths would be impressive.

Color holograms of the Benton type (rainbow holograms) can be either computer generated or photographically recorded as holographic stereograms. A holographic stereogram can be created by using a series of 2D photographic images from which the transmission hologram is composed. To obtain a high-quality holographic image with a large field of view, many 2D images are needed. However, in a white-light viewable rainbow hologram, the color of the image changes as a function of vertical viewer position, which makes them less attractive for accurate color reproduction.

B. Color Reflection Holograms

To obtain realistic-looking holographic images, the preferred type is the reflection hologram. A typical recording setup with three RGB lasers is illustrated in Fig. 13. For most display purposes, the very large field of view obtainable in a single-beam Denisyuk hologram is attractive (180 deg horizontal and 180 deg vertical). The different laser beams necessary for the exposure of the object pass through the same beam expander and spatial filter. The 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: for example, 476 nm, provided by an argon-ion laser; 532 nm, provided by a cw frequency-doubled Nd:YAG laser; and 647 nm, provided by a krypton-ion laser. Two dichroic beam combiners are used for adding the three laser beams. By using such beam combiners, simultaneous exposure of the holographic plate 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, whereas the overall exposure energy is controlled solely by the exposure time.
C. Digitally Printed Reflection Holograms
The most-realistic-looking images can only be obtained by direct recording of an object allowing for both horizontal and vertical parallax. However, recent developments by Brotherton–Ratcliffe [39] at Geola [40] in digitally printed color holograms must be mentioned. The system consists of a digital holographic printer employing a pulsed RGB laser for producing large-format, computer-generated color holograms of the reflection type. It is also possible to record real scenes with this system using a rapid filming device [41]. The camera, which moves along a horizontal rail, produces a sequence of 2D digital photographic images in a format designed to be used with a holographic printer. Large-format holograms (size up to 1.2 m by 2 m) can be printed on a new Russian ultrahigh-resolution silver halide holographic film [42].

6. Recorded and Evaluated Holograms
The authors have tested the new SilverCross emulsion by recording reflection holograms. The holograms were recorded with three primary laser wavelengths at 476 nm provided by an argon laser, at 532 nm provided by a cw Nd:YAG laser, and at 647 nm provided by a krypton-ion laser. The holograms were developed by using the CWC2 holographic developer and PBU-Metol bleach. Details on those processing chemicals can be found in Bjelkhagen [43]. The recording material used was the ultrafine-grain, panchromatic emulsion developed by the SilverCross Project. A photo of a hologram that was recorded and developed by the above method is illustrated in Fig. 14. It is important to point out that due to the ultrafine grains of the recording material (8–15 nm), the holograms demonstrate very low light scattering in the blue region of the spectrum. An important aspect of the hologram is its ability to retain the spectral information of the image recorded. To retain this information, the processed holographic emulsion must not introduce changes to the interference pattern re-
corded. If the emulsion shrinks or swells during the processing of the recorded hologram, it will distort the spectral information and it will introduce a color shift. The spectral stability of the hologram is mainly dependent on the material that is used during the recording. The SilverCross emulsion is designed to provide high spectral stability and thus minimal color distortion. Figure 15 illustrates a spectrogram taken by a spectrophotometer from the hologram that is displayed in Fig. 14. Referring to Fig. 14, it can be observed that the hologram, when illuminated by white halogen light, replays the spectral information of the recorded image, at the exact wavelengths used to record it (476, 532, and 647 nm), which indicates that no shrinkage of the emulsion took place during the recording.

Many holograms have been recorded by the authors on the SilverCross material in order to demonstrate its capabilities. It has been generally discussed that color holograms of some museum objects can in some circumstances replace the original artifacts that are on display today. The ultrafine-grain panchromatic SilverCross emulsion would be ideal for this sort of application. Illustrated in Fig. 16 is a photograph of a color hologram of some items that are found in central Europe. The sculptures are believed to be 2000 years old, and they probably represent mammoth figures. The artifacts were provided on loan from the Arthur Kendall Collection from the Department of Palaeontology at the Natural History Museum in London. Figure 17 depicts a photograph of another hologram made on the SilverCross material; the image of the Franklin Mint decorative plate Princess of the Iris by M. Nolte.

7. Future of Color Holography

Since 1964 various researchers around the world have been trying to make Emmett Leith’s original vision of color holography become a reality. It is only in recent years that color holography has become a truly practical imaging technique with the advent of suitable recording materials, lasers, and display lighting. The recording of large-format color holograms in panchromatic, ultrafine-grain, single-layer, silver halide emulsions is now a most promising way forward. However, the commercial manufacture and distribution of suitable recording materials is required to make the use of color holography popular. The virtual color image behind a holographic plate represents the most realistic-looking image of an object that can be recorded today. The extensive field of view adds to the illusion of beholding a real object rather than an image of it. By choosing the optimum recording laser wavelengths within the spectrum,
good color rendering can be achieved; however, problems connected with color saturation still remain to be solved. The wavefront reconstruction process recreates accurately the laser wavelengths scattered off the object during the recording of the hologram. This 3D imaging technique has many obvious applications, in particular, displaying unique, precious, or expensive artifacts, but there are also many other potential commercial applications of color holograms as well as color HOEs. Today, it is technologically possible to record and replay acoustic waves with very high fidelity. In the future, holographic techniques may be able to offer the same possibility in the field of optical waves, not only for recording and reconstruction but also in real time.

In 1968 H. Bjelkhagen saw a laser-illuminated, off-axis hologram recorded by N. Abramson at the Royal Institute of Technology, Sweden. After that, thanks to Emmett Leith, he decided to devote his life to holography, and he acknowledges many useful and productive meetings and discussions with Emmett Leith over the years, which have had an important impact on his research.

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