Color holography: a new technique for reproduction of paintings

Hans I. Bjelkhagen[a] and Dalibor Vukičević[b]

[a]De Montfort University, Centre for Modern Optics, The Gateway,
Leicester LE1 9BH, United Kingdom
[b]Université Louis Pasteur, ENSPS, Blvd. Sébastien Brant
F-67400 Illkirch, France

ABSTRACT

Until recently display holography was usually associated with 3D imaging. After the appearance of color holography it has become possible, however, to record holographic images of 2D objects, such as, for example, oil paintings. The realistic-looking virtual image recorded in a Denisyuk reflection hologram is the most suitable for such reproductions. A holographic contact recording of a painting reproduces the painting with all its texture details preserved, such as brush strokes, the painter's signature, etc. This means that an exact copy of the painting can be made, which can then be displayed at art exhibitions, museums, etc., when the original is not available. If an expensive painting is concerned, possessing an exact copy of the painting may also be important for insurance purposes, in case the painting is stolen or damaged. The advantage of a color contact hologram is that the hologram reconstruction process can be relaxed, as there is no need of spatial coherence of the white light source used to illuminate the hologram. In addition, no depth distortions are introduced as a function of the light source's distance from the plate. Only the angle of illumination is of primary importance if good color reproduction is to be obtained. The paper discusses the rendition of color in a hologram, which is extremely important in this case. The holographic reproduction process of an oil painting is also described, and the major advantages of holographic reproduction are discussed together with its limitations.

Keywords: holography, display holography, color holography, painting reproduction

1. INTRODUCTION

About thirty thousand years ago the first known paintings were created in caves such as Altamira in Spain and Grotte Chauvet in France. The ancient paintings in France were discovered in 1994 and have been investigated ever since.[1] The temperature in the cave is 13.5°C, and the relative humidity is 99% with a 3% CO_2 concentration. If tourists were to be allowed to enter the cave, its environment conditions would change so drastically that it would have an adverse affect of the paintings. This is why it is important to find new techniques for the reproduction of such unique and ancient paintings. Obviously, since the paintings cannot be moved from the cave, the only way to enable people to see them is to provide perfect reproductions of them.

The caves in France and Spain are not the only places containing unique examples of ancient art. Another area of great concern regarding unique paintings that cannot be removed from their place of residence are the paintings located in the tombs inside the Pyramids. These paintings are being slowly but surely destroyed as a consequence of the large number of tourists visiting the tombs.

Over the centuries, there has been a lot of interest in the preservation and reproduction of various valuable oil paintings. It was common in the past to have famous paintings reproduced by artists who made high-quality copies of them. One artist who made copies of ancient Egyptian art was Joseph Lindon Smith (1863-1950). His painting technique renders stone wall so realistically, complete with chips and cracks, that his paintings are often mistaken for the actual wall surface.

Correspondence: Email: hansholo@aol.com; Telephone: +44-116 250 6374; Fax: +44-116 250 6144

After the invention of photography and, especially of color photography, large numbers of paintings have been photographically reproduced. Such photographs are often used, for example, in art books, exhibition catalogs, museum postcards, posters, etc. An example of an early type of color photography is *Lippmann photography*, also referred to as *interferential color photography*. In 1907 Hans Lehmann used Lippmann photography for the reproduction of an oil painting, entitled *Wäscherinnen am Gardasee*, painted by E. Kulthan from Jena. Since Lippmann photography records the entire color spectrum of a given object, the color reproduction of the said painting was remarkably accurate. A printed color reproduction of this Lippmann photograph was first published in Valenta's book on color photography in 1912.[2] It was also included in the German version of Eder's History of Photography published in 1932.[3]

In addition to perfect color reproduction, a Lippmann photograph has very good archival stability, as no pigments or dyes are embedded in the emulsion - only an interference pattern is recorded in a black-and-white photographic emulsion. The image colors are reproduced by means of illuminating light reflected from and interacting with the recorded interference pattern in the emulsion.

More recently digital photography has been used to reproduce paintings for art exhibitions, where reproductions are intended to be used instead of the original paintings, as their substitutes. The Butler Museum of American Art in Youngstown, Ohio, made a digital reproduction of a fifty-million dollar oil painting *Snap the Whip* by Winslow Homer from 1872, when the original painting, which is otherwise on permanent display at the Butler Museum, was to participate in an exhibition at another museum. During that period of time the Butler Museum did not wish to display an empty space on the wall, and so a special type of digital reproduction called a *giclée* was made. A giclée is a high-resolution digital image printed with an inkjet printer onto an archival-quality canvas, using a special type of ink. The reproduction was made by Digital Color Imaging Inc.,[4] using a Roland Hi-Fi Jet six-color inkjet printer.

Another place where high-quality reproductions of paintings are used is the Otsuka Museum of Art in Japan.[5] The coming into being of this museum, which opened in 1998, is owed to Mr. Masahito Otsuka who wanted to create a museum that could host the most famous paintings in the world under one roof. The museum has many reproductions of great paintings by Picasso, Goya, Rembrandt, van Gogh, Monet, and many other famous artists. Another advantage is that paintings of the same artist, or with the same motif, located normally in different places, can be seen at one and the same place now. For example, all six *High Altar* paintings by El Greco can now be admired at the Otsuka Museum, which is a special treat, since the original paintings are located in different parts of the world. All paintings at the museum are photographic reproductions which have been transferred onto ceramic tiles, using silkscreen printing techniques.

Holography is the imaging technique which is, in our opinion, best suited of all the techniques for the reproductions of paintings. In addition color holograms, similarly to Lippmann photographs, have very high archival stability. To some people it may sound a bit odd to consider an imaging technique primarily associated with 3D imaging to be useful for recording of flat objects. We must remember, however, that today true color holograms can be recorded, which makes holography a serious candidate for this type of application. In the following we will discuss the advantages of using color holograms in the field of graphic arts reproduction. A word of caution needs to be said, however. To be able to obtain a holographic reproduction which is absolutely identical with the original painting some fundamental issues have to be addressed first.

Until now holographic techniques associated with paintings were used in the field of nondestructive testing by means of hologram interferometry. Amadesi *et al.*[6] described a holographic method for detecting separate regions between priming layers and the underlying wood support in an old fifteenth-century Italian painting *Santa Caterina* by Pier Francesco Fiorentino. The support panel of the painting is made of two slabs of poplar wood glued together. Double-exposed holograms of the painting were recorded, the painting having been previously slightly heated by a current of warm air. The two exposures were made with a five-minute interval between them. The separate regions were revealed in the fringe pattern of the recorded hologram. Later, in another publication by Amadesi *et al.*[7] sandwich holography fringe evaluating technique was employed. This technique makes it easier to detect detachments of adhesion in paintings. In this case another fifteenth-century painting of the Perugina School, *Madonna col Bambino*, was examined.

In the past, monochrome display holography has been used to record holograms of some paintings, such as Russian icons for example. However, not until extremely high-quality holographic *color* reproductions can be made of such art pieces and oil paintings, will art museums and the art society show a serious interest in holographic reproductions.

2. COLOR HOLOGRAPHY

The most suitable holographic technique for the recording of color reproductions of paintings is the reflection hologram method.[8,9] Such color holograms offer full parallax and a wide large field of view. The colors do not change when the reproduction is viewed from different directions. To be able to record high-quality color reflection holograms it is necessary to use extremely low-light-scattering materials. This means, that it is necessary to use ultrafine-grain silver halide emulsions (grain size about 10 nm). Currently, the only producer of a commercial holographic panchromatic emulsion is the Micron branch of the Slavich photographic company located outside Moscow.[10] The PFG-03C emulsion coated on glass plates is suitable for such recordings. It has been possible to obtain high-quality color holograms by using special processing chemistry for the PFG-03C emulsion.

2.1 Laser wavelengths for recording color holograms

Choosing the correct recording wavelengths and the exact laser wavelengths is the key issue where accurate color reproduction is concerned. So far most color holograms have been recorded using three primary laser wavelengths, resulting in good color rendition. However, some colors were not identical with the original colors and also *color desaturation* (color shifting towards white) appeared to be a problem.

Hubel and Solymar[11] provided a definition of color recording in holography: "A holographic technique is said to reproduce 'true' colors if the average vector length of a standard set of colored surfaces is less than 0.015 chromaticity coordinate units, and the gamut area obtained by these surfaces is within 40% of the reference gamut. Average vector length and gamut area should both be computed using a suitable white light standard reference illuminant."

One important consideration is the question of whether *three* laser wavelengths are really sufficient for accurate color reproduction in holography. The wavelength selection problem has been discussed in several papers, for example, by Peercy and Hesselink.[12] They discussed the wavelength selection by investigating the sampling nature of the holographic process. During the recording of a color hologram, the chosen wavelengths point-sample the surface-reflectance functions of the object. This sampling of color perception can be investigated by the tristimulus value of points in the reconstructed hologram, which is mathematically equivalent to the integral approximations for the tristimulus integrals. Peercy and Hesselink used both Gaussian quadrature and Riemann summation for the approximation of the tristimulus integrals. In the first case they found the wavelengths to be 437, 547, and 665 nm and in the second case the wavelengths were 475, 550, and 625 nm. According to the above mentioned authors, the sampling approach indicates that three monochromatic sources will almost always be *insufficient* for the accurate preservation of all of the object's spectral information. The authors claim that four or even five laser wavelengths may be required. When using the relative weights from Gaussian quadrature, they obtained the following four wavelengths:

$$\lambda_1 = 424 \text{ nm}, \lambda_2 = 497 \text{ nm}, \lambda_3 = 598 \text{ nm, and } \lambda_4 = 678 \text{ nm}.$$

When the relative weights from Riemann summation were used, they obtained the following four wavelengths:

$$\lambda_1 = 460 \text{ nm}, \lambda_2 = 520 \text{ nm}, \lambda_3 = 580 \text{ nm, and } \lambda_4 = 640 \text{ nm}.$$

Peercy and Hesselink found that for a particular test scene and with four sampling wavelengths, Riemann summation performed significantly better than Gaussian quadrature.

Recently, Kubota *et al.*[13] presented a theoretical analysis of color holography based on four recording wavelengths. Using the 1976 CIE chromaticity diagram, and by minimizing the distance between the selected object points in the diagram and the corresponding reconstructed image points, they were able to obtain four optimal laser wavelengths. The calculation was based on the nonlinear least square method. For the reproduction of nineteen selected color patches of the Macbeth ColorChecker® the following four wavelengths were obtained:

$$\lambda_1 = 459.1 \text{ nm}, \lambda_2 = 515.2 \text{ nm}, \lambda_3 = 585.0 \text{ nm, and } \lambda_4 = 663.2 \text{ nm}.$$

Using these wavelengths, the average distance between the actual points and the recorded image points was 0.0087 CIE 1976 chromaticity units. If the same calculation was performed using only three recording wavelengths the following wavelengths were obtained:

λ_1 = 462.7 nm, λ_2 = 528.0 nm, and λ_3 = 599.6 nm.

In this case the average distance between the actual points and the recorded image points was 0.015 CIE 1976 chromaticity units, which is twice larger than when four wavelengths are used. The four optimal wavelengths quoted in the paper by Kubota *et al.*[13] show good correlation with Peercy and Hesselink's wavelengths obtained when using Riemann summation.

Since it is difficult to find lasers which can provide the optimal four wavelengths in practice, Kubota *et al.*[13] suggested the following laser wavelengths to be employed:

λ_1 = 457.9 nm (Ar-ion), λ_2 = 514.5 nm (Ar-ion), λ_3 = 580.0 nm (dye laser), and λ_4 = 647.2 nm (Kr-ion).

It is obvious that by selecting the optimum four or even more laser recording wavelengths it is possible to record color holograms with extremely good color rendition. Hopefully, tunable lasers may provide the desired wavelengths in the future. Only further experiments will show how accurately holographic color reproduction can be performed in practice. Color rendition is the most important issue here and the question is, whether color holography can really provide an absolutely identical copy of the recorded object.

2.2 Setup for recording color holograms

A typical reflection hologram recording setup is illustrated in Fig. 1, which was used for the reproduction of the painting in this investigation. The different laser beams necessary for the exposure of the object pass through the same beam expander and spatial filter. A single-beam Denisyuk arrangement was used, i.e., the object was illuminated through the recording holographic plate. The light reflected from the object constitutes the object beam of the hologram. The reference beam is formed by the three expanded laser beams. This "white" laser beam illuminates both the holographic plate and the object itself through the plate. Each of the three primary laser wavelengths forms its individual interference pattern in the emulsion, all the patterns being recorded simultaneously during the exposure. In this way, three holographic images (a red, a green, and a blue image) are superimposed on one another in the emulsion. The three laser wavelengths used were: 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 filters were used for combining the three laser beams. By using the dichroic filter beam combination technique it is possible to perform simultaneous exposure recording, which makes it possible to control independently the RGB ratio and the overall exposure energy in the emulsion. The RGB ratio can be varied by individually changing the output power of the lasers, while the overall exposure energy is controlled solely by the exposure time. The overall energy density for exposure is about 3 mJ/cm^2 for Slavich material.

2.3 Processing of color holograms

The processing of holograms recorded in silver halide emulsions is of critical importance. The Slavich emulsion is rather soft, and it is important to harden the emulsion *before* development and bleaching take place. Emulsion shrinkage and other emulsion distortions caused by active solutions used for the processing of holograms must be avoided. The processing steps are summarized in Table 1. It is very important to employ a suitable bleach bath to convert the developed amplitude hologram into a phase hologram. The bleach must create an almost stain-free clear emulsion so as not to affect the color image. In addition, *no emulsion shrinkage* can be permitted, as it would change the colors of the image. Washing and drying must also be done so that no shrinkage occurs. Finally, to prevent any potential emulsion thickness changes caused by variations in humidity, the emulsion needs to be protected by a glass plate being sealed onto the holographic plate.

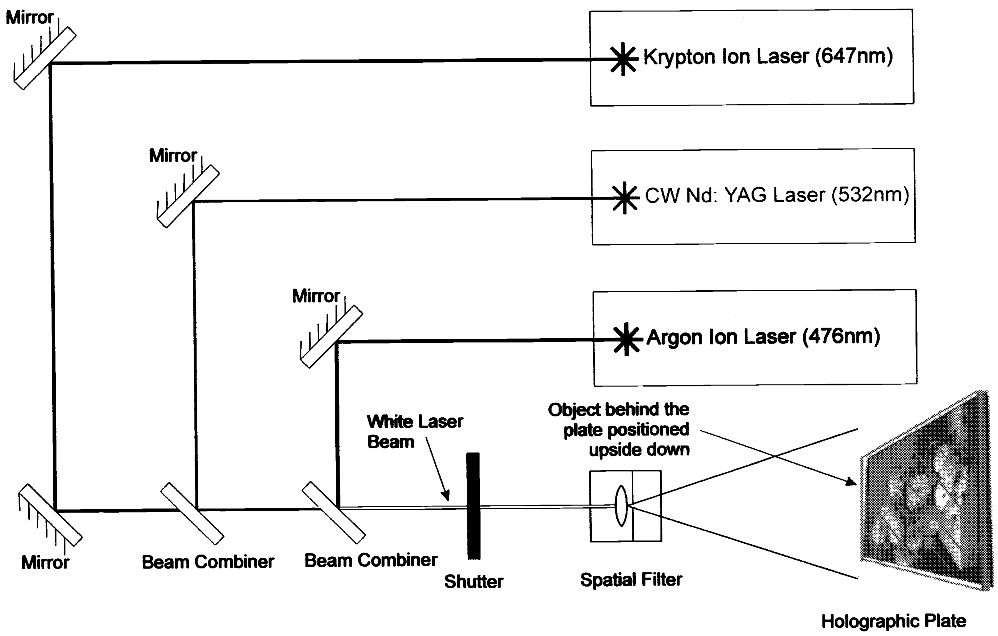

Fig. 1: Setup for recording a color hologram of a painting.

1. Tanning in a Formaldehyde solution	6 min
2. Short rinse	5 sec
3. Development in the CWC2 developer	3 min
4. Wash	5 min
5. Bleaching in the PBU-amidol bleach	~5 min
6. Wash	10 min
7. Soaking in acetic acid bath (printout prevention)	1 min
8. Short rinse	1 min
9. Washing in distilled water with wetting agent added	1 min
10. Air drying	

Table 1: Color holography processing steps.

3. RECORDING OF AN OIL PAINTING

A *still life* oil painting, 20 cm by 25 cm, is shown in Fig. 2. The color print in this figure was photographed from the painting covered with a glass plate so that it looked similar to a hologram. The painting, which is not an art piece or of any significant value, was selected mainly because it was painted on wood with a pronounced surface texture. When cw lasers are used for recording, stability during the recording is important, and it might have been difficult to maintain the stability of a painting painted on canvas. In this investigation only three primary wavelengths were employed. The Denisyuk single-beam holographic setup, described in Section 2 was used to record the color hologram. For the particular Slavich emulsion batch used for the recording the best white balance was obtained by adjusting the output power of the three laser beams determined previously by the recorded color holograms of color test targets. During the recording, the emulsion of the holographic plate was facing the painting and it was brought in close contact with it. The reference beam was introduced at a more oblique angle than it is normally done when recording other color holograms since, in this case, there were no object shadows to consider. By using a steep reference angle it is easy to illuminate the final hologram at that angle with a spotlight located only a short distance away from the hologram plate. We have been trying to simulate the illumination of paintings with a conventional picture lamp attached to the frame. A color photograph of the recorded color hologram reproduction of the painting is shown in Fig. 3.

Fig. 2: Original painting.

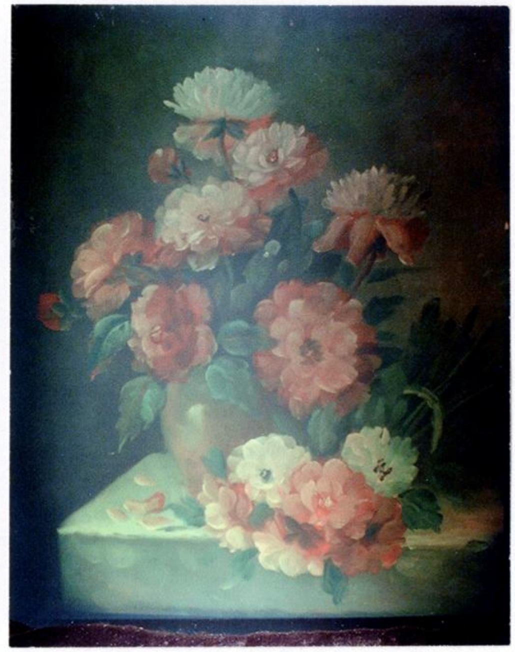

Fig. 3: Holographic reproduction.

Fig. 4: Detail, original painting.

Fig. 5: Detail, holographic reproduction.

Fig. 6: Brush strokes, holographic reproduction.

The main idea behind this project has been to introduce the concept of holographic reproductions of paintings. At this stage it may not be possible to record an absolutely perfect color reproduction with only three laser wavelengths. A detail of the painting texture, visible when observed at an angle, is shown in Fig. 4. The same surface texture from the hologram is also shown in Fig. 5, which illustrates the advantages of using holography. In this case, the hologram is illuminated from the side, not at the correct reconstruction angle, which means that the colors are not expected to be correct here. Nevertheless the holographic reproduction can be studied in more or less the same way as the real painting can be investigated. Another example is illustrated in Fig. 6, where the brush strokes in the hologram can be studied under high magnification.

4. CONCLUSIONS

We have demonstrated the possibility to holographically reproduce an oil painting and described the advantages of such a reproduction method. The recording was performed using three RGB wavelengths from cw lasers. To obtain more accurate color reproduction it may be necessary to use at least four recording laser wavelengths. Employing four wavelengths, very good color rendition can be obtained, as shown by both Peercy and Hesselink[12] and Kubota *et al.*[13] However, there are certain limitations on how accurately colors can be reproduced holographically. Only *laser light* scattered from the painting can be recorded in a hologram. Some colors in a given painting may be the result of fluorescence, which cannot be recorded holographically.

To make it more practical to record paintings painted on a canvas a puled laser is needed, which can emit simultaneously the necessary wavelengths in a few tens of nanoseconds. No such commercial laser exists today. Currently, research on making a pulsed color laser is in progress at the French German Research Institute (ISL), Saint Louis, France,[14] as well as at the Geola company in Lithuania.[15] Another problem is that silver halide materials need to respond to the very short exposure times when employing a pulsed laser. The panchromatic emulsion may have to be modified in order to reduce high-intensity reciprocity failure and latent-image fading associated with nanosecond pulses. A special processing technique is required as well. The energy of laser light required to record a hologram is rather low and there is no risk that the painting itself will be damaged by a laser flash during the recording.

A limiting factor as regards recording paintings in general is the available size of holographic glass plates. Slavich can produce plates of up to 50 cm by 60 cm in format. For very large paintings, holographic film should rather be used. The film can be laminated onto glass once the hologram has been recorded and processed. In this case, only a pulsed laser can be used for the recording. A sheet of film is simply positioned on top of the painting and a white laser flash is emitted. If cw lasers are used instead, the film has to be laminated onto the glass before the recording takes place. A portable holographic system is needed, which can be easily transported to museums and other places where paintings are to be recorded.

The virtual color image appearing behind a color holographic plate represents the most realistic-looking image of a painting that can be obtained today. The size of the image is identical with the size of the original painting. The extensive field of view adds to the illusion of beholding a real painting rather than its reproduction. Museum paintings are often shielded by a glass plate or a plastic sheet to prevent them from being damaged. In this case there will be virtually no difference between the holographic reproduction and the real painting.

Similarly to the idea lying behind the Otsuka Museum of Art in Japan, a fantastic collection of the most impressive oil paintings in the world could be exhibited in art museums in the form of holographic reproductions. Color reflection holograms are much more realistic than the Japanese ceramic tile reproductions. A complete collection of an artist's paintings could be exhibited at one museum, without having to transport any art pieces at all. Holographic reproductions are certainly much more expensive to make compared to photographic reproductions, but the sums of money saved on transportation and insurance are high. In addition, art students and art scholars will have access to the most valuable paintings on the spot. They can study them at leisure, for example, under high magnification. Another important application would be to record paintings that are slowly fading or else changing colors. Finally, insurance companies may require holographic reproductions to be made of extremely valuable art pieces. Such reproductions could be used to repair a damaged painting or identify a stolen painting if found. The probability that real paintings will become less valuable if holographic reproductions become common is not very high. People will continue to want to visit art museums to see real paintings and experience the special atmosphere surrounding them. On the other hand giving an opportunity to many other people who cannot afford to travel around the world to see the old and new masterpieces is a really good idea.

REFERENCES

1. M. Balter, "New light on the oldest art," *Science* **283**, [No.5404], pp. 920-922, 1999.
2. 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, Wilhelm Knapp Verlag, Halle a.S., 1912.
3. J. M. Eder, *Ausführliches Handbuch der Photographie, Geschichte der Photographie*, Band 1, Wilhelm Knapp Verlag , Halle a.S., 1932.
4. Digital Imaging Inc., 388 S. Main St., #401, Akron, OH 44311, USA.
5. Otsuka Museum of Art, 65-1 Tosadomariura Aza Fukuike, Naruto-Cho, Naruto, Tokushima Prefecture 772, Japan.
6. S. Amadesi, F. Gori, R. Grella, and G. Guattari, "Holographic methods for painting diagnostics," *Appl. Opt.* **13**, pp. 2009-2013, 1974.
7. S. Amadesi, A. D'Attorio, and D. Paoletti, "Sandwich holography for painting diagnostics," *Appl. Opt.* **21**, pp. 1889-1890, 1982.
8. H. I. Bjelkhagen, T. H. Jeong, and D. Vukičević, "Color reflection holograms recorded in a ultrahigh-resolution single-layer silver halide emulsion," *J. Imaging Sci. Technol.* **40**, pp. 134-146, 1996.
9. H. I. Bjelkhagen, Q. Huang, and T. H. Jeong, "Progress in color reflection holography," in *Sixth Int'l Symposium on Display Holography*, T. H. Jeong, ed., Proc. SPIE **3358**, pp. 104-113, 1998.
10. SLAVICH Joint Stock Co., Micron Branch Co., 2 pl. Mendeleeva, 152140 Pereslavl-Zalessky, Russia.
11. P. M. Hubel and L. Solymar, "Color reflection holography: Theory and experiment," *Appl. Opt.* **30**, pp. 4190-4203, 1991.
12. M. S. Peercy and L. Hesselink, "Wavelength selection for true-color holography," *Appl. Opt.* **33**, pp. 6811-6817, 1994.
13. T. Kubota, E. Takabayashi, T. Kashiwagi, M. Watanabe, and K. Ueda, "Color reflection holography using four recording wavelengths," in *Practical Holography XV and Holographic Materials VII*, S. A. Benton, S. H. Stevenson, and T. J. Trout, eds., Proc. SPIE **4296**, pp. 126-133, 2001.
14. F. Albe, M. Bastide, Y. Lutz, J.-M. Desse, and J.-L. Tribillon, "Color holography: present state of the research activities at ISL," in *HOLOGRAPHY 2000*, T. H. Jeong and W. K. Sobotka, eds., Proc. SPIE **4149**, pp. 128-136, 2000.
15. Geola, POB 343, Naugarduko 41, LT-2006 Vilnius, Lithunaia.