Colour holography in optics courses at Lund Institute of Technology

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Abstract

Several physics courses are given at Lund Institute of Technology. In the basic courses on ray and wave optics, holography has played an important role both in stimulating the students to curiously investigate the optical world and as an important visualisation of some obvious and interesting parts of the courses. To meet the need for basic laboratory experience, a holographic laboratory has been built based on three holographic tables. One large set-up is designed for making full colour holograms. Normally the students make holograms in the size $4'' \times 5''$, but it is also possible to make holograms up to 30×40 cm. For students interested in a deeper understanding of holography we have another large table where they can make one step rainbow holograms on film in the size 30×40 cm.

Keywords: Holographic system; Colour holography; Pseudocolour holography optics courses

1. Introduction

A four-hour lab session in holography has been an important part in many of the courses given to students that take course at the department of Physics. It has also been valuable that the students obtain their own hologram to show to other students. This stimulates the interest in physics courses in optics, lasers and optical measurement techniques. We started building the lab in the beginning of the 70s and these activities have expanded since then. We now have two large tables and a smaller one. One of the large tables is used for colour holography. The other large table is used for other optical activities such as Fourier optics, phase conjugation experiments and digital holography. This table is also sometimes used for rainbow holography. The smaller table is mainly used for demonstrations, but can also be used for exposing small holograms and for experiments in holographic interferometry. There are not only laboratory sessions in basic courses for students at Lund Institute of Technology. There is also a special course in colour holography that is given to people interested in art and three-dimensional imaging. In this course different aspects of holography, such as transmission holography and reflection holography, are studied. In this course colour is of great importance, so not only true colour holography but also the principles of one step and two step rainbow holography are studied. The students make a 30×40 cm one step rainbow hologram resulting in a three-colour image with false colours. We also have a course that is given to people with a background in natural sciences. For these students a holographic lab session dealing with holographic interferometry is also an important part of the course.

2. Colour holography

The possibility of recording a hologram in full colour was proposed in the early papers of Leith and Upatnieks [1]. Several different methods can produce holograms in colour. One method is to record a transmission hologram in three wavelengths using either a multicolour laser or separate lasers. With separate lasers it is possible to illuminate the holographic plate at different incident angles for the different colours. This eliminates the problem of cross-talk. Cross-talk is in this case the mixing of nine images. In reconstruction each of the three fringe patterns give rise to three different images.

However, the method using separate lasers is rather complicated and not so useful as accurate relative alignment of the beams is needed. If, instead, a multicolour laser or a laser system, where laser beams of different colour overlap on the plate it is necessary to use a narrow bandwidth of the recording material to obtain high quality holograms. The first transmission hologram made by Pennington and Lin [2] was made on a 15 μm thick Kodak 649-F emulsion. This emulsion had a spectral bandwidth of about 10 nm. Other methods eliminating the cross-talk problem are spatial multiplexing and coded reference beams [3] or spatial sampling [4]. These methods have the problem of accurate registration.

Recording a reflection hologram in three colours is another method where the hologram acts as a narrow-band filter. Single-beam reflection holograms were first introduced by Denisyuk [5] and are based on the Lippman colour technique [6]. These holograms are reconstructed in white light and there is no need to separate the beams neither in the set-up nor when the hologram is reconstructed. Lin et al. made the first colour hologram of this type [7]. Before good

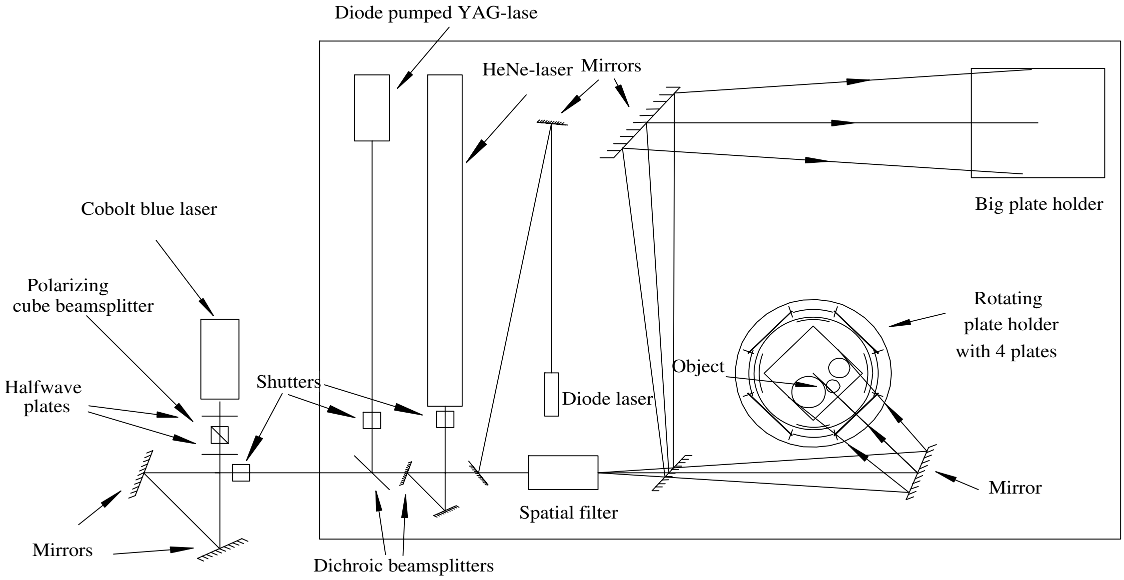


Fig. 1. Optical set-up for true colour holography.

Fig. 2. Pictures of the holographic system. The blue Cobalt laser at the left is outside the table.

panchromatic plates were available different plates had to be combined. Kubota [8] in Japan successfully demonstrated one such combination. To cover the blue and green part of the spectrum he used a dichromate gelatine plate. For the red part of the image he used an Alfa 8E75 silver halide plate. An important step forward in the development of colour holography was the work of Hubbell and Solemner [9]. By using new emulsions from Milford and new combinations of laser wavelengths they obtained high quality holograms. Bjelkhagen and Vukiceviv [10] have also recorded colour holograms in the Russian emulsion PFG-03C. They used a single-beam Denisyuk set-up. By combining this low scattering, ultra-high resolution emulsion with a Western processing technique, holograms of very high diffraction efficiency and good colour rendition have been obtained. A review of different techniques for colour holography can be found in the publication by Hariharan [11].

The first two-colour hologram made in Lund in the beginning of the 70s was a sandwich between a thick Agfa 8E75 plate and an 8E56 plate. The red sensitive plate (8E75) was exposed to HeNe-laser light and the blue and green sensitive plate (8E56) was exposed to light from a Liconix HeCd-laser. Due to the large angle between the object and the reference light it was possible to obtain a rather good hologram with not so much cross-talk.

3. Equipment

The holographic set-up for colour holography at Lund Institute of Technology has been presented in a paper [12] and reported at the holographic conference at St Poelten 2000. Since then the lasers used have been changed. We have also changed the emulsion that we use.

The holographic set-up has three lasers in red, green and blue (Fig. 1). The red laser is now either a 25 mW diode laser from Crystalasers or a 25 mW HeNe laser. The green is a CW diode pumped and frequency doubled Nd:YAG laser with an output of 25 mW. The coherence length of this laser is several meters as the laser uses a very stable ring laser cavity. The blue laser is a 50 mW laser from Cobalt AB with a coherence length of more than 1 m. The red and the green laser are

Fig. 3. The rotating plate holder.

Fig. 5. Contour fringes obtained when a diode laser was used.

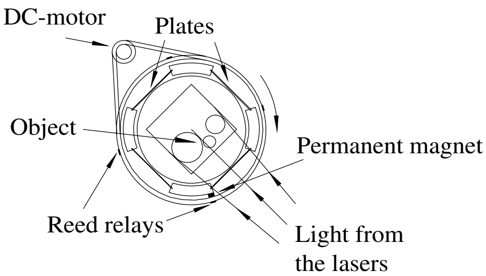


Fig. 4. Principles of the rotating plate holder seen from above.

Fig. 6. Plate holder for 20 × 25 plates. The object is mounted upside down.

placed on top of the 1.5 × 2.9 m big granite table. For the moment the blue laser is free from the table and the beam is introduced from the side of the table (See Fig. 2). To prevent dangerous laser light reaching outside the table, a cardboard cover is used to confine the light to the inside. When we expose plates of the size 4″ × 5″ we have approximately 15–20 $\mu W/cm^2$ in each colour at the plate. The exposure needed is about 1500 $\mu W/cm^2$. The plate is less sensitive to blue light so we use approximately 29% in red, 29% in green and 42% in blue. The exposure time is about 30 s. Separate electronic shutters control all laser beams.

With minor adjustments it is possible to introduce light from the red diode laser for comparison with the He–Ne laser.

The spatial filter used in the set-up has a 40×-microscope objective and a 10 μm hole. Precise alignment is necessary to obtain all beams in the centre of the hole. A mirror is used to direct the light from the spatial filter at an angle of about 45° to the holographic plate. The holographic plate is loaded into a specially designed holographic holder (Fig. 3). The principle of this holder is shown in Fig. 4.

Details of the loading procedure, the exposure and development of holographic plates are described in the paper [12] mentioned above. Since 2000 ultimate plates produced by Yves Gentet have replaced the Russian plates PFG-04 [13]. These plates now have an outstanding quality with very low noise and they give very bright images. It is now also possible to develop 8 plates at the same time. This shortens the time in the lab for the students and we can use more time to investigate other types of holograms.

As mentioned above we could replace the HeNe laser with a diode laser. However this laser does not work consistently as we sometimes observe mode hops. The distance in wavelength was about 0.6 nm. The image in a hologram obtained using this laser can be seen in Fig. 5. Here a red monochrome exposure was made. In the image we can clearly see contour fringes. The short distance between the fringes is due to the small cavity length of the diode laser.

For the special courses in holography we have time to make larger holograms in colour. To do this we introduce a mirror near the spatial filter to redirect the beam to the big plate holder (see Fig. 1). Fig. 6 shows the plate holder with an object mounted upside down close to where the plate will be. Now the intensities are reduced to about 3–5 $\mu W/cm^2$ near the plate. The exposure time is increased to about 2–3 min.

4. Results from the set-up

Fig. 7 shows a 4″ × 5″ hologram of our standard object and in Fig. 8 the hologram is 20 × 25 cm.

Fig. 7. Image obtained from a 4″ × 5″ hologram.

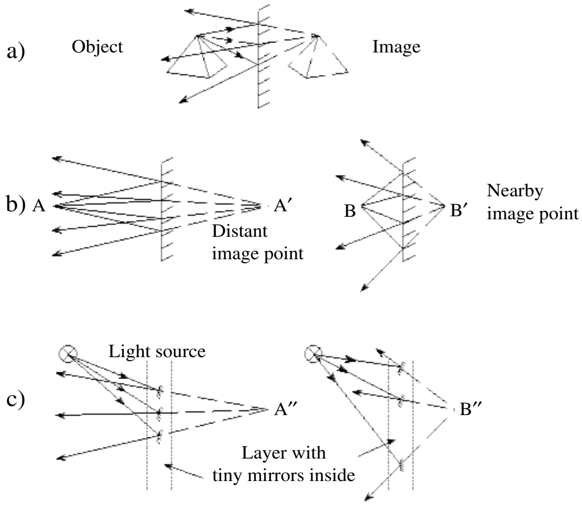


Fig. 9. (a) A mirror creates a virtual image behind the surface. (b) Reflected rays for a distant or a nearby point. (c) Tiny mirrors inside a layer redirect the light for a distant and a nearby point.

Fig. 8. Image obtained of the object seen in Fig. 6.

5. Teaching holography

When the students look at a developed hologram they are astonished by the three-dimensional appearance of the image. At this point during the lab it is very important to stimulate their curiosity and try to explain why the image is 3D and what property a 3D image has. All who have tried to explain to anyone why the image is 3D has a difficult task if the person has little experience in basic ray and wave optics. One way to handle this problem is to use different models where each model gives an understanding of some of the properties of a hologram. Combining different models for the hologram it is possible to understand why the image has the same appearance as a real object illuminated with light. In our courses we use the following models: mirror model, moving Moiré patterns, momentary electrical fields, grating models and complex description of wave front reconstruction.

5.1. The mirror model

All students have seen the image obtained in a mirror and they know that the virtual image seen in the mirror has full 3D properties. For an object that is quite near the mirror, the rays that build up the image are strongly divergent (see Fig. 9). However, if the object is at the longer distance from the mirror, the rays become less and less divergent and will be nearly parallel for a very distant object. Now a hologram can be seen as a collection of small mirrors that together e.g. form a strongly divergent beam when illuminated by light from a spotlight. Another set of mirrors creates a less divergent beam which means that we believe that the light comes from a more distant object.

We have in fact constructed a model with 625 mirrors where all the mirrors are individually adjusted. When moving a screen in front of the hologram two images can be seen on the screen at different distances from the model (see Fig. 10).

5.2. Moving Moiré pattern

A parallel light beam can be illustrated by a moving grating structure as shown in Fig. 11(a). The angle between the beams determines the fringe spacing obtained where two such beams intersect. For a small angle between the beams the fringes are coarse while a large angle gives finer fringes. This is easily shown by the Moiré pattern obtained when we cross two grating structures (illustrating two parallel light beams). In a computer program, it is then shown that while the two grating structures move, the fringe pattern is stationary and this means that it is possible to record this pattern on some light sensitive material. Now if we store this pattern and afterwards illuminate it with one of the grating structures (a parallel light beam) it is possible to see a Moiré pattern moving in the same direction as the other grating structure (Fig. 11(b)). This illustrates that when one of the

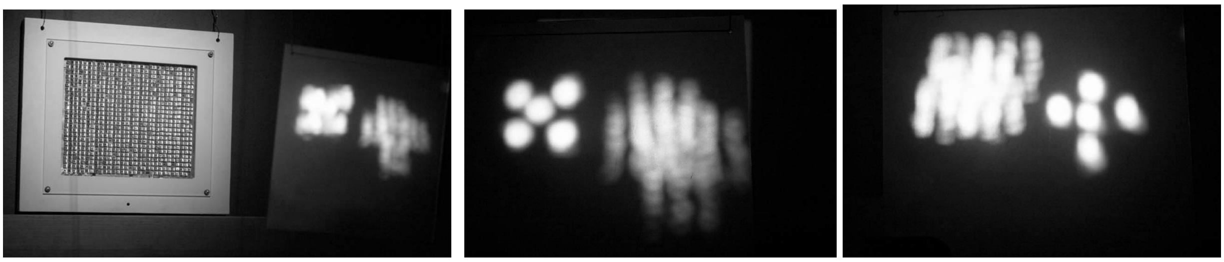


Fig. 10. A mirror model of a hologram. To the right, images obtained on a screen at different distances.

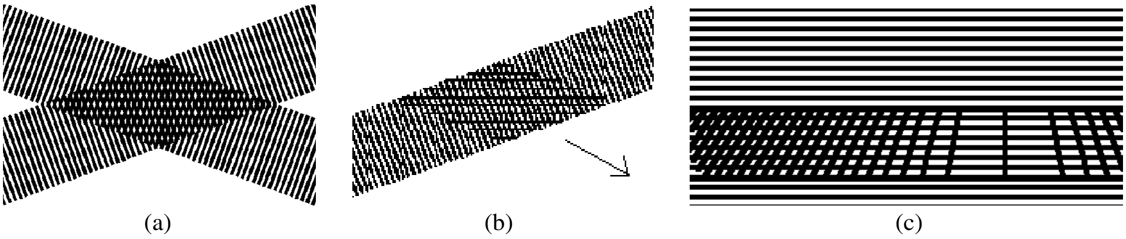


Fig. 11. Images from a program illustrating moving light beams. (a) A stationary interference pattern is obtained in the common area of two crossing plane light beams. (b) A moving light beam is created when the stationary pattern is illuminated by one of the beams. (c) Here a plane beam later illuminates the pattern from one plane and one divergent beam. A moving light field will be created that is spherical and that originates from a point behind the pattern. All this is more clearly seen when running the program.

beams in a holographic set-up illuminates the hologram after development the other beam is recreated. If one of the beams is a divergent beam instead of a parallel beam it is possible to show that now the moving Moiré pattern is spherical and illustrates the light coming from a point behind the stored pattern (see Fig. 11(c)).

5.3. Momentary electric field

The electric field from a light source is fluctuating at a very high frequency and is impossible to detect by a fast detector. However, it is possible to simulate in a computer how the momentary electric field varies during a short period of time. If one looks towards a light source and observes the electric field in a plane perpendicular to the propagation direction we will see expanding circles (see Fig. 11). Another spherical wave from the side gives another system of expanding circles. If both waves are combined on the plate a more complicated pattern is obtained. When looking at this pattern in a time series there are two patterns. One is fluctuating all the time while the other is stationary. Like with the previous model this stationary pattern is what is recorded when we detect it on the recording material. When this pattern is illuminated by one of the waves the other spherical wave field is created.

5.4. Gratings

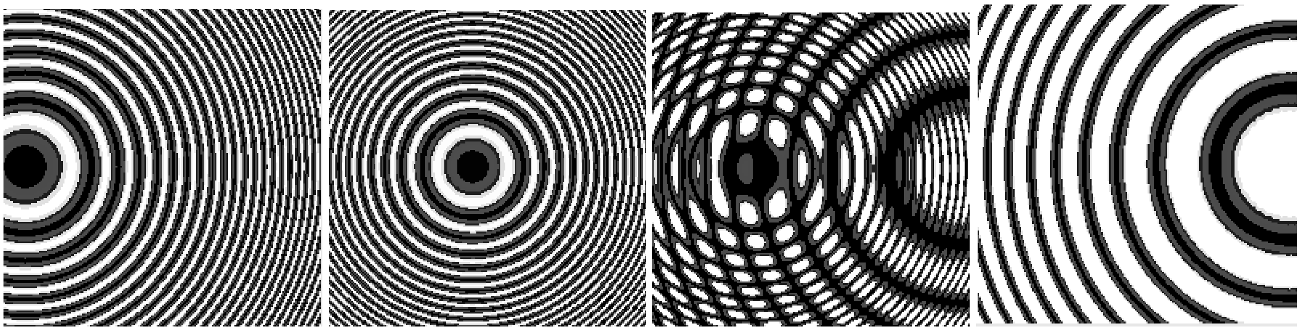
A hologram can be seen as a grating where the grating distance is different at different points on the plate. As an example with the following figure (Fig. 12(a)), with the object at a certain distance from the plate, the grating distance is 0.84 μm (1188 lines/mm) at the left part of the plate and 1.6 μm (622 lines/mm) at the right part of the plate. When such a hologram is illuminated by parallel light from one side, rays appear in the different parts of the hologram so that either a divergent field forms the virtual image or a convergent field forms the real image.

5.5. Complex description of wave front reconstruction

For students with a good background in ray and wave optics it is possible to explain holography by using complex waves. In this model the light leaving the hologram is seen as a product of the transmission function of the hologram $t(x, y)$ and a reconstruction wave C that illuminates the hologram. If C is proportional to the reference wave R there is a component of all wave fields leaving the hologram that can be written as $-kI_RA$ where A is the wave originally coming from the object. Thus there is light leaving the hologram that is a replica of the original wave from the object. The only difference is the intensity of this wave. As the original wave was three-dimensional the replica is also that.

6. One-step rainbow holography

For the students interested in art and three-dimensional imaging the set-up for one step rainbow holography is very popular. The set-up is described in Fig. 14(a). This type of set-up was first introduced in Lund by Marie Andrée Cossette on a course we had in 1989 and was used for some of her holograms that she made that year. As seen in the figure, different objects, preferably transparent ones, are placed near the holographic film. The film is fixed to the film holder



(a) (b) (c) (d)

Fig. 12. Simulation of two spherical waves coming against the holographic plate. (a) and (b) Momentary electric field from two point sources. (c) Momentary interference pattern. (d) Recorded pattern (time-average).

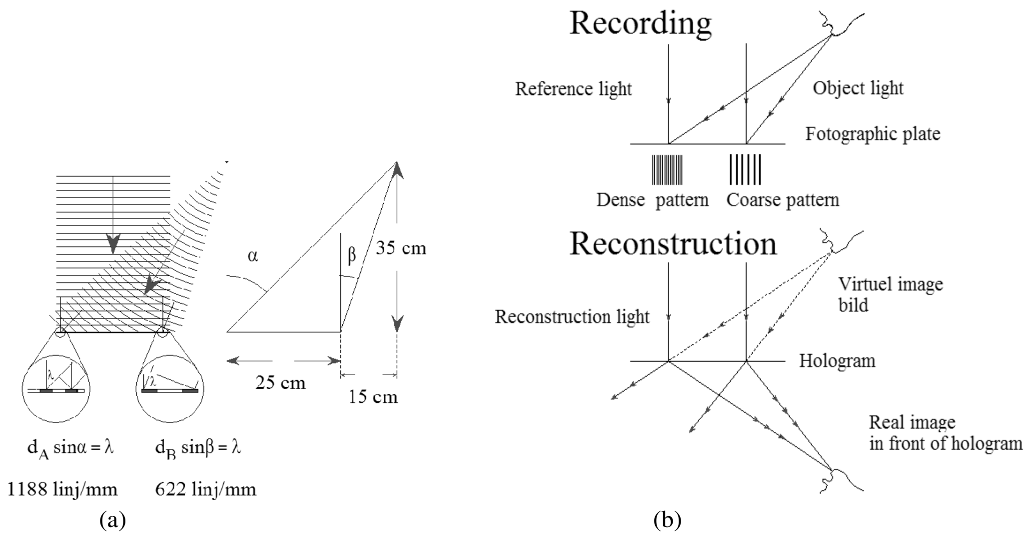


Fig. 13. (a) Geometry for the recording of a hologram of a point source. (b) The creation of fringe patterns in a hologram and the formation of the virtual and real image.

(a) (b) (c)

Fig. 14. (a) One step pseudocolour set-up. (b) Film holder and slits. (c) Object mounted on a glass plate.

by vacuum from a vacuum cleaner as seen in Fig. 14(b). Different colours are obtained by illuminating the plate from different slits illuminated by one of the beams. For artistic purposes, we use the same distance from the slits to the plate. However, if a correct colour rendition is preferred we position the slits at the achromatic angle according to Benton [14]. Fig. 14(c) shows the object used by the artist Melinda Menning and in Fig. 15(a) is an image from one of the holograms that she obtained. The artist Monica Berggren used interference fringes, which she obtained by letting the film hang freely during one exposure (without vacuum), as an extra effect in the image. This can be seen in Fig. 15(b).

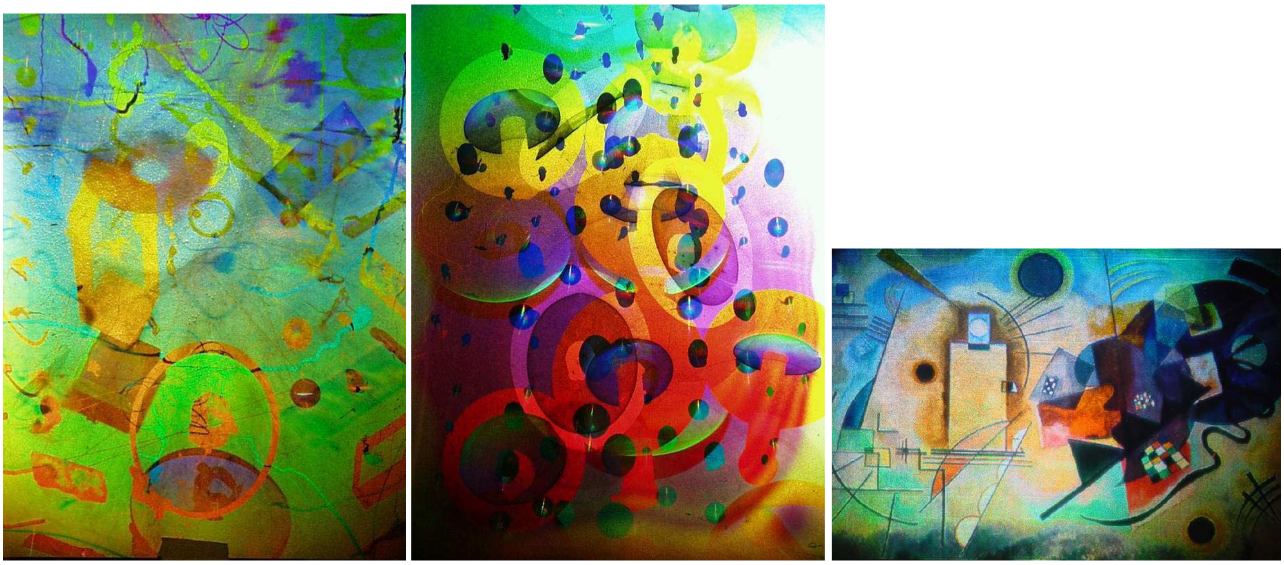


Fig. 15. Images from holograms created in the rainbow set-up. (a) Hologram by Melinda Menning. (b) Hologram by Monica Berggren. (c) A Kadinsky painting recreated as a rainbow hologram.

We have also experimented with colour separated images of well known art pieces. One such image was a Kadinsky painting that we projected on the film by placing three half tone transparencies in front of the spatial filter. With a careful exposure and correct positions for the slits, a flat image was obtained which, in the correct observation position, gives a bright and colourful image quite close in colour to the original image (see Fig. 15(c)). The observer is now free to choose a vertical position to obtain his favourite colours. This gives an extra dimension to the image.

7. Conclusions and future development

Last year (2005) more than 500 holograms were recorded with the previous version of the colour set-up described above. Most of the holograms were very clear and bright and due to the stable set-up very few holograms had fringes. The laboratory sessions involving holography has been very popular and we think the students gained a deeper understanding of holography, colour, interferometry and the properties of light. With continuous improvement of the set-up and the emulsion we hope we will obtain even better holograms.

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References

[1] E.N. Leith, J. Upatnieks, Wavefront reconstruction with diffused illumination and three-dimensional objects, *J. Opt. Soc. Am.* **54** (1964) 1295–1301.

[2] K.S. Pennington, L.H. Lin, Multicolor wavefront reconstruction, *Appl. Phys. Lett.* **7** (1965) 56–57.

[3] R.J. Collier, K.S. Pennington, Multicolor imaging from holograms formed on two-dimensional media, *Appl. Opt.* **6** (1967) 1091–1095.

[4] R.J. Collier, C.B. Burchardt, L.H. Lin, *Optical Holography*, vol. 510–511, Academic, New York, 1971.

[5] Yu.N. Denisyuk, *Dokl. Akad. Nauk. (Academy of Sciences Reports, USSR)* **144** (6) (1962) 1275–1278. [Transl. Photographic reconstruction of the optical properties of an object in its own scattered radiation field]; *Sov. Phys. Doklady* **7** (1962) 543–545.

[6] T. Kubota, Recording of high quality color holograms, *Appl. Opt.* **25** (1986) 4141–4145.

[7] M.G. Lippmann, La photographie des couleurs, *Comptes Rendus Hebdomadaires des Séances de l'Academie des Sciences* **112** (1891) 274–275.

[8] L.H. Lin, K.S. Pennington, G.W. Stroke, A.E. Labeyrie, Multicolor holographic image reconstruction with white light illumination, *Bell Syst. Tech. J.* **45** (1966) 659–661.

[9] P.M. Hubel, L. Solymar, Color reflection holography: theory and experiment, *Appl. Opt.* **30** (1991) 4190–4203.

[10] H.I. Bjelkhagen, D. Vukiceviv, Lippmann color holography in a single-layer silver-halide emulsion, *Proc. SPIE* **2333** (1994) 34–48.

[11] P. Hariharan, Colour holography, in: *Progress in Optics*, vol. 20, North-Holand, Amsterdam, 1983, pp. 263–324.

[12] S.-G. Pettersson, A holographic system for fast exposure of true colour holograms, World Congress of Holography 2000, St Poelten, Austria.

[13] Y. Gentet, P. Gentet, "Ultimate" emulsion and its applications: a laboratory-made silver halide emulsion of optimized quality for monochromatic pulsed and full color holography, in: T.H. Jeong, W.K. Sobotka (Eds.), *HOLOGRAPHY 2000*, in: Proc. SPIE, vol. 4149, 2000, pp. 56–62.

[14] S.A. Benton, The mathematical optics of white-light transmission hologram, in: *International Symposium on Display Holography*, vol. 1, Lake Forest, 1982, pp. 5–14.