Cand. scient. thesis in Optics and Laser Physics

Holographic multi-stereogram constructed from computer images : Applied 3-D printer

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Preface

This study constitutes thesis work for the Cand. scient. degree at the Department of Physics, University of Bergen.

The motivation for this thesis work is the firm EPM Consultants who are interested in developing a method to make holograms from computer images. This thesis work builds on Olav Birkeland′s Cand. scient. thesis ″ Construction of holographic printer for automatic production of holograms from a 3-D computer model ″, where the aim was to make the production of holographic multi-stereograms automatic.

In this thesis work the purpose is to develop a method to produce high quality holographic multi-stereograms constructed from computer images. The production of reflection hologram are given the highest priority, because in my opinion, reflection holograms have the best chance to succeed in 3-D visualisation.

I will like to thank my supervisor at the university of Bergen, Ingar Singstad for guiding me in this project, and thanks are also due to Thor.E.Grahl-Nielsen and Olav Birkeland of EPM Consultants for my stay with the firm. I will also like to thank the work-shop at the Institute of Physics for building some of the optical equipment used in this thesis work.

Kjell Einar Olsen

Summary

The aim of this thesis is to develop a method to convert computer images to a holographic film plate. In the recording process of holographic multi-stereograms, one uses a liquid crystal display (LCD) to show 70 different pictures of a constructed object. These pictures show the object from 70 different positions, and in a sequence the object appears as though turned over the LCD. Each of the pictures is exposed in a different area of the film and the film position is controlled by the holographic printer. The result of this recording process is a 3-D image of the object with horizontal parallax, constructed from 70 different 2-D computer pictures.

At the start of thesis search for relevant literature was given high priority, where the purpose was to find what kind of optical equipment and quality was needed for these experiments. Most papers recommended the He-Ne laser, silver halide film emulsion and developers like Agfa GP 62 and Kodak D-19. As for the quality of the optical equipment, mirrors need a flatness of the order of $1/10 \cdot \lambda$, and lenses must have minimal aberrations.

Before the making of a holographic multi-stereogram, the optical equipment and set-up for recording holograms together with developing process were examined. In order to find a practical favourable method, preliminary holography experiments where carried out. In these experiments, there were practical problems like instability, reflections, depolarisation and exposure. The developing and bleaching processes were also tried out, and gave good results.

In order to produce a holographic multi-stereogram, it was necessary to procure some more optical equipment. Some of the equipment was made in the work-shop in the Institute of Physics:
- Micrometer screws for the spatial filter. It is possible to change the pinhole from 25μm to 10μm. The result is a cleaner laser beam.
- New slit on the holographic printer. The angle is larger and the possibility of shadows is reduced.
- Micrometer screws on the holographic printers slit. It is possible to adjust the width of the slit easily and precisely to the right size.
- Table extension for the optical breadboard, used in the production of reflection and rainbow holograms.
- Table holder for breadboard and the table extension.
- Mirror holder to transfer laser light from the optical table (lower level) to the breadboard (upper level).
- Glass cage mounted on the optical table to protect the equipment from air vibrations.

Other optical equipment bought from different companies : [4] [34] [35]
- High quality lenses
- Mirrors with flatness $1/10 \cdot \lambda$.
- Liquid crystal display (LCD).
- Optical breadboard. The optical breadboard made it possible to arrange the optical

[4] Annual reference catalog for optics, science and education, Edmund scientific, 1995
[34] Melles Griot product catalog, 1995 / 1996
[35] Opto-mechanics, Spindler and Hoyer, 1989 / 1990

equipment at two levels on the table. This is very practical in the production of holographic multi-stereograms.
- High power red He-Ne laser with 24 mW output power.

The production of holographic transmission multi-stereogram is time-consuming; the recording time can be 30 minutes and for reflection holograms several hours. Therefore, the laser output power stability must be constant in the exposure of holographic multi-stereogram. The power stability is measured for 2 different periods at different sampling rate, which shows the laser power stability is very good. It is important the laser is sufficiently heated before recording holograms. The heating time must be at least 1 hour.

The laser's coherence length is measured with help of Michelson's set-up, and is measured to be 30 cm. From the visibility plot the contrast of the hologram will fall from 1 to 0.8 for 5 cm laser beam path difference. It is very important that the reference and object beam have the same path length.

To produce high quality holograms the stability of the laser beam and the optical equipment must be good. Vibrations of the interference fringes on the film plate for more than $1/10 \cdot \lambda$ reduce the brightness of the hologram. Therefore, the optical equipment's stability and quality have to be very good to meet this requirement.

Several different vibrational measurements have been made on the optical table. The first is made with the glass cage and the second without. The plot shows distinctly that the measurement without the glass cage has higher vibrational amplitude than the measurement with the class cage. A vibrational measurement of the recording process of the holographic multi-stereogram recording is also made. This measurement shows the printer makes a high vibration amplitude when the motor is running, but the optical table is stable 1-2 seconds after the motor has stopped. There are no vibrations measured when the shutter moves (open/close). With the use of the printer and the shutter, which is the equipment that moves under the recording process, there are no vibrational problems for the production of holographic multi-stereogram.
The thermal stability requirement for the film plate is very high, a change of temperature for more than 0.1°K makes reduction of the hologram quality.

Several holographic recordings were made: transmission, reflection and rainbow holograms made with 1-step and 2-step methods. For all of the recordings made with the 1-step method, it is not possible to get rid of the vertical lines from the slit of the printer. With the use of the 2-step method, where a master hologram is copied onto a new hologram the problem of lines from the slit was solved. From a master transmission holographic multi-stereogram, high quality 2-step reflection and rainbow holograms were produced.

There were also produced 13 reflection holograms of good quality for EPM Consultants, who have co-operated in this thesis work.

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Chapter 1 : Introduction

The interest in holographic applications has in the latest years opened up for new optimism in the expanding holographic community. One of the reasons for this is the development of new technology in optics and computers.
There seems to have been no particular reason why holography should have been such a late developer. Although today a hologram is invariably produced by using a laser as the light source, holograms can - and have been - made by other light sources, even, most improbably, with white light. The theoretical principles underlying holography could well have been worked out as early as 1816, when Auguste Fresnel clothed Thomas Young's 1802 theory of diffraction and interference with the respectable garment of mathematical rigor, at about the same time, when the first experiments that resulted in photography where carried out. In 1856 Scott Archer discovered how to produce a light sensitive material coated on glass. The monochromatic property of the golden-yellow sodium flame was well known, and it would at that time have been just possible to make a Denisyuk-type reflection hologram.
But the history of technology tells us that inventions appear only when contemporary culture is ready for them.
In 1947 Denis Garbor carried out his experiments using visible light from a filtered mercury arc. Because of the limited coherence of his source his holographic images were restricted to transparencies little larger than a pinhead. Garbor`s two papers (A new microscopic principle and microscopy by reconstructed wavefronts) for which he was subsequently to be awarded a Nobel prize in 1971, were published respectively in 1948 and 1949.
Meanwhile, in the Soviet Union, Yuri Denisyuk was experimenting with an optical configuration that was radically different from Garbor`s. In this configuration the reference and object beams where incident on the photographic plate from opposite sides. This was achieved by placing the film plate between the light source and the subject matter, so that the portion of the reference beam not absorbed by the emulsion passed through and was reflected back from the object, forming the object beam. By 1962 Denisyuk had succeeded in producing holograms in which the image could be reconstructed using a point source of white light. This was a considerable advance in comparison to other configurations which required a monochromatic reconstruction beam.
The appearance of a workable laser in 1962 gave holography the impetus it needed. Its importance centred round the large increase in the coherent length. It now became possible to make holograms of solid objects. Leith and Upatnieks produced the first laser transmission hologram of a solid object in 1963, and Denisyuk began to produce holograms of art objects in the same year.
After this holography began to develop rapidly. A good deal of the process consisted of small improvements in optical components, holographic emulsion and processing methods, combined to a growing mastery of the techniques by practitioners.
By restricting the vertical parallax, Stephen Benton produced in 1968 a transmission hologram which could be replayed using white light.
The principle of transfer images was quickly extended to reflection holograms. Thus holograms could now be produced with an intermediate stage. Just as in creative photography, it now became possible to introduce artefacts into the final hologram.
In 1974 Michael Foster introduced a method for duplicating holograms mechanically by using them in the same way as audiodisks. It became possible to mass-produce holograms at very low cost, holograms which, turned into reflection holograms by aluminium backing, could be

used in textbooks, art publications and publicity hand-outs, and on credit cards as a security device.
The past two decades have seen many more advances in holographic technologies, such as live portraiture, natural colour and holographic stereograms made from movie and computer graphics, which the present report is about.
Production of holographic stereogram from two-dimensional photographs is an established technique. This technique was first described by De Bietetto (1969). Each image is projected in turn on to a diffusing screen, while a movable mask (which is stepped between exposures) is used to define a narrow strip on the holographic plate. The complete hologram then contains a series of strip exposures. When it is viewed, the observer sees the image reconstructed by a single strip. As the observer moves, the reconstructed image appears to rotate, giving the illusion of three-dimensionatity.[2]

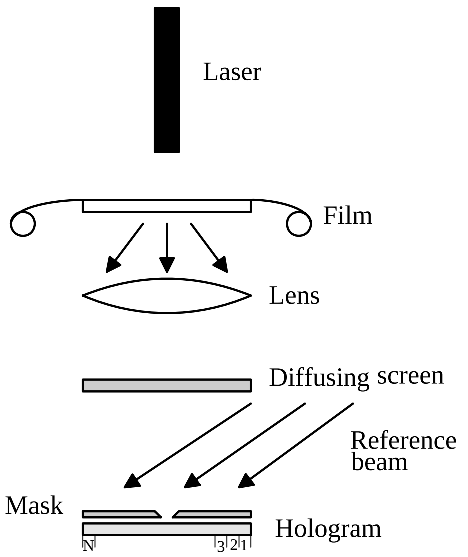

Figure 1-1 Set-up for recording partitioned holograms.

A holographic stereogram can of course be cylindrical, for all-round view. In this case, the transparencies can be made by photographing a rotating subject from a fixed position. If the subject articulates as well, each frame is a record of a particular aspect at a particular time. A rotating cylindrical holographic stereogram made from successive frames of movie film can then show an apparently three-dimensional display of a moving subject. This technique was originally invented by Cross in 1977.[26]

[2] M.C.King, A.M.Noll, D.H.Berry : A new approach to computer generated holography, Applied optics, Vol.9, 1970
[26] B.Kluepfel and F.Ross : Holography marketplace, Ross Books, Fourth edition, 1993

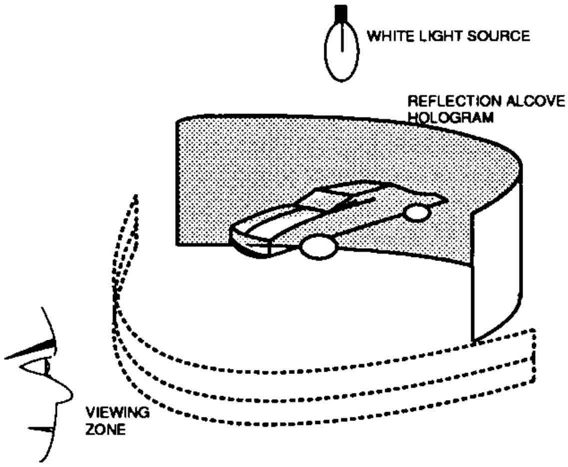

Figure 1-2 Oblique view of reflection alcove hologram.

Liquid crystals where actually discovered over 100 years ago, but they did not find commercial applications until the invention of the twisted nematic (TN) LCD by Schadt and Helfrich in 1971.[30] By the mid-1980s, it was becoming obvious to display industry experts that the Japanese displays industry was beginning to make significant breakthroughs in technical developments and in the manufacturing of liquid crystals displays (LCDs). In Japan, the stage is nearly complete for the production of flat panel displays (FPDs) through the end of the 1990s. The LC FPD industry is now orders of magnitude ahead of the other FTB technologies. The research, development, and production activities in Japan are so focused on LCD technology that funding for advancing electroluminescent (EL), plasma, and other FPD technologies is diminishing. In Japan, LCDs are perceived as clearly being the leading edge technology, but the cost and complexity of the new amorphous silicon (a-Si) LCD factory are so extensive that the larger machines of the next generation will not be attempted until the present generation of machines have completely proven and been paid for.

The aim of the present thesis is to develop methods for producing holograms from computer images. In this method, holograms are made from non-existing objects, that is, images produced on the computer. This means that it is not necessary to make prototypes of a new product in order to get it visualised in 3 dimensions. The computer image of the product can be directly converted to a holographic filmplate, and the product can be shown in 3 dimensions. There are economic advantages, if it becomes possible to skip the building of prototypes, which is often a very expensive and a time consuming operation.
This thesis work builds on the conclusion drawn in Thor Erling Grahl-Nielsen diploma work NTH-1992, [24] and a further thesis work of Olav Birkelands Cand. scient thesis UIB-1994.[10]

[30] R.Ondris-Crawford, G.P.Crawford, J.W.Doane : Liquid Crystals : The phase and the future, 1995
[24] T.E.G-Nielsen : Holography, a current technology, from presentation of geometrical product models within marine and mechanical enterprises ?, Diploma NTH, 1992.
[10] O.Birkeland : Construction of holographic printer for automatic production of hologram from a 3D computer model**,** UIB, 1994.

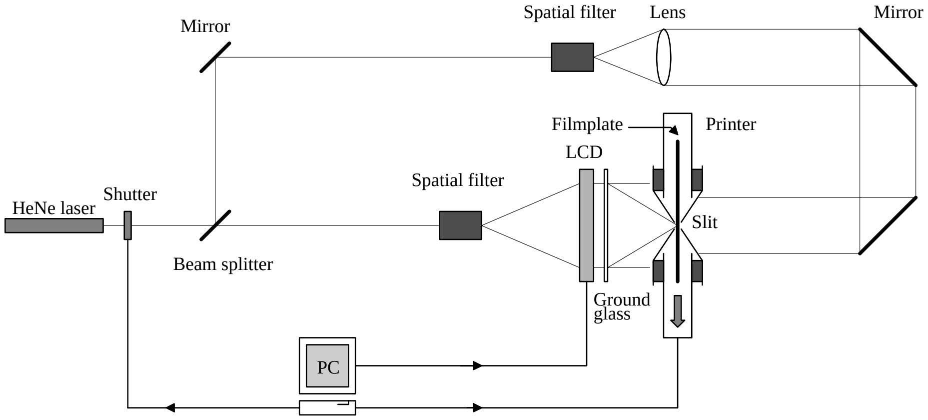

Figure 1-3 The set-up for production of holographic multi stereogram.

The purpose of the present thesis work is to examine the best methods for producing high quality holographic multi-stereograms from computer images.[9] In particular, reflection and rainbow holograms are produced from master holograms by the two step method.

A hologram is a very good way to display an object in three dimensions. To make a good reflection hologram is more difficult than transmission and rainbow holograms. I believe the reflection hologram has the best chance to be a success in 3D visualisation, when this can be reproduced in white light.

In finding the right set-up for production of high quality holographic multi-stereograms, there was a great deal of optical equipment and procedures that had to be inspected. Therefore, the thesis work started with a simple holographic record of an object. When the result of the recording and developing processes were satisfactory, the set-up was changed step by step until the final set-up for the recording of high quality holographic multi-stereogram was found and tried out in some detail.

[9] R.Andreassen, O.Birkeland, T.E.Grahl-Nielsen, K.E.Olsen, I.Singstad : Technical digest series, Vol.4, 1996

Chapter 2 : Holographic methods

2.1 What is a Hologram ?

A hologram is a record of the interaction of two beams of coherent light, in the form of microscopic pattern of interference fringes. It is a photographic registration of the interference pattern formed by two laser beams of coherent light. One beam goes straight from the light source and the other is scattered from a physical object. The photographic film or plate is exposed by two laser beams and is processed in such way that when illuminated appropriately a three-dimensional image is produced.
People often seem to think of a hologram simply as some sort of a three-dimensional photograph. Certainly, both photography and holography make use of photographic film, but that is about all they have in common.
The most important difference is the way the image is produced. A photographic image produced by a camera lens can be described fairly accurately using a simple geometric or ray model for the behaviour of light, whereas the holographic image cannot be described by this simple ray model. Its existence depends on diffraction and interference, which are wave phenomena.

2.2 Applications of holograms

Holography represents one of the most fascinating examples of recombining of scattered radiation to produce pictures. It has been a well used method to produce image, and a important tool in science and technology.
Holography is now spreading from the research laboratory to industry, and finds wider employment in communication and other engineering problems. A hologram can store numerous quantities of information. In the computer technique one can make a memories which are much larger and faster than in today’s computers, but this has still not been realised even if the improvement are fast.
The use of small holograms in credit cards, which are made to prevent falsification, has made holograms a well known concept. Holograms show up more and more often on tickets and on original covers on software computer programs.
An example of an important area of application is bar-code readers in shops, warehouses, libraries and so on. A code reader like this is based on the application of holographic components like optical gratings. This large important industry has contributed to make holography an industrial success.
In the aircraft industry head-up displays (HUD) are an impotant example of holographic technology. HUD helps the pilots so they do not need to look down onto the instrument panels, because the instruments are projected onto the windscreen with help of holographic technology, and thus make flying easier.
Holography is also in use for making holographic optical elements (HOE), based on interference. The HOE are optical diffraction gratings, mirror, lenses and so on. This technique is used in bar-code readers.

2.3 The most common types of holograms [38]

2.3.1 Transmission hologram [6]

In the figure 2-1 is depicted the set-up for recording transmission hologram. To make a hologram we need two coherent light waves, laser light. One beam is reflected from the object and carries information about the object. This wave is called the object beam. The other one is a plane wave without information, which is called reference beam. The object beam (OB) and the reference beam (RB), generate an interference pattern which is recorded in the form of a hologram on film emulsion.
Absolutely stable conditions are required during the exposure of the film. If we have an instability of one tenth or more of a wavelength (633 nm), the result will be low diffraction efficiency and a weak image reconstruction.
This type of hologram is called transmission hologram because the light passes through the holographic plate. An other characteristic of transmission holograms is that the object beam and the reference beam come in from the same side of the holographic film plate during the exposure.

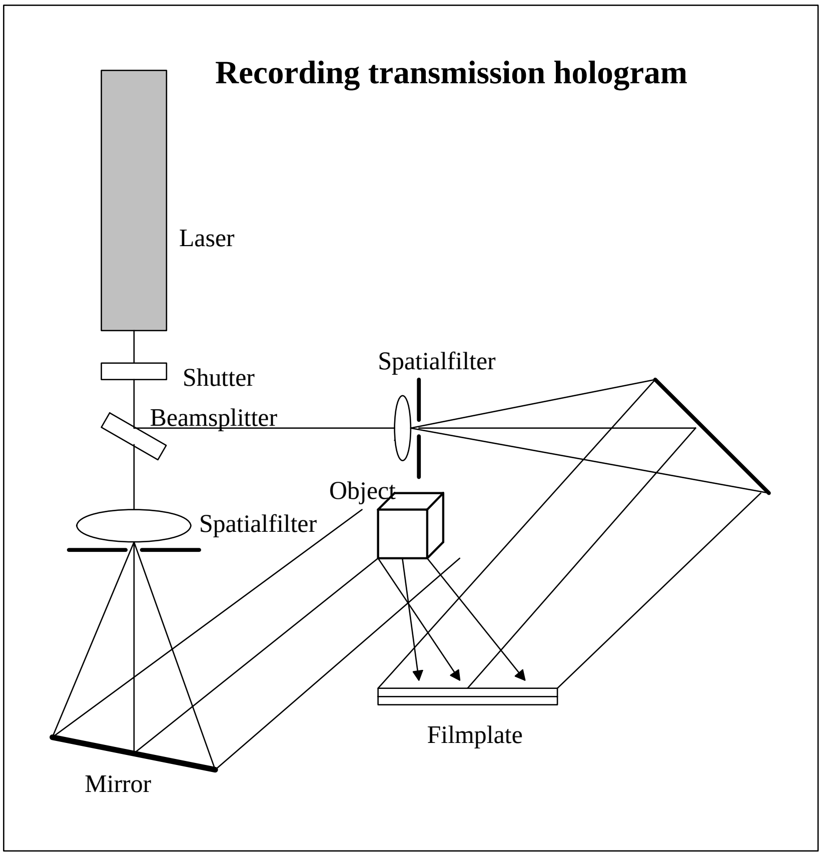

Figure 2-1 Recording transmission hologram

[38] G. Saxby : Practical holography, pp 42-52, 1988
[6] I.Singstad : Classical holographic technique, p 4, UiB, 1993

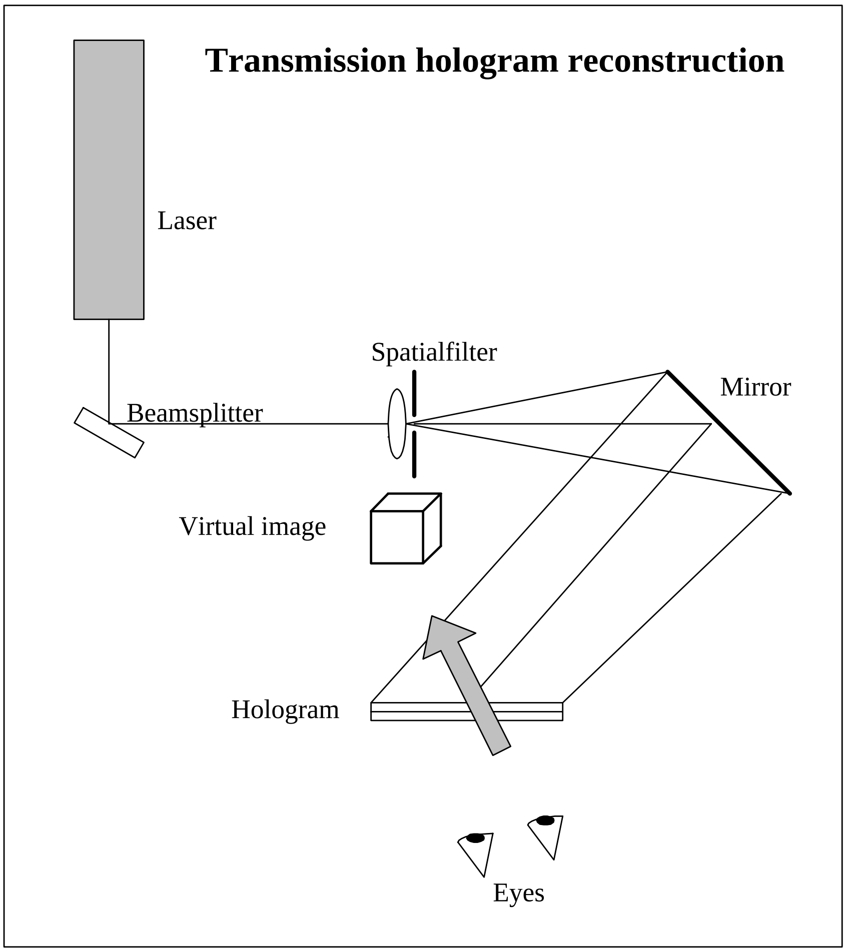

Figure 2-2 Transmission hologram reconstruction

To reconstruct the holographic image, we develop the hologram and place it in its original position in the reference beam as during its recording. If we look along the reconstructed object beam we see a replica of the object, and as we shift viewpoints we see object from different perspectives. Thus the object appears to be three-dimensional (3D). The light does not actually pass through the image, but only generates a wavefront that makes it appear as though the light had been generated in the position of the object. This image is called virtual image.
In contrast to the virtual image, an image that light has actually passed through is called a real image. The difference between the real image and the virtual image is that the real image can be caught on a screen placed in its plane without additional lenses. The real image is used in the two-step process which really is a hologram of a hologram. The real image is focused just in front of the recorded filmplate and so a reflection hologram can be produced.
Figure 2-3 and figure 2-4 shows us the virtual and the real image of a transmission hologram.

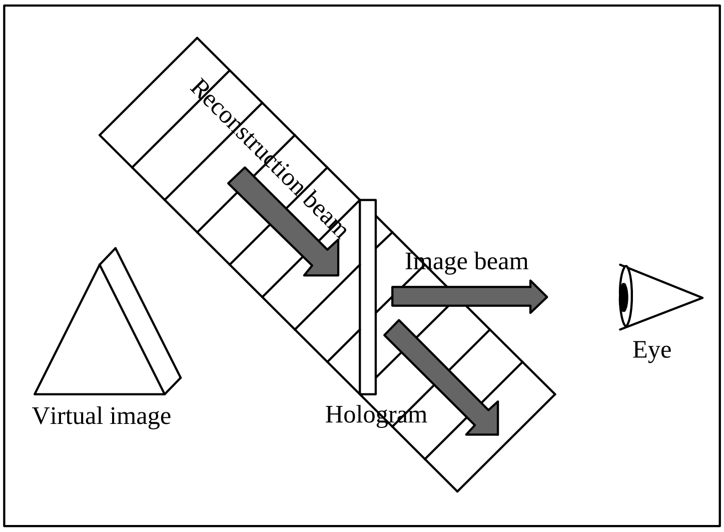

Figure 2-3 Virtual image in a transmission hologram

In figure 2-4 the hologram is turned 180 degrees.

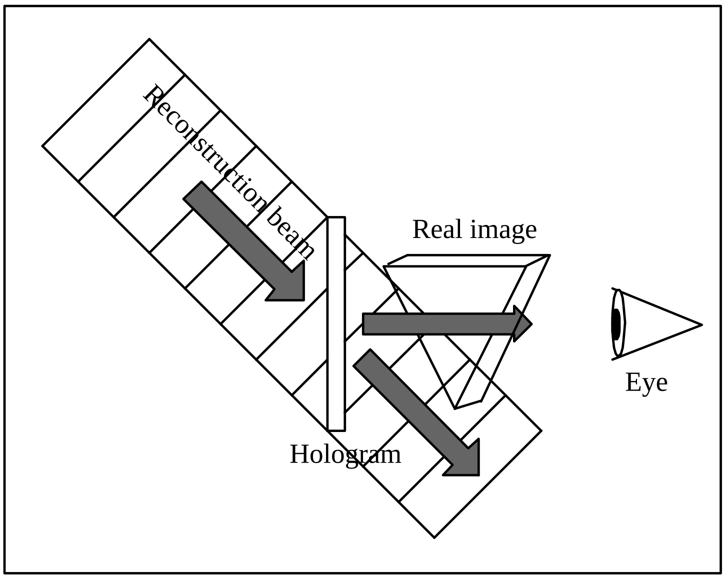

Figure 2-4 Real image of a transmission hologram

To get a 3 dimensional image of the object, we have to recreate the original wavefront. That means that the hologram must be illuminated by a wave like one of the original waves which was used during the exposure.

When the developed film is illuminated, diffraction and interference will give rise to a new wavefront which is quite like the original wavefront. The result is that, it is difficult to see the difference between the object and the image. The image appears to us as though it is formed at a distance behind the filmplate as shown in figure 2-3. The plane of the image is called the holographic window. This image is the virtual image.

2.3.2 Reflection hologram [6] [8]

During the recording a reflection hologram, the reference beam and the object beam illuminate the filmplate on opposite sides as shown in figure 2-5. As a consequence of this, the resolution of film emulsion must be very high. The recording of a reflection holograms needs 10 to 100 times as much power as for a transmission hologram. The result is that the exposure time will be long, and we need an optical arrangement which is multi-stabile.

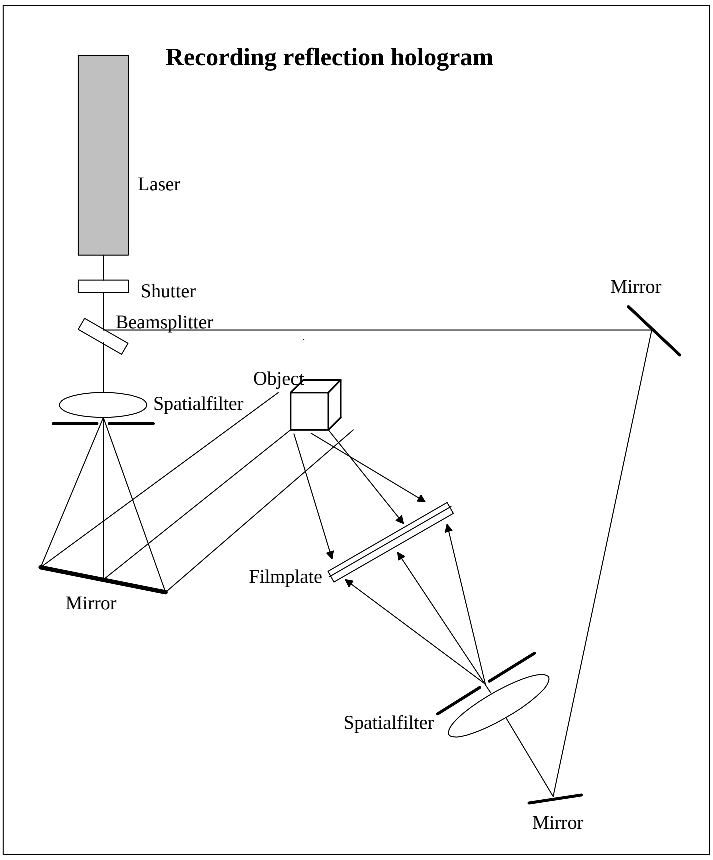

Figure 2-5 Recording reflection hologram

The interference fringes are formed by standing waves generated when two beams of coherent light travelling in opposite directions interact. The fringes formed are in layers more or less

[6] I.Singstad : Classical holography technique, p 28, UiB, 1993
[8] P.M.Hubel, L.Solymar : Color-reflection holography : Theory and experiment, Applied optics, Vol.30, 1991

parallel to the surface of the emulsion, and these sheets are roughly one half-wavelength apart. Under these circumstances, Bragg diffraction is the controlling phenomenon in image formation. The diffraction efficiency can be very high, in certain types of hologram it can approach 100 %. In addition, we can replay the hologram using white light. A reflection hologram reflects light only within a narrow band of wavelength, so if we illuminate it with a highly directed beam of white light such as is given by a spotlight or light from the sun, the hologram will select the appropriate band of wavelengths to reconstruct the image, the remainder of the light passing straight through. In the work with the 3-D printer we concluded, however, that this one step method is not practical.

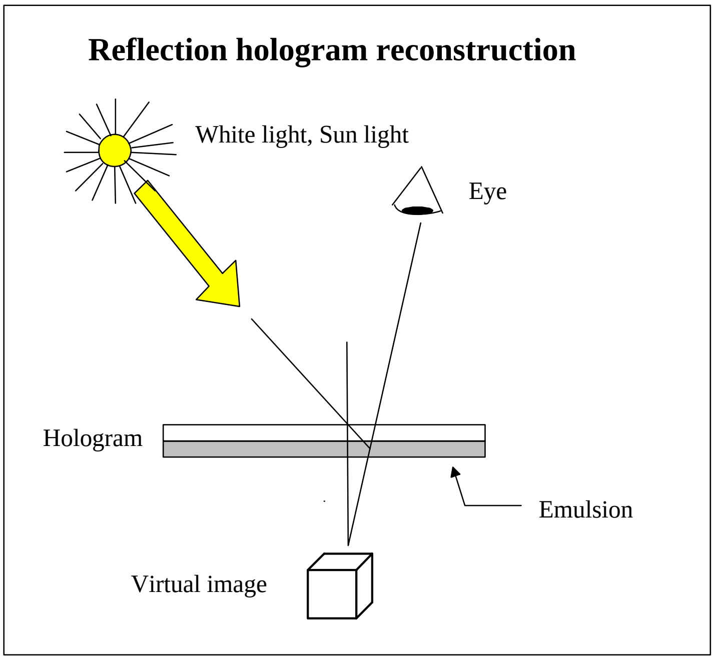

Figure 2-6 Reflection hologram reconstruction

As already mentioned, another common method to make a reflection hologram is to use two steps in the production, what we call 2-step reflection hologram. First we make a transmission hologram called H1, because it is the first hologram or a master hologram. Sometimes the H1 is the master hologram from which we make multiple copies . A high quality transmission hologram is often used as a master hologram. Transfer copies (making another hologram using the image on the master as the subject) can be made in quantity from the master. These transfer holograms can either be other laser-visible transmission holograms or reflection holograms H2.

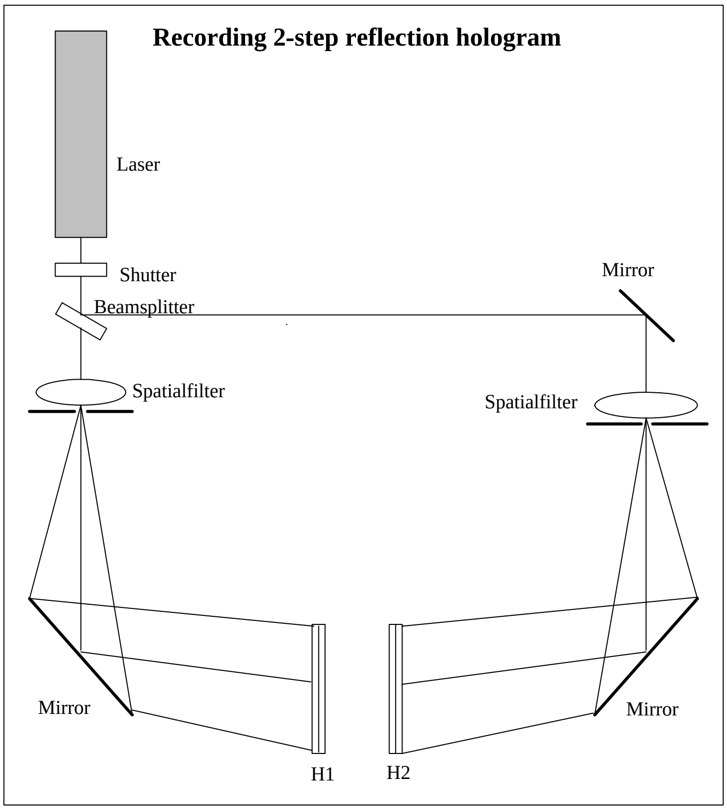

Figure 2-7 Recording 2-step reflection hologram

Historically one of the big problems that holographers used to have was placing the object to be holographed exactly where they wanted it.
For example, we want the object in the final hologram to appear half in front and half behind the recording plate. The way in which we have to do this is to first make a transmission hologram. We call this H1 because it is our first hologram. Now, since we can make a hologram of the H1's image, we take time to move the image around to wherever we want it positioned. In this case, we adjust the H2 recording plate so that the image of the object is half in front and half behind the plate and then make our H2. The problem of getting half the object in front of the plate, and half behind, is solved.

2.3.3 Rainbow hologram [31]

The rainbow hologram separates out components wavelengths of white light and sends them in different directions, so that the viewer sees the image by light of only one wavelength, the actual wavelength being determined by the viewpoint. In order to achieve this, the hologram contains a plain diffraction grating which disperses the light into a vertical spectrum with red at the top and violet at the bottom. This diffraction grating is produced in the transfer process, and takes the place of the vertical parallax. So when we view a rainbow hologram at average height the image appears yellow-green. If we stand a little higher, it changes to orange or red, and if we dip, it becomes blue or violet.

[31] G.Saxby : Manual of practical holography, pp 93-94, 1991

In the horizontal plane the image has full parallax, and appears in three dimensions, as does any other type of hologram.

We may mention that the concept of two-steps rainbow hologram is practical in the 3-D printer recording process.

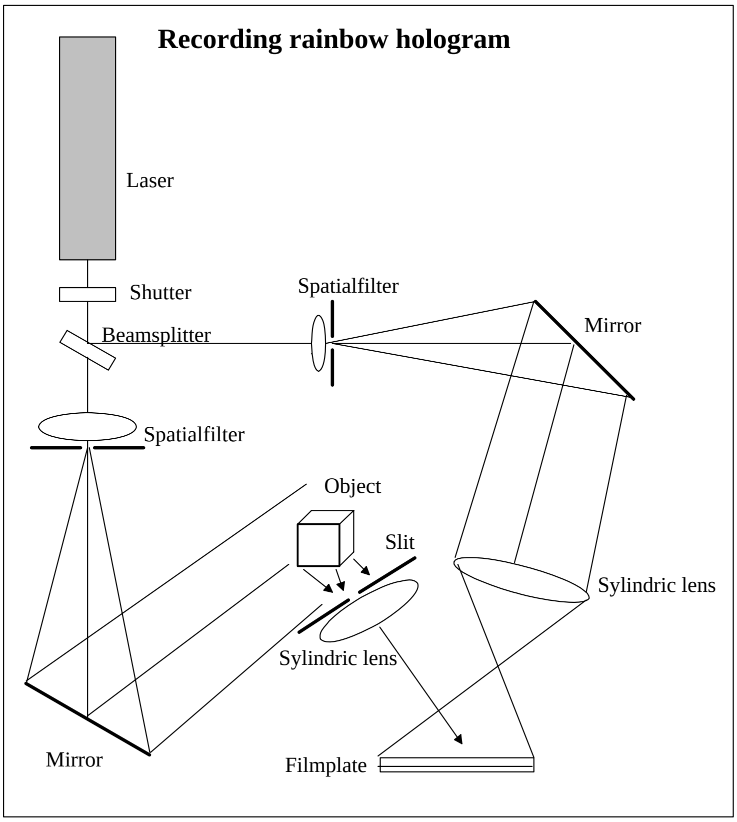

Figure 2-8 Recording rainbow hologram

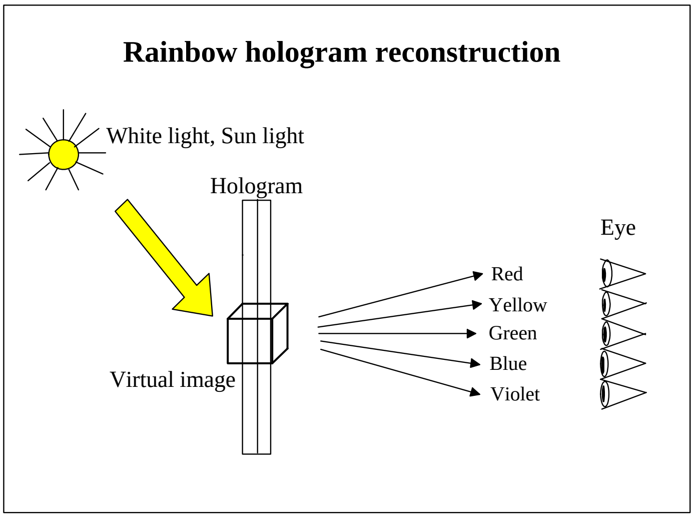

Figure 2-9 Rainbow hologram reconstruction

2.3.4 Thick and thin holograms

Another broad classification of holograms is made when differentiating between thick (called volume [39]) holograms or thin holograms. One of the reasons the words thick and thin are used in conversation is that they allow one the instantly get an idea of some of the properties of the hologram. Very thin holograms provide little depth to their object upon reconstruction. Embossed holograms, such as the images on bank cards, are examples of thin holograms. Thick holograms have the ability to replay or reconstruct the image with considerable depth or projection.
A hologram is considered to be thick if the thickness of the recording medium is greater than the spacing between the interference fringes. Otherwise the hologram is considered a thin hologram.
The distance between interference fringes recorded on the film will depend on a number of things, such as the wavelength of light being used, and the density of particles in the emulsion of the film plate.
These interference fringes are called *Bragg planes*, and actually go all the way through the medium, but are visible to our eye only where they meet the surface.
In a reflection hologram, the reference beam and the object beam strike the plate from opposite sides, the Bragg planes slice through the medium at very shallow angles.

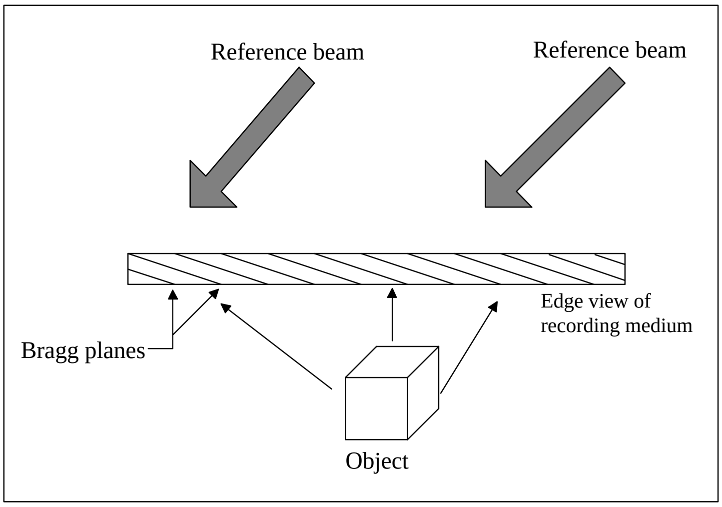

Figure 2-10 Bragg planes in a reflection hologram

Conversely, in a transmission hologram, where the reference beam and the object beam strike the plate from the same side, the Bragg planes cut the emulsion at much sharper angles and thus are further apart.

[39] R.R.A.Syms : Practical volume holography, pp 21-23, 1990

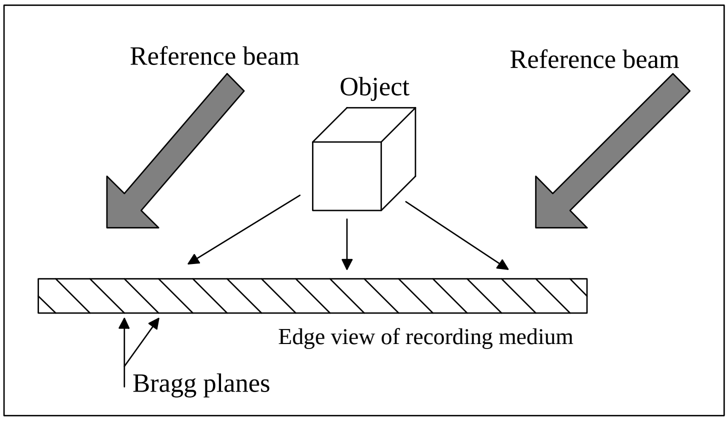

Figure 2-11 Bragg planes in a transmission hologram

2.4 Embossed holograms [31]

Embossed holograms are holograms which are mass-produced by taking a shim, or metal negative of the holographic image, and making impressions of the image onto a desired substrate. Foil is probably the most popular due to its low cost.
The major drawback of embossed holograms is that they lack depth. It is difficult to obtain a depth of more than 1 inch.
There are great advantages with embossed holograms, and there are tricks one can use to get around the problem of depth. For example, since a photograph is 2D and has no depth, it is an ideal subject. Furthermore, there is no reason why can not take several photographs, splice them together in extremely small strips and produce a three-dimensional effect for the viewer.

2.5 Holographic optical elements (HOE)

Holographic optical elements (HOEs) are lenses, mirrors, gratings, prisms and beam splitters made by holographic methods. Although they work by diffraction rather than by reflection or refraction, they obey all the rules of geometrical optics, and can be used for any purpose that conventional optical elements can be used for, with only one provision: they operate efficiently only over a narrow band of wavelengths. However, this is not of importance in holography, as careful processing can ensure the diffraction efficiency is a maximum at the wavelength of the laser that was used to make the HOE.

2.6 Head-Up Display (HUD)

A Head-Up Display projects the display image onto a partially transparent screen called a combiner that reflects the display to the viewer while allowing the viewer to see through to the outside world.

[31] G.Saxby : Manual of practical holography, pp 162-163, 1991

The advantage of a HUD is that it allows the viewer to see the projected display information while still looking at the scene beyond. An example of how useful this can be is in allowing a pilot to see both the runway and his instruments simultaneously during landings.
Another advantage is that the distant display image saves the time needed to refocus the eyes between nearby instruments and the world outside.

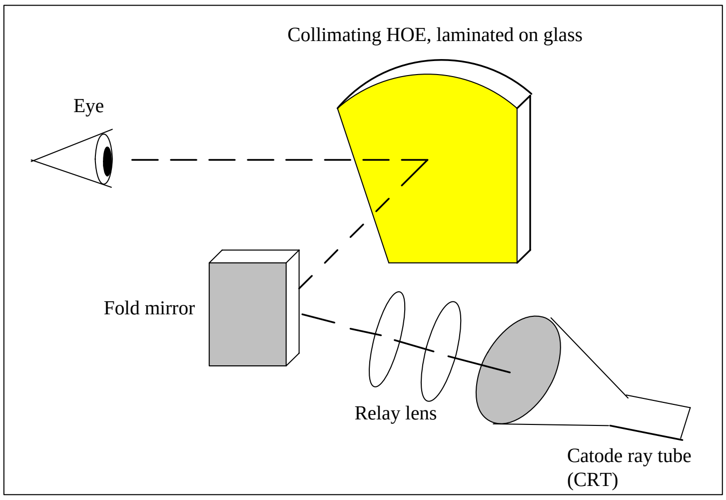

Figure 2-12 Aircraft Head-Up Display

One of the advantages of a holographic HUD combiner is its ability to reflect only a very narrow wavelength spectrum. This means that the reflectivity can be very high for the wavelength for the display while still remaining very low for all other wavelengths in the field of view.
By using a narrow band display source such as a phosphor cathode ray tube the HUD display can be both very bright and very transparent, with minimum coloration of the see-through scene.

Chapter 3 : Theory

3.1 Formation and reconstruction of a Hologram [6] [7] [14]

There are several ways of writing down the equation for a travelling wave, and some are more rigorous than others.
These expressions are given as exponential functions

$$O = E_o e^{(i\phi o)}$$
$$R = E_r e^{(i\phi r)}$$

where

O - Object wave
R - Reference wave
I - Intensity
E - Amplitude
ϕ - Phase angle

We can write the formula for the intensity in the hologram

$$I = (O + R) \cdot (O^* + R^*) \qquad (3.1a)$$

$$= (E_o e^{i\phi o} + E_r e^{i\phi r}) \cdot (E_o e^{-i\phi o} + E_r e^{-i\phi r}) \qquad (3.1b)$$

$$= E_o^2 e^{i\phi o - i\phi o} + E_o Ere^{i(\phi o - \phi r)} + E_r E_o e^{-(\phi o - \phi r)} + E_r^2 e^{i\phi r - i\phi r} \qquad (3.1c)$$

$$= E_o^2 + E_r^2 + E_o E_r e^{i(\phi o - \phi r)} + E_o E_r e^{-i(\phi o - \phi r)} \qquad (3.1d)$$

The phase information is contained in the two last terms.

While an ordinary picture records only the intensity distribution in the object, the hologram contains also information about the phase. It means all information about the object is saved in the hologram, and we get an image in 3 dimensions.

A transmission distribution can be carried out for when the film plate is exposed

[6] I.Singstad : Classical holographic technique, pp 7-8, UiB, 1993
[7] W.Lauterborn, T.Kurz, M.Wiesenfeldt : Coherent optics, Springer-verlag, pp 99-106, 1993
[14] Born and Wolf : Elements of the theory of diffraction, Principles of optics, Pergamon press, 1959

Where

T = Transmission distribution on the filmplate
T_0 Transmission constant for the filmplate
β = Film parameter
I = Exposure intensity
t = Exposure time

We have the following function for the transmission distribution

$$T = T_0 - \beta It \qquad (3.2)$$

We put in the formula for the intensity (3.1d) into formula (3.2), and we get for the transmission distribution

$$T = T_0 - \beta(E_o^2 + E_r^2 + E_oE_re^{i(\phi o-\phi r)} + E_oE_re^{-i(\phi o-\phi r)})t \qquad (3.3a)$$

$$T = T_0 - \beta t\,(E_o^2 + E_r^2) - \beta t\,EoEr(e^{i(\phi o-\phi r)} + e^{-i(\phi o-\phi r)}) \qquad (3.3b)$$

This equation describes the exposure of a holographic filmplate. This means that the equation describes a hologram.
For the reconstruction of the hologram, we have to illuminate the holographic plate with a beam which is similar or nearly similar to the reference beam.

The reconstruction can then be expressed as

$$E_R = E_r\,e^{i\phi_R}\,T \qquad (3.4)$$

The use of R instead of r is justified as the reconstruction beam is not necessarily the same as the reference beam.

$$E_R = Er\,e^{i\phi_R}\,T_0 - Er\,e^{i\phi_R}\,\beta t\,(E_o^2 + E_r^2) - Er\,e^{i\phi_R}\beta tE_oE_r\,(e^{i(\phi o-\phi r)} + e^{-i(\phi o-\phi r)}) \qquad (3.5a)$$

This equation can also be written as

$$E_R = -\beta tE_rE_o^2e^{i\phi_R} + E_re^{i\phi_R}\,(T_0-\beta tE_r^2) \qquad (3.5b)$$

$$- \beta tE_oE_r^2e^{i(\varphi o-\varphi r+\varphi_R)}$$

$$- \beta tE_oE_r^2e^{i(-\varphi o+\varphi r+\varphi_R)}$$

The first term of the equation (3.5b) represents a wave which travels in $E_re^{i\phi_R}$ direction.[25]
E_r is a wave which spreads from the object and is not constant. The wave is a function of (x,y).

[25] O.J.Loekberg and K.Dybvik : Holography and optical filtration, Report AF-1, pp 6-8, 1968

The second term represents the virtual image. If the phase of the reference and reconstruction wave is equal, the second term will be identical to the object wave, with the exception of the amplitude. We have also reconstructed the object completely.

The third term represent the real image. Except for small angles (ϕ_r) will it not be possible to see the virtual and the real image at the same time. From the equation (3.5b) we can see that the phase of the object wave (ϕ_o) is positive for the real image and negative for the virtual image. This means that the virtual image and the real image lie on opposite sides of the holographic filmplate.

The real image is created by waves which travel in the positive direction. This direction is the same as the direction of the reference beam.
The virtual image is created by waves which travel in the negative direction, which is in the opposite direction to the reference beam.

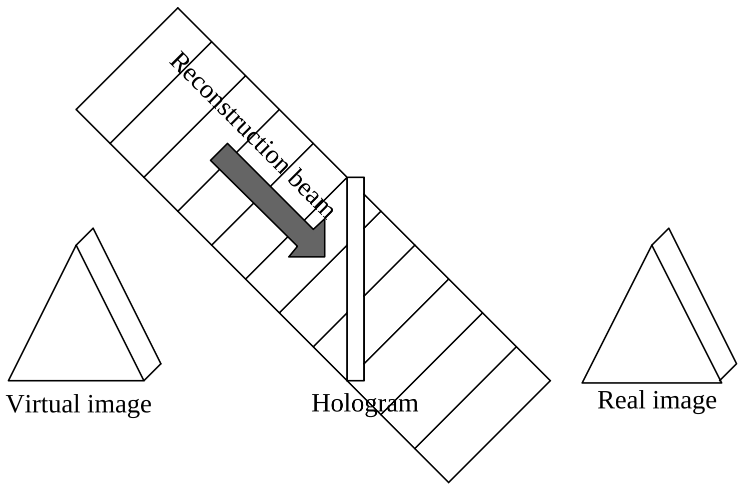

Figure 3-1 Reconstruction of a hologram

Chapter 4 : He-Ne laser [40]

There are several different lasers which are used in the production process for holograms. The most common lasers used in holography are Helium-neon (He-Ne), Helium-cadmium (He-Cd), Argon-ion (Ar^+) and Krypton-ion (Kr^+) lasers.[38] Many types of CW lasers can also be operated in a pulsed mode, though so far none of them seems to be suitable for holography. Monocrystalline aluminium oxide doped with lanthanide elements such as yttrium (yttrium aluminium garnet, or YAG crystal) can be used to change the wavelength of a laser.
A semiconductor laser is a special kind of light-emitting diode. It produces a beam of light in the near infrared with a divergence of about 15°, but the cone of emitted light is elliptical rather than circular, so that the beam appears to have originated from a line rather than a point. If the astigmatism of this beam is corrected by means of aspherical optics, a spatially-coherent beam can be obtained, and this has been used experimentally for making holograms. The main attraction of semiconductor lasers is that they are cheap and very small. They also operate at comparatively low voltages and art similar power range to that of He-Ne lasers.

There are a number of things to be considered in the choosing of a laser. A laser used to produce holograms needs good stability, and must be free from vibrations.[37] The laser beam must be as plane as possible. A laser beam with multi modes is useless for making holograms. We want that the laser should have a circular beam diameter without any noise. The beam diameter is the important parameter in the calculation of the pinhole of the spatial filter.
The coherence length of the laser should be as large as possible. If the coherence length is small, the requirements of the path difference between the object and reference beam become harder to meet. This means that the path difference between these beams must be nearly zero. The number of modes in the laser is also an important parameter. In holography we prefer a laser with as few as possible modes. If we use a multi mode laser, we have problems with low visibility and the contrast in the hologram will be low.

4.1 The laser principle[50]

The laser consists mainly of three parts. The resonator, an active medium in the resonator and an energy source for activating the medium. With these components it constitutes a self-excited oscillator.

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[40] O. Svelto : Principle of lasers, pp 298-302, 1989
[38] G.Saxby : Practical holography, 1988
[37] A.D.White : Power fluctuation in He-Ne lasers, Laser focus, 1985
[50] J.Hecht : The laser guidebook, pp 101-119, McGraw-Hill inc., 1992

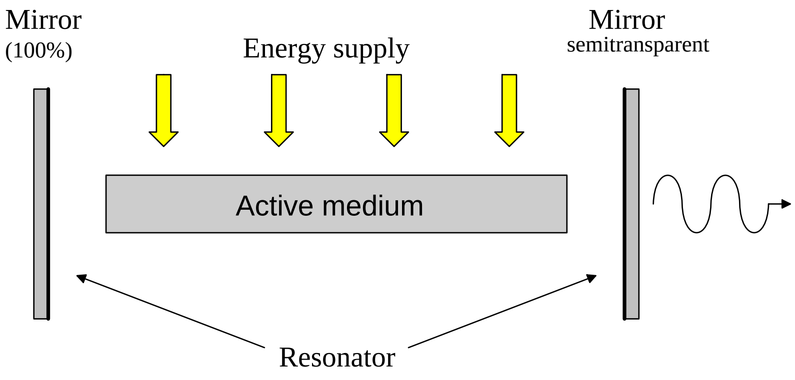

Figure 4-1 The basic element of the laser

Three basic interaction process of light with matter are important for the laser.[40] These are absorption, stimulated emission, and spontaneous emission. We assume that two states, of energies E_1 and E_2, take part in the interaction.[7]

Absorption is when a photon of energy *hv* strikes an atom of the laser medium in the state E_1 and disappears, exciting the atom to the higher state E_2. The photon can only be absorbed, if the absorption energy is $hv = E_2 - E_1$. When no suitable energy level is available, no absorption takes place, and the medium is transparent for photons of this energy.

We have stimulated emission when the atomic system has absorbed the energy *hv* and thus the upper level is occupied, a second photon of energy *hv* may cause this energy to be emitted as a photon.[33] Then two photons having identical properties leave the atom. Upon absorption, the atomic system starts from the state of lower energy, upon stimulated emission it starts from the state of higher energy. The transmission probability is equal for both processes.
In spontaneous emission the atomic system in the state of higher energy, E_2, decays into a state of lower energy, E_1, by the emission of a photon. The word spontaneous indicates that the transition take place with the randomness that is characteristic for quantum processes.

Where the frequency is given by

$$\nu = \frac{E_2 - E_1}{h} \qquad (4.1)$$

E_1 = Energy level 1, also called ground level.

E_2 = Energy level 2, also called excited level.

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[40] O.Svelto : Principles of lasers, 1989
[7] W.Lauterborn, T.Kurz, M.Wiesenfeldt : Coherent optics, Springer-verlag, pp 180-182, 1993
[33] R.Seyway, C.Moses, C.Moyer : Modern Physics, pp 1036-1038, 1989

h = Planck constant

v = frequency

The helium-neon laser, usually abbreviated to He-Ne, is the most common type of gas laser. The tube contains helium gas at a pressure of about 1 torr and neon pressure of about 0.1 torr. (a torr is a unit of pressure equivalent to 1/760 of an atmosphere). The main purpose of the helium is to act as a continuos reservoir of energy (supplied with electrical discharge) for the neon. This laser is the one that is best suited to general-purpose holography.

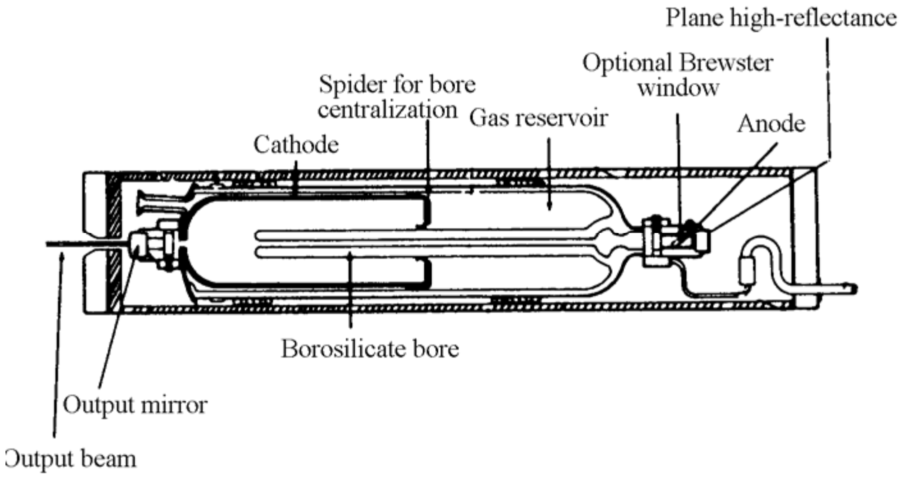


Figure 4-2 Internal design of a modern helium-neon laser

He-Ne lasers as used for holography operate at a wavelength of 632.8 nm, with a power ranging from 0.5 mW to 100 mW. The randomly-polarised type are unsuitable for serious holography, as the direction of polarisation[27] is an important factor for obtaining optimum image quality. A laser with Brewster angle windows has a somewhat lower output than its randomly-polarised equivalent, but it has a completely stable plane of polarisation. In this thesis work has the choice of laser fell on red He-Ne lasers. In the beginning of the experimental work there was used a 12 mW red He-Ne laser. During the experimental work this laser was changed to a new and more powerful red He-Ne laser with an output power of 24 mW. The reason for the choice of this type of laser is the He-Ne laser's advantage in laser beam stability, laser modes, beam diameter, coherence length, output power and price. Another reason is that most of the literature recommends the use of He-Ne laser in the production of holograms.

[27] O.S.Heavens, R.W.Dichburn : Insight into optics, pp 79-82, 1991

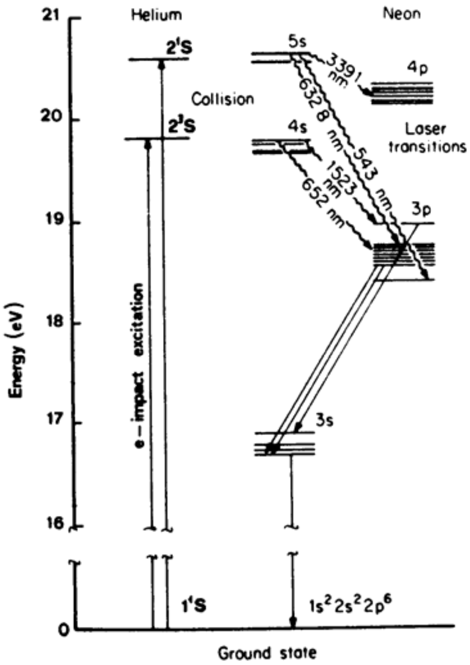


Figure 4-3 Energy levels of He and Ne involved in the He-Ne laser.

4.2 Measurements of laser beam stability [37]

During the recording process for holographic multi-stereograms, it is important that each of the 70 part holograms are evenly exposed. If the exposure of the film is varied, there will be areas of the hologram that are brighter than other and the quality of the hologram will not be as good as desired. This can also happen if some of the part holograms are under-exposed. The power stability of the laser beam is not decisive for the visibility of the hologram, because the ratio between the reference and the object beam will still be constant. For each part of the hologram the exposure time is constant, and it is then important that the laser's output power is constant to get the same exposure.
For measuring the power stability of the 24 mW He-Ne laser the following set-up was arranged on the optical table.

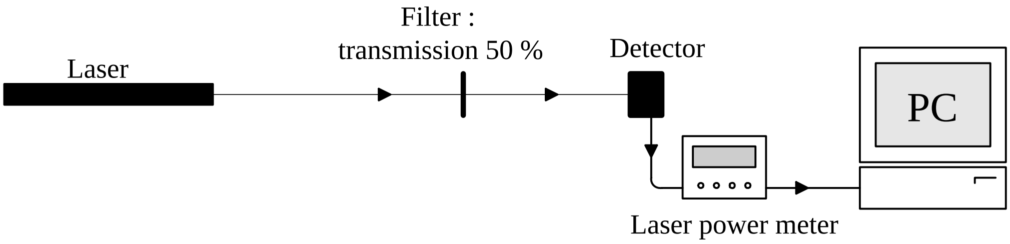


Figure 4-4 Optical set-up for measuring of laser power stability.

[37] A.D.White : Power fluctuations in He-Ne lasers, Laser focus / Electro optics, 1985

The neutral density filter was used to reduce the laser's output power with 50 %, to a readable value for the laser power meter. To detect the power of the laser, the laser power meter reads the data continuously. This data is then logged in the PC [28] by the data logging software program *PICO ADC-12*[36]. The data is logged for two different sampling rates and time lags. The values from *ADC-12* are then converted to LOTUS 1-2-3 to make it possible to present the data in a suitable way.

The first measurement is a short time logging made with sample pr. 100 ms in 10 seconds. The other measurement is a long time logging made with 1 sample pr. second in 30 minutes. The idea behind two different measures is to see how the laser works during holographic recordings (short time) and how stable the lasers output power is over time.

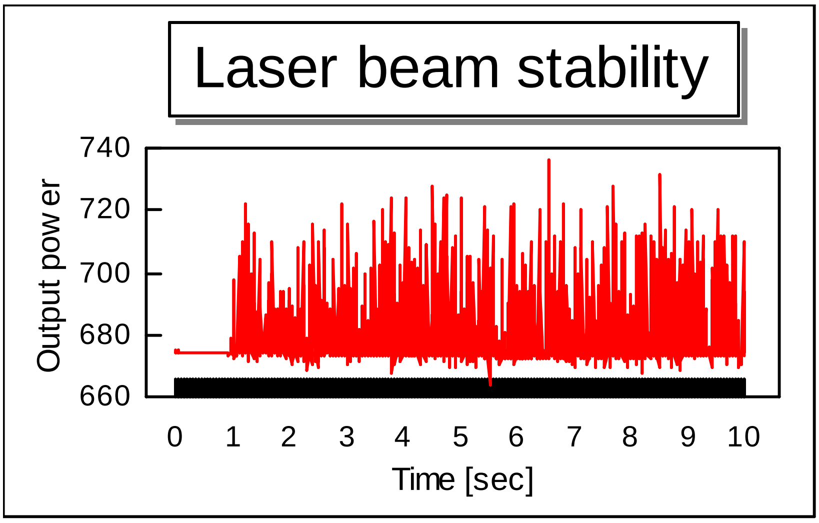


Figure 4-5 Laser beam stability for 24 mW He-Ne laser with sample each 100 ms in 10 seconds.

Laser output power data from sample rate at 100 ms in 10 seconds (short time).

Average value : 680.6
Standard deviation : 13.1
The laser output power stability for this measurement is about 1.9 %.

From Melles Griot product catalog[34] the laser output power stability is given by ± 2.5 %.

[28] G.A.Johansen : Instrumentation with PC and DOS-based software, UiB, 1993
[36] Picolog : Datalogging software, Pico Technology
[34] Melles Griot product catalog, 1995 / 1996

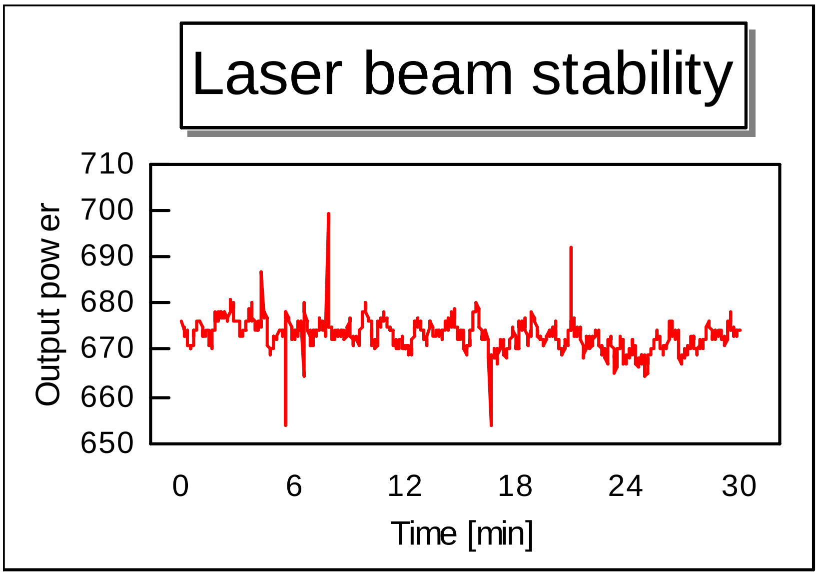


Figure 4-6 Laser beam stability for 24 mW He-Ne laser with sample each second in 30 minutes.

Laser output data from sample rate at 1 second in 30 minutes (long time).

Average value : 673
Standard deviation : 2.8
The output power stability for this measurement is about 0.4 %

During the production of a holographic transmission multi-stereogram, where 70 different part holograms are exposed onto the film, each exposure is about 10 seconds and the entire recording process takes about 30 minutes. From figure 4-5 can we see that the laser power stability for one part exposure of the film is good, and the measurement agrees with the data from the manufacturer, Melles Griot[34]. In practice, the spikes measured in the short time of measurement should not reduce the hologram's visibility.
From figure 4-6 can we see that the output power from the laser is quite stable over the whole recording process of 30 minutes. This means, that each of the part holograms on the multi-stereogram are evenly exposed on the film. The possibility of getting good results in the holographic multi-stereogram production with the use of this laser is good.

The laser was turned on at least 3 hours before the measurement was taken. It is very important that the laser is heated and becomes stable before the recording of holography is started.

[34] Melles Griot product catalog, 1995 / 1996

4.3 Laser modes

Laser resonators have two distinct types of modes, transverse and longitudinal. Transverse modes manifest themselves in the cross-sectional profile of the beam, that is, in its intensity pattern. Longitudinal modes correspond to different resonance's along the length of the laser cavity which occur at different frequencies or wavelengths within the gain bandwidth of the laser. A single transverse mode laser that oscillates in a single longitudinal mode is oscillating at only a single frequency.

Transverse modes are classified according to the number of noughts that appear across the beam cross section in two directions. The lowest-order, or fundamental mode, where intensity peaks at the centre, is known as $TEM_{00.}$ The mode with a single nought along one axis and no nought in the perpendicular direction is TEM_{01} or TEM_{10}, depending on orientation. A sampling of these modes, which is produced by stable resonators, is shown in figure 4-7.[50]

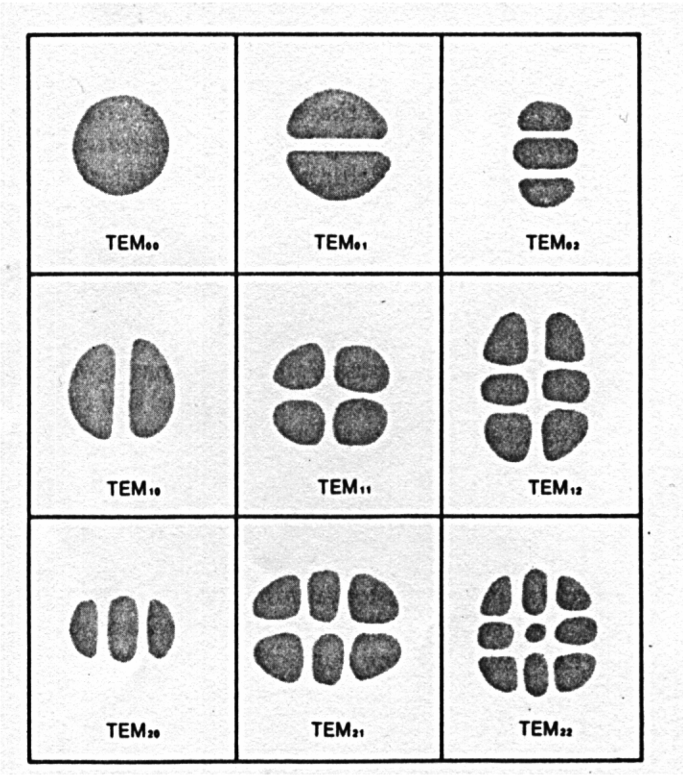


Figure 4-7 Lower-order laser modes that can be produced by a stable resonator.

For most applications for example like holography, the TEM_{00} mode is considered most desirable, but multi-mode beams can often deliver more power in a poorer-quality beam, and thus are acceptable for some uses.

The multiple longitudinal mode structure gives rise to a power fluctuation phenomenon termed mode sweeping. All unstabilized helium neon lasers exhibit this effect, which is due to thermal instability causing variation in the cavity length. As the cavity length changes, there is a small change in mode spacing which is typically 10 kHz or less under normal conditions.

[50] Jeff Hecht : The laser guidebook, McGraw-Hill, pp 32-37 , 1992

However, the absolute wavelength of each cavity mode is also changed by variation in tube length. This is typically $2.5{\cdot}10^{-3}$ nm/°C; i.e., $2{\cdot}10^{3}$ MHz/°C, depending on the glass type used for the tube. In effect, the ″comb″ of longitudinal modes drifts with respect to the Doppler broadened line centre, repeating its initial relative position in less than 1°K. Because of the non-flat, Gaussian profile of the gain curve, the overall power output changes. If the mode spacing is very small, as with a long laser tube, these changes may be very small. On the other hand, a short laser tube may have only one or two cavity modes under the Doppler profile, and the sum of their position on the Gaussisan gain curve.
This effect is almost identical for all unstabilized commercial TEM_{00} tubes and is a function of cavity length. The overall amplitude fluctuations are typical a few percent.
In the production of holographic multi-stereograms, where the recording process can be long, it is very important that the laser is thermal stable. If there is thermal instability and the output power is changing, the hologram can be unevenly exposed.

4.4 Coherence and visibility [6] [29]

Ordinary light is disorganised, not capable of producing interference. Such light is called incoherent. Light from a laser is highly organised, and easily produces interference. Such light is called coherent.
Some electromagnetic radiation such as microwaves, radio waves as well as sound waves, water waves and other mechanical waves can be generated as an infinite number of waves, one after another. Light wave cannot, because light waves always come in wave trains. The wave trains are of finite length, and each train containing only a limited number of waves. The length of a wavetrain is called the coherence length.

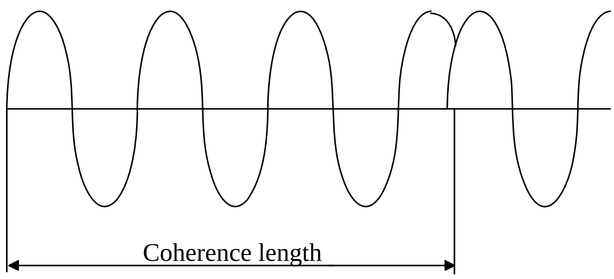


Figure 4-8 Wavetrain from a laser

Coherence length can be expressed as the product of the number of waves, N, contained in the train and their wave length, λ.

The formula for coherence length is then given by

$$\Delta s = N\lambda \qquad (4.2)$$

[6] I.Singstad : Classical holographic technique, pp 14-16, UiB, 1993
[29] J.R.Meyer-Arendt : Introduction to classical and modern optics, pp 220-225, 1995

Since the velocity is the distance travelled per unit of time, it takes a wave train of length Δs a certain length of time, Δt, to pass a given point and we get therefore

$$\Delta t = \frac{\Delta s}{c} \qquad (4.3)$$

where c is the velocity of light, and the length of time Δt is called the coherence time.

In holography it is important that the path difference between the reference and object-beam is zero, or very small.
If the path different between these waves is too long, as long as the coherence length, the contrast of the image will be very weak and it is impossible to see the image.

4.4.1 Measurements of coherence length

To find the coherence length of the laser, we have to know how many modes the laser has. That can be done with help of Michelson interferometer,[7] [41] and plotting the visibility as a function of the path difference between these waves.
With the knowledge of the coherence length and the visibility plot shown in figure 4-10 it is possible to find the difference of the laser beam distance between the reference and object beam, which reduces the hologram′s contrast.

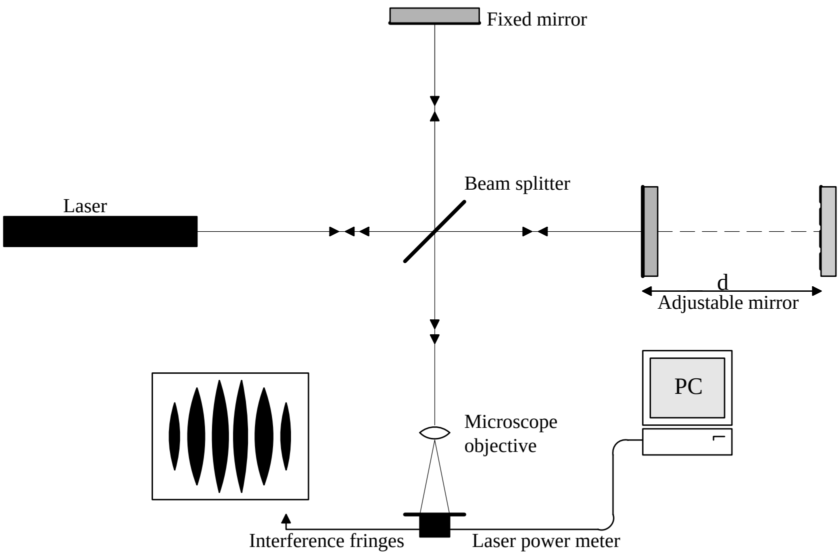


Figure 4-9 The Michelson interferometer.

The light from the laser is divided into two beams by the cube splitter (50 : 50 splitting ratio). One beam is reflected back onto itself by a fixed mirror, the other one is also reflected back by a mirror, but one that can be shifted along the beam. Both reflected beams are divided again into two by the beam splitter, whereby one beam from each mirror propagates to a screen. On

[7] W.Lauterborn, T.Kurz, M.Wiesenfeldt : Coherent optics, pp 32-35, Spinger-verlag, 1993
[41] F.T.Yu, I.C.Khoo : Principles of optical engineering, pp 177-184, 1991

this screen the light intensity is measured by a laser power meter. When the position of the adjustable mirror is changed, the interference fringes on the screen also change. The light intensity from the laser is measured for several different positions of the adjustable mirror.

The light intensity from the laser is measured for 30 different path lengths of the laser-interferometer arm. The adjustable mirror on Michelson interferometer is changed from zero path difference to a total of 150 cm path difference, at a step rate of 5 cm. The data from the measurements is logged with the help of a software program called *Picolo.*[36] The data was logged for one sample for every 100 ms, and a total of 2000 samples. From this data it is possible to find the coherence length of the laser.

The visibility of the fringes is defined as

$$V = \frac{I_{max} - I_{min}}{I_{max} + I_{max}} \qquad (4.4)$$

Because of the light from the background, this must be corrected.

$$V = \frac{I_{max} - I_{min}}{I_{max} + I_{min} - 2 \cdot I_{back}} \qquad (4.5)$$

The theoretical visibility for a laser with 3 modes is given by

$$V = \left| \frac{\sin(3\pi\Delta l)/2L}{3\sin(\pi\Delta l)/2L} \right| \qquad (4.6)$$

The visibility data from the Michelson interferometer visibility measurement and the theoretical visibility is plotted in figure 4-10.

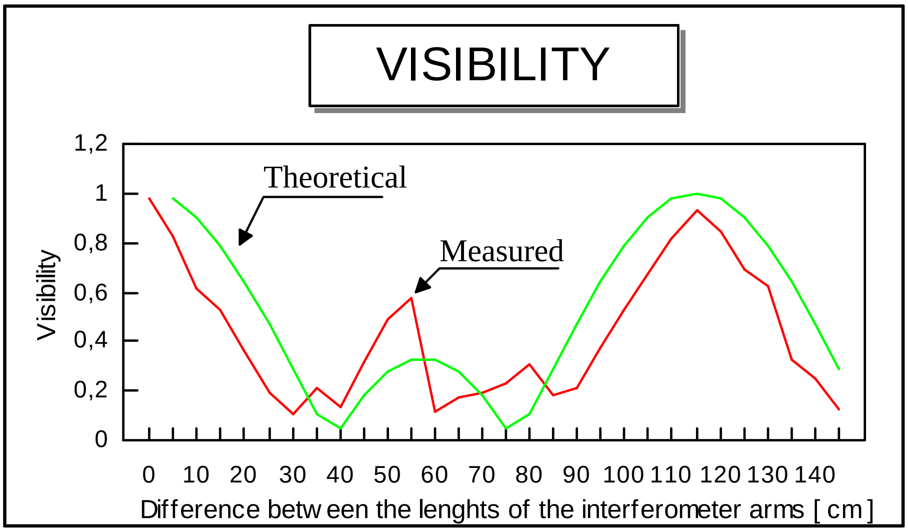


Figure 4-10 Visibility plot for theoretical and measured data.

[36] Picolog : Datalogging software, Pico Technology

From figure 4-10 can we see that the experimental data correspond quite well with the theoretical visibility of a 3-mode laser. This means that the 24 mW He-Ne laser used in this thesis has 3 modes. The practical definition of coherence length is the distance travelled by the laser beam where the visibility is reduced to $1/e^2$, measured with Michelson interferometer.

The plot of measured data shows the coherence length is around 30 cm.
The visibility maximum occur when the path difference is 0 and 115 cm. It means that ($2L$=115cm).

From the technical data for the laser, the longitudinal mode spacing is given as 257 MHz.

The formula for the distance between two longitudinal modes is given by

$$\Delta f = \frac{c}{2L} \quad , \qquad \text{and } 2L = \frac{c}{\Delta f} = \frac{3 \cdot 10^8 \text{ ms}}{257 \text{ MHz}} = 117 \text{ cm} . \qquad (4.7)$$

The measured value for the distance between two longitudinal modes fits the value for the fabrication data of the laser.

The coherence length for a 3-mode laser is given by

$$L_k \cong 0.596 \cdot L \qquad (4.8)$$

From the measured data of visibility plot we know that $2L$ = 115 cm.

$$L_k \cong \frac{0.596 \cdot 115\text{cm}}{2} = 34 \text{ cm.}$$

Thus the He-Ne laser has a coherence length of 34 cm.

In holography this is an important value because the visibility plot gives us an idea of the contrast of the hologram. From the visibility plot of the laser, we can see that the contrast will fall to 0.6 if the different between the object and reference beam is 10 cm. The best result is obtained when the difference between the beams is 0 or 115 cm, when the visibility (contrast) is maximum.

Chapter 5 : Recording materials

5.1 Silver-halide materials [44]

Silver-halide recording materials for holography are interesting for many reasons. Silver halide was the first material used for recording holograms. It is also the most important material for holography in respect of its numerous scientific and artistic applications. In addition, it has high sensitivity in comparison with many other alternative materials. It can be coated on both film and glass, it can cover even very large formats, it can record both amplitude and phase holograms, it has high resolving power, and is easily available. But it has some drawbacks. It is absorptive, it has inherent noise and a limited linear response, it is irreversible, it needs wet processing, it creates printout problems in phase holograms, etc.
In our holographic multi-stereogram development we use silver-halide materials even if in the future photopolymer materials could be the most common.

5.1.1 Holographic film [6] [47]

Photographic materials for holography must meet specific requirements. This is essential with very high resolving power, since the dimensions of the structure of the interference pattern to be recorded are usually of the order of magnitude of the wavelength of the light used for exposure. A high speed is also desirable to allow short exposure time.
High resolving power and high speed are often incompatible properties, which makes it necessary to arrive at a compromise of the highest possible efficiency. The nature of the subject will determine whether the ideal solution of this problem will be slanted towards high speed or high resolving power.

High speed film means that the film is very sensitive to light, and we can take a picture with low intensity of light. This means physically that the size of grain of emulsion must be big and that the resolution will be low. The resolution is expressed in lines pr. millimetre.

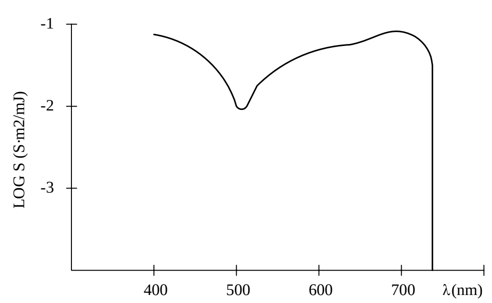
There are a number of different types of filmplates and filmplates from different companies. The filmplates that are chosen in this thesis is AGFA-GEVAERT Holotest, and have the number 10 E 75 and 8 E 75 HD.
These types of filmplate are made to be used with a red light emitting laser.

[44] H.I.Bjelkhagen : Silver-halide recording materials, Springer verlag, 1993
[6] I. Singstad : Classical holographic technique, pp 22-25, UiB, 1993
[47] AGFA-GEVAERT Technical information, Diagnoostic imaging systems, NDT / Holography

Film type	Size of grain	Resolution	Emulsion thickness	Sensitivity at 633 nm
	nm	l/mm	µm	µJ/cm^2
10 E 75	90	3000	7	1
8 E 75 HD	35	5000	7	10

Figure 5-1 Film data from Holotest photographic materials

The emulsion thickness for these films is about 11 times the wavelength of the Helium-Neon laser (632,8nm). This type of hologram is a ″thick″ or volume hologram . What characterises a volume hologram is the depth of the image produced on the film plate. ″Thin″ holograms with emulsion thickness less than the wavelength of the laser have little or no depth.



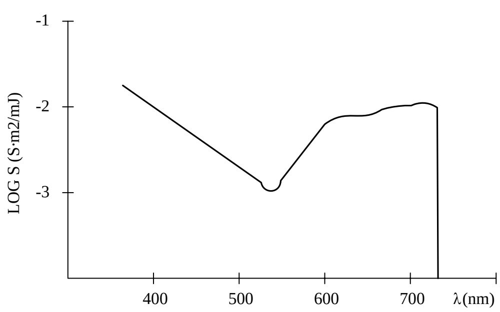


Figure 5-2 Spectral sensitivity for 10 E 75

Figure 5-3 Spectral sensitivity for 8 E 75 HD

The holographic emulsion 8 E 75 HD and 10 E 75 are specially sensitised for wavelengths between 600 and 750 nm, and are intended for use with the He-Ne laser (633nm) and the ruby laser (694nm). The sensitivity for light of wavelengths around 500 nm (green light) is relatively bad. Thus we may use green light with low intensity during the hologram developing process.

Amplitude transmission is defined as the ratio between the amplitudes of a monochromatic plane wave before and after passing through the photographic emulsion.
This quantity T, is expressed as a function of the exposure shown in figure 5-4.
The light intensity is chosen so that the mean value of the transmission is in the linear region.
The optical density D is 0.6.

The blackening of photographic emulsion can be expressed with help of the optical density, D.
The speed or sensitivity of the film is given by DIN or ASA. Both of these are based on the linear part of the curve.

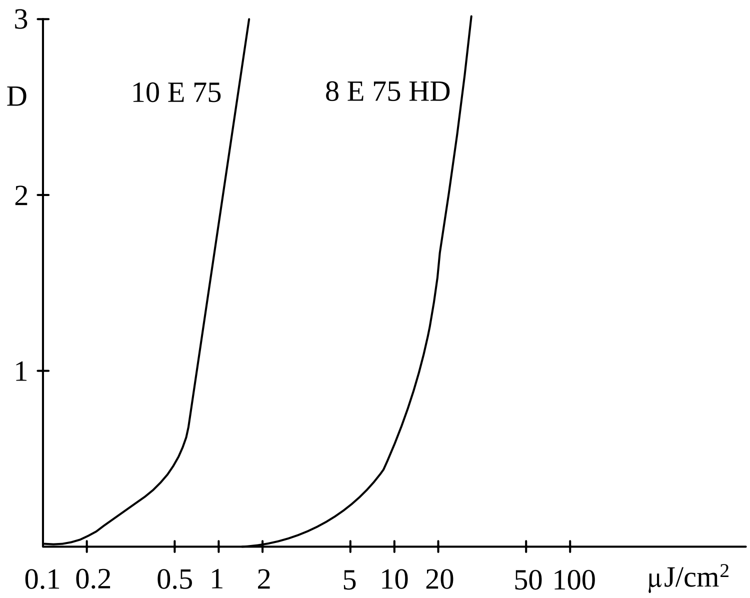


Figure 5-4 The characteristic curves for AGFA Holotest materials.

The relation between transmission T and optical density D is given by the equation

$$T = e^{-1.15 \bullet D} \qquad (5.1)$$

From the amplitude transmission curve we choose T from the linear part of the curve and get T= 0.5

With some manipulation we have

$$D = \ln T /(-1.15) = 0.6$$

From the characteristic curve, shown in figure 5-4, we can see that D = 0.6 is in the non-linear part of the curve. The exposure of the filmplate will then be bad and the brightness of the image will not be very good.
What we want is a brighter image, and so we need a more exposed image. The result of a more exposed image is a over-exposed film plate. To remove the over-exposed material from the filmplate, we have to use a bleacher. The bleaching process transforms the hologram from an amplitude to a phase hologram. The phase hologram gives the best experimental results with D = 2.

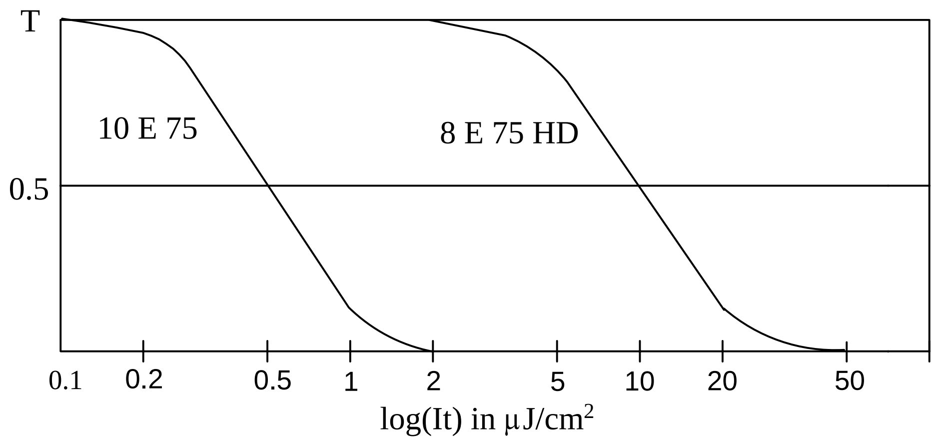


Figure 5-5 Amplitude transmission T versus log exposure curves for AGFA Holotest materials

(It) is the light intensity multiplied against the exposure time.

From figure 5-5 we get the approximate values of light intensities for T = 0.5 $\mu J/cm^2$ for a 10 E 75 filmplate, and for 10 $\mu J/cm^2$ for a 8 E 75 HD filmplate.

We can see from these results that the 8 E 75 HD need 20 times as much energy during the exposure as the 10 E 75 filmplate. That means that the exposure time for a 8 E 75 HD has to be 20 times longer.

5.1.2 The design angle for a holographic set-up[49]

A characteristic parameter of any holographic system is the design angle, i.e. the average angle at which the reference beam crosses the object beam at the filmplate. For an extended object close to the plate, there will be a range of such angles, and it is then safe to take the largest angle as the design angle. There are also other important parameters like the resolving power, the grain size of the optimum recording plate and the effective speed of the optimum recording plate.
The relationship between these parameters is relatively simple. If the reference and object beams cross the plate at angles v_1 and v_2, we expect them to generate fringes of width *d* where

$$d = \frac{\lambda}{\sin v_1 + \sin v_2} \qquad (5\text{-}2)$$

Thus the resolution of the system is of order *d*.

[49] G.L.Rogers : The design of experiments for recording and reconstructing three-dimentional objects in coherent light (Holography), J.Sci.Instrum., Vol 43, 1966

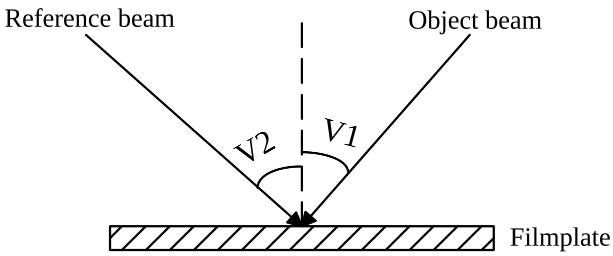


Figure 5-6 Line density for the film

After *d* is decided, one requires a photographic plate capable of recording fringes of this width, even though they may not have a very high contrast. Uncertainty in the contrast is a factor which must be allowed for, and these criteria then allow one to choose a suitable filmplate without an actual test. But it is possible to indicate a range of useful emulsions. Once the emulsion is chosen, its speed is fixed.
It is common to characterise emulsions by a factor *p* which is the number of lines pr. millimetre that the plate will record.
The exposed time goes up as p^2 for moderate *p*, in accordance with the theory, since the number of resolvable points per unit area in two dimensions also goes up as p^2.
In the case of very fine grain plates the penalty in practice may be even higher than indicated in the theory the exposure time can goes up as p^4. There is also a heavy penalty in the form of stricter vibration stability requirements.

5.1.3 Film emulsion for transmission and rainbow holograms

The distance between two interference lines is given by:

$$d = \frac{\lambda}{(\sin\nu_1 + \sin\nu_2)} \qquad (5.2a)$$

With the use of the trigonometric identity : $\sin A + \sin B = 2\sin\frac{A+B}{2}\cdot\cos\frac{A-B}{2}$

$$d = \frac{\lambda}{\left(2\sin\frac{\nu_1+\nu_2}{2}\cdot\cos\frac{\nu_1-\nu_2}{2}\right)} \qquad (5.2b) \quad \text{where } \nu_1+\nu_2=U \text{ and } \nu_1=\nu_2$$

If ν_1 and ν_2 is equal, the distance between two interference lines can be written as:

$$d = \frac{\lambda}{2\sin\left(\frac{U}{2}\right)} \qquad (5.2c)$$

Spatial frequencies are defined as : $f = \frac{1}{d}$, and for U= 90° we get

$$f = \frac{2\sin\left(\frac{U}{2}\right)}{\lambda} = \frac{2\sin\left(\frac{90}{2}\right)}{633.2\cdot 10^{-9}\,\mathrm{m}} = 2230 \text{ lines / mm} \quad (5\text{-}3)$$

The film chosen for the recording of transmission and rainbow hologram is AGFA-Gevaert holotest 10 E 75, which has a resolution of 3000 lines/mm, which is adequate for these holograms.

5.1.4 Film emulsion for reflection holograms

When recording reflection holograms, the reference and object beams illuminate the film on opposite sides. According to the theory for reflection holograms, the distance between the layers is 1/2·λ as shown in figure 5-7.

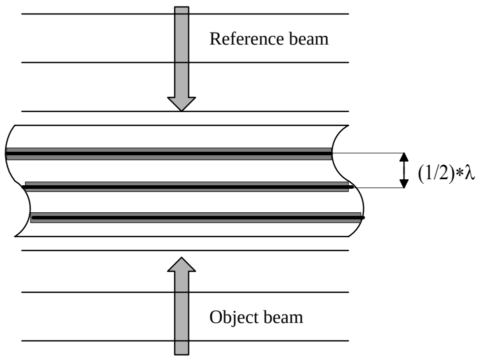


Figure 5-7 Interference lines in the film emulsion produced by plane waves.

The distance between the interference lines or planes is given by :

$$d = \frac{\lambda}{2\sin\left(\frac{\nu}{2}\right)} \quad \text{, where } (\nu = \pi) \quad (5.4) \quad \text{using eq. (5.3)}$$

and

$$d = \frac{\lambda}{2} \text{ ,} \quad \text{where the spatial frequencies is defined as : } f = \frac{1}{d}$$

$$f = \frac{2}{\lambda} = \frac{2}{633.2 * 10^{-9}\,\mathrm{m}} = 3158 \text{ lines / mm}$$

The film chosen for reflection holograms is AGFA-Gevaert Holotest 8 E 75 HD, which has a resolution of 5000 lines/mm.

5.2 Non silver-halide materials [38] [44]

5.2.1 Dichromated gelatine

Dichromated gelatine is currently in widespread use because of its excellent holographic properties, including low scattering and high index modulation. The drawbacks of dichromated gelatine include the raw material's variability, complex wet processing, poor shelf-life, and environmental instability requiring hermetic sealing. In common with other non-silver halide materials, dichromated gelatine is usually sensitive only to UV and blue light. Recent research has made it possible to sensitise it to red laser light, though exposures are still long. The dichromated gelatine material has a rather low sensitivity of about 100 mJ/cm^2 . Silver halide films are used when high exposure sensitivity and/or wide spectral sensitivity is needed, and when lower resolution and greater light scattering can be tolerated.

5.2.2 Du Pont photopolymer materials [20]

Photopolymer materials can be used for recording phase holograms, where applications in mass-production of display holograms and optical elements are of main interest. Normally, the material has a short shelf-life and a rather limited refractive index change. The exposure for transmission holograms is about 5 mJ/cm^2 and about 30 mJ/cm^2 for reflection holograms. Diffraction efficiency can be as high as 60 % for a transmission hologram and 85 % for a reflection hologram, and the signal-to-noise ratio is about 90:1 for exposures which give the highest diffraction efficiency.

5.2.3 Photoresist materials

Photoresists are well-known from the electronic industry, where they are used in the production of circuit boards. In holography, they are employed mainly for the production of master plates for embossed holograms and for manufacturing holographic gratings. The photoresist process can be used for making transmission holograms only. If an embossed hologram is mirror-backed by using e.g. an aluminium coating process, it can be utilised in the reflection reconstruction mode as well. A typical photoresist for holography has a sensitivity of about 10 mJ/cm^2. It is sensitive for UV and for visible light up to 500 nm.

[38] G. Saxby : Practical holography, pp 74-75, 1991
[44] H.I.Bjelkhagen : Silver-halide recording materials, pp 8-11, Springer verlag, 1993
[20] A.M.Weber, W.K.Smothers, T.J.Trout, D.J.Mickish : Hologram recording in Du Ponts new photopolymer materials, SPIE Vol.1212, 1990

Chapter 6 : Developing process

6.1 The developing process in holography[44]

Development is a processing technique by which the latent image recorded during the exposure of the material is converted into a silver image. In chemical development, this processing technique is called chemical reduction. From the chemical point of view, reduction is a process in which oxygen is removed from a chemical complex. The acting compound is called a reducer. Reduction is always accompanied by a reciprocal process called oxidation.

What happens during the development process is that metallic silver-halide crystals containing a latent-image speck (a few silver atoms) are converted into a silver grain by the reduction process triggered off by the reducing agent contained in the developer, and the reducing agent is then oxidised. The development in which the developing agent acts as a reducer is called chemical development. This is the most common way of developing photographic materials, which also applies to the majority of holographic silver-halide materials.

6.1.1 The silver-halide process

Silver chloride, bromide and iodide are collectively known as silver halides. These are used in various proportions in photographic emulsions. In the manufacture of a photographic emulsion the silver halide is formed as a dispersion of exceedingly small particles (microcrystals) in gelatine. When coated on a glass or film base and allowed to dry, this becomes a thin, tough, transparent layer which is very sensitive to short wavelengths of light. When light is allowed to fall on the emulsion its energy is absorbed by silver halide particles, causing local disruptions of some bonds that hold the crystalline structure together and release free silver atoms within the body of the crystal. Above a certain critical energy enough silver atoms are released to form a stable speck of metallic silver, or latent image. The developer is used to turn the latent image into a visible photographic image in metallic silver, a process called reduction. This solution containing a reducing agent is capable of reducing silver halide to silver, but only in the case of those crystals which bear a latent image.

[44] H.I.Bjelkhagen : Silver-halide recording materials, pp 128-151, Springer verlag, 1993

6.1.2 Holographic Developers

Silver-halide materials for holography are all of the fine grained type. Such materials require the application of special processing techniques to achieve the best possible results. Therefore, a great deal of research has gone into the problem of processing methods of holographic silver-halide emulsions.
Since a hologram is something very different from a conventional photographic picture, strict adherence to the processing recommendations just mentioned will not guarantee that a high-quality hologram will be obtained in each and every case.
Back in Lippmann’s times one was faced with a similar problem, namely, that the processing parameters had to be adjusted to suit the development of colour photographs on silver-halide material which is quite similar to the holographic material of today. And thus, the processing techniques used for the development of transmission hologram will differ from those used for reflection holograms. The same goes for the production of amplitude holograms as opposed to phase holograms.
Besides considering the type of hologram being produced, one must also consider other parameters, such as the grain size of the holographic material used. The processing technique will be different for the ultra-fine grained emulsions and for materials with a somewhat larger grain structure. Another example of the importance of matching the processing methods with the type of hologram to be obtained comes from display holography. Here, a phase hologram is desired in which bleaching is done after development. This calls for a developing technique that will match the subsequent bleaching.

6.1.3 Chemical Development

Chemical development is based on the reduction of silver-halide grains by a soluble developer substance. The deposition of silver atoms occurs in the next step. The following equations describe the process.

Oxidation: $Dev_{red} \rightarrow Dev_{ox} + e^-$

Reduction : $Ag^+ + e^- \rightarrow Ag$

The reaction will take place only if the equilibrium redox potential of the system developer / oxidised developer is more negative than that system Ag^+ / Ag.
The latent image consist of ″specks″ residing in silver-halide crystals or grains. The specks have a catalytic effect in that they trigger off the process of chemical reduction in which each speck acts as a microelectrode which brings the developer molecules into electrical contact with the silver ions. A large number of silver atoms is thus created in all the silver-halide crystals with latent image specks. There is a tremendous amplification in this process.

6.1.4 Agfa GP 62 developer

Agfa has formulated a developer based on the combination of metol and pyrogallol, which produces reflection holograms on their materials. The developer is the GP 62 and consists of

Solution A		Solution B	
Metol	15 gram	Sodium carbonate	60 gram
Pyrogallol	7 gram	Deionize water	1 litre
Sodium sulfite	20 gram		
Tetrasodium EDTA	2 gram		
Potassium bromide	4 gram		
Deionize water	1 litre		

Mix 1 part of solution A + 1 part of solution B + 2 parts of deionized water. Developing time is 2 minutes at 20°C.

6.2 Conventional Black and White developers

Today practically all standard Black-and-White photographic developers are of two main types. They are compounded of either metol and hydroquinone (MQ) or else of phenidone and hydroquinone (PQ). The reason for using a combination of two agents in a developer is the superadditivity effect that the two will have together. When combined, the two agents act in such a way that they will produce a higher density in the material than they would if they were used separately.
The induction period (the time necessary for the developer to induce the first signs of a visible image) is shorter for the PQ developer than for the MQ developer. PQ developers are also less sensitive to restrainer build-up because of halide release during development, which is why they give more uniform results when used repeatedly. One disadvantage of using phenidone is that it tends to produce fog, which is why a bromide restrainer is usually required in a phenidone developer.

6.2.1 Kodak D-19

Kodak D-19 Black-and-White developer is the most frequently used conventional developer for both transmission and reflection holograms. Kodak D-19 consists of

Metol	2 gram
Sodium sulfite (anhydrous)	90 gram
Hydroquinone	8 gram
Sodium carbonate (monohydrate)	52.5 gram
Potassium bromide	5 gram
Deionize water	1 litre

Developing time is 4 to 5 minutes at 20°C

The MQ developer is a high-contrast, low fog developer that will produce clean amplitude transmission holograms on the majority of the existing materials.

6.3 Photographic fixation [44]

When the development has been completed a conventional photographic material must be treated in an acid stop bath or it must be rinsed in water, after which it is treated in a fixation bath. The fixation solution will dissolve the unexposed silver-halide crystals leaving only the silver grains in the gelatine. In principle, the fixation step can be expressed by the formula

$$AgBr + 3\ Na_2S_2O_3 \rightarrow Ag(S_2O_3)_3^{-5} + 6\ Na^+ + Br^-$$

The silver thiosulfate ion in the formula is the most important one of the several possible silver thiosulfate complexes. It is easily soluble and will diffuse from the emulsion into the fixing bath. The remaining ions can be readily washed out from the emulsion in the subsequent wash. If the silver concentration in a fixing bath becomes excessive, less soluble complexes are formed which are difficult to wash out. If these remain in the emulsion they can cause yellow silver-sulphide stains. Therefore, the fixing bath should be replaced with a fresh one before the silver concentration becomes too high.
The fixer bath reduces the film emulsion's volume. For transmission holograms, this does not make any difference. For reflection holograms, where the interference fringes are nearly parallel to the emulsion, the reduction of the film emulsion is a problem. Therefore, we do not use fixer bath in the developing process of reflection holograms.

6.4 Bleaching of holographic film emulsions [5] [44]

The conversion of amplitude holograms recorded on silver-halide materials into phase-contrast holograms, commonly referred to simply as phase holograms, was first performed by Rogers and Denisyuk. In the 70's a lot of research efforts went into the discovery of bleaching processes capable of producing both a high diffraction efficiency and a low scattering noise. In the mid 70's the holographic bleaching technique was better understood and became capable of giving more satisfactory results.
Bleaching is a particularly important technique for holograms recorded on Western holographic materials since it constitutes the only way of producing holograms with high diffraction efficiency on these materials.
When a holographic emulsion is developed, all crystals of silver halide which bear a latent image are converted into opaque grains of silver which replicate the pattern formed by the interference of the object and reference beam. If we can turn the silver into a transparent substance of high refractive index, no light will be absorbed. All the light will go to form the holographic image and we get a considerable improvement in diffraction efficiency.

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[44] H.I.Bjelkhagen : Silver-halide recording materials, pp 152-156, Springer verlag, 1993
[5] R.Lamberts : Characterization of a bleached photographic material, Applied optics, Vol.11, 1972
[44] H.I.Bjelkhagen : Silver halide recording materials, pp 167-208

6.4.1 General Bleaching theory

Bleaching is an important phase in the recording of holograms on silver-halide materials, ensuring a high diffraction efficiency, and so important for holographic images.
Bleaching can be regarded as the reversed process of development. During the developing process, a silver ion is reduced to free silver and the developed film appears rather dark, whereas during the bleaching process, metallic silver is oxidised to silver ion. It is interesting to consider the chemical equation for development being reversible. For example, the action of hydroquinone on silver bromide is

$$C_6H_4(OH)_2 + 2AgBr + 2OH \leftrightarrow C_6H_4O_2 + 2Ag + 2Br + 2HOH$$

The reversed action is the formation of hydroquinone and silver bromide caused by the oxidising agent quinone acting on metallic silver. In practice, the reversal (oxidation) can only take place in an acid environment. The development (reduction) only takes place in an alkaline solution.

There are various bleach solutions formulated on the basis of the different oxidisers.

In the mixing of the bleacher deionized water is used. This is very useful since ordinary drinking water contains salts and fluorine.

6.4.2 General considerations

Bleaching of the interference fringes recorded in the emulsion will change the emulsion in such way that the light used for reconstruction of the image will be modulated by retardation of the wave front instead of by attenuation as in the case of amplitude holograms. Theoretically, this can lead to a substantial increase of the diffraction efficiency (100 %) of a hologram. Retardation of the wavefront is caused by variations of the refractive index within the emulsion (inner image) or by local variations of the emulsion thickness (relief image). At high spatial frequencies, the inner image predominates, whereas at low spatial frequencies the relief image is more distinct.
Most often the theories of bleached, silver-halide holograms assume that the hologram is a pure phase hologram of the index or the relief type, or else a combination of the two (phase-only hologram). As a matter of fact, a bleached gelatine emulsion is actually a combination of both an amplitude and phase hologram.

6.4.3 Reversal bleaches for reflection holograms

In reversal bleaching, the developed silver image is converted into a soluble silver complex which is removed from the emulsion during bleaching, leaving the original, unexposed silver halide grains in the emulsion. These crystals modulate the light to reconstruct the holographic image. In reversal bleaching, the hologram is not fixed after the development, as otherwise all the silver halide grains would disappear after bleaching.

Jeff Blyth bleacher consists of

Potassium dichromate ($K_2Cr_2O_7$)	5 gram
Sodium hydrogen sulphate crystals ($NaHSO_4 . H_2O$)	80 gram
Deionized water	1 litre

This bleach removes the silver and leaves the unexposed silver bromide, and is very useful for developed reflection holograms.
The bleaching time is about 90 seconds.

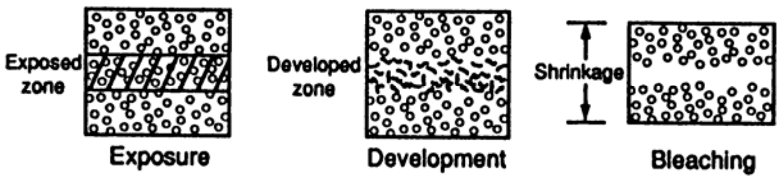

Figure 6-1 Reversal bleaching

6.4.4 Rehalogenating bleaches for transmission and rainbow holograms

In conventional bleaching, the developed hologram containing the silver image is converted into a phase hologram by changing the silver image into a transparent silver halide. This is performed after fixation, after the unexposed silver halide crystals have been removed. We say that the developed silver grains have been rehalogenated.

Ferric Nitrate consist of

Ferric Nitrate	100 gram
Kbr	30 gram
Phenosafranine	0.3 gram
Water	1 litre

The bleaching time is about 5 minutes.

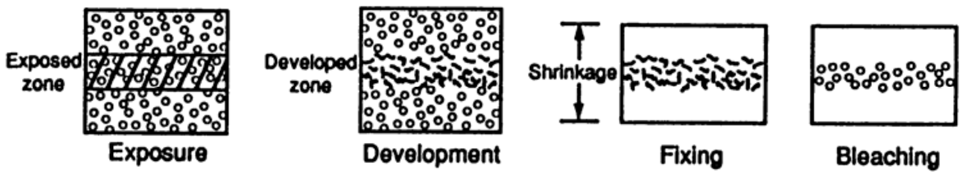

Figure 6-2 Conventional (Rehalogenating) bleaching

6.5 The experimental developer process

6.5.1 Reflection holograms

In the developing process for reflection holograms, a developer from AGFA is used. This developer is based on the combination of metol and pyrogallol, which produces reflection holograms on their materials. This developer is the **GP 62**. The composition is shown in section 6.1.4

Jeff Blyths bleacher is used in the bleaching process of reflection hologram. The composition is shown in section 6.4.3.

The developing process:

1. Put the film in the developer GP 62 bath. The developing time is 2 minutes at 20°C.
2. Wash the film in flowing water for 5 minutes, at temperature 20 °C.
3. Put the film in Jeff Blyths bleaching bath. The bleaching time is 1.5 minutes.
4. Wash the film in flowing water for 5 minutes, at temperature 20 °C.
5. Wash the film in technical spirit for 1.5 minutes.
6. Wash the film in isopropanol for 1.5.
7. Let the film stand still when the plate is drying.

6.5.2 Transmission and rainbow holograms

In the developer process for transmission holograms, a developer from Kodak was used. This developer is a Black-and-White developer called **D-19** . The composition is shown in section 6.2.1.

The fixer bath used in the process is AGEFIX, from AGFA.

Ferric nitrate was also used in the bleaching process of transmission hologram. The composition is shown in section 6.4.4.

The developing process:

1. Put the film in developer **D-19** bath. The developing time is 5 minutes at 20 °C.
2. Wash the film in flowing water for 30 seconds.
3. Put the film in fixing bath. The fixing time is 2 to 3 minutes.
4. Wash the film in flowing water for 30 seconds.
5. Put the film in bleacher for 5 minutes.
6. Wash the film in AGEPON bath for 30 seconds to 1 minute.
7. Wash the film in flowing water until the colour from the bleacher is rinsed away.
8. Wash the film in technical spirit for 1.5 minutes.
9. Wash the film in isopropanol for 1.5 minutes.
10. Let the film stand still when it is drying.

Chapter 7 : Preliminary holography experiments

7.1 Experiment 1: Recording reflection hologram from an object

The optical set-up for this experiment is made very simple as the purpose is to evaluate the optical equipment, recording procedure and the developing process. In the production of holograms by using this set-up, it is possible to control the stability of the optical table and the optical components. Is these good enough ? Optical equipment like lenses, mirrors, filters, etc. has also strict quality requirements which have to be taken into consideration.
In the holographic developing process there are several different chemicals and developers to choose from. In this experiment the whole holographic production process is tried out, and a basic procedure to use in the further work is established. The system is built up step by step from a simple holographic arrangement to an advanced holographic multi-stereogram arrangement.

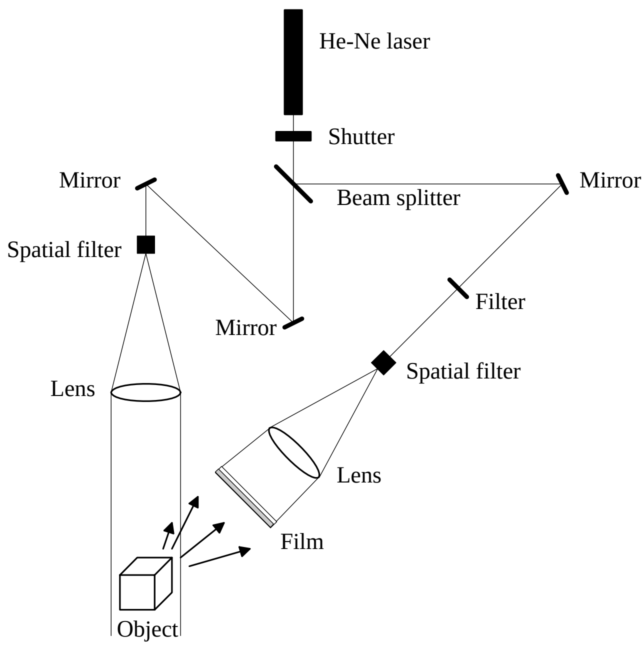

Figure 7-1 Recording reflection hologram.

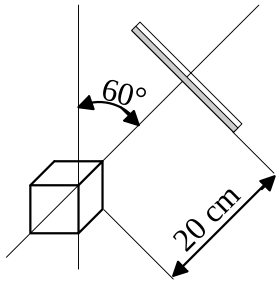

Figure 7-2 The position of the object relative to the film plate

The experimental set-up shown in figure 7-1 was made on the optical table.

Optical equipment used for the recordings :

He-Ne laser : Output power 12 mW. Wavelength 632.8 nm.
Spatial filters : Pinhole size 25 μm. Microscope objectives 45x 0.65
Lenses : Diameter 100 mm. Focal length 175 mm.
Mirror : Flatness λ/10.
Filmplate : Type 8 E 75 HD. Resolution 5000 l / mm.
Filter : Transmission 20 %.

Laserbeam distance: Object beam = 118 cm
Reference beam = 121 cm

Image 1:

Light power on the film : Object beam = 2.4 μW
Reference beam = 4.6 μW

Light power ratio = 4.6 μW / 2.4 μW = 2:1

Exposure time : 40 seconds.

Result : It was possible to see the object in the hologram, but the hologram was not bright. There were also observed ″dark shadows ″or areas without any information. The hologram also had some reflections on the image.

Comment : The poor brightness of the hologram is probably caused by too short exposure. Also, the reflections on the hologram reduce the hologram's quality.

Image 2 :

Light power on the film : Object beam = 2.4 μW
Reference beam = 4.6 μW

Light power ratio = 4.6 μW / 2.4 μW ≈ 2:1

Exposure time : 50 seconds.

Result : This image was better than image 1. There were no dark shadows, and the hologram has information all over the exposed area. The brightness of the hologram could be still better.

Comments : The exposure time is still too short.

Image 3 :

Light power on the film : Object beam = 2.4 μW
Reference beam = 4.6 μW

Light power ratio = 4.6 μW / 2.4 μW = 2:1

Exposure time : 60 seconds.

Result : This was the best image of the 3 holograms. But the image could still be brighter.

Comments : The problem with the brightness of the holograms is caused by the exposure time. It is very difficult to hold the optical equipment steady for more than 1 minute, without any vibrations.

Image 4 :

The purpose of the exposure is to get rid of the problem of reflections on the hologram. One of the problems with the holograms taken in the earlier stages in this experiment, was reflections from the lens. During the studying of the hologram it appears to be the lens in front of the filmplate which causes the problem. To solve this, the direction of the filmplate was changed.
The optical set-up for the exposure of this image is nearly the same as the set-up used earlier in this experiment. The alternation is shown in figure 7-3.

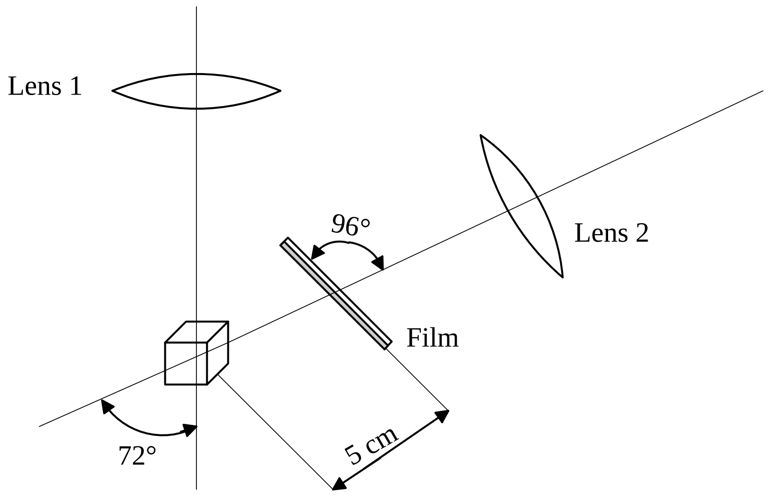

Figure 7-3 Location of optical equipment.

The object was changed to another one with lower depolarisation degree. This was done to get more light reflection power from the object in the same polarisation direction as the reference beam. The filmplate is placed closer to the object to get even more power from the object beam.

Light power on the film : Object beam = 2.3 μW
Reference beam = 4.0 μW

Light power ratio = 4.0 μW / 2.3 μW = 1.7:1

Exposure time : 65 seconds.

Result : This image was better than the holograms exposed on the last set-up. There were no reflections from lens 2, because the filmplate and the lens was not parallel.

Comments : To get a brighter hologram, a more stabile optical set-up is needed. It is completely impossible to get bright holograms without a multi stabile set-up when the exposure time is more than 1 minute. It is also very important that lens 2 and the filmplate are not parallel, because that gives rise to unwanted reflections.

Image 5 :

The purpose of this recording is to make a hologram with optimal brightness and without any visible destructive noise. All the optical components are placed as near as possible to the optical table to reduce the possibility of any vibrations.

The alternation in the optical set-up is shown in figure 7-4.

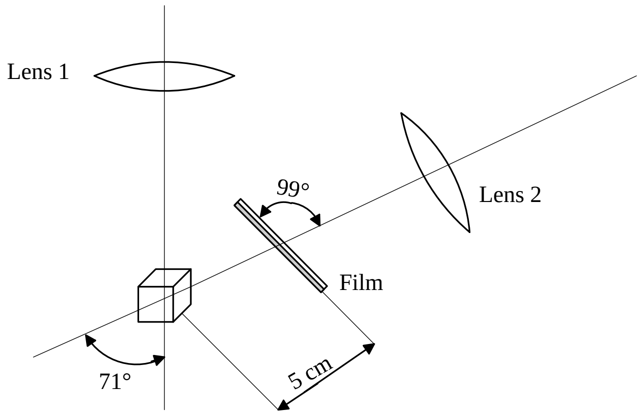

Figure 7-4 Location of optical set-up

The optical equipment used for this exposure is the same as in the earlier experiment.

Light power on the film : Object beam = 1.0 μW
Reference beam = 1.6 μW

Light power ratio = 1.6 μW / 1.0 μW = 1.6:1

Exposure time : 80 seconds.

Result : The hologram is very clear and bright.

Comments: This reflection hologram was very good. This is the desired quality of holograms in the final product. The optical table and the optical equipment are good enough to produce first class holograms.

7.2 Experiment 2 : Recording reflection holograms from a picture on a transparency film

The aim of this experiment is to make high quality reflection holograms from a picture. The image is a 2D black and white picture on a transparency film, and fastened to the ground glass. The transparency film picture is a substitute for a LCD (liquid crystal display). The light from the object beam will illuminate the picture and refract in the ground glass. The information from the picture will be spread in ″all″ directions. This object beam with the information of the object will then illuminate the film. The reference beam without any information will illuminate the film on the opposite side. When these two beams meet each other on the filmplate, they will interfere. A reflection hologram will then be formed.

<u>Optical equipment used for the recordings :</u>

He-Ne laser : Output power 12 mW. Wavelength 632.8 nm.
Spatial filters : Pinhole size 25 μm. Microscope objectives 45 x 0.65
Lenses : Diameter 100 mm. Focal length 175 mm.
Mirror : Flatness λ/10.
Filmplate : Type 8 E 75 HD. Resolution 5000 l / mm.

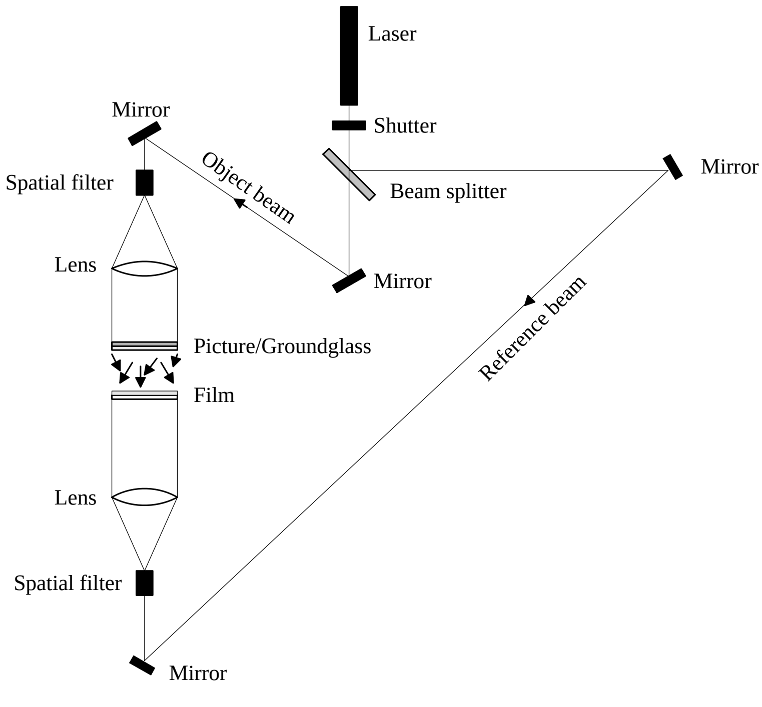

Figure 7-5 Optical set-up for the recording of image 1

The result of this experiment will of course not be a 3 dimensional holographic image, since the picture, shown on figure 7-6, on the transparency film is only in 2 dimensions.

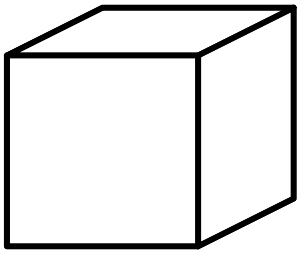

Figure 7-6 Picture of the cube used in the experiment.

Image 1 :

The laser beam distance : Object beam = 167 cm.
Reference beam = 166 cm.

Laser power at the film : Object beam = 3.5 μW.
Reference beam = 6.2 μW.

Light power ratio = 6.2 μW / 3.5 μW = 1.8 :1

Exposure time = 40 seconds.

Result : The hologram was very bad. There was a dark circular area without any information in the centre of the filmplate, shown in figure 7-7.

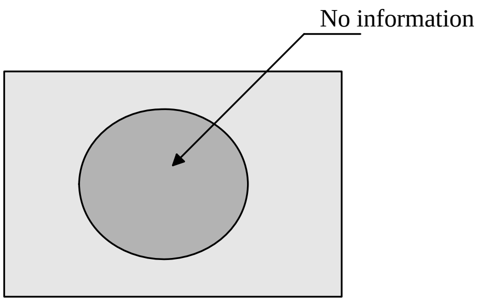

Figure 7-7 Reconstruction of the hologram.

Comments : The dark area on the hologram is caused by reflections from the lens (placed on the reference beam) that are parallel to the filmplate. It is very important that the lenses are not parallel to the filmplate.

Image 2 :

This set-up is a further extension of the recording of image 1. The main difference between these two exposures is that the lens (on the reference beam) is not parallel to the filmplate.

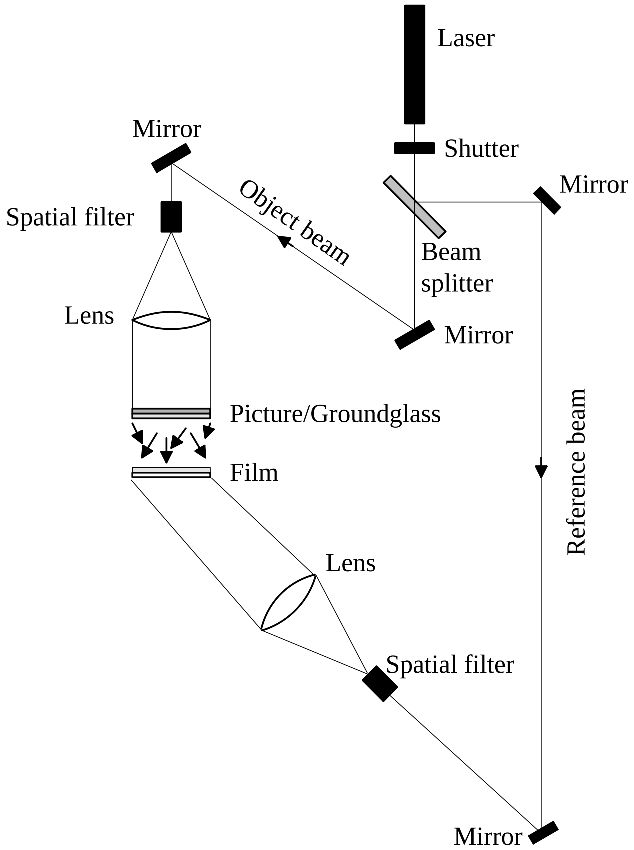

Figure 7-8 Set-up for the recording of image 2.

The laser beam distance : Object beam = 148 cm.
Reference beam = 147 cm.

Laser power at the film : Object beam = 3.5 µW.
Reference beam = 7.5 µW.

Light power ratio = 7.5 µW / 3.5 µW ≈ 2.1 :1

Exposure time = 40 seconds.

Result : The quality of the hologram was not satisfactory. It was possible to see the image on the hologram, but the contrast was bad.

Comments : The bad quality of the hologram is probably caused by reflections from the optical equipment.

<u>Image 3 :</u>

The angle between the reference beam and the filmplate is changed from 53 ° (for image 1) to 55°. This is done to prevent the reference beam from striking the ground glass, and causing reflections which disturb the recording process.

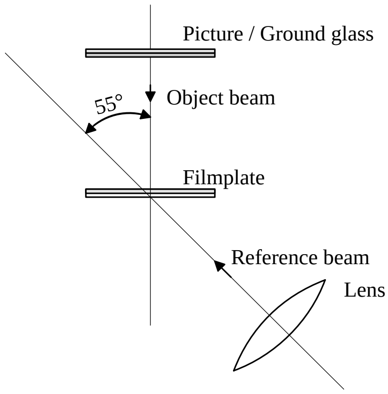

Figure 7-9 Location of optical set-up for image 3.

Light power at the film : Object beam = 3.5 μW
Reference Beam = 7.5 μW

Light power ratio = 7.5 μW / 3.5 μW = 2.1 :1

Exposure time = 60 seconds.

Result : The hologram's image was without any reflections, and the brightness was good.

Comments : It was very important to get good results with this experiment, as this method is the basic principle for further experiments. It is also satisfactory that the optical equipment is stable for an exposure of 60 seconds.

Image 4 :

The idea behind this exposure is to see the purpose of the ground glass. We know that the ground glass spreads the information from the picture (in this case a transparent 2-D draw) in ″all″ directions. This must be done to get the same diffusion which we get when light is reflected from an object.

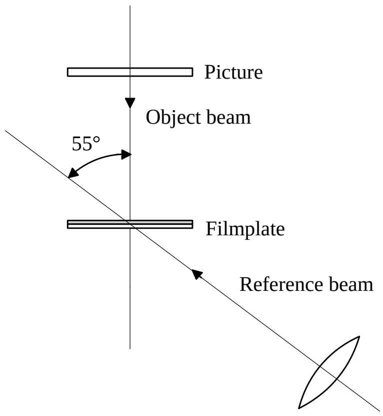

Figure 7-10 Location of optical set-up for exposure 4.

Figure 7-10 shows the changes in the optical set-up used in the recording of image 3. The difference between this and the earlier set-ups is the ground glass. The ground glass is not used in this experiment.

Laser beam distance : Object beam = 148 cm
Reference beam = 147 cm

Laser power on the film : Object beam = 3.5 μW.
Reference beam = 6.0 μW.

Light power ratio = 6.0 μW / 3.5 μW = 1.7 :1

Exposure time = 50 seconds.

Result : The hologram is unusable because the picture is exposed directly on the filmplate like in a photograph.

Comments : To get the picture exposed on the filmplate as a hologram, we have to use ground glass in this type of set-up. This is because each point of the film contains information from the whole picture.

7.3 Experiment 3 : Quality reduction of the hologram caused by depolarising effect from the ground glass

In this experiment the aim is to examine what depolarisation effects have do with the quality of a hologram. The laser is installed so as to ensure that the light beam is plane polarised[27] in the vertical direction. The ground glass spreads the light from the image, and 20 % of the light information of the picture which illuminates the film is depolarised. The depolarisation of the ground glass is found by measure the light power that pass through the ground glass in vertical and horizontal direction.

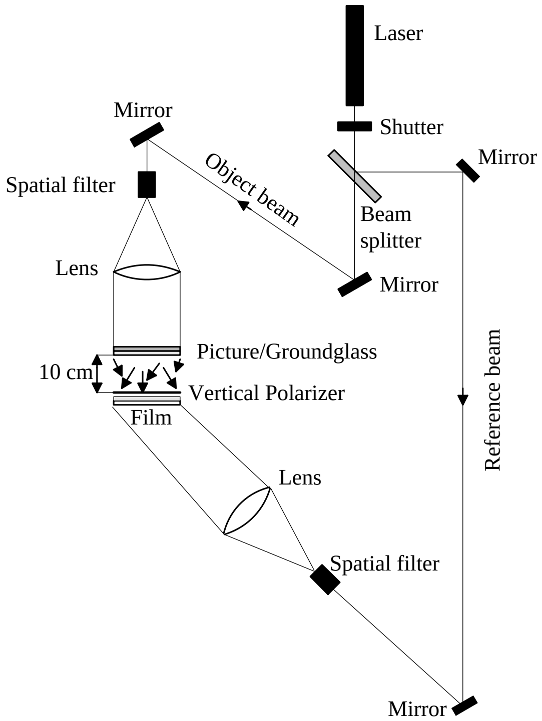

Figure 7-11 Set-up for experiment 3.

A polarizer is placed close to the filmplate, so that the light from the object beam is polarised in the vertical direction when it illuminates the film. The polarizer does not cover the whole filmplate, because one should be able to see the difference between the area with polarizer and the area without.

[27] O.S.Heavens, R.W.Dichburn : Insight into optics, pp 82-83, 1991

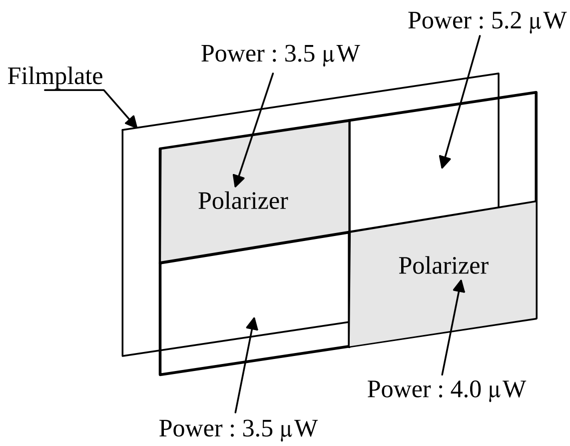

Figure 7-12 The vertical polarizer

Figure 7-12 shows the location and the shaping of the polarizing filter. The film is divided into 4 parts where 2 are with polarizing filter and 2 without. The area behind the polarizing filter is totally polarized in the vertical direction. The light is 80 present polarized in the vertical direction where no polarizing filter is used.
The picture which is fastened to the ground glass is shown in figure 7-6.

<u>Optical equipment used for the recordings :</u>

He-Ne laser : Output power 12 mW. Wavelength 632.8 nm.
Spatial filters : Pinhole size 25 µm. Microscope objectives 45 x 0.65
Lenses : Diameter 100 mm. Focal length 175 mm.
Mirror : Flatness λ / 10.
Filmplate : Type 8 E 75 HD. Resolution 5000 l / mm.

Laser beam distance : Object beam = 148 cm
Reference beam = 147 cm

<u>Image 1 :</u>

Light power on the film : Object beam = 3,5 µW to 5.0 µW
Reference beam = 7.0 µW

Light power ratio = 1.4 : 1 to 2:1

Exposure time 80 seconds.

Result : The quality of the hologram was very good. The image was bright all over the area without any visible loss of information.

Comments : The depolarizing effect of the object beam does not lead to any quality reduction of the hologram. The depolarized light from the object which illuminates the filmplate will not interfere with the reference beam, when this is totally polarized in this vertical direction. Of course, the depolarized light will also blacken the film, but this is not a problem since the film goes through a bleaching process after it has been developed. When we are looking at the hologram can we see the image with and without polarizer, because the polarizer is also recorded in the hologram. The area of the hologram where the polarizer is cover the holographic image has the same quality as the area without polarizer.

Image 2 :

This optical set-up is the same as used for the exposure of image 1, but this hologram is made without using the polarizing filter.

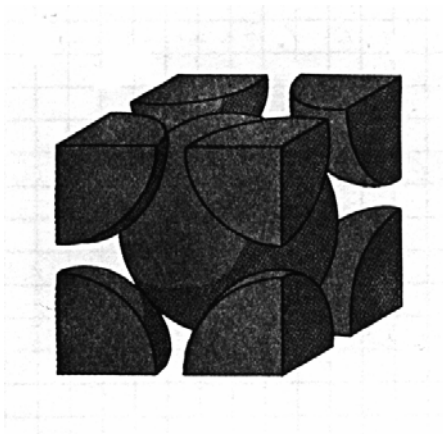

Figure 7-13 Picture of a BCC crystal structure.

The picture in figure 7-13 is copied onto a transparency film and replaced with the image used in the earlier experiments. The picture of the BCC crystal absorbs much more light than the picture which had been used earlier.

Light power on the film : Object beam = 3.7 μW
Reference beam = 6.9 μW

Light power ratio = 6.9μW / 3.7 μW ≈ 1.9 :1

Exposure time = 112 seconds.

Result : The quality of the hologram was very good. The brightness of the image was very satisfactory.

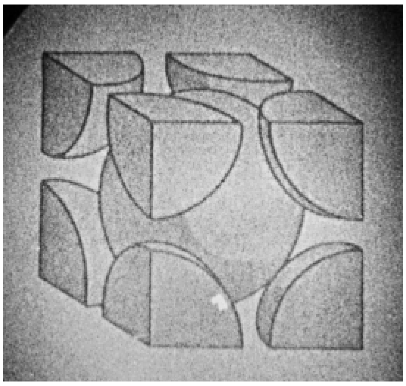

Figure 7-14 Picture of the hologram.

Comments : It appears that the optical equipment and the practical holographic recording procedure works well for this type of experiment.

Chapter 8 : LCD and computer images

8.1 The LCD principle [13] [18]

The LCD (liquid crystal display) used to project the computer picture, in the holographic recording process is of the type IMPACT 256. The display is a full colour super twisted nematic (CSTN)[30] LCD with 256 000 colours. The resolution is 640 x 480 x 3, with the use of the RGB (red, green and blue) technique. By mixing these three primary colours, the desired colour can be created.
Liquid crystal displays (LCD's) use nematic liquid crystals. The molecular order in a nematic liquid crystal, which results from weak intermolecular forces, is easily disrupted. For this reason, the liquid crystals flow like a ordinary liquid. Because of the weakness of the intermolecular forces, the molecules in a nematic phase are easily realigned along new directions.
A liquid crystal display uses this ease of molecular reorientation to change areas of the display from light to dark or coloured, resulting in the patterns that you see in the display. The display consists of liquid crystals contained between glass plates whose interior surfaces are treated to align the molecules in a given direction. The space between the glass plates also contains polarizer sheets and transparent electrodes to reorient the molecules shown in figure 8-1. When the voltage to a set of electrodes in some area of the display is turned on, the molecules of the liquid crystal in that area reorient along a new direction. When this voltage is turned off, the molecules return to their original orientation.

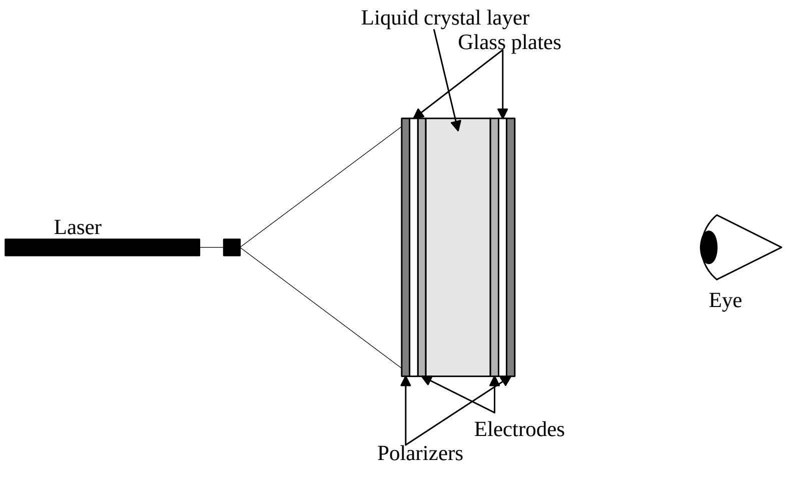

Figure 8-1 The liquid crystal display

The purpose of the polarizer sheets is to make the change of molecular orientation visible by using the ability of the liquid crystal layer to change the plane of polarized light. Light

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[13] L.Tannas, W.Glenn, T.Credelle, J.Doane, A.Firester, M.Thompson : Display technology in Japan, 1992
[18] D.D.Ebbing, M.S.Wrighton : General Chemistry, pp 453-455, Hougton Mifflin company, 1991
[30] R.Ondris-Crawford, G.P.Crawford, J.W.Doane : Liquid crystals : The phase and the future, 1994

from the outside the display passes through the first polarizer, resulting in polarized light, which then passes through the liquid crystal layer. When the voltage to a set of electrodes in an area of the display is off, the liquid crystal layer in that area rotates the plane of the polarized light so that it can pass through the second polarizer. The display area appears bright. When the voltage is turned on, however, the plane of the polarized light is not rotated. In this case, the light can not pass through the second polarizer, and the area appears dark or coloured. The pattern on the display is created by turning sets of electrodes on and off shown in figure 8-2.

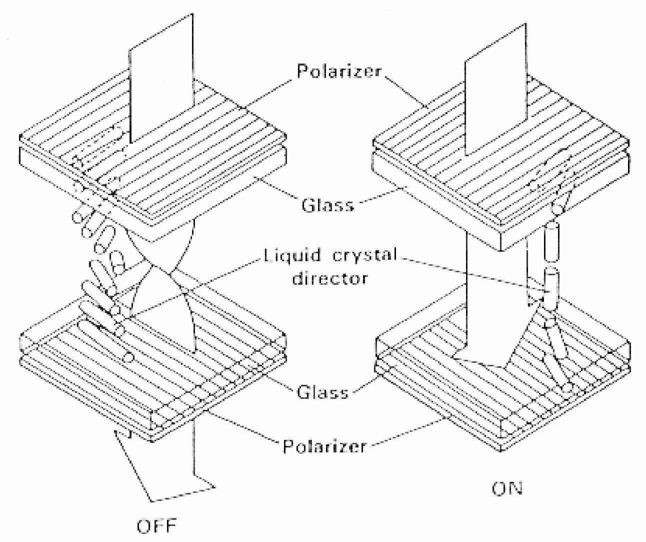

Figure 8-2 Typical twisted nematic LCD

The transmission of the LCD as a function of applied voltage is shown in figure 8-3. There is a threshold behaviour for most LCD's and no change in transmission occurs until a threshold voltage, Vth, is reached. Transmission then decreases as the voltage increases until saturation is reached. Threshold voltage is typical 1.5-2.5 volts, and saturation occurs at about 4-5 volts.

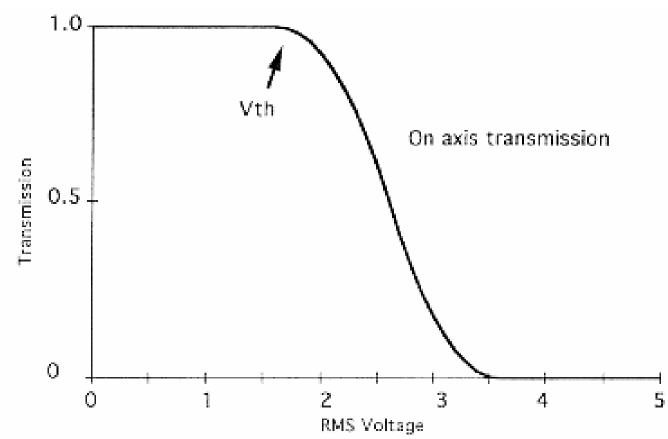

Figure 7-3 LCD transmission (brightness) as a function of applied voltage

The light transmission for IMPACT 256 LCD is measured to 2 %. The measurement is carried out with the help of a computer, laser, laser power meter and the LCD shown in figure 8-4. The measurement is made with and without the LCD. The LCD is connected in parallel with the computer screen, and one of the images used in the recording of holographic multi-stereogram is shown on the LCD.

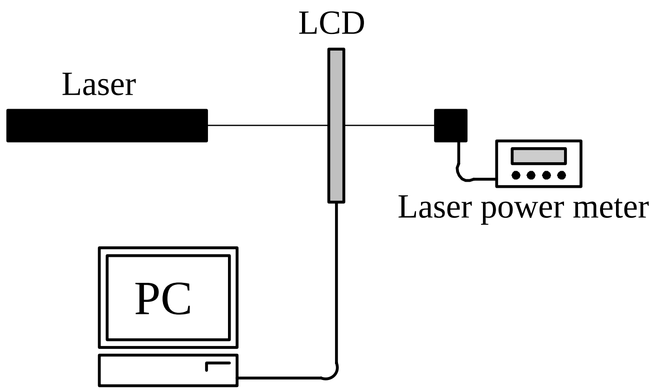

Figure 8-4 Set-up for measurement of light transmission for IMPACT 256 LCD

Laser power without LCD : P = 24.21 mW.
Laser power with LCD : P_w = 0.51 mW.

$$\text{Transmission: } T = \frac{P_w \cdot 100\%}{P} = \frac{0.51\text{mW} \cdot 100\%}{24.21\text{mW}} \cong 2\ \%$$

8.2 Construction of computer images [19]

The computer images used in this thesis work is made with the AutoCAD software program. With the AutoCAD release 13 program, is it possible to make 3 dimensional drawings. When the design stage is finished, we make a camera path where we get the positions of the viewpoints. From this camera path can see the target path, and we are able to see the object in different perspectives.
The light spots in front of the object give the image of the object a natural look. This light spots can be moved or the intensity can be adjusted so that the object gets bright, and we get the desired effect for the picture.

[19] S.Takahashi, T.Honda, M.Yamaguchi, N.Ohyama, F.Iwata : Generation of intermediate parallax-images for holographic stereograms, SPIE Vol.1914, 1993

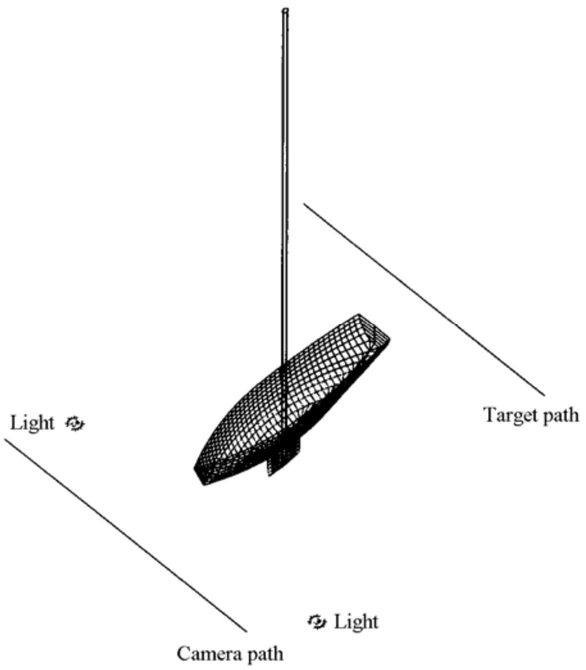

Figure 8-5 Construction of Images used in the holographic proceeding

From the camera path it is possible to see the object in 50 different perspectives. There is also possible to make 50 different images of the object and make one file for each image. If we need more than 50 different perspectives, we have to make more camera paths. Then we can make as many pictures as desired of the object.

This files constructed in the AutoCAD program can be saved as bitmap files. The files that constructed are given the names < *filenameXXX.bmp*> where *XXX* gives the serial number of the image. In this thesis there are files from < *name0000.bmp* > to <*name0069.bmp*>, a total 70 different files.

Bildene er lagt ut pga for stor fil

Figure 8-6 An example on a sailboat seen from 3 different positions.

Figure 8-6 shows 3 different pictures of a sailboat. In an holographic multi-stereogram recording procedure with 70 different pictures, the first picture in the figure above would have the name Sail0000.bmp, the picture in the middle would have the name Sail0035.bmp and the picture to right on the figure would have the name Sail0069.bmp.
This bitmap files from the AutoCad program can be used directly in the ARIP control software program.

Chapter 9 : Holographic printer

9.1 The holographic printer

To transform a 2D perspective image on the computer to a 3D holographic filmplate can be done by several methods. I chose a method with fixed laser beams and changed the position of the filmplate. It appeared that the process of converting a 2D picture to 3 dimensions could be carried out on the computer. What we do is to take the 2D perspective picture of the object, or a drawing of an object, and turn the picture around in the horizontal plane. We will then see the object from different positions.
To execute this process on the computer screen, one image after another is shown on the LCD and the object seems to be turned around on the screen. We can then see the object from the right side, front and finally from the left. To transform these computer pictures to a holographic filmplate and make it 3D is carried out with help of the printer that moves the filmplate to different positions.

For every picture that is shown on the LCD we wish to make a hologram. The printer's step motor will move the filmplate to the right position and hold it fixed when the image is exposed on an area of the filmplate. For each new picture on the LCD, we will see the object from a new position. This new picture will thus be exposed in a new area of the filmplate.

The purpose of the printer is to move the filmplate to the right position and hold it fixed during the exposure.

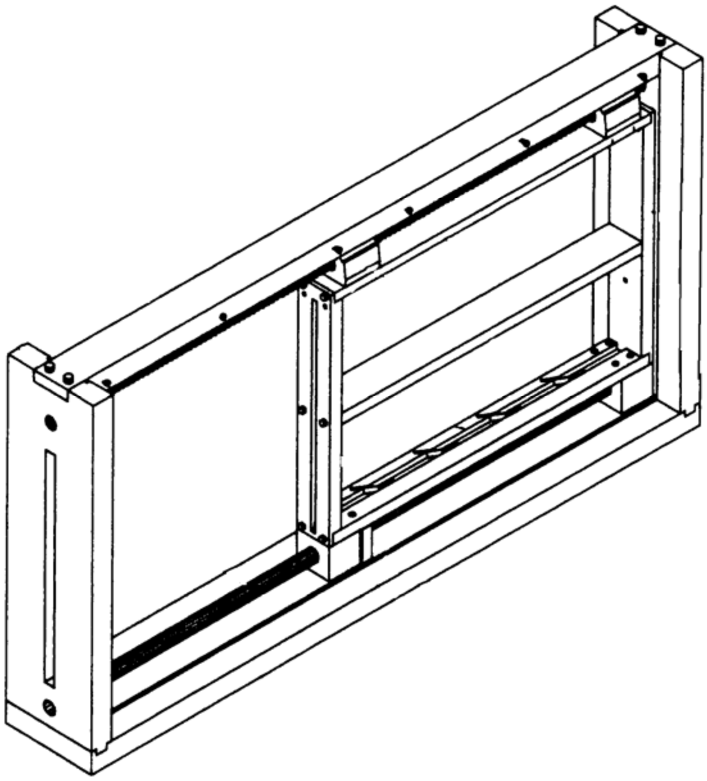

Figure 9-1 The holographic printer

As an improvement a new slit system was made on both sides of the printer. Micrometer screws make it possible to expose only a little part of the hologram. This slit is 90 mm high and the width can be regulated from 0 mm to 5 mm.
The slits are shaped in such a way that they do not cast any shadows on the photographic filmplate.

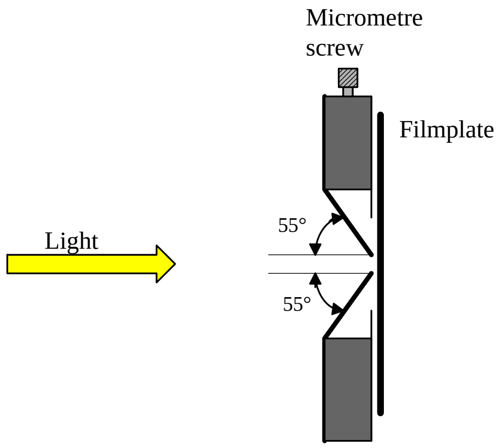

Figure 9-2 The printers slit arrangement (seen from the top)

During the recording of reflection holograms light from the reference and the object beam will illuminate the film from opposite sides. For this reason the printer has an adjustable slit on both sides.
Adjustments can be made with two micrometer screws which are placed on the printers slit. Normally the slits opening are from 1 mm to 2 mm.

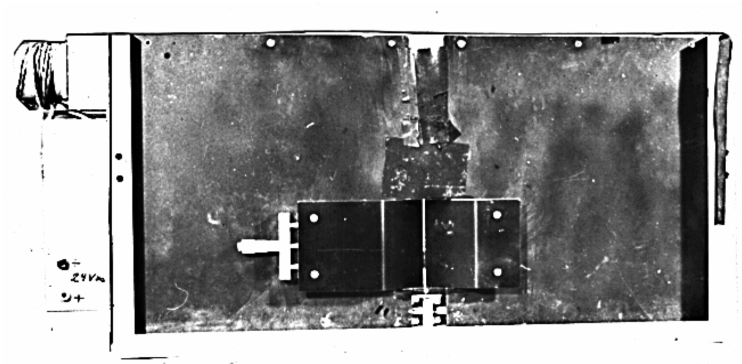

Figure 9-3 Photography of the printer with adjustable slits

The filmplate is installed from the side of the printer, and is placed in a stable position with help of 6 metal springs. 3 springs are placed at the top of the filmplate holder and 3 springs at the bottom of the holder. This is done to ensure stability and facilitate the operating of the printer.

9.2 The micro controller for the holographic printer [10]

The micro controller is the link between the PC and the mechanical printer. It would be possible to let the PC do this controlling process, but it is better to use the PC's capacity to generate images, which is a very time consuming process.
The micro controller's function is to control the position of the filmplate and the shutter for exposure time. It is also possible to control step engine 2, and make holograms with full parallax. In this thesis only step engine 1 is used because only holograms with horizontal parallax are made.
The controller is build up of an 8-bits Intel 8031 chip. This chip consists of an Aritmetric Logical Unit, ALU, two 16-bits counters/timers and a 8-bits ports. The controller unit consists of an EPROM and an EEPROM which contains the driving program for the printer.

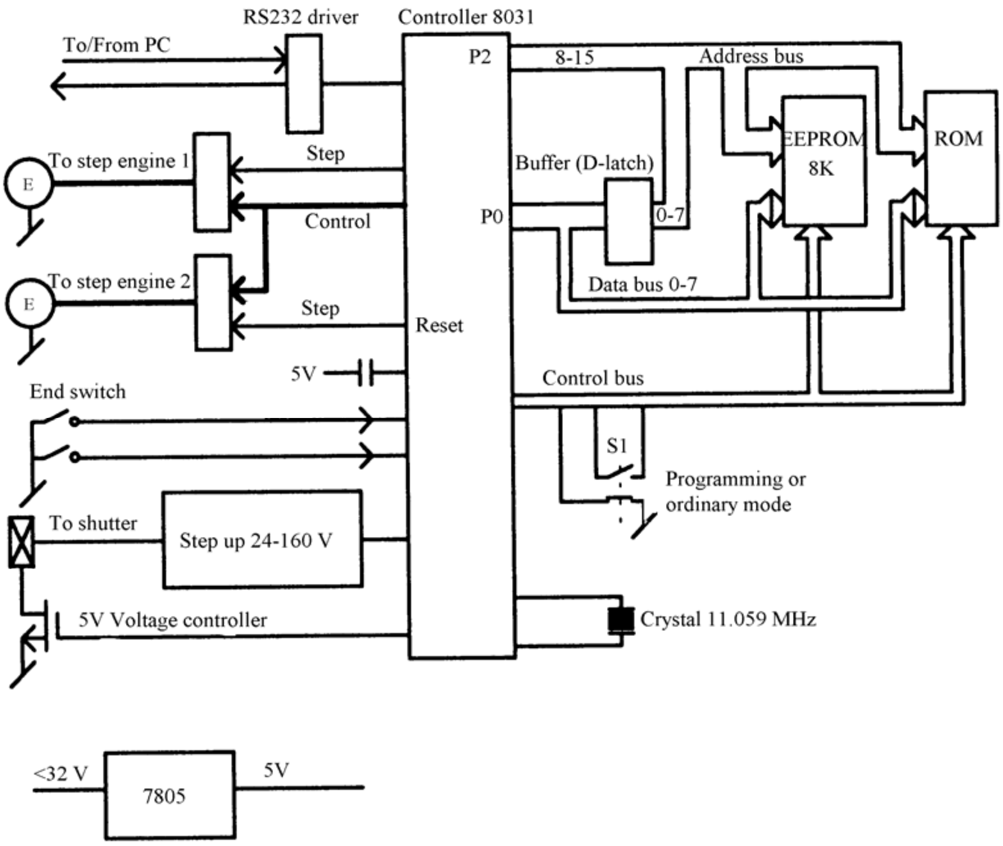

Figure 9-4 Controller for the holographic printer

[10] O.Birkeland : Construction of holographic printer for automatic production of hologram from a 3D computer model, p 33, UiB, 1994

9.3 The shutter controller [10]

The purpose of the shutter is to control the exposure time. When the shutter is open light can pass through it and illuminate the filmplate. When the shutter is closed, the laser beam is blocked and there is no illumination of the filmplate. To open the shutter, a voltage between 80 and 160 V is needed.
The open shutter needs about 20 V to stay open.
To get a high enough voltage to open the shutter one needs a voltage pump.

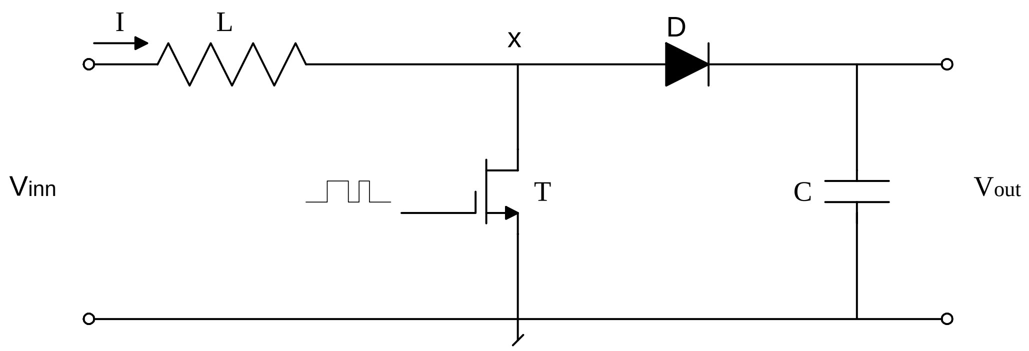

Figure 9-5 Step up circuit

When the transistor T is switched on, the point x is grounded, and the inductor L is recharged. When the transistor is switched off, the inductor will still try to hold the current at a high value. This can only be done if the voltage over the inductor is increased to such a value that current can flow from the inductor, through the diode and the capacitor to the ground.
Each time the transistor switched on and off, the voltage over the capacitor is increased, and the voltage V_{out} becomes higher.

When the shutter is opened, the voltage first gets pulsed to about 140 V. When the voltage reaches this level, the pulsing of the transistor stops, and the shutter is opened. The current over the capacitor will then decrease to 23-24V, and will then remain at that value.

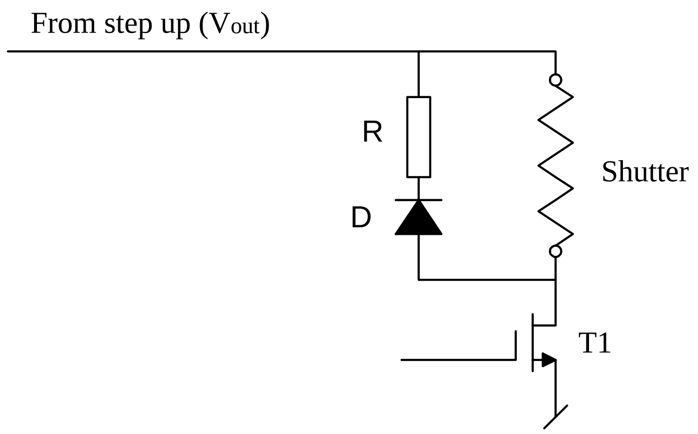

Figure 9-6 The shutter and steering electronics

[10] O.Birkeland : Construction of holographic printer for automatic production of hologram from a 3D computer model, p 36, UiB, 1994

The shutter consist of an inductor as shown in figure 9-6. When the current through the inductor is cut off, T1 is switched off but the inductor still tries to keep up the current. If it is not possible for the current to flow in the circuit, the voltage will build up and will become too high. The transistor T1 will then be destroyed. To prevent this, we use a diode with a resistance in parallel

9.4 The step motor [10]

To drive the printers step-motor there is used a translator/driver circuit UNC5804. The circuit contains the necessary effect transistors to drive the step-motor. The 5804 also contains logical equipment to control the step-motor.

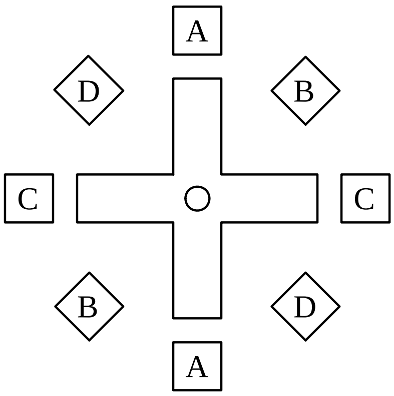

Figure 9-7 Cross-section of the Step-motor

The figure 9-7 shows us a cross-section of the step-motor. The motor has 4 phases given by the electromagnets A, B, C and D. To turn the distributor rotor in the figure one step to the right, we switch on the voltage over phase B. This will turn the rotor 45°. The rotor turns further if we turn off phase B and turn on phase C. To continue this process, the rotor can be turned through 360°, which requires 8 steps.
To turn the rotor to the left, we may set the voltage over phases D, C, B, and so on.

Another way of turning the rotor is the half-step method. This is a combination of the single phase and two phase operation. The turning sequence is A - AB - B - BC - C - CD - D. In this mode the resolution is double. One round trip needs 16 steps. This method give the motor a more silent movement and only small vibrations.

9.5 The software program [10]

[10] O.Birkeland : Construction of holographic printer for automatic production of hologram from a 3D computer model, p 39, UiB, 1994

The holographic printer is controlled by a Windows software program called ARIP Control (Automatic Real Image Printer). This software controls the image generation and gives the necessary signals to the printer controller.
The ARIP Control program requires that the image files are in bitmap (BMP) format.
This means that we can make holograms of nearly all types of pictures. This program is driven by Windows and can be started by clicking the icon ARIP Control with the mouse.

The ARIP control software is versatile, as shown in these examples :

- Photographic pictures shot with a camera can be saved digitally and can easily be transferred to the ARIP Control program.

- Ordinary photographic pictures shot with a camera can also be scanned and converted to a bitmap file.

- Film from a video camera can be converted to pictures with bitmap format. It can then be used in the ARIP Control program.

- A drawing from the most of drawing software programs like AutoCAD can easily be transferred into the ARIP Control program.

In this thesis there has been used a AutoCAD drawing. This image is drawn in perspective and turned in the horizontal direction. For every degree the image is turned through, one bitmap file of the drawing has been made. In this task the drawing is seen from 70 different positions and we have therefore 70 different files. Every image has its own filename of the type *Namexxxx.bmp*, where *xxxx* is the number of the file. The first image will, in this case, have the filename *Name0000.bmp*, and the last image filename will be *Name0069.bmp*.

After clicking on the mouse on the start up icon we get the ARIP Controls main window. The ARIP Control's main window is shown in figure 9-8.
Before recording a hologram, some parameter have to be set to their right values. If we cross the *Save settings on exit*, under the *Options* menu, every change of parameter we make in the program will be saved when we quit the program.

[10] O.Birkeland : Construction of holographic printer for automatic production of hologram from a 3D computer model, pp 77-81, UiB, 1994

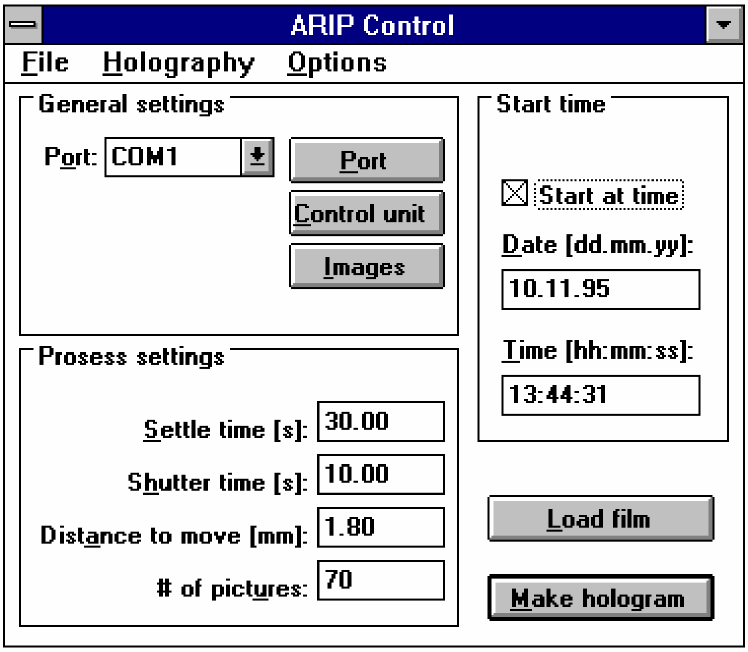

Figure 9-8 The Arip control main window

The ARIP Control main window has 3 sub-windows with parameters which must be set.

The values in the *process settings* control different parameters in the holographic recording.

Load film : Press the button and the film holder will move to the right position, which make it possible to install the filmplate in the printer.

Make hologram : Press the button after the filmplate is installed and the holographic recording starts.

Port : We can make a choice of what computer port the printer is to be connected.
We can choose from COM 1 to COM 4 and NONE. NONE is used when we want to test the image generation without the use of the printer.

Settle time [s] : The number of seconds the table needs to become stable after the printer has moved the filmplate to the right position.

Shutter time [s] : The exposure time for each picture.

Distance to move [mm] : The number of millimetre, the filmplate moves between each exposure.

# of pictures : The number of pictures which get exposed during the hologram recording process.

In the ARIP Control's main window we can cross on the window for *Start time*, and set the date and time the exposure procedure is to start. It is a good idea to start the holographic recording in the night, when it is most silent.

The button *Port* is used to set the parameters for the serial port. The parameter for the RS232 set-up is the values shown in figure 9-9.

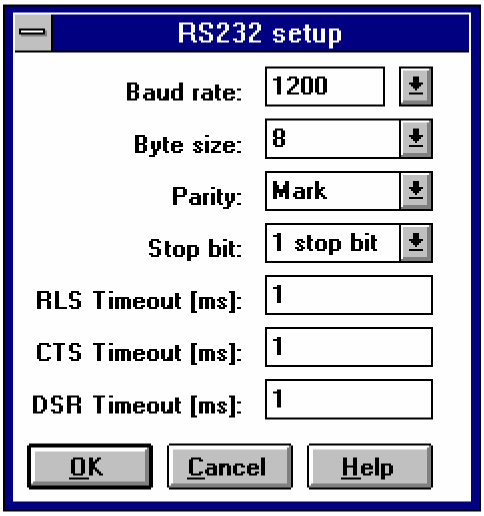

Figure 9-9 Window for the Port button

The button *Control unit* in the main window is shown in the figure 9-10.

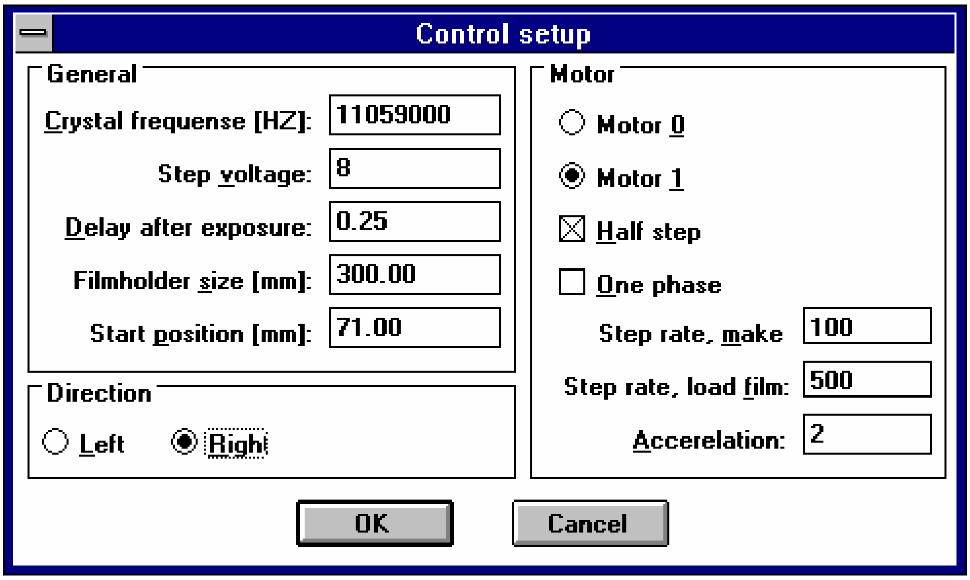

Figure 9-10 Window for control unit button

The values in the control set-up should be like those shown in the figure 9-10.

Crystal frequency [Hz] :	The Crystal frequency which is used to control the microcontroller, is placed in the printers electronic circuitry.
Step voltage :	This value is the time the printer uses to increase the voltage which opens the shutter. The time is given by 0.3 ∗ the value of *step voltage*, and is given in seconds. The value indirectly says how high the voltage will be. A value of 8 would make the time to pulse the voltage 2.4 seconds. The voltage will then receive a value of 140-150 V.
Delay after exposure :	The electrical shutter is somewhat slow. It takes several milliseconds from the time the shutter receives the close signal to the time it actually closes. It is very important that the printer does not move the filmplate before the shutter is closed. Thus the printer waits for the given number of seconds.
Filmholder size [mm] :	The size of the film holder in mm.
Start position :	After the filmplate is placed in the film holder, the film holder moves to the right position before the exposure can start.
Step rate, make :	The speed of the motor. The speed is given by steps between each exposures.
Step rate, load film :	The speed of the motor. The speed is given by steps during the movement of the filmplate before and after the exposure is finish.
Acceleration :	Gives how many steps the step motor should have to accelerate from 0 speed to maximum speed. The value also gives the number of steps used in retarding from maximum speed to 0 speed.

Under the button *Image* on the main window shown in figure 9-8, we have the window *Image set-up*.

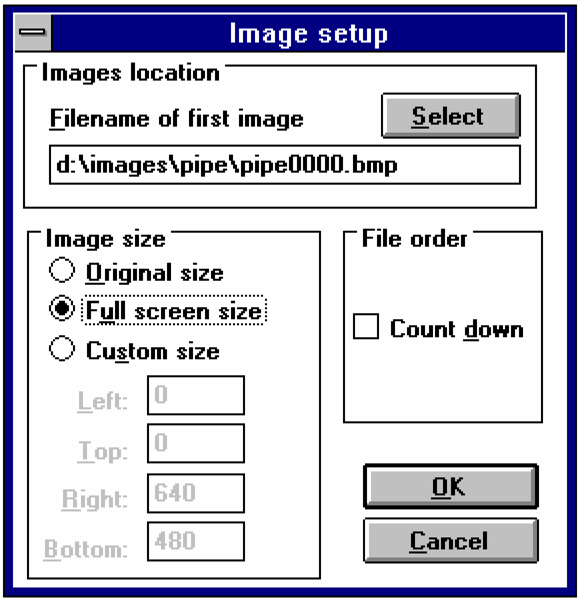

Figure 9-11 Window for Image set-up

Filename for first image :	Takes the first file of a set of files. The files have the name of the type *Namexxxx.bmp*, where *xxxx* is the number of the file.
Count down :	We can make a choice of the files succession. The files can be sent to the screen in the order 0,1,2,3....N, or N, N-1,N-2....0.

There is also a possibility of making a choice of the image size. The choice of full screen has been preferred in this thesis.

Chapter 10 : Holographic multi-stereogram

10.1 Holographic stereogram

Holographic stereograms are hybrids of holography and photography. They have some of the qualities of both media, but each add something of their own. Holographic stereograms are a series of holograms, stripes of maybe hundreds, which are multiplexed into a single hologram. This can be done if we take several photographs of an object from different angles. Each of these pictures are then to be exposed onto a little area of the holographic filmplate.

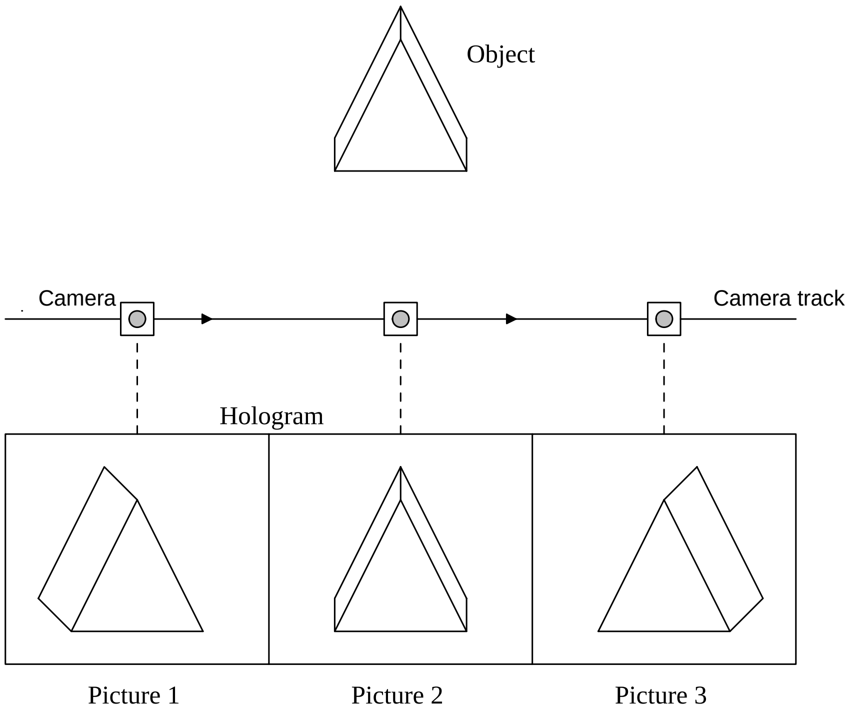

Figure 10-1 Principle of holographic multi-stereogram

The figure 10-1 shows us the principle of a multi-stereogram with 3 pictures which are multiplexed into one hologram. 3 pictures have been used to show the reader the method in an easy way. However, this hologram will have a low resolution. Therefore is it important to use as many pictures as is needed to obtain a good resolution in the hologram. It is common to expose about 1 to 2 mm of the holographic filmplate for each picture.

The figure 10-2 shows us a method to expose a hologram with horizontal parallax, and the filmplate will be exposed in vertical parts.[21] [51]

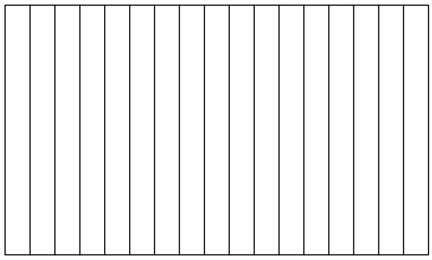

Figure 10-2 Holographic filmplate with horizontal parallax

In this method it is not possible to see the top or bottom of the object in 3 dimensions.
To reproduce the object completely in 3 dimensions, we also need vertical parallax. That means that in practice we have to also move the camera in a vertical direction, and we thus get full parallax.

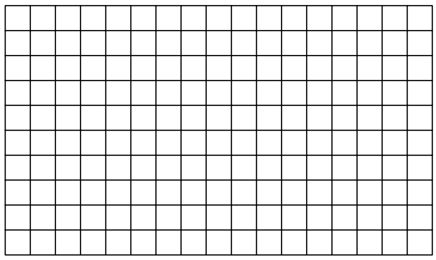

Figure 10-3 Holographic filmplate with full parallax

We would like to make the hologram so good as possible in the shortest time. The solution to this problem is to make a hologram with the fewest possible number of exposures. This must be done without loss in quality or resolution. Besides, it is very important that the pictures which make up the multi-stereographic hologram form one image, and not a sequence of many images.

An other method for make multi-stereograms is to use a computer model instead of pictures of an object.[12] If we get a DAC picture drawn in perspective, we can turn this pictures through different angles over the screen.[32] The exposure will made for each model position, in the same way as for photographic pictures. A perspective drawing is an image where the object which is closer will appear larger than a similar object which is far away.

[21] J.R.Andrews, J.E.Stinehour, M.H.Lean : Holographic display of computer simulations, SPIE Vol.1461, 1991
[51] M.W.Halle, S.A.Benton, M.A.Klug, J.S.Underkoffler: The ultragram : A generalized holographic stereogram, SPIE Vol.1461, 1991
[12] E.v.Nuland, W.Spierings : Development of an office holoprinter III, SPIE Vol.1914, 1993
[32] H.Katsuma, K.Sato, A.Ohmura, M.Fukazawa, T.Igarashi : Many points about recording the important cultural properties by means of holography.

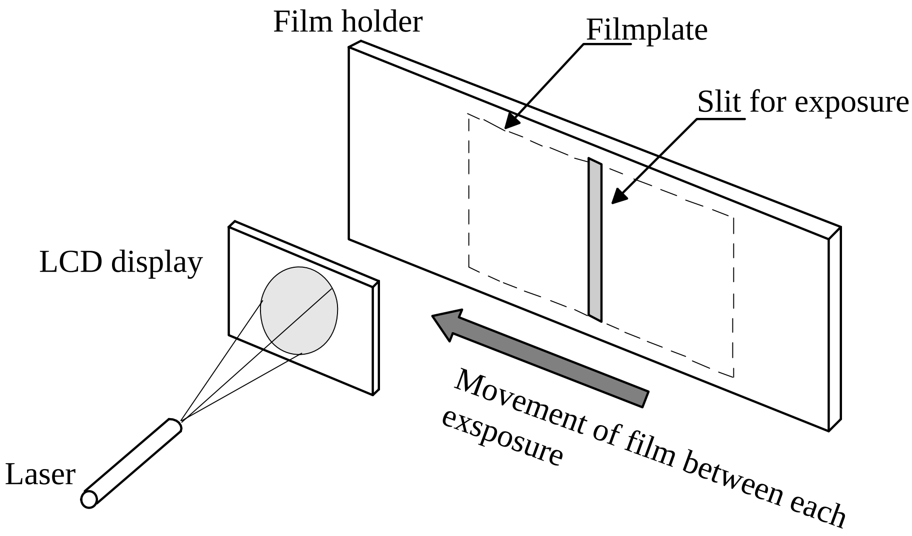

Figure 10-4 Principe of holographic multi-stereogram

The width of each part hologram or exposure is determine of the size of the human eyes pupil. This size varies from 1 to 3 mm in diameter. This is also the ideal size of the exposure area, and under reconstruction of the picture, only one image is seen by each eye.

When the hologram is reconstructed, can we see a 3 dimensional image of the object. If the hologram is exposed in full parallax, the image is completely in 3 dimensions.
The figure 10-5 shows us the principle behind a holographic filmplate which is exposed with horizontal parallax. During the reconstruction only the observer will see the image in different perspectives when he moves his head in horizontal directions. If the observer moves his head in the vertical direction, the image will give no impression of being 3-dimensional.

During the reconstruction of a hologram with horizontal parallax, the observer sees the image of the object in two different perspectives.[1] When we look at a real object, we also see the object in two different perspectives, because there is a space between our eyes.

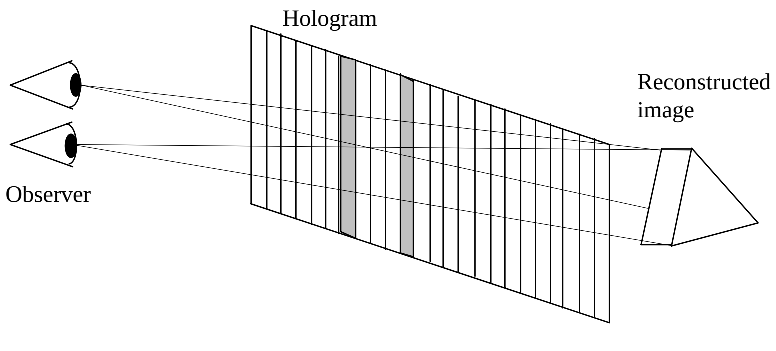

Figure 10-5 Reconstruction of holographic multi-stereogram

10.2 The choice of slit width in HMS [2]

[1] M.A.Klug, M.W.Halle, M.Laucente, W.J.Plesniak : A compact prototype one-step ultragram printer, SPIE Vol.1915, 1993

In order to obtain satisfactory holographic multi-stereograms (HMS) it is necessary to keep the slit width ΔX between 1 mm and 3 mm. The lower limit is chosen such that the hologram does not become a limiting aperture in the optical system under normal viewing conditions. Decreasing the width of the strips increases the resolution in the reconstruction. If the pupil diameter of the eye is taken to be 3 mm, then the eye is the limiting aperture if

$$\Delta X =< 3D / (D+d) \qquad (10.1)$$

Calculation :

D = 250 mm
d = 400 mm

$$\Delta X =< \frac{3 \cdot 250\text{mm}}{250\text{mm} + 400\text{mm}} \approx 1.2\text{mm}$$

where *D* is the distance from the hologram to the image plane and *d* is the distance between the hologram and the observer. The upper limit is chosen to keep the hologram width smaller than the pupil diameter. If the upper limit is exceeded, the discontinuities in the image become noticeable as the hologram is scanned visually.

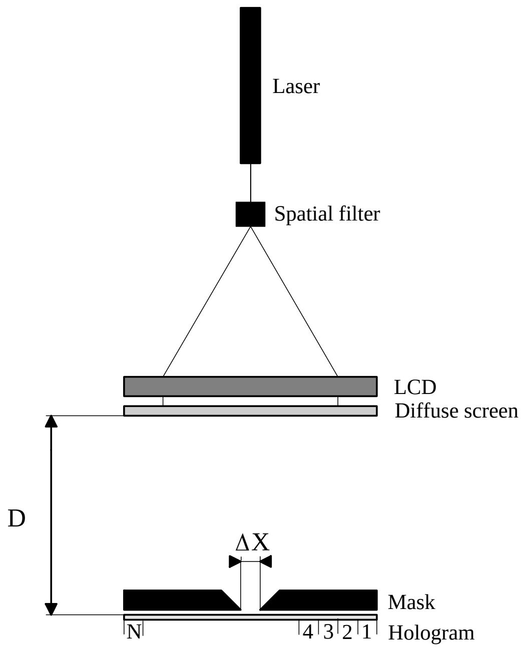

Figure 10-6 Determination of the slit width

10.3 Parallax [19] [22] [23]

[2] M.C.King, A.M.Noll, D.H.Berry : A new approach to computer gernerated holography, Applied optics, Vol.9, 1970

[19] S.Takahashi, T.Honda, M.Yamaguchi, N.Ohyama, F.Iwata : Generation of intermediate parallax-images for

The most important thing which helps us to see the world in three-dimensions is the phenomenon of parallax. When you look at an object, you see only the front side. When you move your head to one side you see the front and another side of the object. This is also very important in holography and constitutes the most common difference between photography and holography. When you are look at a hologram, you can see the image in different visual angles when you move your head to the side just as and when you are looking at a real object. This phenomenon is called parallax. When we look at an object we can see different details depending on whether the head is moved in a horizontal or vertically direction. This means that there is horizontal and vertical parallax.

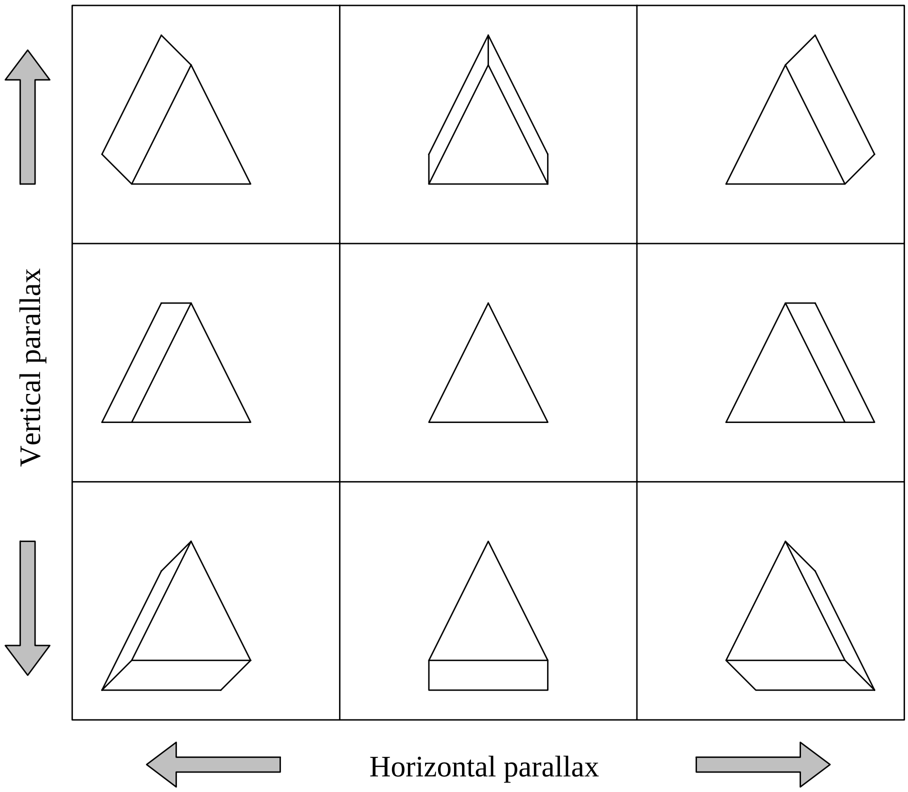

Figure 10-7 Viewpoint of an object of different position

10.4 Exposure

holographic stereograms, SPIE Vol.1914, 1993

[22] M.Yamaguchi, N.Ohyama, T.Honda : Holographic tree-dimensional printer : New method, Applied optics, Vol.31, 1992

[23] M.Yamaguchi, N.Ohyama, T.Honda : Holographic 3-D printer, SPIE Vol.1212, 1990

Exposure of the photographic emulsion is defined as the incident intensity times the time of exposure for the recording material. If the intensity is constant during the whole exposure then

$$H = E \cdot t \qquad (10.2)$$

where

H = Exposure
E = Intensity
t = Exposure time

Radiation measured in radiometric units applies to electromagnetic radiation over the whole spectrum, and is independent of the human eye electron optic sensitive curve. The radiometric equivalent of illuminance is irradiance, and exposure is then defined.

Exposure = irradiance x time

The unit of irradiance is Watt per square meter and the exposure will then be expressed in joule/m^2 . Holographic materials are usually characterised by radiometric units. The sensitivity of a holographic emulsion is most often expressed in $\mu J/cm^2$. If we know the sensitivity of the material used and having measured the irradiance at the position of the holographic plate, the exposure time can be calculated using the formula

Exposure time = sensitivity / irradiance

10.4.1 Exposure of the holograms in HMS

The object beam from the He-Ne laser goes through the spatial filter which consists of a microscope lens and a pinhole. This spatial filter expands the laser beam, so the whole LCD is illuminated. The laser light illuminates the picture of the LCD and gets modulated. The information from the picture is then dispersed when the light passes through the screen of ground glass. The grain structure of the ground glass scatters the information from the image in ″all″ directions.
The light then passes through the slit of the printer and illuminates a small area of the holographic filmplate, shown in figure 10-8. The exposed area of the filmplate receives all the information from the image. The ground glass is essential, and without it the picture on the LCD will be exposed directly on the film, like a photograph (see section 7.2, image 4).

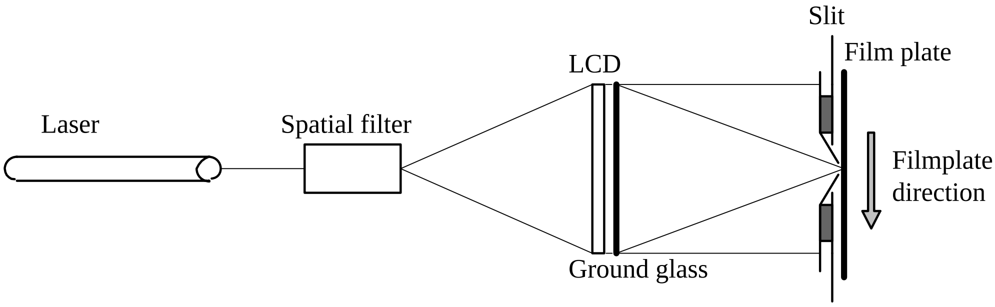

Figure 10-8 Principle of exposure of the film plate

During the processing of transmission hologram, the reference beam must illuminate the filmplate on the same side as the object beam.
For a reflection hologram the reference beam must illuminate the filmplate on the opposite side to the object beam.

Chapter 11 : Stability and calculations

11.1 Vibrational stability of the optical set-up [43]

The problem of vibrational stability intervenes chiefly at the recording stage. The fringe pattern should be stable so that fringe movements are kept below one-tenth of a fringe. For the object wave, this implies very tight tolerances once there is a degree of projective magnification involved.

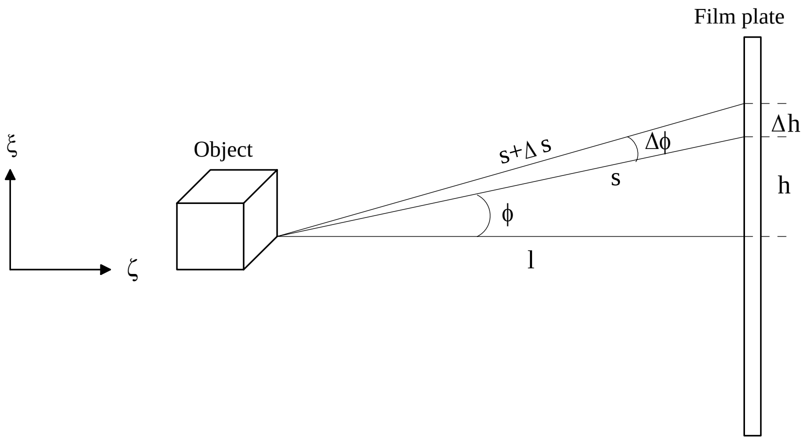

Figure 11-1 Vibrational tolerances

Vibrations introduce a change of the optical path of the interference beams that results in a variation of the phase difference between the object and reference waves and consequently a shift of the interference fringes over the hologram. The complete analysis of the effect requires the examination of the particular geometry of the optical arrangement.

We have from figure 11-1

$$\Delta h \approx l \cdot \Delta\phi \approx (l \cdot \varepsilon)_{\xi} \cdot \tan\phi \qquad (11.1)$$

$$\Delta h = \varepsilon \cdot \lambda \qquad (11.2)$$

$$\Delta\xi = (l \cdot \varepsilon)_{\xi} = \frac{\varepsilon \cdot \lambda}{\tan\phi} \qquad (11.3)$$

The transverse tolerance for the object is the order of

$$\Delta\xi\, s \,\langle\, \varepsilon \frac{\lambda}{\tan\phi_1} \qquad (11.4)$$

[43] O.D.D.Soares : Review of resolution factors in holography, Optical Engineering, Vol.22, 1983

We have also from figure 11-1

$$\cos\phi = \frac{l}{s} \qquad (11.5)$$

$$\Delta s \cdot \cos\phi = \Delta l \qquad (11.6)$$

$$\Delta l = \varepsilon \cdot \lambda \qquad (11.7)$$

$$\Delta\varsigma = \Delta s = \frac{\Delta l}{\cos\phi} = \frac{\varepsilon \cdot \lambda}{\cos\phi} \qquad (11.8)$$

and the longitudinal tolerance is given by

$$\Delta\zeta s \langle \ \varepsilon \frac{\lambda}{\cos\ \phi_1} \qquad (11.9)$$

Calculation of the objects transverse tolerance when ε = 1/10 and ϕ = 30° :

We have from expression (11.4)

$$\Delta\xi s \langle \ \varepsilon \frac{\lambda}{\tan\phi} = 0.1 \cdot \frac{0.63\mu m}{\tan 30°} = 0.11\mu m$$

This means that the transverse tolerance for the object is one tenth of an micrometer.

Calculation of the objects longitudinal tolerance when ε = 1/10 and ϕ = 30° :

We have from expression (11.9)

$$\Delta\zeta s \langle \ \varepsilon \frac{\lambda}{\cos\ \phi_1} = 0.1 \cdot \frac{0.63\mu m}{\cos 30°} = 0.07\mu m$$

From these calculations can we see that vibrations of the object, in this case the LCD, of more than 0.11 μm will make reduction of the holograms quality.

Analogously, the vibrational tolerances for the holographic film plate can be found from

$$\Delta\xi_H \langle \ \varepsilon \frac{\lambda}{2(\sin\phi_1 + \sin\phi_2)} \qquad (11.10)$$

and

$$\Delta\zeta_H \langle \ \varepsilon \frac{\lambda}{\cos\phi_1[1 + \cos(\phi_1 + \phi_2)]} \qquad (11.11)$$

Calculations of the film plates transverse tolerance when $\varepsilon = 1/10$, $\lambda = 0.63$ µm, and $\phi_1 = \phi_2 = 30°$.

We have from expression (11.10)

$$\Delta\xi_H \langle \ \varepsilon \frac{\lambda}{2(\sin\phi_1 + \sin\phi_2)} = 0.1 \cdot \frac{0.63\mu\text{m}}{2(\sin 30° + \sin 30°)} = 0.03\mu\text{m}$$

Calculations of the film plates longitudinal tolerance when $\varepsilon = 1/10$, $\lambda = 0.63$ µm, and $\phi_1 = \phi_2 = 30°$.

We have from expression (11.11)

$$\Delta\zeta_H \langle \ \varepsilon \frac{\lambda}{\cos\phi_1[1 + \cos(\phi_1 + \phi_2)]} = 0.1 \cdot \frac{0.63\mu\text{m}}{\cos 30°[1 + \cos(30° + 30°)]} = 0.05\mu\text{m}$$

From these calculations can we see that vibrations of the film plate or the holographic printer, for more than 0.05 µm will make reduction in the holograms quality.

This kind of analysis extends to the stability of all the components of the optical arrangement with adequate adaptation. It is seen that to use a design angle (see section 5.1.2) much in excess of the resolving power required unnecessarily reduces these tolerances.
These tolerances ensure no loss of the diffraction pattern. However, there is a further aspect of vibrational stability related to the loss of resolving power which is, in principle, comparable to the vibration amplitude. The achievement of high resolution imposes, then, very tight control vibrational stability, in particular, the avoidance of microphonisms on the different components of the experimental arrangements.
In conclusion, a geometry is recommended that meets the following criteria:

- Records in the near field of the diffraction from the object.
- Uses a plane reference wave.

- The reference and the object beam strike the holographic recording layer before going through the holographic plate base.

- The object is placed as near as possible to the holographic film plate.
- The reference beam has the wider angle of incidence
- The holographic film plate normal approximately bisects the angle between the reference and object beams.

11.2.1 Vibration measurement

The aim of this experiment is to measure the vibrations that can be expected during the recording process of holographic multi-stereograms. To get a good image of the process, there has been constructed a Michelson interferometer set-up on the optical table as shown in figure 11-2. One mirror is mounted on the 3-D printer to detect the vibrations created by the printer. The shutter is also mounted on the optical table, and makes it possible to run a recording of holographic multi-stereogram process.

The optical set-up for measuring of vibration stability is shown in figure 11-2.

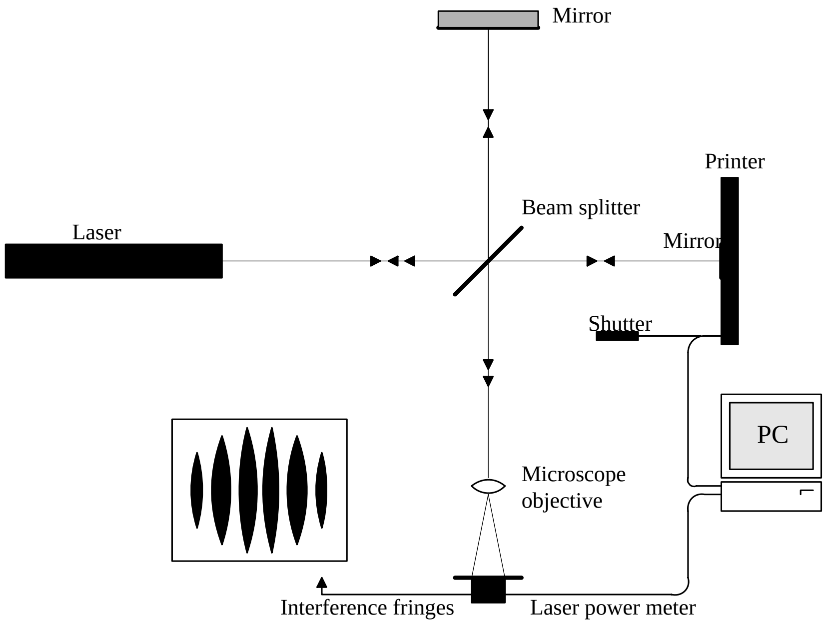

Figure 11-2 Michelson interferometer used in vibration stability measurement.

In this experiment there have been performed several different measurements with different sampling rates over various period.[36] To alternate the sampling rate and the period, it is possible to find the data that can give the result which are best suited for a presentation. There have been made 3 different measurements of stability shown in the list on the following page.

1: Vibration stability measurement of the equipment shown in figure 11-2. This is done when all the optical equipment is mounted to the optical table and the printer and shutter are not moving.

[36] Picolog : Datalogging softwear, Pico Technology

2: Vibration stability measurement when the glass cage is mounted on the table. The printer and shutter are not moving.

3: Vibration stability measurement when the glass cage is mounted on the optical table. The shutter and the printer is activated. This is the same procedure as used during the recording of holographic stereograms.

All of the measured data presented in the plots, is sampled every 500 ms in 250 seconds. In the front of the interference fringes on the optical set-up, shown in Figure 11-2, there is mounted a stable slit of 0.5 mm width and 20 mm length. This slit covers the ″Laser power meters″ detector. The slit's extension (length) must have the same direction as the interference fringes. This method is a well known method to measure movement of interference fringes, i.e. vibrations.

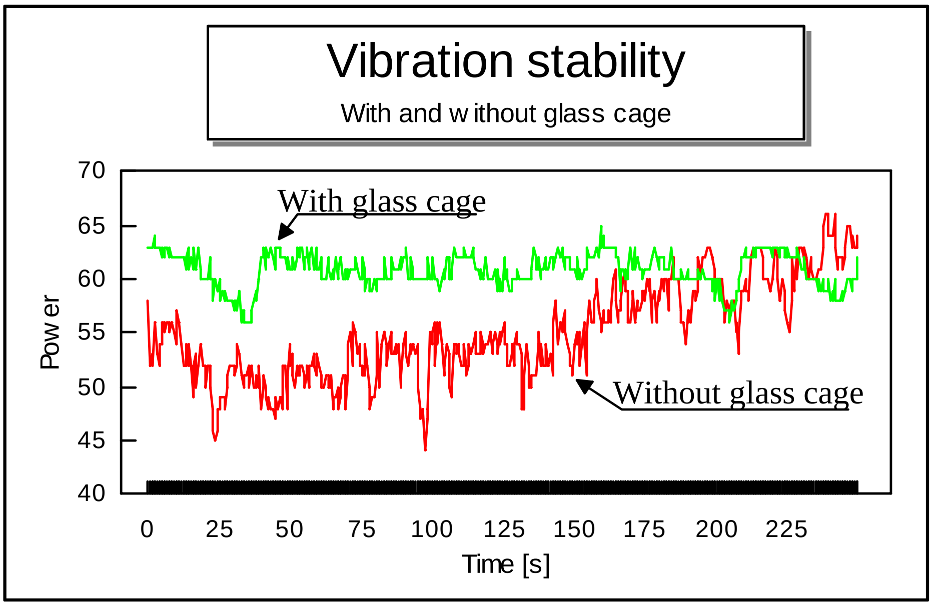

Figure 11-3 Measure of vibrations, with and without glass cage.

Figure 11-3 shows the measurement of vibrations of optical equipment with and without the glass cage. The amplitudes of the peak measurement made without glass cage are bigger than the peaks without glass cage. The stability for the measurements made with the glass cage mounted on the optical table is also better. From other measurements this picture is repeated, and the plot above gives a representative picture of the vibration stability. The purpose of the glass cage is to reduce air vibrations produced by the ventilator and air vibration from talking and doors slamming from other rooms in the building.
An experiment has also be carried out with slamming the door and talking in the laboratory, when the interference fringes have been visually observed. The movements of the interference fringes have a considerably higher amplitude without, than with the glass cage placed on the optical table.

A test of the printers stability during the recording process was done, the set-up shown in figure 11-2 was used. To make holographic multi-stereograms of good quality, the printer (film holder) must be stable during the exposure.
To make the measurement as real as possible the data logging was executed during the recording process.

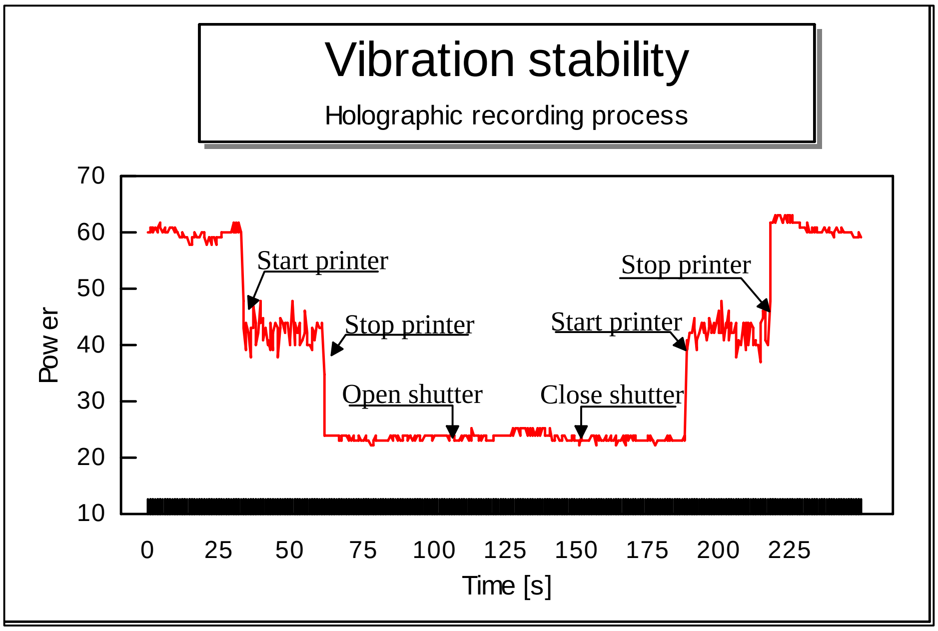

Figure 11-4 Measurement of vibrations under holographic recording process.

The plot, figure 11-4, shows the vibrations measured during a recording process, with the glass cage mounted on the optical table. The measurement time is 250 seconds, where the data logging starts at *t=0,* when nothing is in movement on the table. After 30 seconds the printer motor starts and move the film to the first exposure position of the multi-stereogram. When the printer has reach the position, the printer stops and the equipment is fixed for 30 seconds. At *t=110* seconds the shutter opens to expose the film for 40 seconds, and the shutter then closes. The equipment is fixed to *t=190* seconds before the printer's motor starts to move the film to the next position. At *t=220* seconds the film plate has reached the new position and the motor stops. Then the above procedure is repeated.

When the data logging started the slit and laser power meters detector were placed in the area where the light from the laser has a constructive interference fringe (maximum light power). When the printer motor starts the interference fringes are moving all the time. There is a great deal of vibration from the printer, which can also be seen visually. When the printer reaches the new position and stops, the interference fringes become stable for a short time (1-2 seconds). The vibrations made by the printer quickly die out. This means that the exposure can start 2 seconds after the printer had stopped and the film plate reaches the new position, without any vibrations created by the printer's motor.

The plot, figure 11-4, shows that the interference fringes do not stop at the same position as before the printer was started. This has no practical importance to the quality of the recorded hologram.

The vibrations from the shutter's movement (open/close) was impossible to measure. It was not possible to see any movement of the fringes visually either. So the shutter causes no destructive vibrations during the exposure.
A optical set-up with the use of printer, shutter and glass cage should not cause any vibration problems for the recording of holographic multi-stereograms.

11.2 Depolarisation effects [15]

Recording of a hologram involves the formation of fringes caused by interference between object and reference beams. Constructive and destructive interference between two beams can occur when both beams have light of the same polarisation. Light beams polarised differently or orthogonal to each other can not interfere. The basic equations for holographic exposures have been derived assuming that the two beams are similarly polarised.
The light output from the laser used in this thesis is linearly polarised. Therefore, the reference beam is always linearly polarised. But polarisation of the object beam will depend on the nature of the object surface.

Depolarisation can occur as a result of reflections from metallic and dielectric surfaces. It is also caused by scattering from particles like fog and dust when the laser light goes through them.
The particles of irregular shape and complex refractive index strongly scatter the light beam in all directions. The result is a significant depolarisation of the laser beam.

An LCD is used in the holographic recording process in this thesis. The liquid crystals in the LCD changes the polarising direction. Therefore, most LCD's have polarizers on both sides of the liquid crystal panel. The result is that the light passing through such an LCD is polarised. In holography it is necessary to spread the light from the LCD. In this thesis ground glass is used to spread the light from the LCD. The ground glass depolarises the light with about 20% of the transmitted light (see section 8.1).

The effect of depolarisation is to degrade the reconstructed image's quality with the possibility of a complete loss of information of those parts of the object from where the scattered beam is depolarised.

We let the object beam amplitude be $Oe^{(i\varphi o)}$ and that due to the reference beam be $Re^{(i\varphi r)}$, where O and R are corresponding absolute amplitudes. In conventional holographic recording the irradiance at the recording medium is

[15] P.C.Mehta, R.Hradaynath : Elimination of depolarization effects in holography, Applied optics, Vol.21, 1982

$$I = \left| Oe^{(i\varphi o)} + Re^{(i\varphi r)} \right|^2 \qquad (11.12)$$

$$= O^2 + R^2 + 2OR\cos\varphi`$$

Where $\varphi` = \varphi_o - \varphi_r$ is the phase difference between object and reference beams assuming that both beams are linearly polarised and parallel to each other. If the object beam is depolarised after scattering from the object, the equation over would not be a true representation of the irradiance at the recording plane. If we describe the scattered object beam as $O = O_p + O_n$, where O_p denotes that component of the beam which is polarised parallel to the reference beam polarisation, and O_n denotes the orthogonal component of O.

The degree of polarisation P is defined as

$$P = I_p /(I_p + I_n) = 1 / (1 + \delta) \qquad (11.13)$$

Where

$$\delta = I_n / I_p \qquad (11.14)$$

The reconstruction efficiency η is given by

$$\eta = \frac{4K\alpha}{(1+\alpha)^2 \left[1 + \left(\frac{1 - P}{P}\right)^{1/2}\right]^2} \qquad (11.15)$$

Where K is a constant and depends on the transfer characteristics of the recording medium and α is the reference-to-object beam intensity ratio.

The dependence of (η / K) on the degree of polarisation P is shown in figure 11-6 for different values of α. It is observed that the efficiency of the hologram reduces drastically with a slight decrease in the value of P.

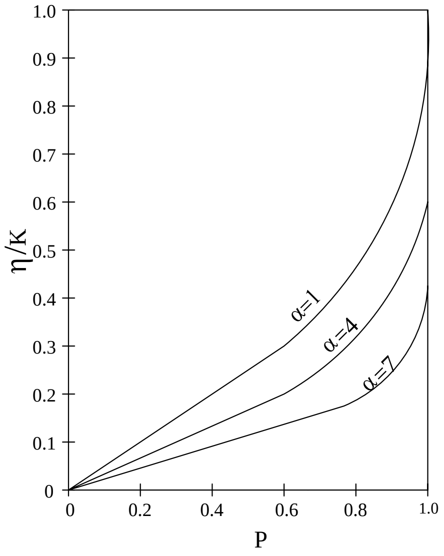

Figure 11-6 Degree of polarisation

There is a 43 % decrease in η when P decreases from 1 to 0.9. When the degree of polarisation becomes zero, i.e. there is no parallel polarised component in the object beam, the efficiency falls to zero.

11.3 Spatial filter

A spatial filter is a device which improves the spatial coherence of a laser beam by effectively removing the background ″noise″, i.e. irregular intensity variations in a raw beam, producing a uniform, near Gaussian energy distribution. The background noise, which can badly degrade sensitive experiments such as holography, can arise from dust particles and material surface imperfections in an optical system which scatter light is unwanted directions.
This spatial filtering is achieved by blocking the higher frequencies associated with a pinhole placed at the focus of a microscope objective so that only the desired smooth intensity profile is transmitted.

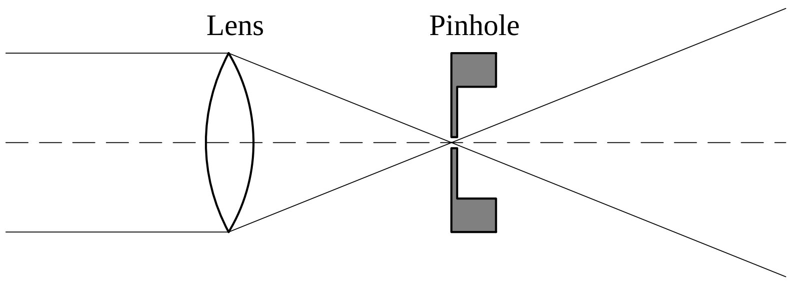

Figure 11-7 The principle of a spatial filter.

An objective should be chosen according to the amount of beam expansion required. A pinhole can then be selected to provide the necessary frequency cut off for a given beam diameter. The pinhole size can be determined using this simplified expression:

$$P = \frac{2.4\,\lambda\,f}{d} \qquad (11.16)$$

where

P = Pinhole diameter.

λ = The lasers wavelength.

f = Focal length of objective lens.

d = Diameter of the laser beam.

11.3.1 Calculation of pinhole

In this thesis two different types of microscope objectives on the spatial filter have been used. For each of these lenses the pinhole size must be calculated to get the best noise filter.

<u>Microscope objective, magnification 63 X</u> :

$$P_{63} = \frac{2.4\lambda f}{d} = \frac{2.4 \cdot 633.2 \cdot 10^{-9}\,\text{m} \cdot 3.1 \cdot 10^{-3}\,\text{m}}{10^{-3}\,\text{m}} = 4.7\,\mu\text{m}$$

<u>Microscope objective, magnification 40 X</u> :

$$P_{40} = \frac{2.4\lambda f}{d} = \frac{2.4 \cdot 633.2 \cdot 10^{-9}\,\text{m} \cdot 4.68 \cdot 10^{-3}\,\text{m}}{10^{-3}\,\text{m}} = 7.1\,\mu\text{m}$$

11.4 Temperature changes of the film during exposure

Normally, the filmplates are placed in a refrigerator. The durability to the filmplate increases when stored in a cold place.
Some time before the recording process of a hologram the filmplate must be taken out of the refrigerator, and be tempered in room temperature.

When the filmplate is heated, the part of the glass plate where the emulsion is bound will expand. When the glass plate expands the grains in the emulsion will also be drawn in the same directions that the glass plate expands. If this happens during the exposure, the image that created in the hologram may lose information.

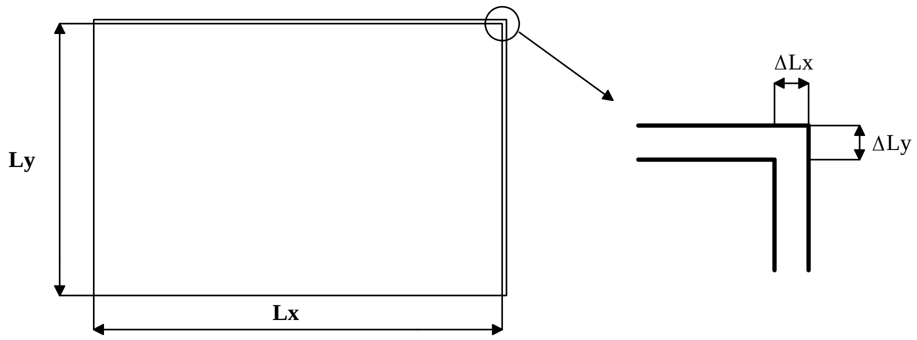

Figure 11-8 Expansion of the filmplate

The expansion of the filmplate can only takes place as shown in figure 11-8.

Technical specifications

$Lx = 127$ mm

$Ly = 102$ mm

$\alpha = 8E^{-6}\ °K^{-1}$

$\lambda = 0.633\ E^{-6}$ m

where

Lx = The filmplates length
Ly = The filmplates height
α = Coefficient of thermal expansion
λ = The lasers wavelength
ΔLx = Thermal expansion in x-direction
ΔLy = Thermal expansion in y-direction
ΔT = Temperature difference in °K

The formula for thermal expansion is generally given by

$\Delta L = \alpha * Lo * \Delta T$ (11.17a)

The thermal expansion of the glass plate in *x* and *y* direction can be written

$\Delta Lx = \alpha * Lx * \Delta T$ (11.17b)

and

$\Delta Ly = \alpha * Ly * \Delta T$ (11.17c)

We know that vibrations and movement of the filmplate, in the range of more than 10 % of the wavelength will create a reduction of the quality of the hologram image. This means that a movement of the filmplate for more than $0.063 \cdot 10^{-6}$ meter will disturb the hologram.
If we illuminate the entire holographic filmplate and look for maximal brightness of the image, there is no possibility of high temperature differences during the exposure.

Calculation of temperature limit for thermal expansion in *x* and *y* directions.

$\Delta Lx = 8E^{-6}\ °K^{-1} \cdot 0.127m \cdot \Delta T$

$0.063 \cdot 10^{-6}\ m = 1.016 \cdot 10^{-6}\ m°K^{-1} \cdot \Delta T$

$\Delta T = 0.06\ °K$

$\Delta Lx = 8E^{-6}\ °K^{-1} \cdot 0.102m \cdot \Delta T$

$0.063 \cdot 10^{-6}\ m = 0.816 \cdot 10^{-6}\ m°K^{-1} \cdot \Delta T$

$\Delta T = 0.08\ °K$

From the calculations above we can see that a temperature variation over 0.06 °K reduce the brightness of the hologram.

During the production of multi-stereograms with horizontal parallax, there is no great problem of thermal expansion in x-directions. This is because the light wave illuminates only 1-2 mm width of the hologram. Even if the slit is only 1-2 mm in width, the slit's height is the same as the filmplate's, so the temperature variation should not be higher than 0.08 °K during the exposure when we use the holographic printer.

Chapter 12 : Holography experiments

The purpose of these experiments is to develop a method for producing high quality holographic multi-stereogram from a computer image sequence.[22] [23] For this to be possible, a good deal of optical equipment had to be obtained, in addition to that used for Olav Birkeland's thesis work.[10] Some of the equipment was made in the workshop of the Institute of Physics and the rest was bought from different optical companies. Equipment bought for this experiment was a transparent LCD, a red 24 mW He-Ne laser, optical breadboard, mirrors, lenses, and different types of optical holders. A lot of equipment was made and some was rebuilt in the workshop. Equipment made in the workshop was the glass cage mounted on the optical table and various special optical holders. The printer's slit was changed from a fixed slit with an angle of 60° to an adjustable slit with an angle of 110°. An other important change was the adjustable screws on the spatial filter. The old screws were changed to micrometer screws that make it possible to adjust the microscope lens precisely in front of the pinhole.

12.1 Experiment 1 : Recording transmission holograms from one computer picture

This optical set-up is for recording transmission holograms from a computer image (computer image is shown in figure 12-2). The optical equipment is placed at two different levels, as this is a more practical way to use the optical table. It is also more natural to have the reference beam coming from above, as this is the same (or nearly the same) wave that is used during the reconstruction of the hologram.

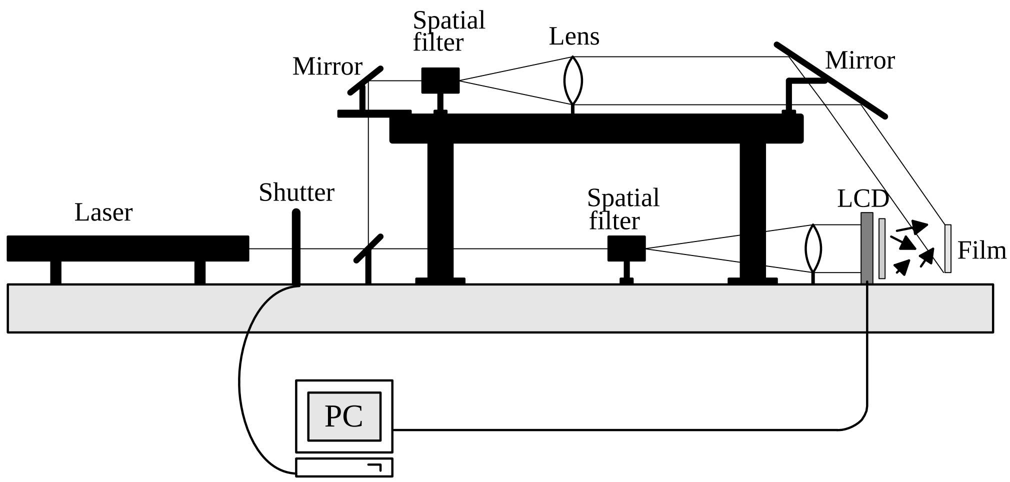

Figure 12-1 Set-up for experiment 1

[22] M.Yamaguchi, N.Ohyama, T.Honda : Holographic three-dimensional printer : New method, Applied optics, Vol.3, 1992
[23] M.Yamaguchi, N.Ohyama, T.Honda : Holographic 3-D printer : SPIE Vol.1212, 1990
[10] O.Birkeland : Construction of holographic printer for automatic production of hologram from a 3D computer model, UiB, 1994

The ground glass is placed close to the LCD, and there is 20 cm between the ground glass and the filmplate.
The function of the computer is to control the exposure and display a picture on the LCD. The exposure time is set on the computer, and the shutter will open to let the laser beam pass through the shutter and illuminate the film. Before the shutter is opened, the computer calls up an image and displays it on the computer screen. The LCD is connected in parallel with the computer screen and the image is shown on the display during the entire exposure.

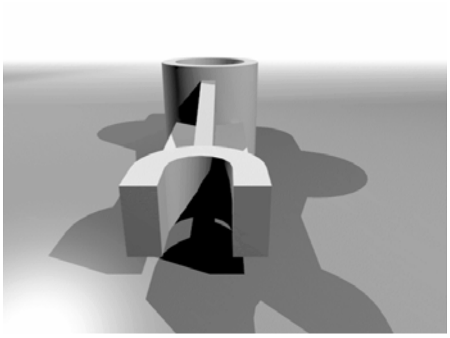

Figure 12-2 Computer image drawn on AutoCAD.

<u>Optical equipment for the recordings :</u>

He-Ne laser : Output power 12 mW. Wavelength 632.8 nm.
Spatial filters : Pinhole size 25 μm. Microscope objectives 40 x 0.65
Lenses : Diameter 100 mm. Focal length 175 mm.
Mirrors : Flatness λ / 10.
Filmplate : Type 10 E 75. Resolution 3000 l / mm.
Filter : Transmission 50 %.
LCD : Transparency LCD

Laser beam distance : Object beam = 233 cm.
Reference beam = 235 cm.

<u>Image 1 :</u>

Light power on the film : Object beam = 1.7 μW.
Reference beam = 4.5 μW.

Light power ratio = 4.5 μW / 1.7 μW ≈ 2.6 : 1

Exposure time = 1 second.

Result : There is some noise in the hologram, but the image is not bad. The brightness of the hologram could have been better.

Comments : The noise in the hologram is probably caused by depolarising effects and/or vibrations.

Image 2 :

The optical set-up for this exposure is the same as used in the recording of image 1, but with the use of a vertical polarizer in front of the film. If the noise on the (image 1) hologram is caused by depolarizing effects, this noise will now be reduced or deleted from the hologram. The polarizer transmits 38 % of the incident light. Therefore, the exposure time should be about 3 times as long as the recording of image 1.

Exposure time = 3 seconds.

Result : The quality and the brightness of the transmission hologram is very good.

Comments : There seems to a be problem with the depolarizing of the light during the process of exposure. This problem seems to be solved with the use of a polarizer.

After a close study of the optical set-up, the cause of the depolarizing was found. The mirror which reflected the reference beam from the lower table to the upper table changed the direction of polarisation. This mirror changed the depolarizing direction by 24°, and the result was problems with interference on the film.

Image 3 :

The optical set-up for this exposure is the same as used for earlier recordings in this experiment. The mirror which change the depolarizing direction is adjusted, and the polarizing direction of the reference and the object beams is vertical.

Light power on the film : Object beam = 0.2 μW.
Reference beam = 0.7 μW.

Light power ratio : 0.7 μW / 0.2 μW = 3.5 :1

Exposure time = 4 seconds.

Result : The quality of the hologram is very good.

Comments : It is very important to control the polarizing direction of the laser beams, since an unfortunate placing of mirrors can change the polarizing direction.

12.2 Experiment 2 : Recording 2-step reflection hologram

The aim of this experiment is to produce a reflection hologram from a master transmission hologram. This kind of hologram is called 2-step reflection hologram, where a master transmission hologram is copied into a reflection (white light) hologram.

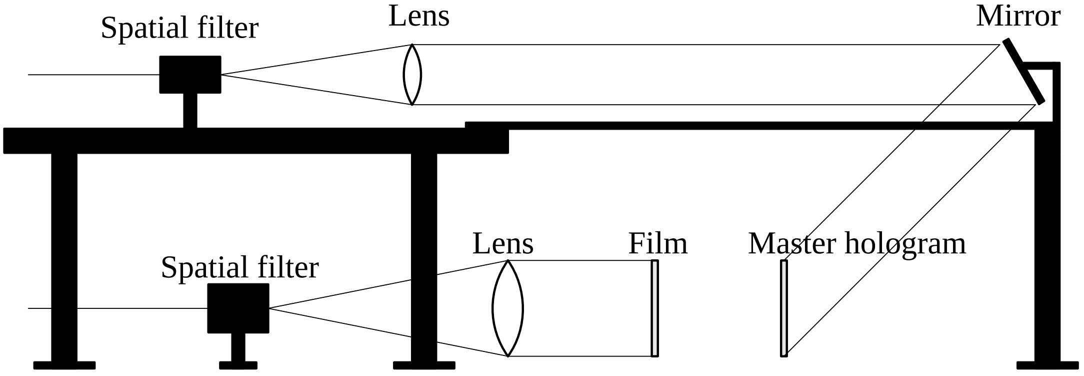

Figure 12-3 Parts of the optical set-up for 2-step reflection hologram recording.

The distance between the transmission master hologram and the filmplate is 14 cm. The master hologram has the focus of the real image 11 cm behind the hologram. (The left side of the master hologram is shown in figure 12-3).

<u>Optical equipment used for the recordings :</u>

He-Ne laser : Output power 12 mW. Wavelength 632.8 nm.
Spatial filters : Pinhole size 25 μm. Microscope objectives 45 x 0.65
Lenses : Diameter 100 mm. Focal length 175 mm.
Mirror : Flatness λ / 10.
Filmplate : Type 8 E 75 HD. Resolution 5000 l / mm

<u>Image 1 :</u>

Laser beam distance : Object beam = 190 cm.
Reference beam = 190 cm.

Light power on the film : Object beam = 1.2 μW.
Reference beam = 2.6 μW.

Light power ratio = 2.6 μW / 1.2 μW ≈ 2.2:1

Exposure time = 100 seconds.

Result : The quality of the hologram is very bad. It is impossible to see the image in the hologram, but it is possible to see the lens used in the reference beam on the hologram.

Comments : The bad quality of the hologram is probably caused by reflections from the lens. (The lens is placed at the ground level on the optical table, as shown in figure 12-3).

Image 2 :

To solve the problem of reflections on the film, the master hologram and the filmplate are turned. Figure 12-4 shows the changes in the optical set-up made to avoid problems with reflections.

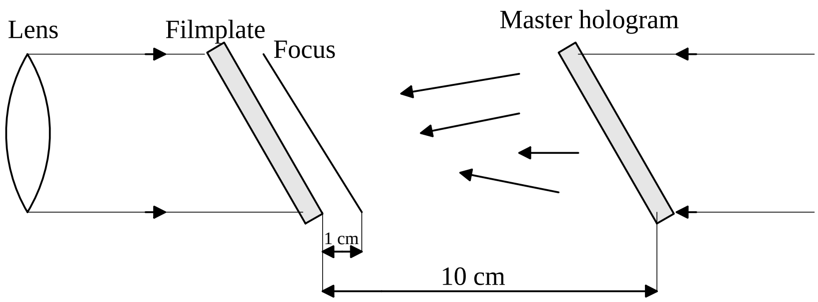

Figure 12-4 Changes in the optical set-up.

The master hologram and the filmplate are turned through 74° with respect to the incident light.

Laser beam distance : Object beam = 190 cm.
Reference beam = 190 cm.

Light power on the film : Object beam = 1.2 μW.
Reference beam = 2.2 μW.

Light power ratio = 2.2 μW / 1.2 μW ≈ 1.8:1

Exposure time = 100 seconds.

Result : The brightness of the hologram is bad, but it is possible to see the image in the hologram. It is also still possible to see the lens in the hologram.

Comments : There are still some reflections from the lens onto the hologram. The problem must be solved before any high quality holograms can be made.

Image 3 :

The problem with reflections on the hologram can only be solved by change the position of the lens. It is important that the lens is not parallel to the filmplate.

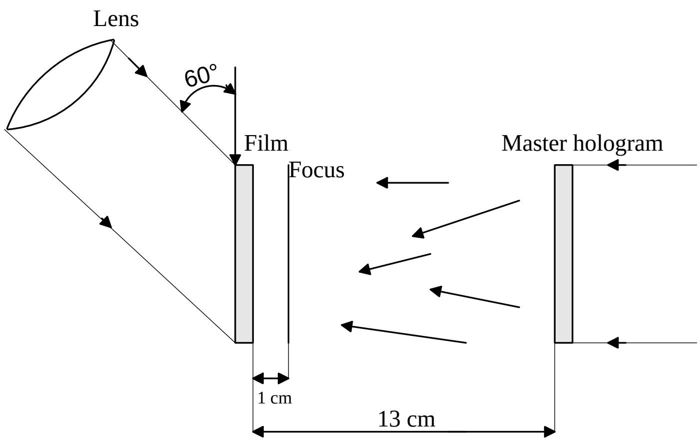

Figure 12-5 Changes on the optical set-up (seen from above).

Laser beam distance : Object beam = 210 cm.
Reference beam = 210 cm.

Light power on the film : Object beam = 0.9 μW.
Reference beam = 1.4 μW.

Light power ratio = 1.4 μW / 0.9 μW ≈ 1.6:1

Exposure time = 100 seconds.

Result : The brightness and the quality of the hologram are very good.

Comments : The problem of reflections seems to be solved, and it is also possible to hold the optical equipment stable for 100 seconds.

12.7 Experiment 7 : Recording 2-step rainbow holograms from a master transmission multi-stereogram [6] .

The purpose of this experiment is to produce rainbow holograms of good quality. The production method is to copy a master transmission hologram to a rainbow hologram. This is a method called 2-step rainbow hologram. The master transmission hologram used in this experiment is the same as used in the production of 2-step reflection holograms.

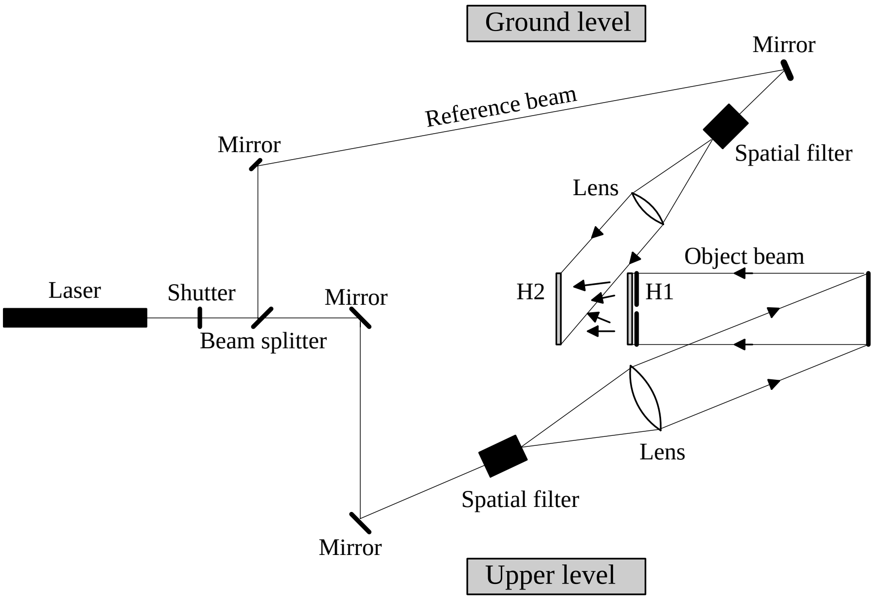

Figure 12-22 The optical set-up for recording 2-step rainbow hologram (seen from above).

The focal point for the transmission master hologram (H1) is 13 cm behind the hologram. This is the distance between the master hologram and the film (H2) in the optical set-up. The filmplate (H2) is also placed in the focal point of the transmission master hologram. Light from the reference beam illuminates the film plate with a incident angle of 30 degrees.
An other important parameter is the width of the slit, it is set to 2 mm.

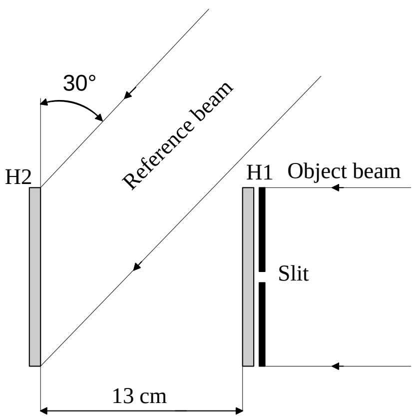

Figure 12-23 Location of optical equipment.

[6] I.Singstad : Classical holographic technique, p 35, UiB, 1993

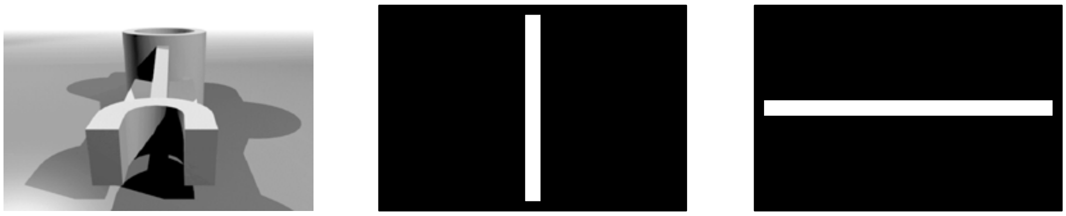

Figure 12-24 shows a picture of the master hologram with vertical and horizontal slits.

<u>Optical equipment used for the recordings :</u>

He-Ne laser : Output power 24 mW. Wavelength 632.8 nm.
Spatial filters : Pinhole size 10 μm. Microscope objectives 40 x 0.65
Lenses : Diameter 100 mm. Focal length 175 mm.
Mirror : Flatness λ / 10.
Filmplate : Type 10 E 75. Resolution 3000 l / mm.
Filter : Transmission 3 %.

Laser beam distance : Object beam = 175 cm.
Reference beam = 176 cm.

<u>Image 1 :</u>

The optical set-up for the exposure of this image is the same as shown in figure 12-22, where the slit is placed in front of the master transmission hologram, and is located in the vertical direction.

Light power on the film: Object beam = 0.14 μW.
Reference beam = 0.38 μW.

Light power ratio = 0.38 μW / 0.14 μW ≈ 2.7 :1

Exposure time = 10 seconds.

Result : The brightness of the rainbow hologram is good, but the image has no depth.

Comments : The image has no depth because the position of the slit is wrong. The slit must be turned 90° to the horizontal position. This is because the master transmission hologram is exposed with horizontal parallax.

<u>Image 2 :</u>

The optical set-up for this image is the same as used for the exposure of image 1. The slit in front of the master hologram is turned 90° in the horizontal direction. This is done to give the image of the rainbow hologram depth.

Light power on the film: Object beam = 0.08 μW.
Reference beam = 0.35 μW.

Light power ratio = 0.35 μW / 0.08 μW ≈ 4.4 :1

Exposure time = 10 seconds.

Result : The brightness of the rainbow hologram is good and the depth of the image is also good. The angle of the incident light used for the reconstruction could be bigger.

Comments : The slit's position is decisive for the depth of the hologram image. If the slit had been in a vertical position and the master hologram is made with the same direction of the slit, only one or two images will be illuminated during the copying process of the rainbow hologram. With the use of a slit in the horizontal direction a part of all of the 70 images on the master hologram will be illuminated. The produced rainbow hologram then consists of 70 different images. The rainbow hologram has a image of 3 dimensions, and the depth is achieved.

Image 3 :

This image is made to make a rainbow hologram with a larger reconstruction angle. With a larger reconstruction angle, it will be easier to reconstruct the hologram. The light from the reference beam has incident angle of 45°. This angle is the same the incident light has in the reconstruction of the rainbow hologram.

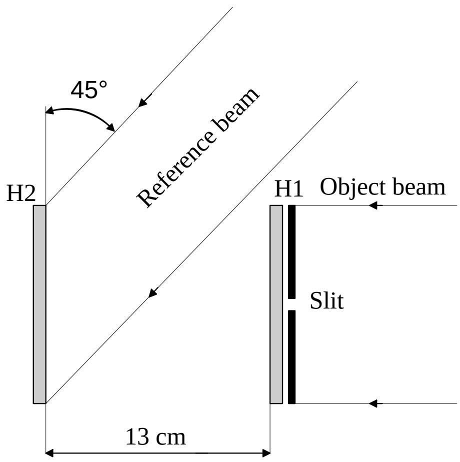

Figure 12-25 Location of optical equipment.

The reference beam is not parallel, but is weakly converging.

Light power on the film: Object beam = 0.08 μW.
Reference beam = 0.42 μW.

Light power ratio = 0.42 μW / 0.08 μW ≈ 5.3 :1

Exposure time = 10 seconds.

Result : The quality of the rainbow hologram is good.

Comments : It is more advantageous to use a big incident angle of the reference beam, because it is easier to use a bigger angle than a smaller angle in reconstruction. An incident angle of 45° for the reference beam is practical in this case.

Image 4 :

The optical set-up for this image is the same as used for the exposure of image 3. In the recording of image 3, the exposure was made with a converging reference beam. In this exposure the recording will be made with a diverging reference beam. The purpose of the change from converging to diverging reference beam is to see if it makes any difference in the quality of the hologram.

Light power on the film: Object beam = 0.08 μW.
Reference beam = 0.27 μW.

Light power ratio = 0.27 μW / 0.08 μW ≈ 3.4 :1

Exposure time = 12 seconds.

Result : The rainbow hologram is good.

Comments : The brightness for image 3 is better than for this image. In this experiment, the best result were with the hologram exposed with converging reference beam.

Image 5 :

This image is made with the same set-up as used in the production of image 3 and 4. The reference beam is converging during the exposure of this image. The purpose is to make the rainbow hologram as good as possible.
The spatial filter is tuned to the object beam which illuminates the film with maximum light energy.

Light power on the film: Object beam = 0.10 μW.
Reference beam = 0.55 μW.

Light power ratio = 0.55 μW / 0.10 μW ≈ 5.5 :1

Exposure time = 15 seconds.

Result : The quality of the rainbow hologram is very good.

Comments : The desirable quality of the rainbow hologram is achieved.

All of the rainbow images produced in this experiment had some pattern in the filmplates emulsion. This pattern is caused by light reflection on the filmplate. To solve this problem the thickness of the filmplate is changed from 1.5 mm plates to 3 mm thick film plates.

Image 6 :

The optical set-up of recording image 6 is the same as used under the exposure of image 5. The filmplate used in this exposure is 8 E 75 HD film with the thickness of 3 mm and a resolution at 5000 lines/mm.

Light power on the film: Object beam = 0.10 μW.
Reference beam = 0.55 μW.

Light power ratio = 0.55 μW / 0.10 μW ≈ 5.5 :1

Exposure time = 150 seconds.

Result : The quality of the rainbow hologram is very good.

Comments : The problem with the undesirable pattern on the film emulsion is solved.

12.3 Experiment 3 : Recording reflection holograms from one computer picture

The purpose of this experiment is to record (1-step) reflection holograms from one computer picture. The advantage with a 1-step reflection hologram is that the recording process can be carried out in one round. We do not have to first produce a transmission master hologram, and then copy it into a reflection hologram, as in the 2-step procedure. Having two different set-ups for recording holograms is time consuming. The disadvantage is the difficulty of producing high quality 1-step reflection holograms. This problem with quality arises from long exposure time and vibrations.

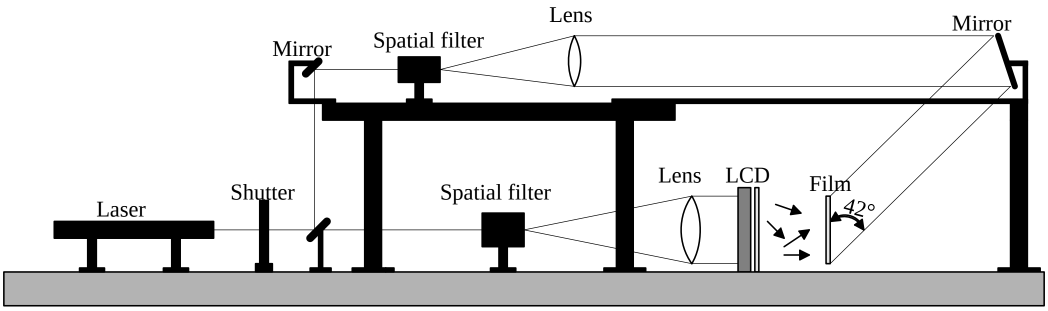

Figure 12-6 Experimental set-up for reflection hologram recording.

The LCD and the shutter is connected to computer, where the LCD is connected in parallel to the computer screen. The computer image used in this experiment is the same as used in experiment 1, shown in figure 12-2. The distance between the LCD and the film is 11 cm, and the ground glass is fastened to the display.

<u>Optical equipment used for the recordings :</u>

He-Ne laser : Output power 24 mW. Wavelength 632.8 nm.
Spatial filters : Pinhole size 25 µm. Microscope objectives 45 x 0.65
Lenses : Diameter 100 mm. Focal length 175 mm.
Mirror : Flatness λ / 10.
Filmplate : Type 8 E 75 HD. Resolution 5000l / mm.
Filter : Transmission 50 %.
LCD : Transparency LCD

Laser beam distance : Object beam = 199 cm.
Reference beam = 199 cm.

Image 1 :

Light power on the film : Object beam = 0.8 μW.
Reference beam = 1.8 μW.

Light power ratio : 1.8 μW / 0.8 μW ≈ 2.3 :1

Exposure time : 100 seconds.

Result : The brightness of the hologram could have been better.

Comments : It seems that the hologram had been unevenly illuminated during the exposure. This can be seen from the reconstruction of the hologram, where the brightness is not even over the whole area of the filmplate.

Image 2 :

Before this exposure the spatial filter was adjusted, and the reference beam illuminates the film uniformly over the whole area.

Light power on the film : Object beam = 0.8 μW.
Reference beam = 2.0 μW.

Light power ratio = 2.0 μW / 0.8 μW = 2.5:1

Exposure time = 100 second.

Result : The quality and the brightness of the hologram were very good.

Comments : This type of set-up (optical set-up in two levels) is very flexible, and it is possible to make good transmission and reflection holograms. Therefore this 2 level set-up will be preferred in further experiments.

12.4 Experiment 4 : Recording holographic transmission multi-stereograms

In this experiment the aim is to produce transmission holograms from computer pictures. In the earlier experiments, holograms were made from one computer picture only. When only one picture is used, the result will only be a 2-dimensional holographic image of the computer picture.
In this experiment the purpose is to make 3-dimensional hologram from 70 different pictures. These pictures are drawn with AutoCAD, where the drawn object is turned over on the screen, and make it possible to see the image from the left, front and from the right side. These 70 pictures are exposed on 70 different area of the filmplate with the help of the holographic printer.

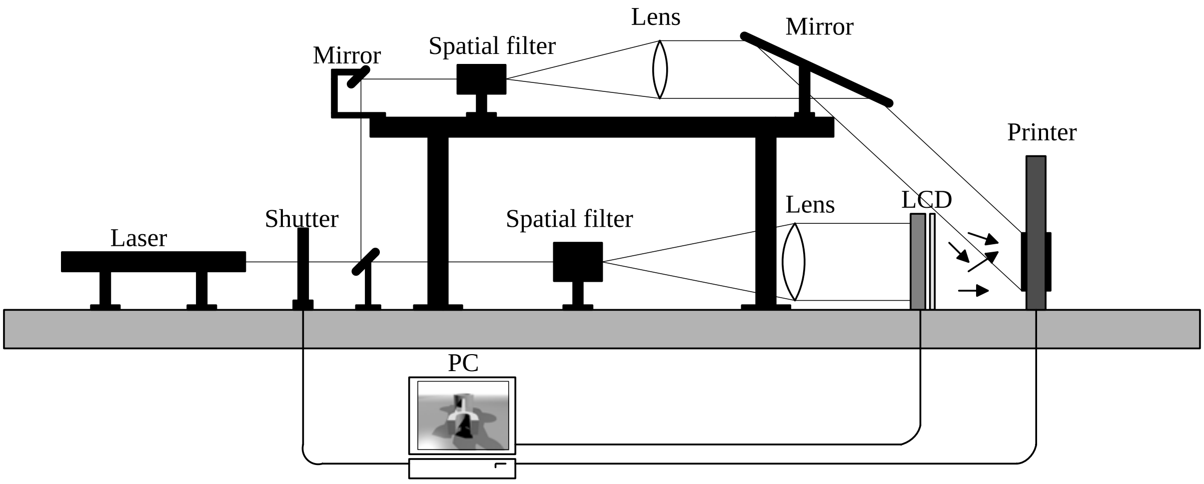

Figure 12-7 Experimental set-up for recording transmission holograms with the use of a 3-D printer.

The computer screen is connected in parallel with the transparent LCD, and is illuminated by the object beam.

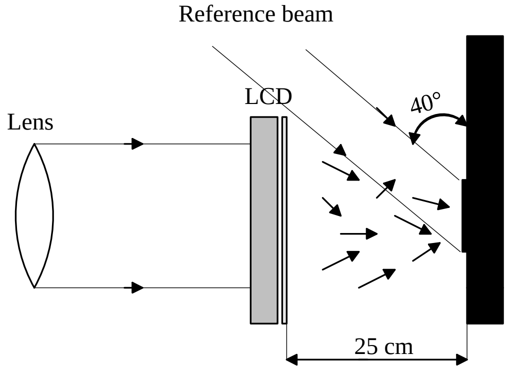

Figure 12-8 Location of optical equipment.

The picture of the object is made by turning the perspective AutoCAD drawing from right to left or in the opposite direction. For every degree the picture is turned we have a new image. The total visible angle is about 70 ° (from the first to the last picture).
Figure 12-9 shows an example of the picture used in the process (here only 3 different pictures are shown).

Fjernet bildene pga størrelsen paa filen

Figure 12-9 Pictures used in the recording process.

Every one of the 70 pictures is exposed on different areas of the filmplate.
The printer that moves the filmplate to the right position is described in section 9.1 ″The holographic printer ″.
The picture exposed onto the film must be the right image, exposed on the right area of the filmplate. The filmplate is illuminated in vertical columns which can be adjusted from 0 mm to 5 mm width.

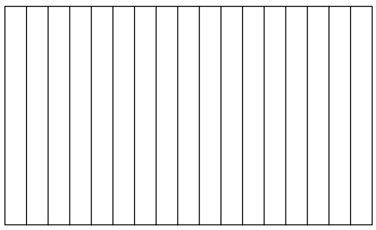

Figure 12-10 Exposures of the filmplate.

The first computer picture is exposed in the first position of the filmplate, and the second picture is exposed in the second position and so on. Totally 70 different pictures are exposed onto the filmplate in the 70 different vertical columns.
During the reconstruction of the hologram we can see the image from the left side when we look at the hologram from the left side. If we look at the hologram from the front, we will see the image from the front, and of course if we look at the hologram at the right side we will see the image from the right side. Holograms produced in this method will give us a hologram with the image in 3 dimensions (3-D) image. This means that we get a hologram made from 70 different holograms, which we perceive as one hologram with a 3-D image.

<u>Optical equipment used for the recordings :</u>

He-Ne laser : Output power 24 mW. Wavelength 632.8 nm.
Spatial filters : Pinhole size 10 μm. Microscope objectives 45 x 0.65
Lenses : Diameter 100 mm. Focal length 175 mm.

Mirrors : Flatness λ / 10.
Filmplate : Type 10 E 75. Resolution 3000 l / mm.
Filter : Transmission 20 %.
LCD : Transparency LCD

Laser beam distance : Object beam = 155 cm.
Reference beam = 155 cm.

The ground glass is changed to ground paper to get a better spreading of light from the LCD. The disadvantage with the use of ground paper is its bad transparency. This means there will be a greater loss of light power of the object beam than there would have been with the use of the ground glass.

Image 1 :

To obtain the maximum light power on the filmplate during the exposure, the polarisation direction of the laser was turned so that the LCD could transmit the maximum possible light power.

Light power on the film : Object beam = 0.05 μW.
Reference beam = 0.10 μW.

Light power ratio = 0.10 μW / 0.05 μW = 2:1

Slit width = 1.90 mm.

Distance the film is to be moved = 1.75 mm.

The slit width is chosen a to be slightly wider than the distance the filmplate moves, in order to overlap and reduce the effect of vertical lines.

Settle time = 5 seconds.

Exposure time = 30 seconds.

Result : The hologram is good, but the lowest part of the hologram is brighter than the top.
The vertical lines on the hologram are very distinct.

Comments : The lowest part of the film had the weakest reference beam. This means that the ratio between the reference beam and the object beam should be less than 2:1.

Image 2 :

The optical set-up for image 2 is the same as used in the recording process of image 1.

The reference and the object beams were adjusted to obtain a more uniform illumination of the film.

Light power on the film : Object beam = 0.02 μW.
Reference beam = 0.02 μW.

Light power ratio = 0.02 μW / 0.02 μW = 1:1

Slit width = 1.90 mm.

Distance the film is to be moved = 1.75 mm.

Settle time = 5 seconds.

Exposure time = 30 seconds.

Result : The hologram is good and the brightness is better than for image 1. The vertical lines on the hologram are still very distinct.

Comments : The slit width or the movement of the filmplate must be changed to reduce the vertical lines in the hologram.

Image 3 :

The optical set-up for image 3 is the same as that used earlier in experiment 4.

Light power on the film : Object beam = 0.02 μW.
Reference beam = 0.02 μW.

Light power ratio = 0.02 μW / 0.02 μW = 1:1

Slit width = 1.90 mm.

Distance the film is to be moved = 1.64 mm.

The distance the filmplate is to be moved between the exposures is reduced to get a bigger overlap.

Settle time = 5 seconds.

Exposure time = 15 seconds.

The exposure time is reduced to the half of that used for the earlier image recordings in this experiment. The purpose of this new exposure time is to try to reduce the time of the recording process and also to reduce the possibility of instabilities. The exposure time must not be to short, because if the hologram is under-exposed the brightness will be bad.

Result : The hologram is good and the brightness is the best so far in this experiment. The vertical lines from the slit are more pronounced than ever.

Comments : In this experiment the movement of the filmplate was reduced, and it brought a larger overlap. It appears that if the overlap is too large, the vertical stripes from the slit become more visible. The exposure time seems to be suitable, since the brightness of the hologram is good.

Image 4 :

The optical set-up for image 4 is the same as that used earlier in experiment 4.

Light power on the film : Object beam = 0.02 μW.
Reference beam = 0.02 μW.

Light power ratio = 0.02 μW / 0.02 μW = 1:1

Slit width = 1.90 mm.

Distance the film is to be moved = 1.80 mm.

The distance the filmplate is to be moved between the exposures is increased to give a smaller overlap.

Settle time = 5 seconds.

Exposure time = 17 seconds.

The exposure time is increased by 2 seconds in order to get a brighter hologram.

Result : The hologram is good and the vertical lines are minimal.

Comments : It would be difficult to use the holograms produced in this process as master holograms for a recording process of 2-step reflection holograms. This is because the size of the real image is too big.

Image 5 :

To solve the problem of too large real image, and obtain holograms which can be used as master holograms in a 2-step reflection hologram recording method, the reference beam and object beam were adjusted to be parallel. Has this anything to do with the size of the real image ?

The optical set-up for image 5 is the same as used earlier in experiment 4.

Light power on the film : Object beam = 0.02 μW.
Reference beam = 0.02 μW.

Light power ratio = 0.02 μW / 0.02 μW = 1:1

Slit width = 1.90 mm.

Distance the film is to be moved = 1.85 mm

The distance the filmplate is to be moved between the exposures is increased to give a smaller overlap.

Settle time = 5 seconds.

Exposure time = 17 seconds.

Result : The quality of the hologram is good, but the size of the real image is still too big. The vertical lines from the slit are smaller than ever.

Comments : The change from not parallel to parallel reference and object beams makes no alteration in the size of the real image.

Image 6 :

To get a smaller real image on the hologram, the LCD is placed closer to the filmplate. Because of the size of the LCD's cover, it is impossible to get LCD nearer the film without blocking the reference beam. This problem is solved by removing the cover from the LCD.

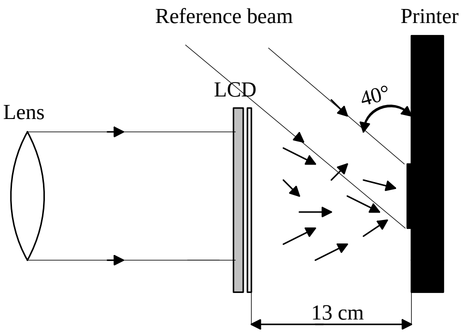

Figure 12-11 Location of optical equipment.

The optical set-up for image 6 is the same as used earlier in experiment 4.

Light power on the film : Object beam = 0.04 μW.
Reference beam = 0.08 μW.

Light power ratio = 0.08 μW / 0.04 μW = 2:1

Slit width = 1.90 mm.

Distance the film is to be moved = 1.85 mm.

Settle time = 5 seconds.

Exposure time = 15 seconds.

The exposure time is reduced by 2 seconds because the light power in the object and the reference beams have increased.

Result : The hologram is good and the real image is smaller than the earlier images in this experiment.

Comments : The size of the real image depends on the distance between the LCD and the film.

Image 7 :

The holographic film needs more light power to reduce the exposure time. Therefore the ground paper was changed to ground glass which is more transparent. The purpose of this exposure is to test whether the quality of the ground glass is good enough for use in holography. Will the ground glass spread the light from the LCD well enough, and is the transparency of the ground glass much better than the transparency of the ground paper ?

The optical set-up for image 7 is the same that used earlier in experiment 4.

Light power on the film : Object beam = 0.25 μW.
Reference beam = 0.45 μW.

Light power ratio = 0.45 μW / 0.25 μW = 1.8:1

Slit width = 1.90 mm.

Distance the film is to be moved = 1.85 mm.

Settle time = 5 seconds.

Exposure time = 10 seconds.

The exposure time is reduced by 5 seconds because the light power of the object beam and the reference beam have increased.

Result : The quality of the hologram is bad because it is strongly over-exposed.

Comments : The ground glass transmits over 10 times so much light as the ground paper. In image recording is it impossible to draw any conclusions about the quality of the ground glass.

By correcting the position of some of the optical components, it is possible to place the LCD nearer the film. This is done to reduce the size of the real image, and it will be possible to use it as a master transmission hologram.
The LCD changes the polarisation direction by 20°. To correct this a half-wave plate[17] is mounted on the reference beam on the optical set-up.

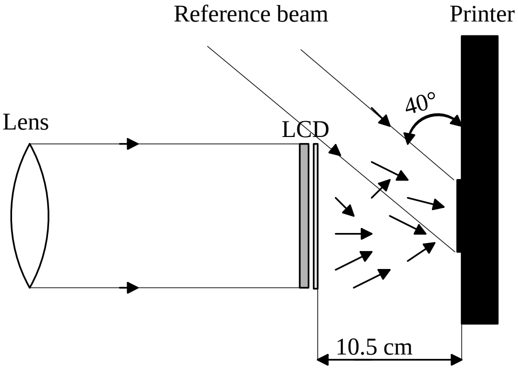

Figure 12-12 Location of optical equipment.

<u>Optical equipment used for the recordings :</u>

He-Ne laser : Output power 24 mW. Wavelength 632.8 nm.
Spatial filters : Pinhole size 10 μm. Microscope objectives 45 x 0.65
Lenses : Diameter 100 mm. Focal length 175 mm.
Mirror : Flatness λ / 10.
Filmplate : Type 10 E 75. Resolution 3000 l / mm.
Filter : Transmission 50 %.
LCD : Transparency LCD
Half-wave plate : 20°

Laser beam distance : Object beam = 155 cm.
Reference beam = 155 cm.

Fjernet bilde pga størrelen på filen

Figure 12-13 Picture of one of the images created on the ground glass.

[17] O.Espedal : Experimental methods in holography, pp 8-9, UiB, 1993

Image 8 :

Light power on the film : Object beam = 0.13 μW.
Reference beam = 0.30 μW.

Light power ratio = 0.30 μW / 0.13 μW ≈ 2.3:1

Slit width = 1.90 mm.

Distance the film is to be moved = 1.85 mm.

Settle time = 5 seconds.

Half-wave plate 20 °.

Exposure time = 7 seconds.

Result : The brightness of the hologram is very good, but the vertical stripes from the slit are very pronounced.

Comments : The brightness of the hologram was satisfactory, but the problem of the embarrassing vertical lines is still not solved.

Image 9 :

The purpose of this recording is to solve the problem of vertical lines from the slit.

Light power on the film : Object beam = 0.13 μW.
Reference beam = 0.30 μW.

Light power ratio = 0.30 μW / 0.13 μW ≈ 2.3:1

Slit width = 1.90 mm.

Distance the film is to be moved = 1.71 mm.

The distance the film is to be moved between each exposure is decreased to get a bigger overlap.

Settle time = 5 seconds.

Half-wave plate 20 °.

Exposure time = 7 seconds.

Result : The brightness of the hologram is still very good, but the vertical lines from the slit should be less visible.

Comments : The size of the vertical lines on the hologram is not reduced. There will be further efforts to solve the problem.

Image 10 :

The optical set-up is the same as used earlier in this experiment.

Light power on the film : Object beam = 0.13 μW.
Reference beam = 0.30 μW.

Light power ratio = 0.30 μW / 0.13 μW ≈ 2.3:1

Slit width = 1.90 mm.

Distance the film is to be moved = 1.64 mm.

The distance the film is to be moved between each exposure is decreased even more to get a bigger overlap.

Settle time = 5 seconds.

Half-wave plate 20 °.

Exposure time = 7 seconds.

Result : The brightness of the hologram is very good, and the vertical lines on the hologram are minimal. The quality of this hologram is quite satisfactory.

Fjernet bilde pga størrelse på filen

Figure 11-28 Picture of a holographic transmission multi-streogram.

Comments : The real image is very bright and we have a perfect size for use as master hologram.

12.5 Experiment 5 : Recording 2-step reflection holograms from a master transmission multi-stereogram.

In this experiment the purpose is to make high quality 2-step reflection holograms from a master transmission hologram. The master hologram used in this experiment is the transmission hologram produced as image 10 in experiment 4. The quality of this hologram is so good that it should be possible to copy it onto a reflection hologram.

One of the biggest challenges in this experiment is to keep the optical equipment stable during the exposure. This can be very difficult because the exposure time is very long for reflection holograms. The film used in transmission hologram (10 E 75) do not have high enough resolution to be used in the recording process of reflection holograms. Reflection holograms need higher resolution of the filmplate, and we use AGFA 8 E 75 HD filmplates, which have a resolution of 5000 lines/mm. This filmplate need about 20 times more light energy than 10 E 75. It means that the exposure time will be about 20 times longer for recording reflection holograms than for recording transmission holograms, if the filmplate is illuminated with the same light power.

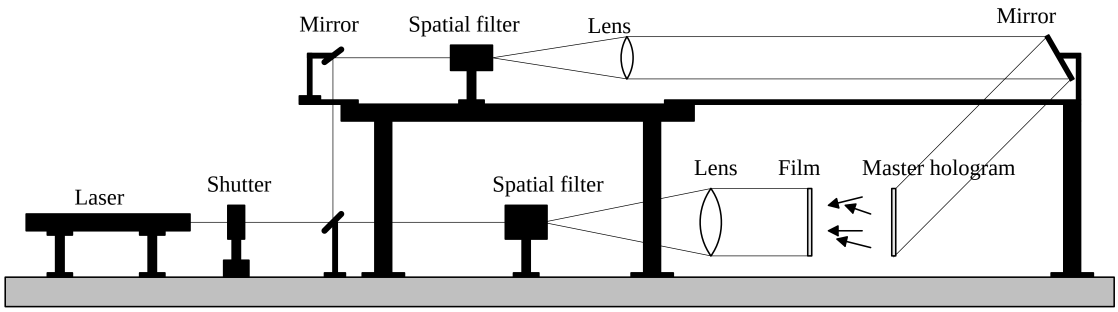

Figure 12-15 Optical set-up for recording 2-step reflection hologram (Seen from the side) .

We know from experiment 2 that the lens and the film must not be parallel, because it can give rise to reflections and lead to destructive interference of the film plate. The result can be a loss of information, and a bad quality hologram.

The distance between H1 (master transmission hologram) and H2 (film plate for reflection hologram) is 13 cm. The focus of the real image is placed between the master hologram (H1) and the film (H2). The distance between the master hologram and the focus is 12 cm, and the distance between the focus of the real image in the master hologram and the film is also 1 cm.

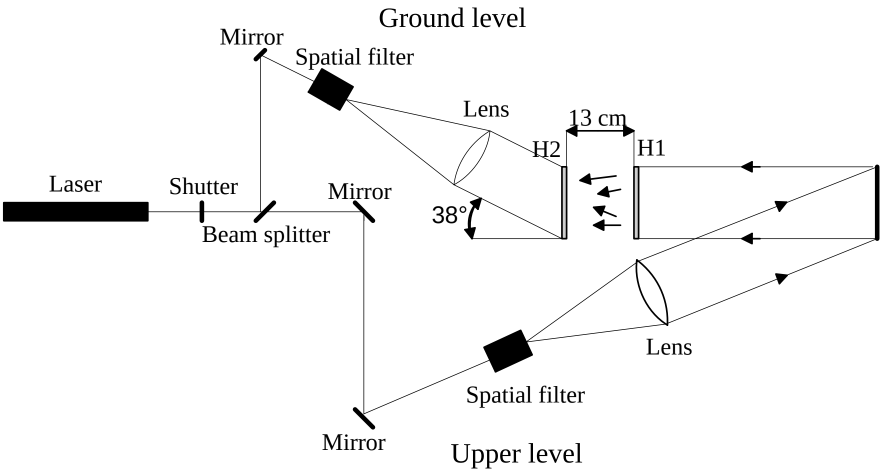

Figure 12-16 Optical set-up for recording 2-step reflection hologram (Seen from the side).

<u>Optical equipment used for the recordings :</u>

He-Ne laser : Output power 24 mW. Wavelength 632.8 nm.
Spatial filters : Pinhole size 10 μm. Microscope objectives 45 x 0.65
Lenses : Diameter 100 mm. Focal length 175 mm.
Mirror : Flatness λ / 10.
Filmplate : Type 10 E 75. Resolution 3000 l / mm.
Filter : Transmission 50 %.

Laser beam distance : Object beam = 205 cm.
Reference beam = 205 cm.

Image 1 :

The set-up for this recording process is the same as described above.

Light power on the film : Object beam = 0.95 μW.
Reference beam = 1.50 μW.

Light power ratio = 1.50 μW / 0.95 ≈ 1.6:1

Exposure time = 100 seconds.

Result : It is impossible to see the image in the hologram, and so the hologram is unfit for use.

Comments : The bad quality of the hologram is probably caused by reflections or vibrations of the optical equipment.

Image 2:

There are some alternations in this recording, where the reference beam's incident angle on the film is changed from 38° to 44°. This alternation is made to decrease the possibility of reflections between the lens and the film.

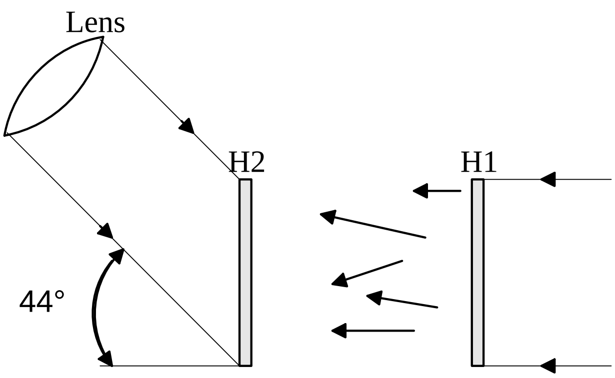

Figure 12-17 Alternation in the recording of image 2 (Seen from above).

The distance between the master hologram (H1) and the film plate (H2) is still 13 cm, and the focus of the real image to the master hologram is still 1 cm from the film.

Light power on the film : Object beam = 0.95 µW.
Reference beam = 1.50 µW.

Light power ratio = 1.50 µW / 0.95 ≈ 1.6:1

Exposure time = 100 seconds.

Result : The hologram is good, but the brightness can be still better.

Comments : There are several things which could have gone wrong during the exposure, and lead to lack of desired brightness.

<u>Image 3 :</u>

The optical set-up is nearly the same as that used for the holographic recording process of image 2. The only difference between this recording and the recording of image 2 is that the reference and object beams are tuned finer, and a better focusing of the beams in the spatial filter is obtained.

Light power on the film : Object beam = 0.95 µW.
Reference beam = 1.50 µW.

Light power ratio = 1.50 µW / 0.95 ≈1.6:1

Exposure time = 100 seconds.

Result : The quality of the hologram is very good. The brightness of the image is also very good.

Comments : With this hologram it has been shown that it is possible to make good 2-step reflection holograms from computer images. An advantage with the 2-step method is that the vertical lines from the slit on the master transmission hologram disappear when it is copied to a new hologram.

An important parameter is the time from when the filmplate is taken out from the refrigerator to when it is used in the holographic recording process. The temperature in the refrigerator is about 4°C and the temperature in the laboratory where the recording process is carried out is about 22° C. There is therefore a temperature difference on the film of 18° C. The emulsion on the film is placed on a plate of glass, and this glass plate will expand when it is heated. This is explained in section 11.4 ″Temperature changes of the film during the exposure″.

Image 4 :

The optical set-up in the recording process of this image is nearly the same as used during the recording process of image 3. The only difference is the short time the film is tempered in the laboratory before the exposure. The temper time is 30 minutes for this image.

Light power on the film : Object beam = 0.95 μW.
Reference beam = 1.50 μW.

Light power ratio = 1.50 μW / 0.95 ≈ 1.6:1

Exposure time = 100 seconds.

Result : The hologram is bright, but there are a area of the hologram that has no information.

Bilde slettet pga for stor størrelse på filen

Figure 12-18 Reconstruction of the reflection hologram.

Comments : The bad quality of the hologram is caused by the lack of thermal stability of the filmplate during the exposure.

<u>Image 5 :</u>

The optical set-up in the recording process of this image is the same as used for the recording process of image 3 and 4. The temper time is 24 hours for this image. The temper time was made so long to ensure that there is no thermal instability on the filmplate.

Result : The hologram is very good.

Bildet slettet pga for stor størrelse på filen

Figure 12-19 Reconstruction of the reflection hologram.

Comments : It is very important that the filmplate is tempered is thermally stable during the exposure.

13 holograms were produced with this optical set-up. The recording data is the same as that used for the production of image 3. Too short a temper time lead to a bad quality hologram. This is solved by using a temper time of 4 hours before exposure.
The quality of these holograms are very good.

12.6 Experiment 6 : Recording 1-step holographic reflection multi-stereograms.

The purpose of this experiment is to make a 1-step reflection hologram from 70 different computer pictures. One of the problems I would have in this experiment is the long exposure time. When we use an exposure time for reflection holograms of about 1 minute and include settle time between each exposure for a total of 70 exposures, we get a total recording time for nearly 2 hours. Another problem with one step hologram is the vertical lines from the slit, which are difficult to remove.

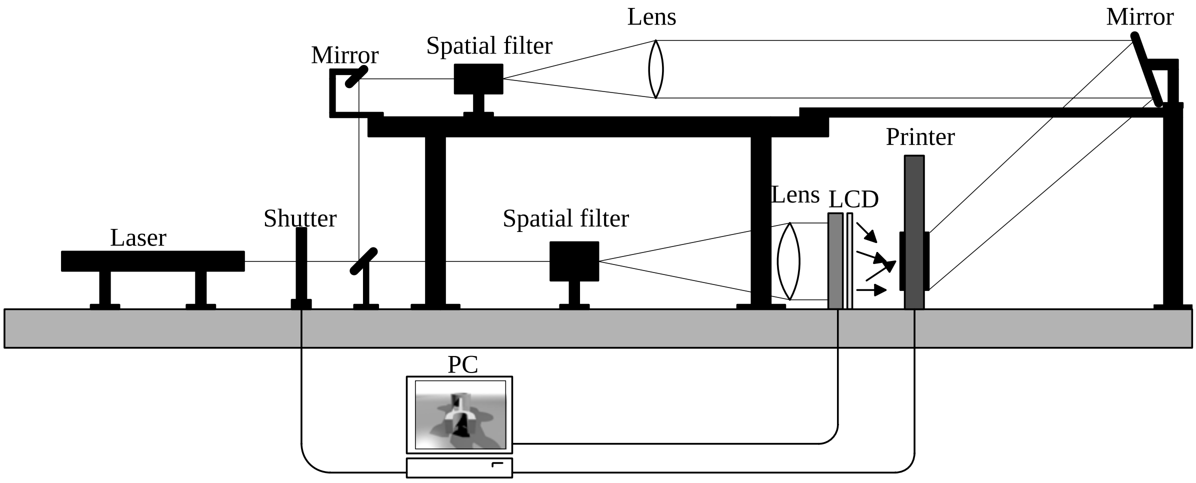

Figure 12-20 Optical set-up for recording 1-step reflection hologram.

<u>Optical equipment used for the recordings :</u>

He-Ne laser : Output power 24 mW. Wavelength 632.8 nm.
Spatial filters : Pinhole size 10 μm. Microscope objectives 45 x 0.65 and 63 x 0.85
Lenses : Diameter 100 mm. Focal length 175 mm.
Mirror : Flatness λ / 10.
Filmplate : Type 8 E 75 HD. Resolution 5000 l / mm.
Filter : Transmission 50 %
LCD : Transparent LCD

Laser beam distance : Object beam = 218 cm.
Reference beam = 209 cm.

<u>Image 1 :</u>

The optical set-up for the exposure of this image is generally the same as shown in figure 12-20. The only difference is that this image is recorded without the holographic printer and with only one exposure. It is an advantage to use only one image exposure when the purpose is to find the right exposure time and to test the optical set-up. Another advantage is the total recording time is for one exposure only instead of for 70, which also reduces the element of unsteadiness like vibrations from the printer.

The ground glass is mounted close to the LCD, and the distance between the LCD and the filmplate is 10 cm. The reference beam illuminates the film from the upper level, and has a incident angle of 50 °. To get the same polarisation direction of the reference and object beam, a half-wave plate is mounted between the mirror and the spatial filter on the reference beam.

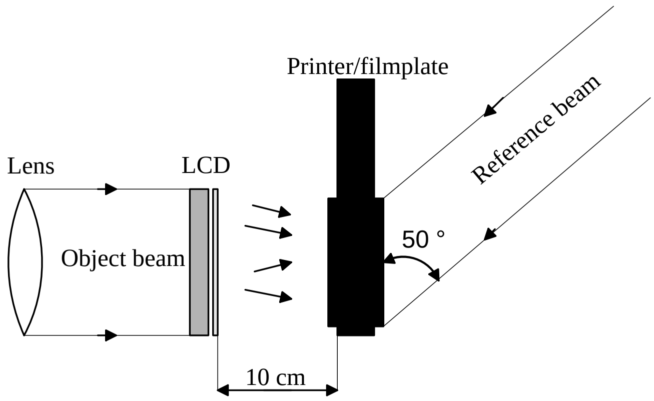

Figure 12-21 Location of optical equipment (seen from the side).

Light power on the film : Object beam = 0.5 μW.
Reference beam = 3.0 μW.

Light power ratio = 3.0 μW / 0.5 μW = 6:1

Half-wave plate = 22 °.

Exposure time : 50 seconds.

Result : The quality of the hologram is good.

Comments : There are no embarrassing reflections on the hologram and so the set-up is used for further image recording. The brightness of the hologram is good, and the exposure time appears to be correct for this light power.

<u>Image 2 :</u>

The aim of this recording process is to make 1- step reflection hologram of computer pictures. To make a holographic image in 3 dimensions, the use of the holographic 3-D printer is necessary. The optical set-up is shown in figure 12-20, where the picture gets exposed with horizontal parallax.

Light power on the film : Object beam = 0.6 μW.
Reference beam = 1.9 μW.

Light power ratio = 1.9 μW / 0.6 μW ≈ 3.2:1

Slit width = 1.70 mm.

Distance the film is to be moved = 1.60 mm.

Half-wave plate = 22 °.

Exposure time : 80 seconds.

The exposure time is longer for this exposure than for image 1, because the light power is lower.

Result : The brightness of the image is good, but the hologram is disfigured by vertical lines from the slit.

Comments : It seems to be impossible to get rid of the vertical lines from the slit.

Chapter 13 : Conclusion

The production of holograms requires high quality and stable optical equipment during the recording process. To meet stability requirements, we need an optical table to reduce the vibration from the ground. To reduce air vibrations in the laboratory a glass cage is mounted on the optical table. Vibrational amplitude were reduced, and the optical set-up became more stable.
The optical set-up for recording holographic multi-stereogram constructed from computer images was arranged in two levels. This makes the set-up more flexible, and it is natural to have reference beam from above, as this is the direction of the reconstruction beam.
To produce 1-step holograms without embarrassing vertical lines from the slit of the printer is impossible. Therefore, the 2-step method is used to produce high quality multi-stereograms without lines from the slit. The master hologram's lines are not transferred to the new hologram in a 2-step procedure.
From a master transmission multi-stereogram high quality 2-step reflection and rainbow holograms are produced. This is also the method to be use in a mass production of holograms, since the recording time for a 1-step reflection hologram is about 2 hours and for a 2-step transmission hologram about 1 minute. There were produced 13 reflection holograms of good quality for EPM consultants, with the use of the 2-step method. Producing 2-step reflection and rainbow holograms from a transmission multi-stereogram was very successful.
To obtain a larger angle of view, and get a better 3-D image on the hologram, the computer pictures should have a longer camera path in the picture production.

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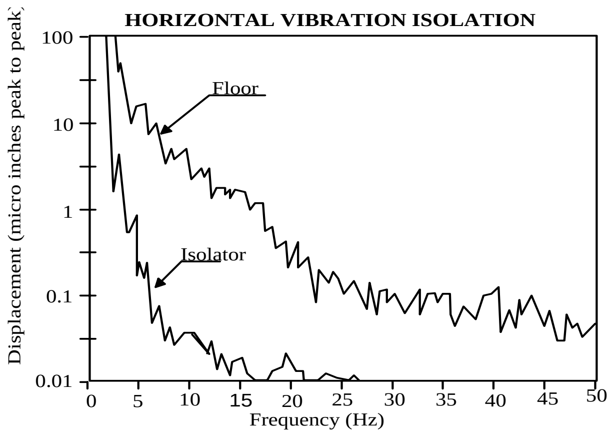
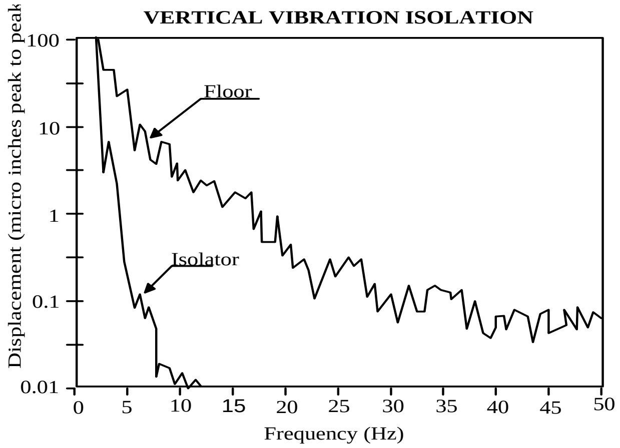
Chapter 15 : Equipment list

Equipment spesifications

Optical table : Technical Manufacturing Corporation (TMC)
Table top dimension : 1220 x 1830 mm, Thickness 200 mm
Hole pattern : 25 mm centres - M6
Load capacity : 1800 kg
Height : 900mm
Vibration isolation system : TMC`s Gimbal Piston isolator, attenuates horizontal and vertical inputs equally
Table pressure : Nitrogen , 5 bar





Optical Breadboard :	Melles Griot Table dimension : 300 x 600 mm, Thickness 60 mm Hole pattern : 25 mm centres - M6 Weight : 25 kg
Standoff posts :	Workshop, Institute of physics : Feet for optical breadboard Height : 310 and 370 mm Diameter : 50 mm Material : Steel Colour : Black
Table extension :	Workshop, Institute of physics Dimension : 480 x 200 mm, Thickness 10 mm Material : Steel Colour : Black
Laser :	Melles Griot : High power red Helium Neon, cylindrical laser head Wavelength : 632.8 nm output Wavelength Power : Minimum CW power output at 632.8 nm is 17 mW Maximum measured CW power is 24 mW Beam diameter : 1 mm Beam divergence : 0.81 Longitudinal mode spacing : 257 Mhz Polarisation ratio : 500:1 Weight : 0.80 kg Static Alignment : Centred to outer cylinder within 0.25 mm and 1.0 mrad Angular drift : < 0.03 mrad after 15 minutes Noise amplitude : < 0.5 % (30 Hz - 30 Mhz rms) typical Starting voltage : 10 kV (DC)
Power Supply:	Melles Griot : Laboratory laser power supplies for cylindrical HeNe laser heads Input voltage : 115 / 230 VAC $\pm$ 10 % Input frequency : 50-60 Hz Input power (max) : 40 W Output current : 7 mA Operating voltage : 2500- 4100 VDC Starting voltage : > 11 kVDC Time delay : 3.5 - 7 seconds

Lenses : Melles Griot : Symmetric-convex glass lenses
Diameter : 100 mm
Focal length : 175 mm
Design wavelength : 546.1 nm
Design index : 1.5187

Square mirrors : Melles Griot : Square flat mirrors
Flatness : $\lambda/10$ at 546 nm over central 90 % of aperture
Surface quality : Low expansion borosilicate glass (LEBG) :
60-40 scratch and dig
Dimension : square 25 mm

Round mirrors : Melles Griot : Round flat mirrors
Flatness : $\lambda/10$ at 546 nm over central 90 % of aperture
Surface quality : Low expansion borosilicate glass (LEBG) :
60- 40 scratch and dig
Dimension : 25 mm diameter

Mirror : Mirror for expanded reference beam
Dimension : 100 x 127 mm

Spatial filters : Ealing Electro optics : spatial filter
The filter is a precision spatial filter with highly stabile unit for tables.

Pinhole : Ealing Electro optics : pinholes
The hole is centred in a 3mm diameter disc of unmounted nickel shim stock 40 microns thick.
Size : 10μm and 25μm.

Microscope objectives : Melles Griot : Achromatic microscope objectives
Power N.A : 63 x 0.85 (N.A $\equiv n \sin\theta = \phi / 2f$)
Working distance : 0.14 mm
Focal length : 3.1 mm
Coating : MgF_2 antireflection coating

Spindler & Hoyer : Microscope objectives

	Power N.A : 40 x 0.65 (N.A $\equiv$ n sin θ = ϕ / 2f) Working distance : 0.67 mm Focal length : 4.68 mm Coating : antireflection coating
Holders for optical equipment's :	Spindler & Hoyer : Adjustable mounts for mirrors Newport : Filmplate holder Melles Griot : Adjustable lens holders Melles Griot : Magnetic holders Melles Griot : Adjustable mirror assemblies and precision beamsteerers Melles Griot : Different types of post holders
Beamsplitter :	Neutral beamsplitter
Shutter :	Electrical exposure shutter, directed by the computer
Half wave plate :	The half wave plate is used to change the direction of polarisation
Polarizator :	Edmund Scientific : Polarizator with extremely good colour reproducibility Colour : grey UV absorption : > 99 % Average extinction (crossed) : 0.04 % Transmission : 38 % Dimensions : 300 x 350 mm, Thickness : 0.4 mm
Ground Glass :	The ground glass are spreading the light from the LCD display
Computer :	IBM PC : 433 DX Microprossesor : 486 DX RAM : 16 MB
Display :	ASK : Impact 256 Size : 310 x 310 x 40 mm

Weight : 2200 grams
Power : -5, -12, 5 V (Universal)
LCD cell : Double scan CSTN
Colour resolution : 256 thousand
Response time : 130 ms
Contrast ratio : 18 :1
Pixel resolution : 640 x 480 x 3
Resolution : 640 x 480 (VGA Mode)
: 800 x 600 (SVGA Mode)
Video frequency : 25 - 35 Mhz
Horizontal sync : 15 - 40 kHz
Vertical sync : 60 - 76 Hz (VGA)
: 56 - 60 Hz (SVGA)

Software : Windows 3.0
Arip Control : Controls the Dac pictures to the LCD screen, and conduct the 3D printer and the exposure

Pico Log : Data logging software
Lotus 1-2-3, 4.0
Word 6.0
Symphony
AutoCAD release 13
Corel
Visio 4.0

Printer : Moving the Holographic film plate to the right position, an keep it fixed under the exposure.

Film : Holographic film fro AGFA Gevart Holotest.
Transmission and rainbow holograms : 10 E 75
Reflection holograms : 8 E 75 HD

Photometer : Metrologic
Laser power meter
Power range 0.01µW to 20 mW.