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Holography

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Abstract

The goal of this experiment is to understand the main concepts of holography. For this reason two different types of experiments are conducted, a reflection holography and transmission holography.

Contents

1 Introduction

Holography is a two step process developed by Dennis Gabor in 1948. Gabor recognized that when a suitable coherent *reference wave* is present simultaneously with a wave diffracted by an object, information about both the amplitude and phase of the diffracted wave can be recorded, even though the recording media responds only to light intensity. It was not, however, until the 60's that a true revolution in holography began, the emerging technology of the lasers enabled to preform lensless three-dimensional photography, in which an image is captured not as an image focused on film, but as an interference pattern in the film. Typically, coherent light from a laser is reflected from an object and combined at the film with light from a reference beam. When developed this recorded interference pattern, referred to as a *hologram*, actually contains much more information than a focused image, and enables the viewer to view a true three-dimensional image which exhibits parallax. That is, the image will change its appearance if you look at it from a different angle, just as if you were looking at a real 3D object. However many of the most interesting and useful properties of holography are quite independent and separated of the three-dimensional image capability.

2 Wavefront Reconstruction

The fundamental problem addressed by holography is that of recording, and later reconstructing, both the amplitude and and phase of an optical wave arriving from a coherently illuminated object. This problem is sufficiently general to be of interest for electromagnetic waves in all regions of the spectrum, as well as acoustic and seismic waves. However, our consideration here will be restricted to the optical problem.

2.1 Recording Amplitude and Phase

Since recording media respond only to light intensity it is required that phase information will be somehow converted to intensity variations for recording purposes. A standard technique to accomplish that is *interferometry*; that is, a second wavefront, mutually coherent with the first and with a known amplitude and phase, is added to the unknown wavefront, as shown in figure 1.

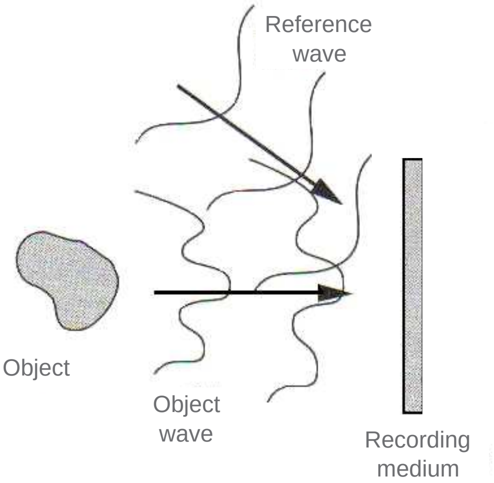

Figure 1: Interferometric recording

The intensity of the sum of two complex fields then depends on both the amplitude and phase of the unknown field. Thus if

$$a(x,y) = |a(x,y)|\, e^{-i\phi(x,y)} \tag{1}$$

represents the wavefront to be detected and reconstructed, and if

$$A(x,y) = |A(x,y)|\, e^{-i\psi(x,y)} \tag{2}$$

represents the reference wave with which $a(x,y)$ interferes, the intensity of the sum is given by

$$\mathcal{I}(x,y) = |A(x,y)|^2 + |a(x,y)|^2 + 2|A(x,y)|\,|a(x,y)|\,\cos[\psi(x,y) - \phi(x,y)] \tag{3}$$

While the first two terms of the above expression depend only on the intensities of the individual waves, the third depends on their relative phases. Thus information of both amplitude and phase of $a(x,y)$ have been recorded, and *the resulting patten of interference between the object wave and reference wave is referred to as hologram.*

2.2 The Recording Medium

2.2.1 Amplitude Transmittance vs. Exposure

When a photographic film or plate exposed to coherent light is used as an element of a *coherent* optical system it should be regarded as providing a mapping of complex amplitude incident during exposure ($\mathcal{I}$) into complex amplitude transmitted after development (t_A). Since the complex amplitude of the transmitted light is an important quantity, it is necessary to describe the transparency[1] in terms of its *complex amplitude transmittance* t_A. Figure 2 shows a plot of amplitude transmittance vs.

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[1] of a developed film or plate

exposure (the $t_A - E$ curve) for a typical negative transparency. Where the exposure (E) is defined as the energy incident per unit area on a photographic emulation during the exposure time (T). The exposure can also be written as a product of the incident intensity at each point and the exposure time.

$$E(x, y) = \mathcal{I}(x, y)T$$

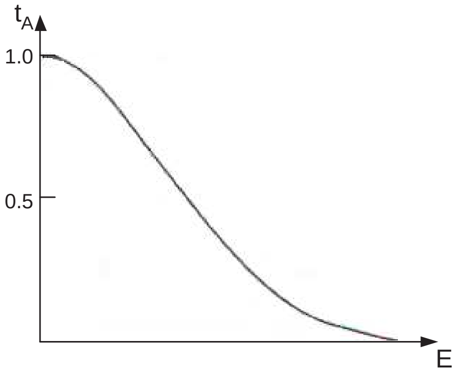

Figure 2: Typical amplitude transmittance vs. exposure curve.

As can be seen from the graph, if a film is "biased" to an operating point that lies within the region of maximum linearity of this curve, than over a certain dynamic range of linearity we obtain,

$$t_A \approx t_b + \beta(E - E_b) = t_b + \beta'|\Delta U|^2 \tag{4}$$

where E_b represents the bias exposure and t_b the corresponding transmittance amplitude, β is the slope of the curve at the bias point, ΔU represents the incremental amplitude changes and β' is the product of β and exposure time.

2.2.2 Recording Media for Holograms

The material used to record the interference patten will be assumed to provide a linear mapping of intensity incident during the detection process ($\mathcal{I}$) into amplitude transmitted by (or reflected from) the material during the reconstruction process (t_A). Usually both light detection and wavefront modulation are preformed by photographic film or plate. The linear relation is then provided by operation in the linear portion of the t_A vs. E curve of the emulation as explained above[2]. However, many other materials suitable for holography exist, including photopolymers, dichromated gelatin, photorefractive materials etc. It is even possible to detect the interference pattern electronically and reconstruct the wavefront with a digital computer. Yet, photographic materials remain the most important and widely used recording medium.

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[2] Note, however, that the transparency $T = |t_A|$ of the developed material has a nonlinear relationship to the exposure E $T = 1 - \gamma E^2$.

Thus we assume that the variation of exposure remain within the linear zone of the t_A vs. E curve. In addidtion we assume that the Modulation transfer function of the recording material extends to sufficiently high spatial frequency to record all the incident spatial structures. Finally we assume that the intensity $|A|^2$ of the reference wave is uniform across the recording material. In this case the amplitude transmittance of the developed film or plate can be written

$$t_A(x,y) = t_b + \beta'(|a(x,y)|^2 + A^*(x,y)a(x,y) + A(x,y)a^*(x,y)). \tag{5}$$

This might be also the place to note that one of the most unique properties of holographic materials is that they must be capable of recording extremely fine structures, as compared with the structures encountered in ordinary photography. The spatial frequency response of holographic recording materials often exceeds 2000 cycles/mm, whereas in conventional photography, a spatial frequency response of 200 cycles/mm is considered high. An outcome of this fact is the low sensitivity of holographic materials in relation to photographic materials. High resolution is achieved by constructing emulsion with very small grain size, but a certain number of photons must be absorbed by each grain to make it developable[3]. From this follows that the energy density needed to expose high-resolution materials are much greater than those required for low-resolution materials.

2.3 Reconstruction of the Original Wavefront

Once the amplitude and phase of the object $a(x,y)$ have been recorded, the reconstruction of that wave from the developed hologram is the last step to complete the process. Suppose that the developed transparency is illuminated by a *reconstruction wave* $B(x,y)$. The light transmitted by the transparency is given by

$$\begin{aligned} B(x,y)t_A(x,y) &= t_bB + \beta' aa^*B + \beta' A^*Ba + \beta' ABa^* \\ &= U_1 + U_2 + U_3 + U_4. \end{aligned} \tag{6}$$

If B is an exact duplication of the original uniform reference wavefront A the third term of this equation becomes

$$U_3(x,y) = \beta'|A|^2 a(x,y). \tag{7}$$

Since the intensity of the reference wave is uniform, the reconstructed wave component $U_3(x,y)$ is, up to a multiplicative constant, an exact duplication of the original wavefront $a(x,y)$. In a similar manner, if $B(x,y)$ is chosen to be the conjugate of the original reference wave, the fourth term becomes

$$U_4(x,y) = \beta'|A|^2 a^*(x,y). \tag{8}$$

which is proportional to the conjugate of the original wavefront. Both cases are illustrated in figure 3.

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[3] A more detailed description of the work mechanism and structure of the photographic film is given in a later section

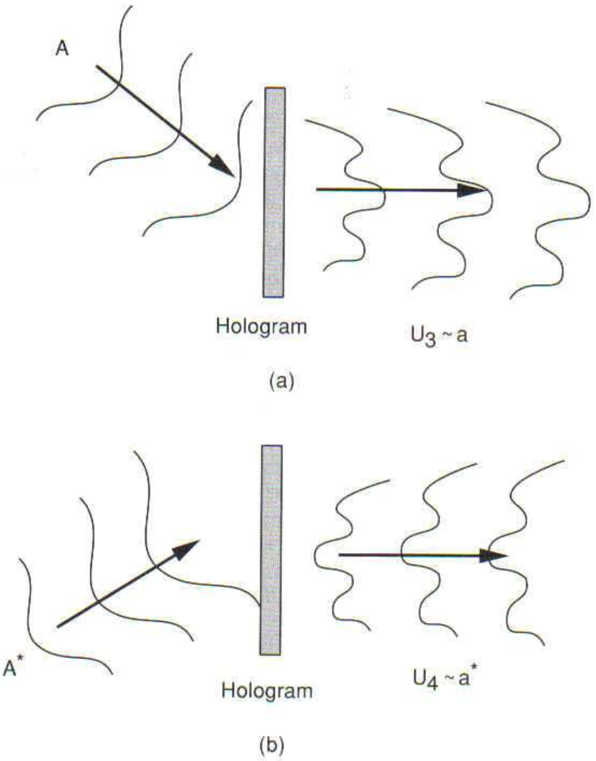

Figure 3: Wave front reconstruction with (a) $B(x, y) = A(x, y)$ and (b) $B(x, y) = A^*(x, y)$.

Not that in either case the field component of interest is accompanied by three additional field components, hence a method for separating these components of transmitted light is required.

2.4 Image Formation

So far we considered a problem of reconstructing the wavefront which arrived at the recording medium from a coherently illuminated object. A small change of view point is required to regard the wavefront reconstruction in means of *image formation.*

To adopt this point of view the wave component $U_3(x, y)$ of equation (7), must appear to the observer as diverting from the original object, even though the object has been removed. Consequently, when the reference wave $A(x, y)$ is used as illumination during reconstruction, the transmitted wave component $U_3(x, y)$ generates a *virtual image* of the original object. This case is illustrated in figure 4(a) and (b) for the case of a simple point-source object.

In a similar way, the usage of $A^*(x, y)$ as illumination during reconstruction will generate an image from wave component $U_4(x, y)$ of equation (8). This is a *real image* that corresponds to an actual focusing of light in space. To prove this assertion, we invoke the linearity property of $U_4(x, y)$, considering an object which consist of a single point source. The corresponding result for more complicated objects can then by found be linear superposition of point-source solutions.

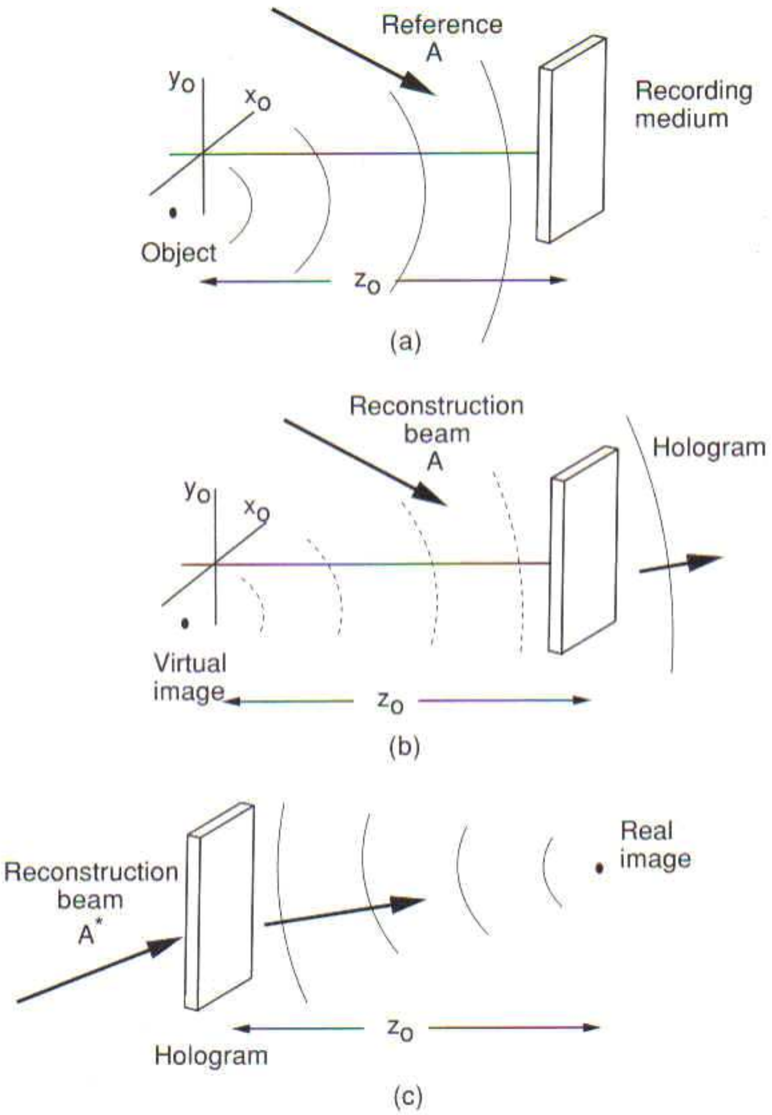

Figure 4: Imaging by wavefront reconstruction. (a) recording the hologram of a point-source object; (b) generation of the virtual image; (c) generation of the real image.

As illustrated in figure 4(a) the sum of the reference wave $A(x, y)$ and a simple spherical object wave is incident on the recording medium. The spherical wave can be written as

$$a(x, y) = a_0 \exp\left[ik\sqrt{z_0^2 + (x - \hat{x}_0)^2 + (y - \hat{y}_0)^2}\right]$$

where $(\hat{x}_0, \hat{y}_0)$ are the coordinates of the object point, and z_0 is its distance from the recording plane. Illuminating the developed hologram with a reconstruction wave

$A^*(x,y)$ we obtain the transmitted wave component

$$\begin{aligned} U_4(x,y) &= \beta'|A|^2 a^*(x,y) \\ &= \beta'|A|^2 a_0^* \exp\left[-ik\sqrt{z_0^2+(x-\hat{x}_0)^2+(y-\hat{y}_0)^2}\right], \end{aligned} \tag{9}$$

which is a spherical wave that *converges* toward a real focus at distance z_0 to the right of the hologram as shown in figure 4(c).

2.5 Axial and Transverse Image Magnification

As can be seen in figure 5(a) we take for this discussion the reference wave to be a *spherical wave* created by a point source located at coordinates (x_r, y_r, z_r). Since the mapping of object amplitude into image amplitude is linear, once the necessary separation of the different field components is done, it is sufficient to consider the object as a single point source located at coordinates (x_o, y_o, z_o).

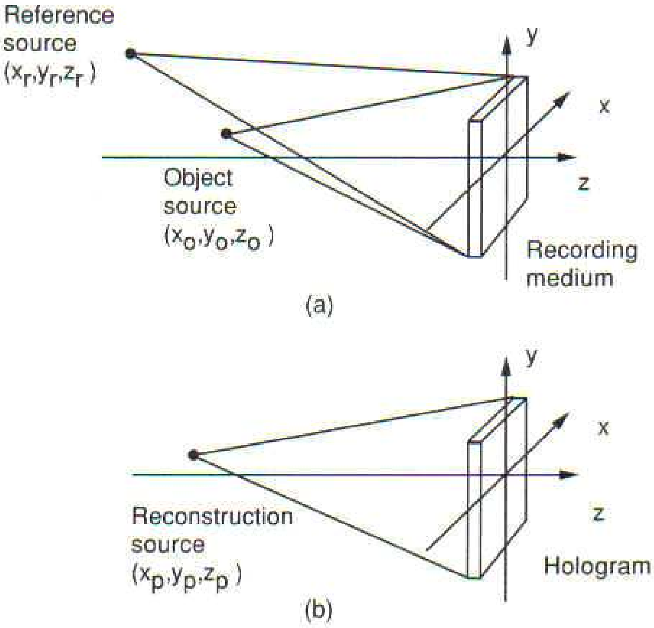

Figure 5: Generalized (a) recording and (b)reconstruction geometries.

During the reconstruction step, illustrated in figure 5(b), the hologram is assumed to be illuminated by a spherical wave originating from a point source at coordinates (x_p, y_p, z_p). To be as general as possible we allow the recording and reconstructing processes to involve radiation of different wavelength. The recording wavelength will be noted as λ_1 and the reconstruction wavelength as λ_2.

Taking the coordinates of the images to be (x_i, y_i, z_i), one can write the transverse magnification as

$$M_t = \left|\frac{\partial x_i}{\partial x_o}\right| = \left|\frac{\partial y_i}{\partial y_o}\right| = \left|\frac{\lambda_2 z_i}{\lambda_1 z_o}\right| = \left|1 - \frac{z_o}{z_r} \mp \frac{\lambda_1 z_o}{\lambda_2 z_p}\right|^{-1}$$

and the axial magnification as

$$M_a = \left|\frac{\partial z_i}{\partial z_o}\right| = \left|\frac{\partial}{\partial z_o}\left(\frac{1}{z_p} \pm \frac{\lambda_2}{\lambda_1 z_r} \mp \frac{\lambda_2}{\lambda_1 z_o}\right)^{-1}\right| = \frac{\lambda_1}{\lambda_2} M_t^2$$

where the upper set of signs applies for one image and the lower set of sings for the other. As can be seen, the transverse and axial magnification are generally not identical. This will create a distortion of the images in the case of three dimensional objects. To fix these distortion one can *scale* the hologram itself between the recording and reconstruction processes. Such manipulation of the hologram will not be necessary in our experiment.

3 Leith-Upatnieks Transmission Hologram

3.1 Recording the Hologram

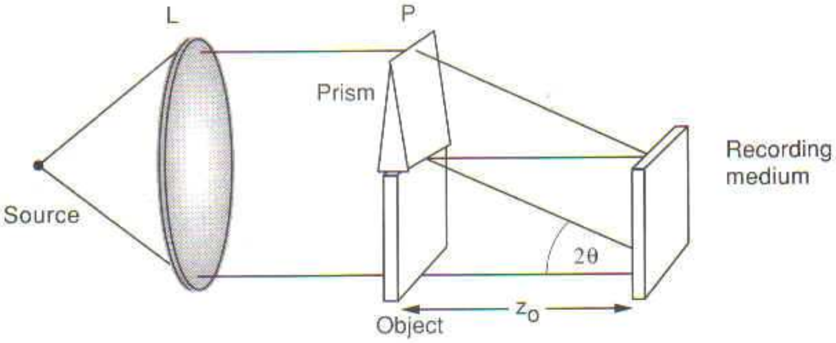

Figure 6: Recording a Leith-Upatnieks hologram.

Figure 6 illustrates one of the possible geometries to record a Leith-Upatnieks hologram. The light from a point illumination source is collimated by the lens L. A portion of the resulting plan wave strikes the object, which is taken to be a transparency with a general amplitude transmittance of $t(x_0, y_0)$. A second portion of the plain wave hit a prism P located above the object and is deflected downwards at an angle 2θ with respect to the norm of the recording plain. As a result a sum of two mutually coherent waves is incident on the recording surface. Hence, the amplitude distribution incident on the recording plane can be written as

$$U(x, y) = A \exp(-i2\pi\alpha\, y) + a(x, y), \tag{10}$$

where the spatial frequency α of the reference wave is given by

$$\alpha = \frac{\sin(2\theta)}{\lambda} \tag{11}$$

The intensity distribution across the recording plane is then

$$\begin{aligned}\mathcal{I}(x,y) = |A|^2 &+ |a(x,y)|^2 \\ &+ A^* a(x,y) e^{i2\pi\alpha\, y} + A a^*(x,y) e^{-i2\pi\alpha\, y}.\end{aligned} \tag{12}$$

Substituting equation (1) in the above equation we obtain

$$\mathcal{I}(x,y) = |A|^2 + |a(x,y)|^2 + 2|A|\,|a(x,y)| \cos[2\pi\alpha\, y - \phi(x,y)]. \tag{13}$$

The phase and amplitude recording of $a(x,y)$ can clearly be seen in the last expression, as well as the amplitude and phase modulation of the spatial carrier of frequency α. If the carrier frequency is high enough, the amplitude and phase distribution can be unambiguously recovered from this pattern of interference.

3.2 Obtaining the Reconstructed Image

The recording and development processes yield a transparency with an amplitude transmittance proportional to exposure, the film transmittance is therefore

$$t_A(x,y) = t_b + \beta' \left[|a(x,y)|^2 + A^* a(x,y) e^{i2\pi\alpha\, y} + A a^*(x,y) e^{-i2\pi\alpha\, y}\right]. \tag{14}$$

Assuming that the hologram is illuminated by a normally incident uniform plain wave B, as shown in figure 7 . The field transmitted by the hologram has four distinct components:

$$\begin{array}{ll} U_1 = t_b\, B & U_3 = \beta' B A^* a(x,y) \exp(i2\pi\alpha\, y) \\ U_2 = \beta' B |a(x,y)|^2 & U_4 = \beta' B A a^*(x,y) \exp(-i2\pi\alpha\, y). \end{array} \tag{15}$$

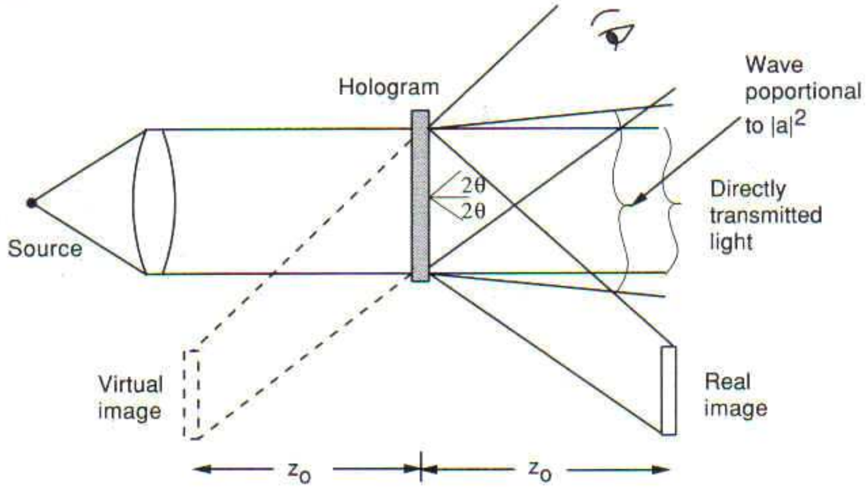

Figure 7: Reconstruction of images from a Leith-Upatnieks hologram.

Field component U_1 is simply an attenuated version of the incident reconstruction illumination, representing a plane wave traveling down the optical axis. The second term U_2 is spatially varying and therefore has plane wave components traveling at various angels with respect to the optical axis. However, if the bandwidth of $a(x, y)$ is sufficiently small compared to the carrier frequency α, the energy of this wave component remains close enough to the optical axis and thus allow spatial separation between this wave component and the images of interest[4].

The wave component U_3 is proportional to the original object wavefront $a(x, y)$ multiplied by a linear exponential function. The fact that this wave component is proportional to a implies that it generates a virtual image of the object at a distance z_0 to the left of the transparency while the linear exponential factor $\exp(i2\pi\alpha\, y)$ indicates that this image is deflected away from the optical axis at an angle 2θ, as shown in figure 7. In a similar way, U_4, which is proportional to the conjugated waveform $a^*(x, y)$ multiplied by $\exp(-i2\pi\alpha\, y)$ indicates the formation of a real image at a distance z_0 to the right of the transparency, this image is deflected at an angle -2θ from the optical axis. All the different wave components in the reconstruction process are illustrated in figure 7.

This means that by using a tilted reference wave in the recording process, we can achieve the desired separation of the different components of the transmitted field from each other during the reconstruction process. Another important point to note is that of the chosen reconstructing wave. Although we chose B as a normally incident plane wave, which is neither a duplication of the original reference wave nor of its complex conjugate, we still obtained both the real and virtual images simultaneously. Clearly, our conditions concerning the required nature of the reconstructing illumination were over restrictive. However, when we will consider the effects of the thickness of the emulsion on the reconstructed wavefronts, the exact nature of the reconstructed wave will become more important.

4 Reflection Hologram

In the *transmission* type of holograms discussed above, we view the images in light that has been transmitted through the hologram. Such holograms are reasonably tolerant to the wavelength used during the reconstruction process[5] in the sense that a bright image can be obtained without exactly duplicating the wavelength used during exposure. However, the usage of white light leads to chromatic blur in this type of holograms, which means that some filtering of the source is generally required.

In the *reflection* type of holograms, on the other hand, we view the images in the light that is reflected from the hologram. The most widely used type of reflection hologram is that invented by Y. Denisyuk, the method for recording such a hologram

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[4] Carrier frequencies α, for which the spatial frequency spectra of the different terms of hologram transmittance t_A do not overlap are given by $\alpha \geq 3B$, where B is the highest spatial frequency component. This corresponds to $2\theta_{min} = \sin^{-1}(3B\lambda)$.
If the reference wave is much stronger than the object wave, *i.e.* $|a| \ll |A|$, the last requirement is reduced to $2\theta_{min} = \sin^{-1}(B\lambda)$.

[5] The amount of tolerance depend on the thickness of the emulsion

is illustrated in figure 8(a).

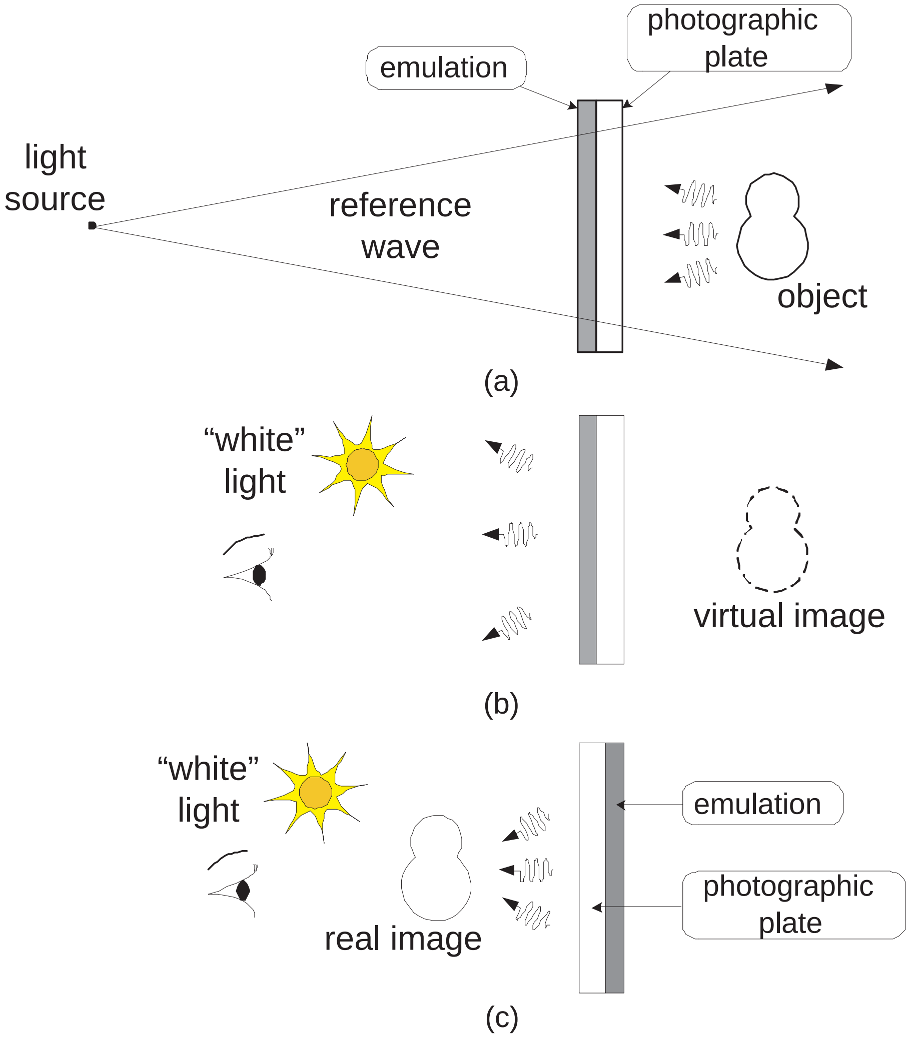

Figure 8: (a) Recording a reflection hologram, and reconstructing the (b) virtual and (c) real image in reflected light.

As can be seen there is only one illumination beam, which supplies both the object illumination and the reference beam simultaneously. The incident beam first falls upon the holographic emulsion, were it serves as a reference wave. It then passes through the photographic plate and illuminates the object, which is usually three dimensional. Light scattered backwards from the object, towards the recording plane, and passes through the emulsion traveling in a direction that is approximately opposite to that of the original incident beam. The two beams interfere within the emulsion to produce a standing interference pattern with extremely fine fringes. As will be seen next, the fringes are oriented such that they bisect the angle between the directions of travel of the reference and object waves, and are therefore approximately *parallel to the surface of the emulsion for a reflection hologram.* We will also see that the period of sinusoidal fringe formed when two plane waves traveling at angle 2θ with respect to each other interfere is given by

$$\Lambda = \frac{\lambda}{2\sin\theta}$$

and if $2\theta = 180^{\circ}$, as in the case of a reflection hologram we get

$$\Lambda \approx \frac{\lambda}{2}.$$

Figure 8(b) shows how to obtain the virtual image from the recorded reflection hologram. The hologram is illuminated by a duplication of the original reference wave, and a duplicate of the object wave is generated, which is in this case a reflected wave. The observer looks into the reflected wave and sees the virtual image in the original location of the object, behind the hologram.
This type of holograms can be illuminated with white light since it is highly wavelength selective. The wavelength that satisfies the Bragg condition will automatically be reflected, while others will not. It should also be noted that photographic emulsion usually suffer from shrinkage during the chemical processing and drying steps, and therefore the color of the light reflected from this type of hologram will usually be different than that used during recording.

5 Influence of Emulsion Thickness

Although the treatment of a hologram so far was as if it was made from a *thickless* layer of emulsion, a hologram is, in fact, a stationary grating. While the typical emulsion thickness on a holographic plate is 6-17 μm, the transversal period of interference pattern is about the same order of magnitude as the wavelength of the recording wave. In our experiment, the recording wave arrives from a He-Ne-Laser, which has a wavelength of 6328 Å or 0.63 μm, thus up to 20 periods of interference can be recorded on the emulsion. Holograms behave differently depending on the relation between period of finest fringe they contain and the thickness of the recording medium. It is therefore common to categorize holograms as *thick* or *thin*, depending on this relation.

5.1 Recording a Volume Holographic Grating

Consider the simple case of a plane reference wave and a plain object wave incident on a emulsion of a nonneglectable thickness. These two plain wave generate a simple holographic grating, as illuminated in figure 9. We assume for simplicity that the two wave normals (represented by arrows and pointing in the direction of the two $\vec{k}$ vectors), are each inclined at angle θ to the surface normal. Successive lines of zero phase are shown dotted; the wavefronts of each wave are spaced by a distance of one wavelength. Along the lines (points in this two dimensional figure) within the emulsion where the wavefronts of the two waves intersect, the two amplitude add in phase, yielding high exposure. As time progresses, the wavefronts move in the direction of their respective wave normals, and the lines of constructive interference move through the emulsion, tracing out *planes* of high exposure. Simple geometry shows that these planes bisect the angle 2θ between the two wave normals and occur periodically throughout the emulsion[6].

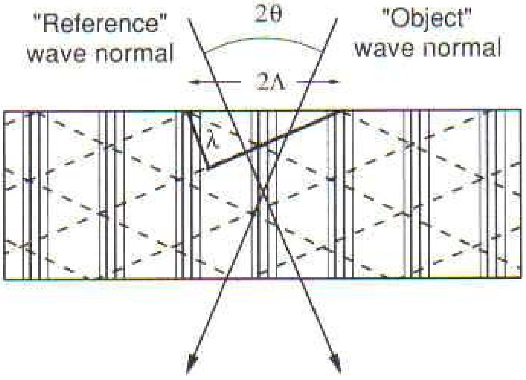

Figure 9: Recording an elementary hologram with a thick emulsion.

From figure 9 we can also deduce the period Λ of the grating as

$$2\Lambda \sin\theta = \lambda. \tag{16}$$

When the photographic plate is developed, silver atoms will appear concentrated along the quasi-planes of high exposure, which we will call silver platelets. The distance between these platelets is the Λ specified above.

5.2 Reconstructing Wavefronts from a Volume Grating

When trying to reconstruct the object plane wave by illuminating the volume grating with a reconstructing plane wave, a question arises as to what angle of illumination should be used to obtain a reconstructed object wave of maximum intensity. To answer this question we can regard each silver platelet as a partially reflecting mirror, which diverts part of the incident wave according to the usual low of reflection, and transmits part of the wave. [7] If the plane wave illumination is incident on the silver

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[6] The fringes formed in the recording medium are *always* oriented locally to bisect the angle between the two interfering waves within the medium. One should remember, though, that the angle between the two waves within the recording medium is different than the angle between them external to the medium, due to the generally higher refractive index of the recording medium.

[7] As will be described later, we use a process called *bleaching* in our experiment. The bleaching process removes the silver atoms and causes refractive index variation within the emulsion according to the change in silver atoms density. It is clear, in this case, that also the plane between the two different index of refraction (concerning the simple case) transmits part of the wave and reflects the other part. Since the outcome in both cases is the same, the description of the following regards both cases.

platelets at an angle α, as shown in figure 10 the reflected wave will travel in a direction satisfying the law of reflection. The reflections occur at all the platelets and the different partial reflections are to be added in phase, hence it is essential, that the various path-lengths traveled by waves reflected from adjacent platelets will differ by an *integer number of optical wavelength.* We will consider here only the case of a path length-difference of exactly one optical wavelength, which corresponds to the first order diffracted wave. From the geometry plotted in figure 10 we can deduce that this requirement will be satisfied only if the angle of incident light satisfies the Bragg Condition.

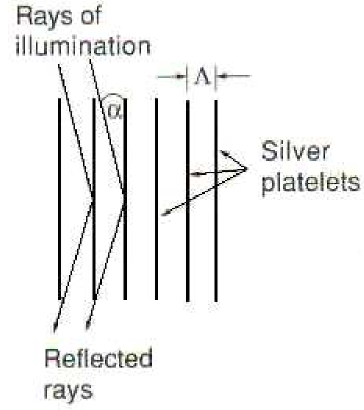

Figure 10: Reconstruction geometry.

$$\sin\alpha = \pm\frac{\lambda}{2\Lambda}. \tag{17}$$

Comparison of equations (16) and (17) shows that the maximum intensity of the diffracted wave will be obtain only if

$$\alpha = \begin{cases} \pm\theta \\ \pm(\pi-\theta). \end{cases} \tag{18}$$

This is a very important result, as it indicates the condition necessary to obtain a reconstructed plane wave of maximum intensity.

6 The Photographic Film, Structure and Principle of work

An unexposed photographic film or plate generally consist of a large number of tiny silver-halide grains (most often AgBr) suspended in a gelatin support, which is attached to a firm "base" consisting of acetate or mylar[8] for films, and glass for plates. The soft emulsion has also a thin protective layer on its exposed surface, as

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[8] Mylar basis should be avoided when coherent light is used

shown in figure 11. The atoms in the silver-halide crystals are arranged in a cubic lattice and each crystal contains many point defects, where a silver ion is displaced and is free to move through the crystal. In addition certain sensitizing agents are added to the gelatin; these agents have a strong influence on the introduction of dislocation centers[9] within the silver-halide crystals.

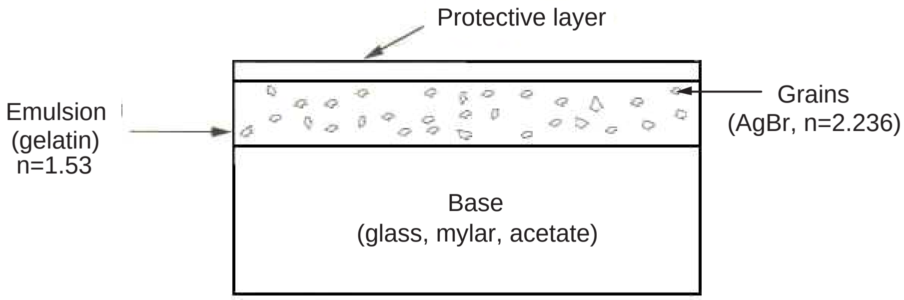

Figure 11: Structure of a photographic film or plate

Light incident on the emulsion initiates a physical process that is outlined as follows:

1. A photon incident on a silver-halide may or may not be absorbed by that grain. If absorbed, an electron-hole pair is released within the grain.
2. The resulting electron is in the conduction band and is mobile within the silver-halide crystal. This electron has a certain probability to become trapped at a crystal dislocation.
3. The trapped electron electrostaticaly attracts a silver ion within the silver-halide crystal. This ions are mobile even before exposure due to thermal agitation.
4. The electron combines with the silver ion to form a single silver atom of metallic silver at the dislocation site. The lifetime of this single atom is rather sort, of the order of a few seconds.
5. If within the lifetime of the single silver atom a second silver atom is formed by the same process at the same site, a more stable two atom unit is formed with the lifetime of a few days.
6. A few more silver atoms have to be added to the silver speck in order for it to be developable. The existence of a threshold, requiring several trapped electrons to activate the development process is responsible for good stability of unexposed film on the shelf.

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[9] A dislocation is like a defect except that instead of just one lattice ion missing, a whole plane of the crystal may be offset.

The collection of silver specks present in an exposed emulsion is referred to as the *latent image*, at this point the film is ready for the development and fixing processes. The exposed photographic transparency is immersed in a chemical bath of the *developer*, which acts on silver specks with more than the threshold[10] number of silver atoms. For such grains, the developer cause the hole crystal to be reduced to metallic silver. At this point we have two types of grains in the emulsion, those that became silver and those that did not absorbed enough light to form a development center. The second type are still silver-halides, and without further processing will turn silver themselves through thermal processes. To assure stability of the image, the undeveloped silver-halides crystals are removed from the emulsion in a process called *fixing*. This is done by immersing the developed transparency in a second chemical bath. At the end of this process only the developed metallic silver is left in the emulsion. The processes of exposure, development and fixing are illustrated in figure 12.

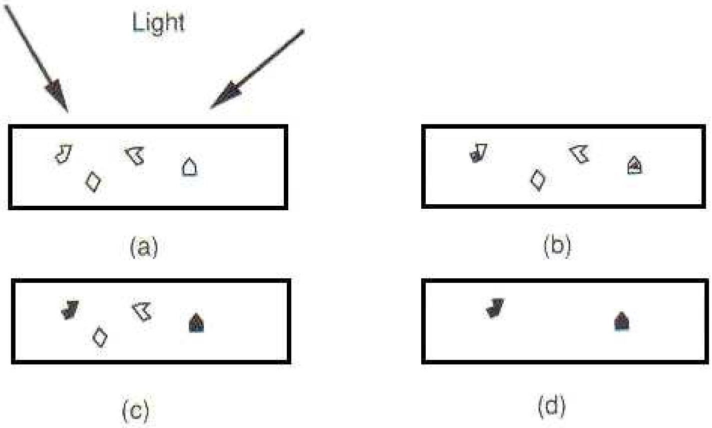

Figure 12: Pictorial representation of the photographic process. (a) Exposure, (b) latent image, (c) after development and (d) after fixing.

6.1 Bleaching of Photographic Emulsion

conventional photographic emulsions modulate light primarily through absorption caused by the metallic silver present in the transparency. As a result, significant amounts of light are lost when an optical wave passes through such a spatial modulator. In holography, as well as in many other applications, a more efficient modulator in required, one that operates primarily through *phase modulation* rather than absorption. Such structures can be realized with photographic materials using *chemical bleaching*.

The bleaching process removes metallic silver from the emulsion and leaves in its place either an emulsion thickness variation or a refractive index variation within the emulsion. A *tanning bleach* causes a thickness variation while a *nontanning bleach* modulates the refractive index.

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[10] The threshold is actually not a fixed number but a statistical one, which we can approximate as four silver atoms

The chemical agents used in a tanning bleach release certain chemical byproducts as they remove the metallic silver. These byproducts causes a cross-linking of the gelatin molecules within the emulsion in regions in which the the silver concentration was high. As the transparency drys the hardened areas shrink less than the unhardened areas, resulting in a so called *relief image*. In a relief image the thickest region in the emulsion is the region that had the highest concentration of silver and the thinest region is the one that had the lowest concentration of silver.

A nontanning bleach, on the other hand, produces an internal refractive index change rather than a relief image. It changes the metallic silver within the developed transparency back to transparent silver-halide crystals, which have a much higher refractive index than the surrounding gelatin, see figure 11. In addition, the bleach must remove the sensitizing agents found in unexposed silver-halide crystals to prevent them from turning to metallic silver due to thermal effects and additional exposure to light. In this experiment we will be using a nontanning bleach that is already combined with a fixing agent.

7 Experiment

7.1 Reflection Hologram

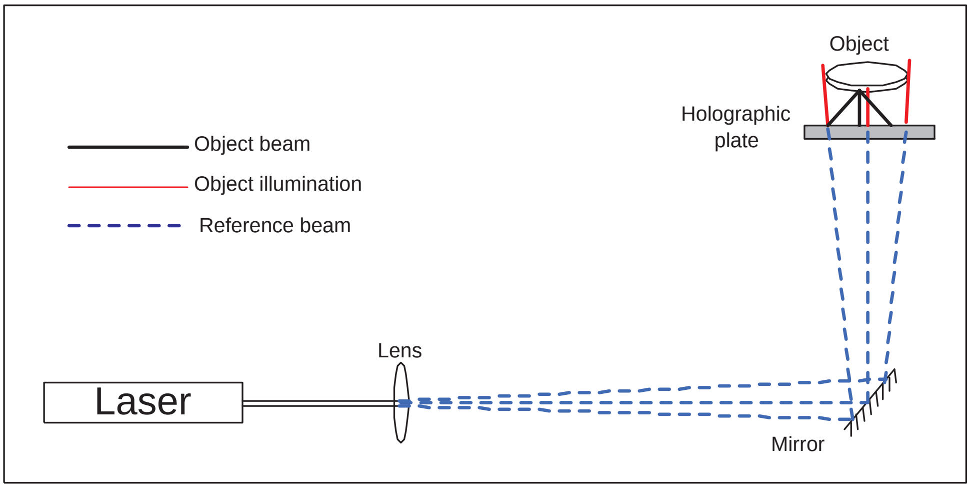

Figure 13: Experimental setup for reflection hologram.

To create a reflection hologram one should use the setup shown in figure 13. As discussed before the reference and object beam should illuminate the emulsion from opposite sides to create this type of white light hologram.

To obtain maximal intensity of the object wave we should use metal or aluminum objects and place them as close as possible to the photographic emulsion. Using other objects or placing objects far from the emulsion will make it to difficult to produce a hologram with our equipment. We therefore use a setup in which the photographic plate will also be used as a "table" to place the objects. Place the magnetic optical board transverse to the table. Switch on the 632.8 nm red laser beam and adjust its pass to be parallel to the table. The beam should then incident on the center of the mirror and be reflected upwards on to the photographic plate holder. Once all is ready you can start the recording process, *from this stage on the room should be completely dark!* Take the box with the photographic plates to the dark room, open it, and place one plate in the plate holder while the shutter of the laser is closed. To record the hologram, open the shutter for 5-7 sec.

7.2 Transmission Hologram

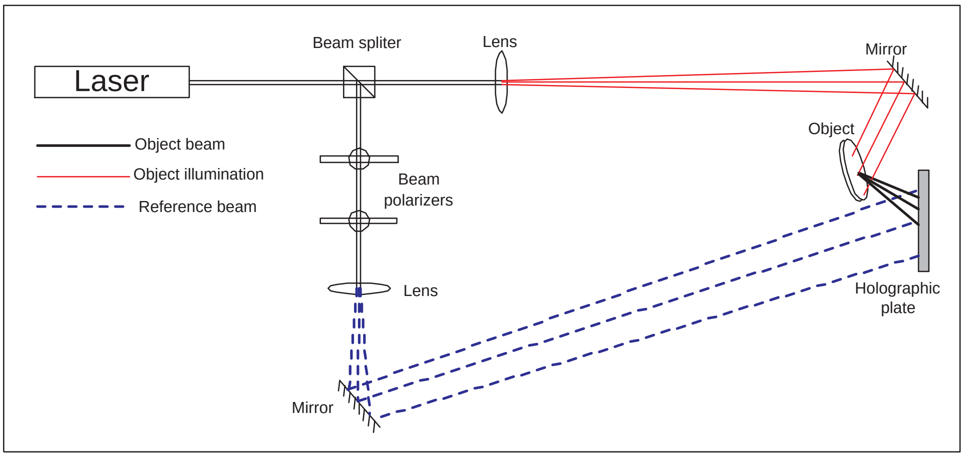

Figure 14: Experimental setup for transmission hologram.

The setup for recording and reconstructing a transmission hologram is shown in figure 14. As can be seen, the laser beam passes through a polarizer and than splits to a reference beam and an abject beam by a beam splitter. The reference beam passes than again trough a second polarizer; witch is used to control its intensity.

Lay the magnetic optical board parallel to the table and place all optical elements apart from the object according to figure 14. Set both beam polarizes to zero and adjust the laser beam such that you'll get a clean reference beam in the middle of the plate holder, make sure that the beams pass through the center of each optical element. Change the angle of the second polarizer to block the reference beam and place the object on the object stand. Adjust the object beam to obtain a bright image in the middle of the plate holder, fine tune by turning the object itself to find the position that gives maximal intensity. Turn the angle of the second polarizer back toward zero. At this stage you should have a good image in the middle of the plate holder of the object interfering with the reference wave. The reference beam should be weaker then the object beam.

Before Exposure prepare solutions for developing, bleaching and drying. In a dark room take out a photographic plate and place it in the plate holder while blocking the laser beam. This type of hologram requires a longer exposure time than the reflection hologram, and will yield results for exposure times between 30 seconds and 4 minutes, exposure time of around 2 minutes is most recommended.