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Holography
Instructions

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Abstract

The goal of this experiment is to understand how interference phenomena can be used to store a three dimensional image and how to reproduce it at a later time. This manual is an introduction to the principle of holography and provides instructions on how to set up and use photo plates to make a hologram of an object.
This is accomplished by recording the interference pattern of the scattered light from an object with a reference wave and later using the diffraction of the same reference wave at the recorded pattern to restore the original image.

Contents

1 Introduction

The name holography is composed of the Greek words "ὅλος" meaning entire, and "γραφη" meaning scripture. Gàbor Dénes, who first wrote down the principle of holography in 1950, wanted to emphasise with his choice of name that a hologram captures all the information contained in a light wave.
Common photography can only focus on one plane of the object, the rest of the object will be more or less blurred. The photographic plate captures the intensity distribution in the plane of the plate, and the resulting image is two dimensional. Photography does not produce true three dimensional images. While stereo photography can produce a spatial image of an object with a pair of images, it will only work for one fixed point of observation. Unlike holography, this technique works with any light source.

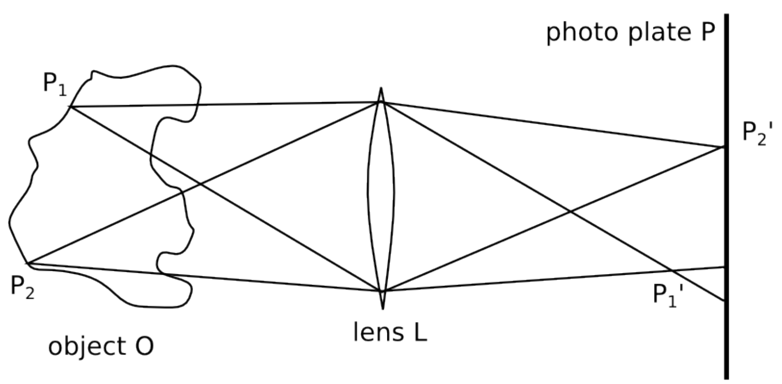


Figure 1: Image of an object O with a lens L onto a photo plate P

2 Theory of a Hologram

2.1 Monochromatic Waves

For this experiment we describe light as a scalar wave. A monochromatic scalar wave field of frequency ν is described by the following function

$$\begin{aligned} u(\vec{x},t) &= \mathfrak{Re}\{u(\vec{x})e^{-i2\pi\nu t}\} = \mathfrak{Re}(u(\vec{x})e^{-i\omega t}) \\ \omega &= 2\pi\nu \end{aligned} \tag{1}$$

$u(\vec{x},t)$ is called the real amplitude of the field. $u(\vec{x})$ is in general a complex function

$$u(\vec{x}) = |u(\vec{x})|e^{i\varphi(\vec{x})}. \tag{2}$$

This complex amplitude function $u(\vec{x})$ has the following meaning: $|u(\vec{x})|$ is the maximum value of the wave $u(\vec{x},t)$ oscillating with frequency ν, $\varphi(\vec{x})$ is the spatial phase of the wave at point $\vec{x}$. The scalar function $u(\vec{x},t)$ can be understood as a component of the electric or magnetic field vector.
No detector is capable of measuring the amplitude oscillating with $10^{14} Hz$ to $10^{15} Hz$ directly. A detector measures the time average of the intensity, the square of the amplitude

$$I(\vec{x},t) = \frac{1}{T}\int_{t-T/2}^{t+T/2} u^2(\vec{x},\tau)d\tau \tag{3}$$

In the case of scalar waves this results in

$$I(\vec{x}) = \frac{1}{2}|u(\vec{x})|^2. \tag{4}$$

2.2 Phase Information

An object O is illuminated with monochromatic laser light of frequency ν. The waves are reflected by the object. These waves are referred to as the object waves. This is also a monochromatic field with the same frequency. Assuming the object does not move (no Doppler effect), this field has the following form:

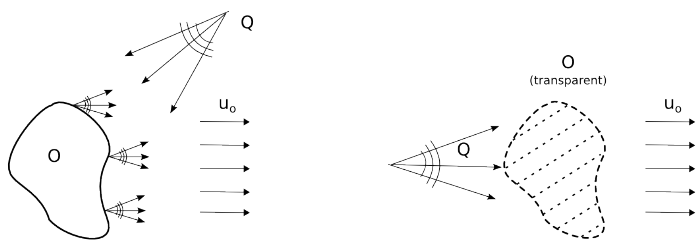
$$u_o(\vec{x},t) = \mathfrak{Re}\{u_o(\vec{x})e^{-i2\pi\nu t}\} \tag{5}$$

$$u_o(\vec{x}) = |u_o(\vec{x})|e^{i\varphi_o(\vec{x})} \tag{6}$$

$$u_o(\vec{x},t) = |u_o(\vec{x})|\cos(2\pi\nu t - \varphi_o(\vec{x})). \tag{7}$$

This wave carries the entire optical information about the object: its shape, size, position and optical properties (absorption, refractive index).

To make a hologram, the field $u_o(\vec{x}, t)$ must be recorded, stored and later



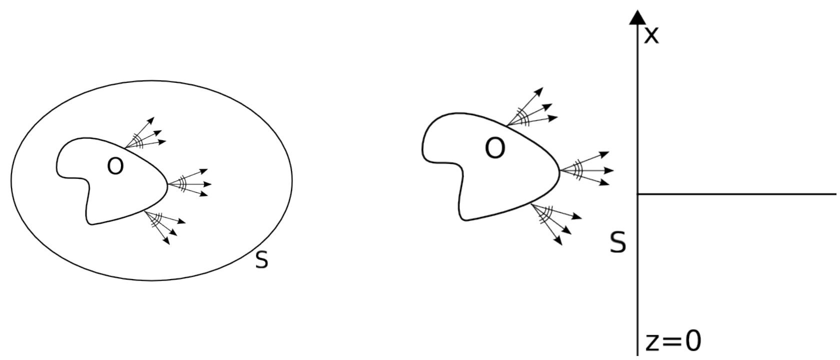
(a) solid object (b) transparent object

Figure 2: The creation of the object wave: (a) by reflection, (b) by transmission. The light source Q illuminates the object. The field is generated by diffraction at the object Q. For a reflective (transparent) object the wave field is the superposition of all spherical waves starting at a certain point on the object's surface (volume).

reconstructed. For monochromatic fields there exists the following theorem: A wave field radiating outward of a space enclosed by the surface S is completely determined by its complex amplitude on the surface S. This theorem can be used for the plane $z = 0$ with sources in $z < 0$. Then the amplitude in $z = 0$ determines the field in the entire half-space $z < 0$. For this theorem only the complex amplitude needs to be recorded on a surface S around the object. The problem is that the detectors register only the intensity of incoming light given by

$$I(\vec{x}) = \frac{1}{2} u_o^*(\vec{x}) u_o(\vec{x}) \tag{8}$$

but are insensitive to the phase. Measuring the phase of the wave is only possible by using interference phenomena. Adding a reference wave with known phase with respect to the original field results in an interference field whose intensity is dependent on the phase difference between the two fields; therefore the intensity contains the desired phase information. This is the basis for the method of holography.



(a) closed surface S (b) half-plane z=0 as surface S

2.3 Capturing a Hologram

The object field u_o is superposed with a reference field u_r (cf. Fig. 4). The reference field needs to have the same frequency ν as the field u_o and must be in a fixed phase relation (coherence). The amplitude is given by $u(\vec{x}) = u_o(\vec{x}) + u_r(\vec{x})$. The resulting intensity distribution is given by the following equation:

$$\begin{aligned} I(\vec{x}) &= \frac{1}{2}u^*(\vec{x})u(\vec{x}) \\ &= \frac{1}{2}[u_o^*(\vec{x}) + u_r^*(\vec{x})][u_o(\vec{x}) + u_r(\vec{x})] \\ &= \frac{1}{2}\Big[|u_o(\vec{x})|^2 + |u_r(\vec{x})|^2 + u_o^*(\vec{x})u_r(\vec{x}) + u_r^*(\vec{x})u_o(\vec{x})\Big] \end{aligned} \tag{9}$$

with

$$\begin{aligned} u_o(\vec{x}) &= |u_o(\vec{x})|e^{i\varphi_o(\vec{x})} \\ u_r(\vec{x}) &= |u_r(\vec{x})|e^{i\varphi_r(\vec{x})}. \end{aligned} \tag{10}$$

This can be rewritten as:

$$I(\vec{x}) = \frac{1}{2}\Big[|u_o(\vec{x})|^2 + |u_r(\vec{x})|^2 + 2|u_o(\vec{x})||u_r(\vec{x})|\cos(\varphi_r(\vec{x}) - \varphi_o(\vec{x})\Big] \tag{11}$$

In order to capture a hologram of good quality, the reference wave must create a homogeneous intensity pattern on the photo plate.

$$|u_r(\vec{x_H})|^2 \approx \text{const.}\forall x_H \in \text{Photo plate} \tag{12}$$

This condition is fulfilled if the reference wave can be approximated by a plane wave or spherical wave in its far field, and the object wave u_o creates a smaller intensity than u_r

$$|u_o(\vec{x_H})|^2 \ll |u_r(\vec{x_H})|^2 \tag{13}$$

Then the intensity given in Eq. (9) can be written as

$$\begin{aligned} I(\vec{x_H}) &= \bar{I} + \Delta I(\vec{x_H}) \\ \text{with } \bar{I} &= \frac{1}{2}|u_r(\vec{x_H})|^2 = \text{const.} \\ \Delta I(\vec{x_H}) &= \frac{1}{2}\{u_o^*(\vec{x})u_r(\vec{x}) + u_r^*(\vec{x})u_o(\vec{x})\} \end{aligned} \tag{14}$$

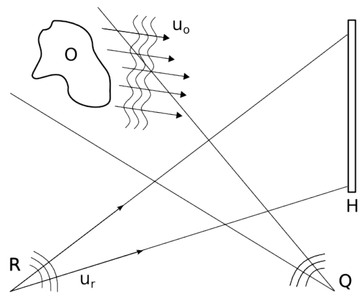
This interference pattern is recorded on a surface around the object O, or captured on a part of the surface of a photo plate, respectively. A photographic emulsion is darkened proportionally to the amount of energy density (Intensity×exposure time) used during exposure. The developed and fixed photo plate is the hologram. According to Eq. (11) the darkened patterns contain the full information about the complex amplitude $u_o(\vec{x})$, meaning the information represents the amplitude $|u_o\vec{x}|$ as well as the phase $\varphi_o(\vec{x})$.

2.4 The Reconstruction

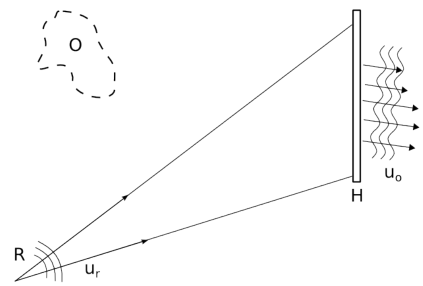
The reconstruction of the 3-dimensional object wave field $u_o(\vec{x})$ is done by exposing the holographic plate with the reference wave field $u_r(\vec{x})$ in the same geometric arrangement. The holographic plate represents a generalized diffraction grating. The original wave field is equivalent to a certain order of diffraction generated by illumination of the hologram with the reference wave field. In general, diffraction on a grating is described by its amplitude transmission. A 2-dimensional object lies directly in front of the $z = 0$ plane and is illuminated by the monochromatic wave $u_B(\vec{x})$. The resulting amplitude directly behind the object is

$$u(x, y, 0) = T(x, y)u_B(x, y, 0) \tag{15}$$

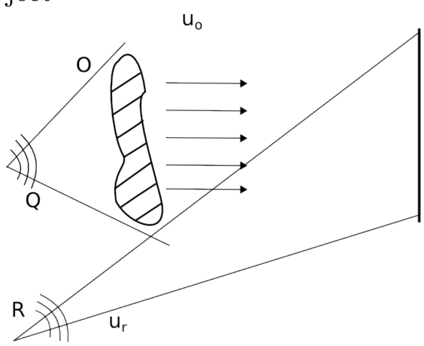
$T(x, y)$ is the amplitude transmission function and describes how the object changes the incoming light waves. This description is possible because we analyse planar holograms. The amplitude transmission $T(\vec{x})$ of an exposed



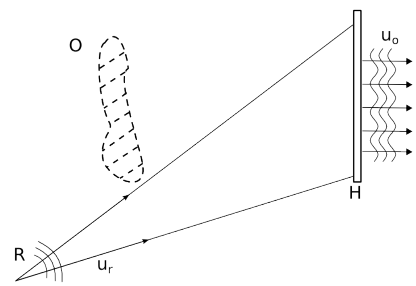
(a) image taken of an opaque object



(b) image reconstruction of the object



(c) image taken of a transparent object



(d) image reconstruction of the object

Figure 4:
Recording and reconstruction of a hologram: O object; H photo plate; Q light source; R reference source; u_r reference wave field; u_o object wave field

photo plate is a function of the exposure time. In the vicinity of the operating point, as a first approximation the transmission can be written as

$$T(\vec{x_H}) = T_0 - \text{const } I(\vec{x}) \tag{16}$$

Together with Eq. (14) this results in Eq. (17):

$$T(\vec{x_H}) = T_0 - \alpha\{u_o^*(\vec{x_H})u_r(\vec{x_H}) + u_r^*(\vec{x_H})u_o(\vec{x_H})\} \tag{17}$$

The information about the object is recorded in the transmission function of the hologram as the interference term $u_o^*(\vec{x})u_r(\vec{x}) + u_r^*(\vec{x})u_o(\vec{x})$.
Now the hologram is illuminated with a wave of frequency ν_c

$$u_c(\vec{x}, t) = u_c(\vec{x})e^{-2\pi i\nu_c t}. \tag{18}$$

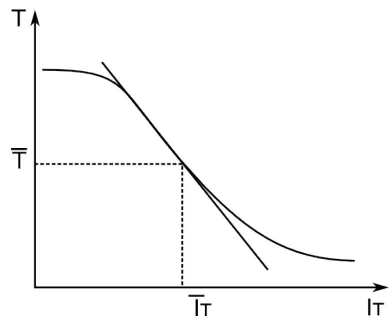


Figure 5: Amplitude transmission T of a photographic emulsion as function of the exposure τI, where I is the intensity and τ is the exposure time. $(\bar{I}\tau/\bar{T})$ is called the operating point.

The wave field diffracted by the hologram has the same frequency ν_c. The amplitude directly behind the hologram is given according to Eq. (17).

$$\begin{aligned} u(\vec{x}_H) &= T(\vec{x_H})u_c(\vec{x}_H) \\ &= \Big\{\bar{T} + \alpha[u_o^*(\vec{x}_H)u_r(\vec{x}_H) + u_r^*(\vec{x}_H)u_o(\vec{x}_H)]\Big\}u_c(\vec{x}_H) \end{aligned} \tag{19}$$

The first term in Eq. (19) describes the part of the wave $u_c(\vec{x})$ passing the grating without diffraction. Two new wave fields $u(\vec{x})$ and $\bar{u}(\vec{x})$ are generated right behind the hologram with amplitudes

$$u(\vec{x}_H) = \alpha\Big[u_r^*(\vec{x}_H)u_o(\vec{x}_H)\Big]u_c(\vec{x}_H) \tag{20}$$

$$\bar{u}(\vec{x}_H) = \alpha\Big[u_o^*(\vec{x}_H)u_r(\vec{x}_H)\Big]u_c(\vec{x}_H). \tag{21}$$

The hologram is supposed to capture the phase information of the light diffracted by the object. The result of Eq. (11) shows that all but the sign of the phase can be captured ($\cos(\Delta\varphi) = \cos(-\Delta\varphi)$). In interferometry, only the absolute value of the phase difference can be measured; one cannot differentiate between the advanced and retarded phases. Therefore, two wave fields u and u^* appear as indicated by the form of Eq. (11). The real intensity is the sum of two complex conjugate terms. u^* is called the complex conjugate wave field.

2.4.1 The Object Wave Field

The hologram is illuminated by the reference wave $u_r(\vec{x})$ used while recording the hologram.

$$\begin{aligned} u_c(\vec{x}) &= u_r(\vec{x}) \\ \nu_c &= \nu \end{aligned} \tag{22}$$

Due to Eq. (20) and Eq. (22) the amplitude of the field $u(\vec{x})$ directly behind the hologram is

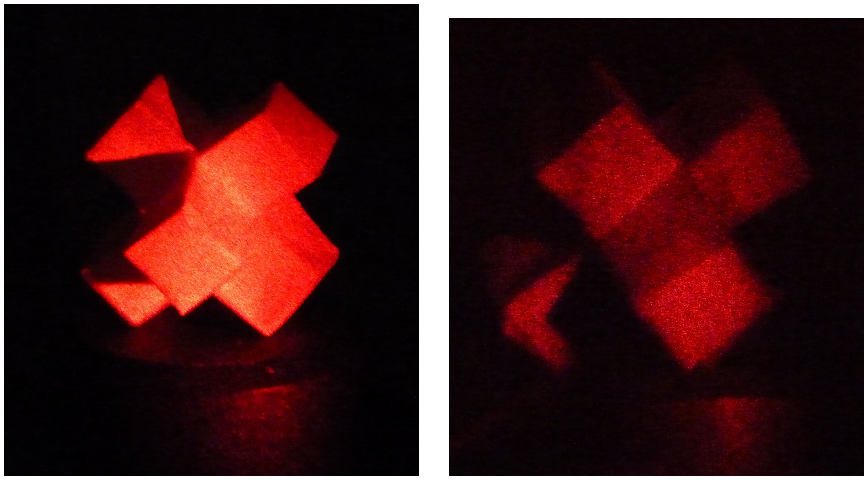
$$\begin{aligned} u(\vec{x}_H) &= \alpha |u_r(\vec{x}_H)|^2 u_o(\vec{x}_H) \\ &= \alpha' u_o(\vec{x}_H) \end{aligned} \tag{23}$$

if the intensity of the reference wave is approximately constant in the hologram plane (cf. Eq. (12)) . Directly behind the hologram the amplitude of the wave field $u(\vec{x})$ is the same as that of the object wave field $u_o(\vec{x})$, except for a pre factor α', and is oscillating at the same frequency. Due to the theorem about the propagation of monochromatic fields, the fields $u(\vec{x})$ and $\alpha' u_o(\vec{x})$ are equal in the entire space behind the hologram. Diffraction of the illuminating wave (Eq. (22)) at the hologram reconstructs the object wave.

$$\begin{aligned} u(\vec{x}) &= \alpha' u_o(\vec{x}) \\ u(\vec{x}, t) &= \alpha' u_o(\vec{x}, t) \end{aligned} \tag{24}$$

An observer looking through the hologram can see the object in its original position relative to the hologram in three dimensions. This image is called virtual, as it appears to an observer to be located behind the holographic plate. A hologram is usually not captured on the entire surrounding area S, but just on the area available on the photo plate. Only the part of the field u_o passing through the plate is reconstructed. The reconstructed object is visible like through a window in an invisible wall. The point of observation can be chosen freely, contrary to stereo photography, where the point of observation is precisely defined. Independent of the form of $u_r(\vec{x})$, u_o is reconstructed accurately, if only Eq. (22) is fulfilled.

What happens in case of $u_r \neq u_c$ or $\nu \neq \nu_c$? Generally it is too complicated to tell what is happening, except in the case where u_c and u_r are spherical or plane waves. Then a variance from Eq. (22) results in an optical transformation of the reconstructed wave field u_o. The object appears as if it



(a) Illuminated object (b) Reconstructed image

Figure 6: Photos of holograms in the lab

were mapped by an optical device (lens, prism) in the plane of the hologram. According to the optical imaging equations the position and size of the holographic image change, which can be a real image as well, meaning that the object appears to be located between the observer and the photo plate.

2.4.2 The Conjugate Wave Field

This section considers in detail the meaning of the second interference term in Eq. (11) leading to the field $\bar{u}(\vec{x})$ in Eq. (21). Every object wave field can be considered as a superposition of elementary waves radiated from every individual point of the object. Consider a case of a single radiating point P in an arrangement as depicted in Fig. (8). Assume the reference wave u_r is perpendicular to the holographic plane. The object wave is a spherical wave starting at P. A Hologram like this is called a Fresnel zone plate (concentric circles, whose centre (0,0,0) does not necessarily lie in the holographic plate). In the following section the mathematical description of this situation is presented:

$$\begin{aligned} \text{object field: } u_o(\vec{x}) &= \frac{u_o}{r} e^{ikr} \\ \text{with } k = \frac{2\pi}{\lambda}, r &= \sqrt{x^2 + y^2 + (z + z_o)^2} \end{aligned} \tag{25}$$

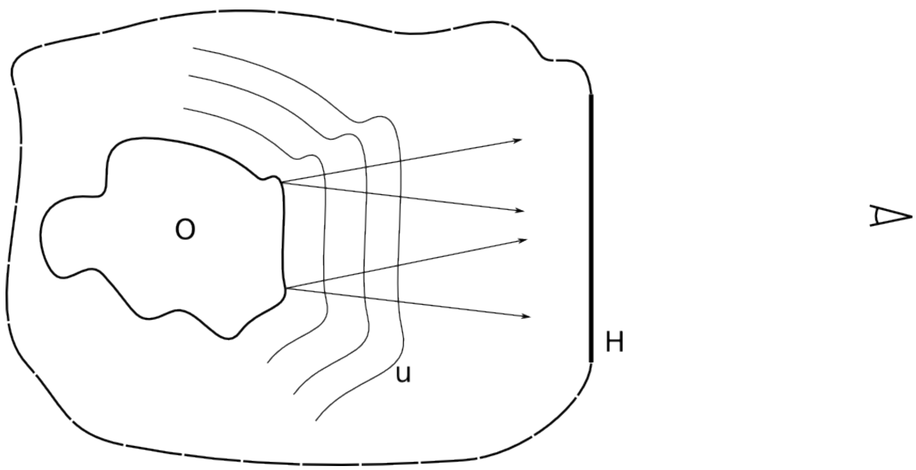


Figure 7

The reference wave is given by the following equation:

$$\begin{aligned} u_r(\vec{x}) &= u_r e^{ikz} \\ u_c(\vec{x}) &= u_r(\vec{x}), \nu_c = \nu \end{aligned} \tag{26}$$

Using Eq. (20) yields the following expression:

$$u(\vec{x}_H, z=0) = \alpha' |u_r|^2 u_o(\vec{x})\Big|_{z=0} \sim u_o(\vec{x}_H, z=0) \tag{27}$$

This amplitude distribution $u(\vec{x}_H)$ in $z = 0$ creates the object wave field in the half space $z > 0$ due to the theorem of wave-propagation (outgoing spherical wave). Analogously, Eq. (21) results in the conjugated field

$$\begin{aligned} \bar{u}(\vec{x}_H, z=0) &= \alpha' u_r^2 \frac{u_o^*(\vec{x})}{r} e^{i(2kz-kr)}\Big|_{z=0} \\ &= \alpha' u_r^2 \frac{u_o^*(\vec{x})}{r} e^{-ikr} \sim u_o^*(\vec{x}_H, z=0) \end{aligned} \tag{28}$$

The amplitude distribution $\bar{u}(\vec{x}_H)$ creates a spherical wave

$$\bar{u}'(\vec{x}, t) = \mathfrak{Re}\left(\frac{\bar{u}'}{\bar{r}} e^{-i(k\bar{r}+\omega t)}\right) \tag{29}$$

converging to a point $\bar{P}(0, 0, z_o)$, where $\bar{r} = \sqrt{x^2 + y^2 + (z - z_o)^2} =$ constant is the distance from $\bar{P}$ and u' a constant. In the plane of the hologram, $z = 0$,

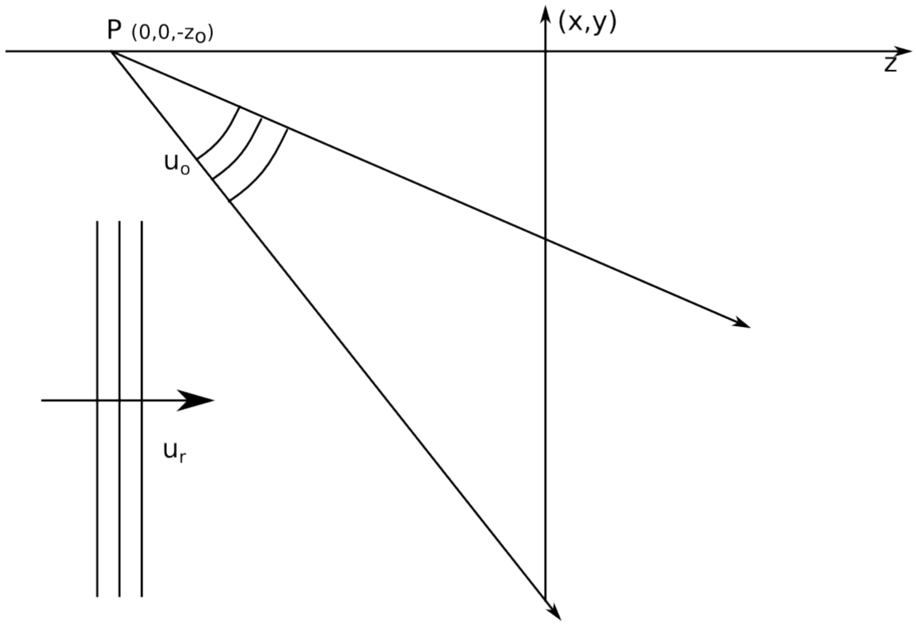


Figure 8: Image recording of the hologram

this spherical wave has a complex amplitude

$$\bar{u}'(\vec{x}_H) = \frac{\bar{u}'}{r} e^{-ikr} \tag{30}$$

where $r = \bar{r}$ in this plane, due to symmetry. The amplitude in Eq. (30) is the same as in Eq. (21). According to the theorem of wave propagation $\bar{u}(\vec{x}_H)$ must create the spherical wave $\bar{u}'(\vec{x}, t)$ converging in $\bar{P}(0, 0, z_o)$, similarly to the determination of the propagation of waves in the half space $z > 0$. $\bar{P}$ is a real image point.
The name conjugated wave field comes from the fact that the field $\bar{u}$ is dependant on the conjugated complex amplitude u_o^*. The change to the conjugated amplitude corresponds in common notation to a time reversal $t \to -t$:

$$\begin{aligned} \bar{u}(\vec{x}, t) &= \mathfrak{Re}\left(\bar{u}^*(\vec{x}) e^{-i\omega t}\right) \\ &= \mathfrak{Re}\left(\bar{u}(\vec{x}) e^{i\omega t}\right)^* \\ &= \mathfrak{Re}\left(\bar{u}(\vec{x}) e^{i\omega t}\right) \\ &= u(\vec{x}, -t) \end{aligned} \tag{31}$$

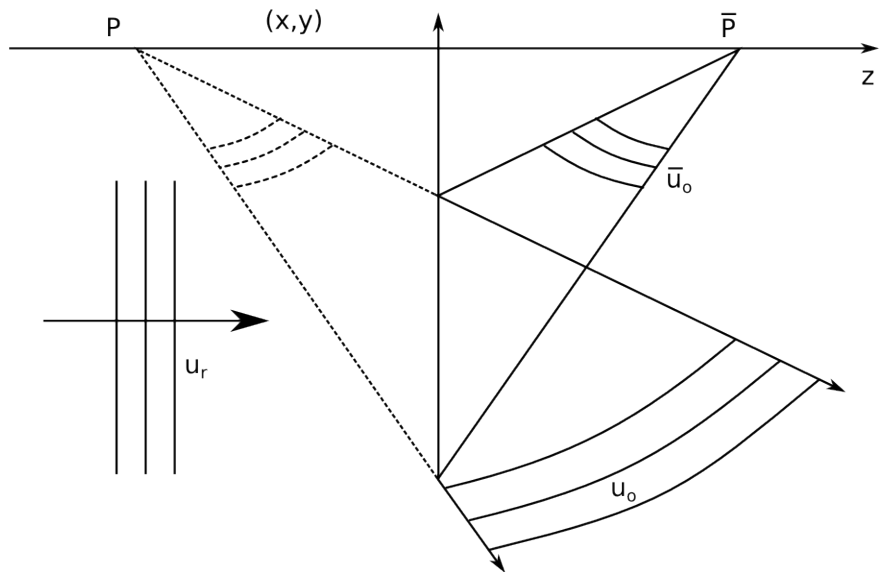


Figure 9: Geometry of the conjugated field

The physical interpretation of time reversal is that wave fronts are moving backwards; for example an outgoing spherical wave becomes a converging wave.
An arbitrary object can be thought of as to be composed of many points. Each point is projected in the way above. This conjugated image has a peculiar property. Consider an object composed of a point P and a surface F as depicted in Fig. (10). The wave field of the point P is partially obscured by F during the image taking; no light of P reaches the upper part of the holographic plate H. This is manifested in the property of the reconstructed field $u(\vec{x})$: an observer sees that P is obscured by F, like the original object. For an observer looking at the conjugated image the point $\bar{P}$ is obscured by the surface $\bar{F}$ lying behind (!) the point. The conjugated image $\bar{u}(\vec{x})$ is pseudoscopic. On the contrary the image produced by $u(\vec{x})$ is orthoscopic, meaning the observer has the same impression seeing the image as seeing the original object.
This discussion on the conjugated image is based on the assumption that the reference wave is a plane wave perpendicular to the holographic plate. Only in this particular setup both images are symmetric to the plate. In case of u_r and u_c being arbitrary plane waves or spherical waves, the conjugated image is subject to optical transformations.

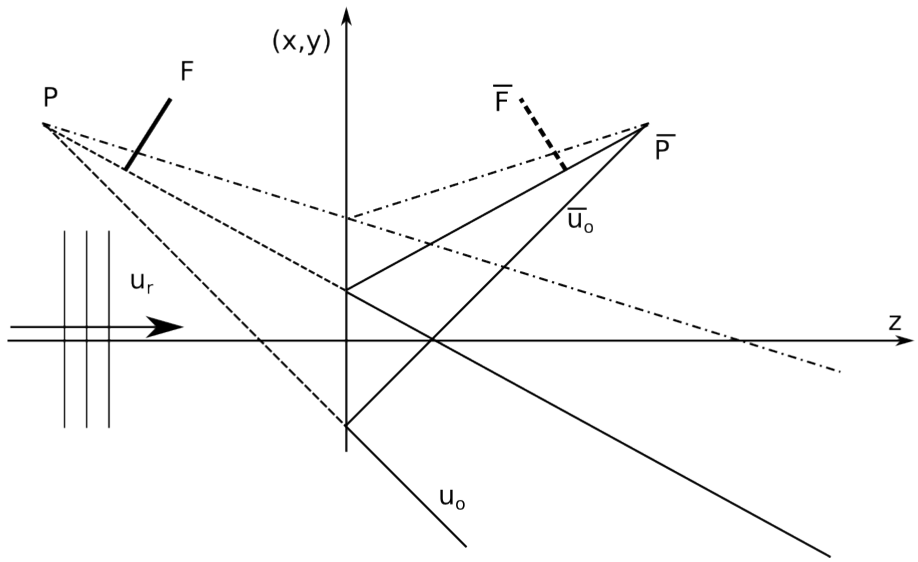


Figure 10: Point source with a blind

In summary: only the original field $u(\vec{x})$ is reconstructed. The field $\bar{u}(\vec{x})$ never existed before, it is created by the holographic process due to the ambiguity of the phase measurement.

2.5 Classification of holograms

a) **Method of storage**

Amplitude Hologram: contains the information in the form of an optical density distribution.

Phase Hologram: contains the information in the form of a variation of the refractive index.

b) **Dimension of the medium**

Surface Hologram: Storage media can be described as 2-dimensional.

Volume Hologram: contains the information in 3 dimensions.

c) **Geometry of the set up**
Depending on the geometry one can differentiate between Fresnel, image plane and Fourier holograms.

3 Experimental Set Up

3.1 Remarks

3.1.1 Warning: Laser

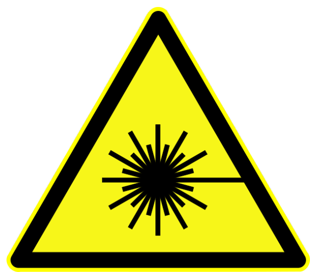


Figure 11: laser warning sign

The radiation of a laser can be dangerous to the eye. As the beam is a nearly perfect parallel bundle, it can be focused on a very small spot (⌀ few μm). For this reason, special laser protective glasses are required while working with the laser beam. In particular, watches or other objects with highly reflective surfaces should be removed before starting to work with lasers.

3.1.2 Using optical mechanical components

The quality of the hologram is strongly related to the stability of the experimental set up. Therefore very stable and precise components are required. This requires a careful treatment of these components. It is forbidden to touch or clean optical surfaces (mirrors, beam splitters, etc.).

3.1.3 Model Usage

There is a 1:4 magnetic scale model of the components that should be used to design the experimental set up. The set up should be discussed with the assistant before attempting to experiment with the real optical components.

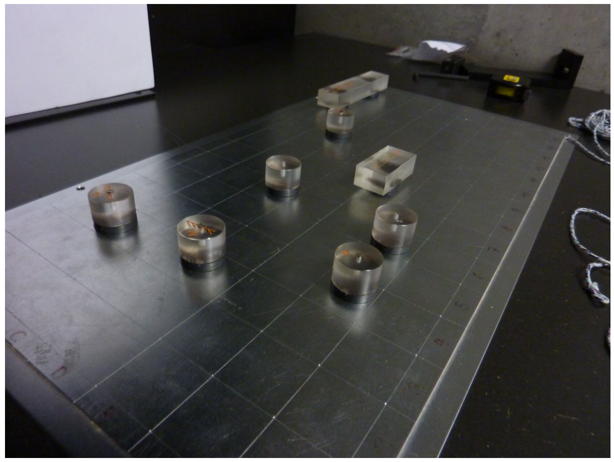


Figure 12: Magnetic Model

3.2 Description of the Components

3.2.1 Laser

The intensity distribution of the laser beam in every plane perpendicular to the direction of propagation is a rotational symmetric Gaussian distribution:

$$I(r) = I_0 e^{-\frac{2r^2}{r_0^2}} \tag{32}$$

For $r = r_0$ the intensity of the beam drops from I_0 in the centre to I_0/e^2. The diameter of the beam ($1/e^2$ points) changes with distance l from the laser approximately by

$$2r_0(l) = \delta l + 2r_0 \tag{33}$$

with δ the beam divergence and $2r_0$ the beam diameter on the laser mirror.

Specifications of He-Ne-Laser (Melles Griot 25-LHP-925-230)

Power Output: 17 mW

Wavelength 632.8 nm

Polarisation linear

Beam diameter 0.96 mm ($\frac{1}{e^2}$)

Beam divergence 0.84 mrad

Axial mode distance 257 MHz

Warning: Do not operate the power supply without connected load (i.e. without the laser)!

3.2.2 Shutter

Figure 13: The shutter

The electric shutter is positioned right after the laser in the set up. Vibrations caused by the shutter should be dampened by the corresponding support. For short shutter settings precise centring of the aperture is important. The shutter can be kept open for adjustments by clamping the plate on the trigger cable.
For precise exposure the shutter can be used in two ways:

- with fixed times from $\frac{1}{125}$ s - 32 s adjustable on the knurl ring
- with continuous times from 0.1 s - 33 s; the knurl ring is set to pos. EXT and the time is set on the accessory device

If possible the shutter should not be directly connected to the table, but supported separately.

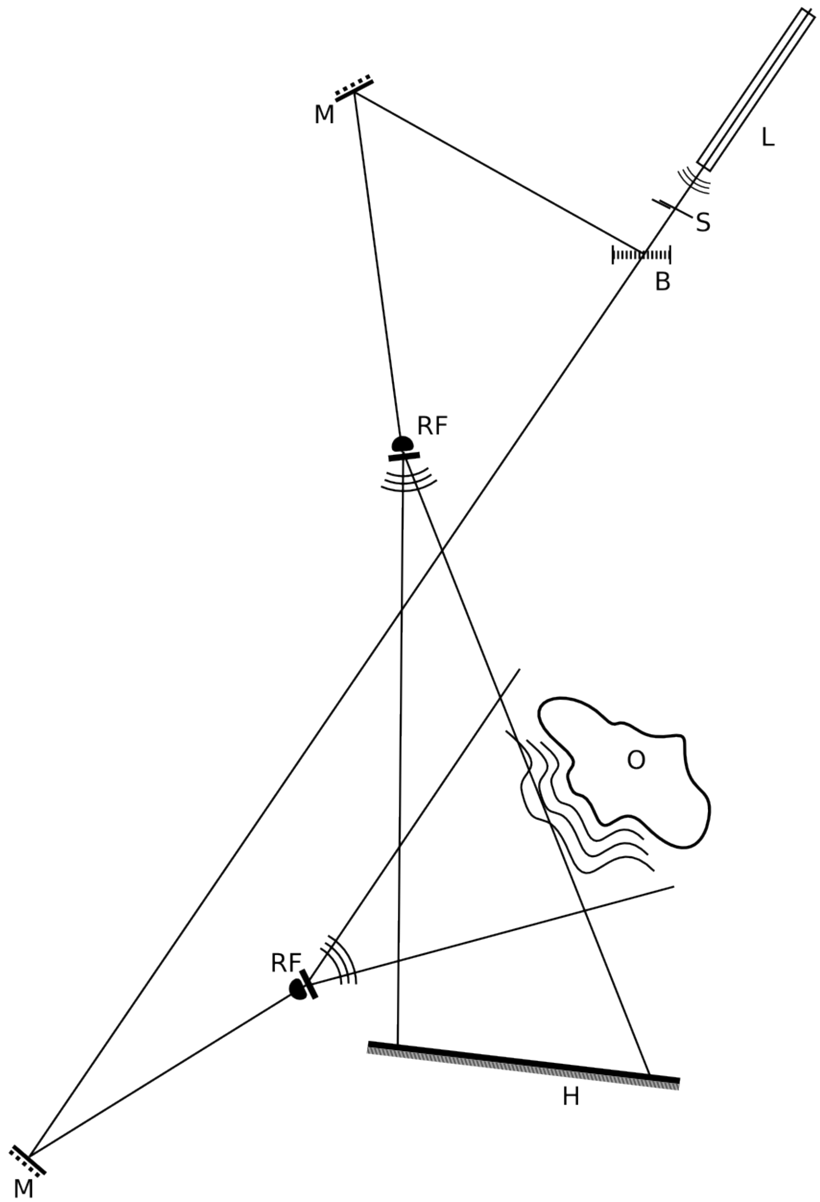


Figure 14: Schematic set up of the experiment; L laser, B beam splitter, RF spatial filter, O object, H hologram, M mirror, S shutter

3.2.3 Beam Splitter

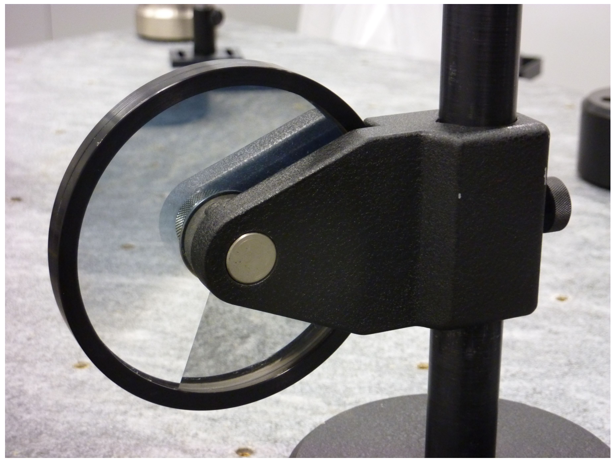


Figure 15: Circular beam splitter

The beam splitter, a partially transparent mirror with variable transmission, produces both waves, the object wave and the reference wave respectively. One of the beams is used to illuminate the object thus creating the object wave, while the other is used as a reference (Fig. (14)). The ratio of the two beams can be changed by turning the wheel.

3.2.4 Beam expanders (Spatial filters)

Generally, a holographic set up needs two or more expansions of the beam

1. to produce the reference wave and
2. to produce the object wave

The expansion is accomplished by using micro object lenses (magnification x20 or x40), with an aperture at its focal point. The aperture is used as a spatial frequency filter where only the lowest spatial frequencies can pass. Higher frequencies produced by dust, scratches on optical surfaces, optical inhomogeneities and multiple reflections (in the object lens) cannot pass the aperture and are blocked (Figure (17)).

The aperture is fixed permanently to the micro object lens. When the puncture of the optical axis is adjusted with the focal plane, the entire unit

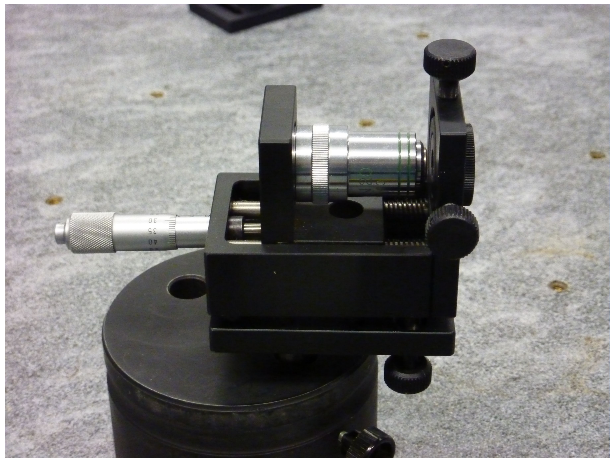


Figure 16: A spatial filter

forms a spatial filter.

Exercise 1: Calculate the minimal diameter of the aperture under the following conditions:
focal length of the object lenses 40 x : $f_{40} = 4.3$ mm
20 x : $f_{20} = 7.5$ mm
wavelength of the laser $\lambda = 632.8$ nm
beam diameter $(1/e^2)$ $d = 0.65$ mm

The axis of the spatial filters needs to coincide with the axis of the laser beam in order to function properly.

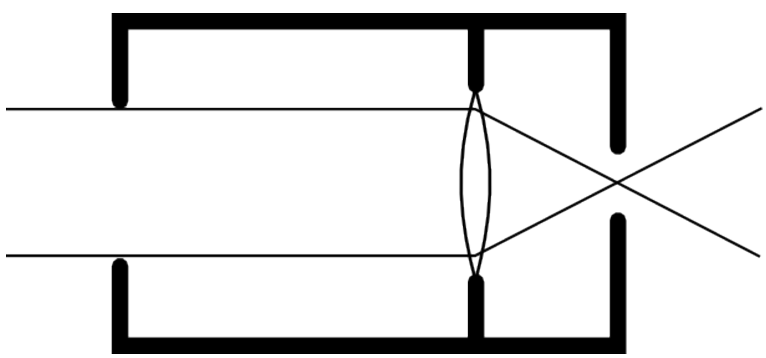


Figure 17: Spatial Filter

3.2.5 Mirror

The purpose of the mirror is to change the optical path defined by the geometry of the setup. Do not touch the reflecting surface while adjusting the magnetically supported mirrors.

3.2.6 Hologram Support

This device holds a photographic plate suitable for holography. It fixes the photographic plate while recording the hologram relative to the interference field. This is achieved using a three-point fixture.
The photographic plate rests on three pins and is clamped by three sliders to firmly fix the plate.
The plate is mounted with the side coated with photo emulsion touching the support, such that the sliders do not scratch the emulsion. As this step must be performed in complete darkness, this should be practised with normal glass plates or old holograms beforehand.

After clamping the plate, one should wait a few minutes before taking an

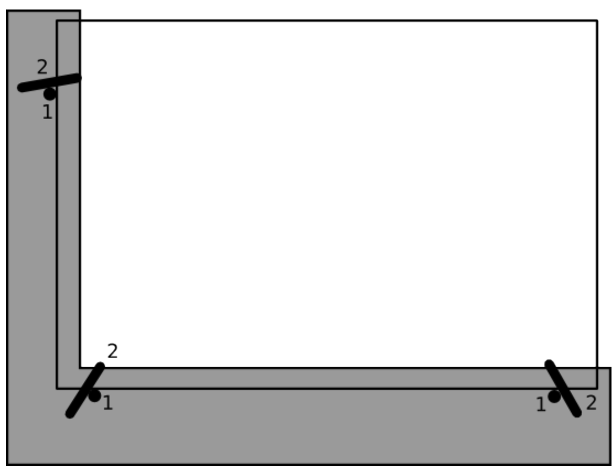


Figure 18: The plate rests on the pins (1) and is fixed with the clamps (2)

image to allow the optical table to return to equilibrium.

3.2.7 Advice for Choosing an Object

The target object can be chosen by the student him-/herself. One should consider following criteria in order to achieve sufficiently short exposure times with the available power of the laser:

- The object should not exceed a volume of 10 cm x 10 cm x 15 cm
- The object should absorb as little light as possible
- The laser light should be diffracted in a diffuse way
- The diffracted laser light should be non-polarised

3.3 Construction of the set up

3.3.1 Interference in the Plane of the Hologram

In the simplified case of two planar waves interfering in the plane of the hologram, the resulting intensity distribution has the following curve (Fig. (**??**)). The average value $\bar{I}$ is the sum of the individual intensities $|u_r|^2$ and $|u_o|^2$ and can be determined by themselves. The fluctuations depend on the following criteria:

- The direction of polarisation ($\vec{E}$-vectors) of u_r and u_o must be parallel for maximal ΔI
- The frequency spectrum of the laser results in a loss of coherence for large path differences $\Delta L = L_2 - L_1$ (Fig. (19)). The coherence length is given by: $l_c = c/2\pi\delta\nu$, where $\delta\nu$ is the linewidth of the laser. For this laser, typically the linewidth is 1-10 MHz, which puts the coherence length at around 5-50 m. The coherence, which gives the approximate contrast of the interference pattern is given by: $C = e^{\Delta L/l_c}$.

3.3.2 Stability of the holographic set up

In an ideal case, the interference field is at rest relative to the recording medium, i.e. ΔL (Fig. (19)) is constant. In practice, there are always changes in ΔL due to:

a) Oscillations in the holographic set up

b) Creeping motion inside the components

c) Variations of the refractive index of the air

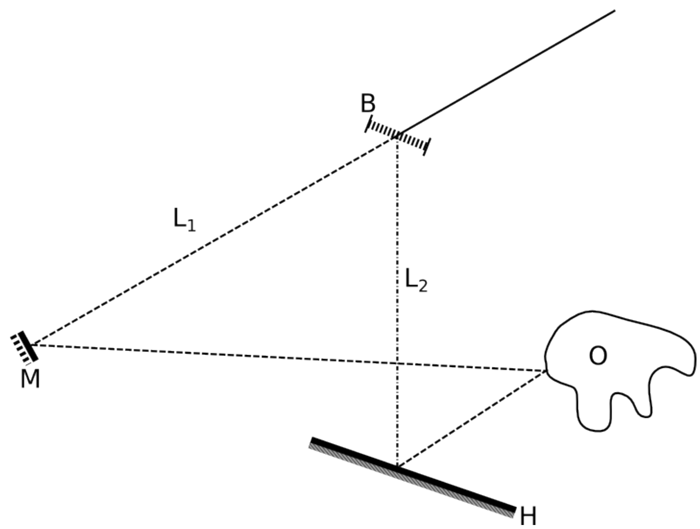


Figure 19: Diagram of the path difference ΔL

Useful counter-measures are

a) Set up (table and components) should be massive and the beam path on the optical table should be as short as possible to reduce the oscillation amplitudes of components. The shutter should not be placed on the table but mounted externally.

b) Inhomogeneous temperature and stress fields deform components. Therefore care should be take while clamping components with warm hands; wait several minutes for temperature to equilibrate.

c) Choose short exposure times.

3.4 Exposure

3.4.1 Recording Medium

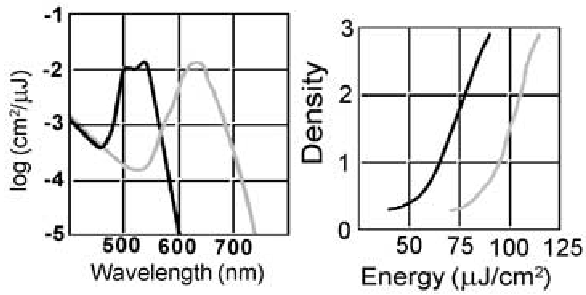


Figure 20: spectral sensitivity(left) and optical density versus incident intensity (right) for the emulsion used in the experiment (PFG-01). Refer to the light gray curves

The recording medium must be able to resolve the high spatial frequencies of the interference field and capture these in the shortest time possible in a linear fashion. These conditions are only fulfilled by fine grained photographic special emulsions, with the drawbacks of one-time use and time-consuming chemical development. For stability reasons emulsions on glass carriers are preferred over emulsions on tridcetate basis (film material).
The plate is often coated with an absorbing layer (anti halo layer) to remove disrupting reflections from the backside. Fig.(20) shows the dependence of the optical density on the incoming energy per unit surface for the type of emulsion used in the experiment (light curve). To achieve the desired linear recording of the interference pattern, some special properties of the emulsions need to be considered.

a) For normal development the intensity variations are turned into large transparency variations.

b) The scope of the exposure is to exploit the quasilinear section of the emulsion.

As can be seen in Fig. (20) the emulsion PFG-01 has an optimal incident energy of 100 $\mu J/cm^{-2}$.
As the incoming total intensity I is composed of the object wave intensity I_o and the intensity of the reference wave I_r, the modulation depth of the

intensity variation in the holographic plane depends on the ratio $\frac{I_r}{I_o}$. Normally one chooses

$$0.1 < \frac{I_r}{I_o} < 10 \tag{34}$$

Exercise 2: Discuss the reasons why one cannot conclude from the ratio $\frac{I_r}{I_o}$ to an optimal recording of the interference pattern. How does the object field influence an optimal recording of the interference pattern?

Using the approximation of two planar waves shining symmetrically under an angle φ onto the holographic plate. The waves are parallel polarised with amplitudes u_r and u_o, respectivelly. This results in an intensity distribution in the plane of the hologram

$$I(x) = I_o + I_r + 2\sqrt{I_o I_r}\cos(\frac{4\pi x}{\lambda}\sin(\frac{\varphi}{2})) \tag{35}$$

Exercise 3: Derive Eq. (35)

Figure 21

This intensity distribution shall now be transformed by the photo plate linearly into the amplitude transparency t. Simplifying the characteristics of the emulsion as shown in Fig. (22) the conclusion for I_o and I_r is:

a) $(I_r+I_o)\tau = \bar{I}\tau$ must result in an exposition in the middle of the quasilinear part of the characteristic line.

b) For optimal recording the amplitude $2\sqrt{I_r I_o}$ must not exceed the linear part.

c) Conditions a) and b) should be fulfilled for the whole photographic plate.

Fluctuations of the values $\bar{I} = I_r + I_o$ and I_r/I_o over the measurable area of the plate smaller than $10\% - 20\%$ are considered as acceptable.

Exercise 4: A beam with intensity distribution as in Eq. (32) enters a spatial filter with focal length f. A circle with radius r in the plane H should be optimally illuminated (variations smaller than 20%) with the expanded beam. Calculate the approximate distance of the plane H from the spatial filter.

3.4.2 Light Exposure Measurement

The measurement apparatus is a modified LUNASIX 3-device. The measured values can be converted to erg $s^{-1}cm^{-2}$ using a calibration curve. The exposure time τ determined by the exposure of the plate can be calculated from these values.
Warning: The measurement apparatus should be used only under stable conditions of the laser. Mind the strong directional nature of the photo cell; always measure perpendicularly to the incoming wave field. The photo cell must lie in the holographic plane.

3.4.3 Light Exposure

Vibrations While taking the hologram avoid vibrations (walking, door, pushing the table). Wait 1 - 3 minutes before exposure to reduce vibrations; dont speak and breath in direction of the setup.

Reflections Reduce reflections at the wall with the shields.

Light sources After put off the fluorescent tubes wait 10 minutes minimum, use the table lamp during adjusting.

Outside lights Shield the door at the bottom from outer light.

Exposure series Use the paper template to take an exposure series; use exponential number series, for example 5, 10, 20 and 40 seconds.

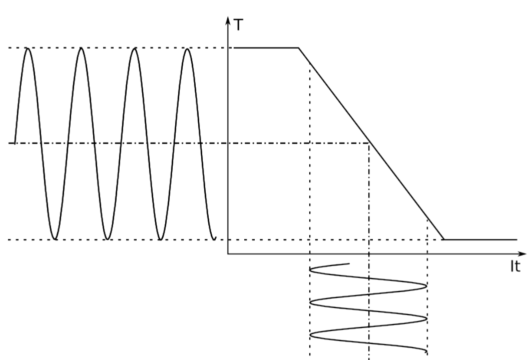


Figure 22

3.5 Developing

The exposed plates can be processed either in complete darkness or under dark chamber illumination (dark green). The photo chemicals should be obtained from the assistant or the laboratory technician.

Development bath 4-5 min. in G3p at $20°C$ under constant motion of the plate in the developer.

Fixing bath 4 min. under constant motion.

Watering 15 min. At this point regular light can be used again.

Drying Use pressurized air from the tank.

Developer reuse If developer chemicals are using longer than one day, use the argon gas to block the oxygen.

Warning: Use gloves and protective goggles and wear a lab coat while working with chemicals!

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