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Theoretical and experimental optical holography

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THEORETICAL AND EXPERIMENTAL
OPTICAL HOLOGRAPHY

by

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Abstract

The intent of this paper is to present an analysis of optical holography. Both the physical theory behind holography, and the experimental techniques used in making holograms will be presented. To accomplish this goal, the paper is divided into two independent sections: the theoretical section followed by the experimental section. Each section is intended to be a complete unit.

The Theoretical Section is an exposure to the theory behind holography. This consists of a review of the concepts of interference and diffraction, followed by a brief review of partial coherence. The remaining part of the Theoretical Section is devoted to the mathematical analysis of optical holography.

The Experimental Section begins with an introduction to the equipment and facilities currently available for optical holography at Colby College. Holographic procedures is dominated by the description of transmission holography (v.s. reflection, or white-light, holography). After these general holographic procedures a few variations on the basic transmission hologram are presented. The experimental section will end with an introduction to holographic interferometry, a major application of holographic techniques.
Introduction

The intent of this paper is to present an analysis of optical holography. I will expose the reader to both the physical theory behind holography, and the experimental techniques used in making holograms. To accomplish this goal, the paper is divided into two independent sections: the theoretical section followed by the experimental section. Each section is intended to be a complete unit in and of itself.

In the Theoretical Section, the reader is exposed to the theory behind holography. This will consist of first reviewing the concept of interference and diffraction which will be followed by a brief review of partial coherence. The remaining part of the Theoretical Section will be devoted to the mathematical analysis of optical holography.

In the Experimental Section the reader will first be introduced to the equipment and facilities currently available for optical holography. Holographic procedures will be dominated by transmission holography (v.s. reflection, or white-light, holography) because my own concentration has been in transmission holography. After these general holographic procedures I will present a few variations on the basic transmission hologram. The experimental section will end with an introduction to holographic interferometry, a major application of holographic techniques.

The bibliography includes not only materials that I have worked with this year, but also material that I have
used in past research of optical holography. Throughout the paper references will be denoted by [number] and the references are located at the end of each section, respectively. When a reference is marked at the beginning of a section, the majority of the details in that section would be drawn from that reference. Any further references will be marked in the text proper.
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Theoretical Section

IA) Interference and Diffraction

IA1) Properties of Coherent Fields

The detected quantity of an optical field $V(x,t)$, (i.e., an optical field that depends both on the spatial coordinate $x$ and time $t$), is the intensity $I(x)$, defined by

$$ I(x) = \langle V(x,t)V^*(x,t) \rangle. \quad (1) $$

Here the angle brackets denote a time average and the star denotes a complex conjugate. Equation (1) is valid regardless of whether the optical field is incoherent, or partially coherent, or totally coherent.

A field is said to be incoherent if at any two points, $x_1$ and $x_2$, the time averaged cross correlation of the two fields is zero.

$$ \langle V(x_1,t)V^*(x_2,t) \rangle = 0 \quad (2) $$

This implies that the disturbance at one point in space is totally unrelated, in a time averaged sense, to the other point in the field.

By contrast, a field is completely coherent if the time averaged cross correlation of the fields at points $x_1$ and $x_2$ assumes a maximum value;

$$ \langle V(x_1,t)V^*(x_2,t) \rangle = \text{max. value.} \quad (3) $$

If a field is coherent the function $V(x,t)$ can be separated into time- and space-independent parts, since the cross correlation term would be independent of the time averaging. We can say
Theoretical Section

The complex amplitude $\psi(x)$ and the frequency $\nu$ are related to the intensity of the field at position $x$ and time $t$. Thus, for example,

$$\langle V(x,t)\psi^*(x,t) \rangle = \psi(x)\psi^*(x,t).$$

The intensities at $x_i$ and $x_\alpha$ for a coherent field are also simplified:

$$I(x_i) = \langle V(x_i,t)\psi^*(x_i,t) \rangle = |\psi(x_i)|^2$$

$$I(x_\alpha) = \langle V(x_\alpha,t)\psi^*(x_\alpha,t) \rangle = |\psi(x_\alpha)|^2$$

It is conventional to express the amplitude and the phase of the complex amplitude as a pair of functions, one real and one imaginary,

$$\psi(x) = a(x)e^{i\phi(x)}.$$  

Here $a(x)$ is the amplitude and is a real and positive function; $\phi(x)$ is the phase. The intensities then further reduce to

$$I(x) = |\psi(x)|^2 = a^2(x).$$

Also,

$$\psi(x_i)\psi^*(x_\alpha) = a(x_i)a(x_\alpha)e^{i(\phi(x_i) - \phi(x_\alpha))}.$$  

Now we are ready to look at the addition of two coherent fields. Let $\psi(x)$ and $\psi_\alpha(x)$ be the complex amplitude functions of the two fields we wish to examine. The resulting complex amplitude is given by

$$\psi_\beta(x) = \psi(x) + \psi_\alpha(x).$$
Theoretical Section

From equation (7) we have

\[\Psi_i(x) = a_i(x) \exp[i \varphi_i(x)]\]
\[\Psi_\lambda(x) = a_\lambda(x) \exp[i \varphi_\lambda(x)]\]

so equation (10) transforms to

\[a_\lambda(x) \exp[i \varphi_\lambda(x)] = a_i(x) \exp[i \varphi_i(x)] + a_\lambda(x) \exp[i \varphi_\lambda(x)].\]  

(11)

The quantity of the resultant field which we are interested in is the intensity, \(I_R(x)\). From equation (6) we have

\[I_R(x) = \Psi_R(x) \overline{\Psi_R(x)} = [\Psi_i(x) + \Psi_\lambda(x)]^2\]
\[= |a_i(x) + a_\lambda(x)|^2 + a_i(x) a_\lambda(x) + a_i(x) a_\lambda(x) \exp[2i(\varphi_i(x) - \varphi_\lambda(x))].\]

(12)

This can be written in terms of the interference law

\[I_R(x) = I_i(x) + I_\lambda(x) + 2I_i(x) I_\lambda(x) \cos(\varphi_i(x) - \varphi_\lambda(x)).\]

(13)

where \(I_i(x)\) and \(I_\lambda(x)\) are the intensities of the fields 1 and 2 respectively.

**IA2) Addition of Two Coherent Waves**

To understand the addition of coherent waves, we must first look at how light propagates. The optical field
Theoretical Section

\( V(x,t) \) propagates according to a wave equation

\[
\nabla^2 V(x,t) = \frac{1}{c^2} \frac{\partial^2}{\partial t^2} V(x,t),
\]

where \( \nabla^2 \) is the second partial derivative with respect to the space coordinates and \( c \) is the speed of light. If the light is coherent, we can substitute Eq. (4) into Eq. (14) to obtain

\[
\nabla^2 \psi(x) + k^2 \psi(x) = 0
\]

where \( k = \frac{2\pi}{\lambda} \), \( \lambda \) being the wavelength of the light). Two important solutions of this wave equation are

(1) a plane wave propagating along the \( z \) axis

\[
\psi(z) = Ae^{\pm ikz}
\]

where \( A \) is a constant; and

(2) a converging (negative exponent) or diverging (positive exponent) spherical wave solutions

\[
\psi(r) = A e^{\pm ikr}/r.
\]

where \( r \) is the radius of the spherical wave.

We will now look at the addition of various combinations of these two waves, (the addition of two plane waves, the addition of a cylindrical [or spherical] and a plane wave, and finally the addition of two cylindrical [or spherical] waves).

**IA2a) Addition of Two Plane Waves**

We will consider the addition of two equally intense
Theoretical Section

plane waves at an angle $2\Theta$ to each other. Each plane wave will make an angle $\Theta$ with respect to the plane in which one wishes to record the intensity (see Fig. 1).

We will assume that the two plane waves have the same phase at the origin. From equations (10) and (11) we can find the resultant complex amplitude of this addition. From Eq. (16), for a plane wave propagating along an axis perpendicular to the wavefront, $\psi = A\exp(ikz')$. Here $z'$ is in the direction of propagation of wavefront one (or two). We want to measure the complex disturbance in a plane perpendicular to the optical axis, in Fig. 1. In terms of $x$, $z' = x\sin(\Theta)$. Or

$$\psi = A\exp(ikx\sin\Theta).$$  

Equation (18) is the same except in the (relative) opposite direc-

---

**Figure 1**

Addition of two planes waves each at an angle $\Theta$ with respect to the optical axis.
Theoretical Section

Equation, \( z' = x \sin(-\theta) = -x \sin(\theta) \).

\[ \psi = A \exp(-ikx \sin \theta) \quad (19) \]

From Eq. (11) we see that

\[ A \exp[i\phi(x)] = A \exp[ikx \sin \theta] \]

\[ + A \exp[-ikx \sin \theta] \quad (20) \]

where \( x \) is the distance perpendicularly away from the optical axis, in the plane of observation.

If angle \( \theta \) is small, \( \sin \theta \approx \theta \) and the resultant intensity in the observation plane \( I_R(x) \) is given by Eq. (13):

\[ I_R(x) = 2I(1 + \cos kx \theta), \]

\[ = 4I \cos^2(kx \theta) \quad (21) \]

where \( I \) is the intensity of the plane waves, assumed to be equal for both waves.

For the purpose of understanding holographic procedures it is worthwhile to write Eq. (21) in the form of Eq. (12):

\[ I_R(x) = 2I \exp(ikx \theta) + I \exp(-ikx \theta). \quad (22) \]

If we take a photograph of \( I_R(x) \) and then illuminate the film with a coherent plane wave \( \exp(ik\theta) \), it will be shown that the second and third terms recreate the original wave and its conjugate image.

The resultant intensity in the plane of observation from the addition of these two plane waves is a set of cosine squared interference fringes. This result is illustrated in Fig. 2b. Figure 2a shows the result when the two waves are incoherent; they merely add in intensity uniformly.
to give a net intensity of $2I$ (assuming again that the intensity of each wave front is equal to $I$).

**IA2b) Addition of a Cylindrical (or a Spherical Wave) and a Plane Wave**[5]

We will assume that the plane wave is propagating along the optical axis of the system and the plane and cylindrical waves have zero path difference, and hence zero phase difference, at the point $O$ (see Fig. 3).

---

**Figure 2**

An illustration of the resultant normalized intensity formed when two waves at an angle 2 with respect to each other are added: (a) incoherently, (b) coherently, and (c) partially coherently.[4]
If we assume small angles, the path difference at a point in the observation plane between these two waves is then given by \( x^2/2r \), where \( x \) is the distance away from the optical axis and \( r \) is the radius of the spherical wave. This implies that the phase difference is then \( kx^2/2r \). The resultant complex amplitude in the \( x \) plane can be written as

\[
a_R \exp\{i\Phi_R(x)\} = a + a \exp\{ikx^2/2r\} \tag{23}
\]

and the resultant intensity as

\[
I_R(x) = I[2 + \exp\{ikx^2/2r\} + \exp\{-ikx^2/2r\}] \tag{24}
= 4I \cos^2(kx^2/4r). \tag{25}
\]

From Eq. (24) we see the holographic effect as we saw before for the case of two plane waves. It will be shown that the second and third terms recreate the original wave.
and its conjugate. From Eq. (25) we see the overall behavior of the optical field. The resultant intensity is a cosine squared set of interference fringes that vary with the square of the x-coordinate. The result is shown in Figure 4. If one uses a spherical wave and a plane wave, instead of a cylindrical wave, the result would be similar to that given in Eq. (25) but the linear coordinate x would become a radial coordinate and the resultant intensity would be radially symmetric.

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**Figure 4**
An illustration of the intensity distribution produced by the interference of a plane wave and a cylindrical wave. (a) Intensity plot of the profile and (b) photograph. [6]
Theoretical Section (10)

IA2c) Addition of Two Cylindrical (or Spherical) Waves[7]

This is as almost as before, but now we have two cylindrical waves. The resultant complex amplitude in the $x$-plane can be written as

$$a_a \exp[i \Psi_a(x)] = a \exp[i k x^2/2r_a] + a \exp[i k x^2/2r_b]$$

where $r_1$ and $r_a$ are the radii of the two cylindrical waves. (See Fig. 5a). The resultant intensity is given by

$$I_R(x) = I(2 + \exp[(ikx^2/2)(1/r_1 - 1/r_a)])$$
$$+ \exp[(-ikx^2/2)(1/r_1 - 1/r_a)])$$
$$=2I(1 + \cos[(kx^2/2)(1/r_1 - 1/r_a)])$$
$$=4I \cos^2[(kx^2/4)(1/r_1 - 1/r_a)]. \quad (27)$$

We have taken the two cylindrical waves to have zero phase difference at the origin of the coordinate $x$ of the plane in which the intensity is to be recorded.

If the two cylindrical (or spherical) waves are propagating at an angle to each other (see Fig. 5b), then there exists a linear term and quadratic term in $x$ and

$$a_a \exp[i \Psi_b(x)] = a \exp[i k(x^2/2r_a + x\theta)]$$
$$+ a \exp[i k(x^2/2r_b - x\theta)] \quad (28)$$

and

$$I_R = 4I \cos^2 k[(x^2/4)(1/r_1 - 1/r_a) + x\theta] \quad (29)$$

Equation (29) contains the results of Eq.s (21) and

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Figure 5
Addition of two cylindrical waves propagating in the same direction (a), and at an angle to each other (b).

(27) in a combined form.

1A3) Two beam interference[8]

We will move further toward a real situation by considering light from two idealized point sources of equal intensity at $P_r$ and $P_a$ (see Fig. 6). These two points illuminate a plane $X$ at a distance $z$ from the plane containing the point sources. We will assume that $z$ is large compared to the separation $2d$ of the point sources and also the maximum distance $x$, the point of observation, away from the optical axis.

The path difference from point $P_r$ and $P_a$ to some general point in the $x$ plane is given by $2dx/z$ if $\phi$ is small.
Theoretical Section

Thus

\[ I_K(x) = 4I_0 \cos^2(kdx/z). \]  

(30)

This is approximately the form of Eq. (29) with the quadratic term being much smaller than the linear term.

Equation (30) is one form of the interference law for which the fringe pattern is often called Young's fringes. If the two intensities are not the same, then

\[ I_K(x) = I_0 + I_\alpha + 2(I_0 I_\alpha)^{1/2} \cos(2kdx/z) \]  

(31)

IA4) Propagation of Coherent Light --- Fresnel and Fraunhofer Diffraction[9]

In real life situations one rarely has light from two

---

**Figure 6**

Interference from two coherent point sources
point sources, but rather light that has passed through various apertures. One must consider the effect that these finite apertures have on a coherent field.

The wave equation that governs the propagation of the complex amplitude has been given in Eq. (15). Likewise, the plane and spherical wave have been defined in Eq's (16) and (17) respectively. We will now apply these solutions to the propagation of light through an aperture. The aperture and system of interest is shown in Figure 7. If the light originates from effectively a point source at $P_o$ in the $x_o, y_o$ plane, it will illuminate the aperture in the $(\xi, \eta)$ plane and will propagate to the receiving plane $(x, y)$.

---

**Figure 7**
Diagram to define coordinates for the propagation of light through a finite aperture.
Theoretical Section

We want to be able to describe the complex amplitude at any point \( P \) in the \( xy \) plane beyond the aperture. If we limit ourselves to small angles, the Kirchhoff diffraction formula can be written\(^{10}\)

\[
\psi(P) = -iA/2\lambda \int \exp[i(kr + s)] dQ/\rho rs \quad (32)
\]

where \( A \) is a constant, \( r \) is the distance from point \( P_0 \) to the general point \( Q \) in the aperture and \( s \) is the distance from \( P \) to the same general point \( Q \). \( dQ \) is the elemental area in the aperture at the general point \( Q \). It can be understood where this equation comes from by considering the following argument: the point source at \( P_0 \) generates a spherical wave \( \exp(ikr)/r \) that fills the aperture. The aperture truncates this spherical wave and now each point in the aperture becomes a source of a new spherical wave \( \exp(iks)/s \); thus the integral is taken over all the points \( Q \) in the aperture. Equation (32) can be written in the coordinates of the situation described in Fig. 7.

\[
\psi(x, y) = -iA/2\lambda \exp[i(kz_0 + z)]/z_0 z \exp[i(k/2z_0)(x_0^2 + y_0^2)]
\]
\[
\times \exp[i(k/2z)(x^2 + y^2)] \int \int \psi(\xi, \eta) d\xi d\eta
\]
\[
\exp[i(k/2z_0)(\xi^2 + \eta^2)(1/z_0 + 1/z)]
\]
\[
\times \exp[-ik\xi(x_0/z_0 + x/z)]
\]
\[
\times \exp[-ik\eta(y_0/z_0 + y/z)] d\xi d\eta. \quad (33)
\]

This distribution \( \psi(x, y) \) is the Fresnel diffraction pattern of the aperture \( \psi(\xi, \eta) \).

A special case of Fresnel diffraction is when the quadratic term in \( \xi \) and \( \eta \) can be eliminated. This special case
Theoretical Section

occurs when the far-field or far-zone condition, defined in Eq. (34), are satisfied.

\[ z_o \gg (\xi^2 + \eta^2)_{\text{max}} / \lambda, \]  
\[ z \gg (\xi^2 + \eta^2)_{\text{max}} / \lambda. \]  

Under this special condition, the distances \( z_o \) and \( z \) are considered to be essentially infinite, and

\[ \psi(x,y)=C \iint \psi(\xi,\eta) \exp[-ik(p\xi + q\eta)] \, d\xi \, d\eta \]  

where \( p=(x_o/z_o) + (x/z) \), \( q=(y_o/z_o) + (y/z) \), and \( C \) contains various constant and phase terms. Equation (35) represents the Fraunhofer diffraction pattern. There is a fixed functional relationship between the aperture function \( \psi(\xi,\eta) \) and the field \( \psi(x,y) \). Specifically, \( \psi(x,y) \) and \( \psi(\xi,\eta) \) are a Fourier transform pair. The complex amplitude \( \psi(x,y) \) in Fraunhofer diffraction is the two dimensional Fourier transform of the aperture function, \( \psi(\xi,\eta) \).

If the conditions of Eq. (34) are met by illuminating the aperture with light from an infinite source, (or using a collimated beam produced by lenses), the Fraunhofer diffraction of Eq. (35) becomes

\[ \psi(x,y)=-iA/2A \exp(ikz/Z) \exp(ik/2z)(x^2 + y^2) \iint \psi(\xi,\eta) \exp(-ik/z)(x\xi + y\eta) \, d\xi \, d\eta. \]  

Here the source point has been put on the optical axis so that the quadratic terms in \( x_o \) and \( y_o \) are also removed.

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Theoretical Section


IB1) Mutual Coherence Function

In section IA1, I described the concept of coherent fields. One limiting case is complete coherence, which we defined in Eq. (3) to mean the time-averaged cross-correlation of any two points in a field is a maximum. The other limiting case is an incoherent field, which was defined in Eq. (2) to mean the cross-correlation of any two points in a field equals zero. Now I will describe in detail the more general case between these two limiting cases: the situation of partial coherence.

The intensity at a point \( x \) was defined in Eq. (1). The more general definition is the time-averaged cross-correlation function between two different points in a field, \( x_i \) and \( x_A \). This function is termed the mutual coherence function, and is defined as

\[
\Gamma_{iA}(\tau) = \langle V_i(\bar{x}_i, t) V_A^*(\bar{x}_A, t) \rangle \tag{37}
\]

where \( V_i \) is the optical field at a point \( \bar{x}_i \), \( V_A \) is the optical field at a point \( \bar{x}_A \), \( \tau = \tau_A - t_i \), and is given by \( \Delta l/c \) (\( l \) is the path difference between the two points and c is the speed of light in the medium), and the angle brackets again denote a time average. Equation (37) reduces to the intensity at a point \( \bar{x} \), given in Eq. (1), if \( \bar{x}_i = \bar{x}_A \) and \( \tau = 0 \). That is,
The complex degree of coherence is defined as the normalized mutual coherence function

\[ \mathcal{K}_n(\tau) = \frac{\mathcal{R}_n(\tau)}{\mathcal{R}_n(0) \mathcal{R}_n(0)} \]  

Both the modulus and the phase of \( \mathcal{K}_n(\tau) \) are measurable quantities.

**182) Addition of Two Partially Coherent Fields**

If we assume the quasimonochromatic approximations

\[ a \ll c/a \]  
\[ v \ll v' \]  

we can assume \( \tau = 0 \). If we add two optical fields \( V_1(x,t) \) and \( V_2(x,t) \), the resultant optical field is

\[ V_R(x,t) = V_1(x,t) + V_2(x,t) \]  

and

\[ I_R(x) = <V_R(x,t)V_R^*(x,t)> = I_1(x) + I_2(x) + \int_{\lambda_1} + \int_{\lambda_2}. \]

That is,

\[ I_R(x) = I_1(x) + I_2(x) + 2[I_1 I_2]^x \text{Re}(\mathcal{K}_n), \]

where Re denotes a real part. The complex degree of coherence can be written in terms of a modulus and phase

\[ \mathcal{K}_n = |\mathcal{K}_n| \exp[i\beta_n]. \]

Equation (43) then reduces to

\[ I_R(x) = I_1(x) + I_2(x) + 2[I_1 I_2]^x |\beta_n| \cos(\beta_n). \]

Equation (44) is the generalized interference law for partially coherent quasimonochromatic light. If the light is incoherent, \( |\mathcal{K}_n| = 0 \), and Eq. (44) reduces to

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Theoretical Section

\[ I_R(x) = I_1(x) + I_A(x) \]  \hspace{1cm} (45)

which implies that there is no interference, just a superposition of intensity, which was to be expected. If the light is coherent, \(|\mathcal{M}_A| = 1\), and \(\beta_A = 0\), and Eq. (44) reduces to

\[ I_R(x) = I_1 + I_A + 2[I_1 I_A]^\frac{1}{2} |\mathcal{M}_A| \cos(\beta_A) \]  \hspace{1cm} (46)

which is the well known interference law for coherent radiation. For two point sources, Eq. (46) would be the same as Eq. (31) presented earlier in Section IA3. For the case of intermediate values of \(|\mathcal{M}_A|\), the field is considered to be partially coherent, and the resulting interference is governed by Eq. (44). For the case of two point sources considered in Section IA3 (the arrangement discussed in Figure 6), Eq. (44) would reduce to

\[ I_R(x) = I_1 + I_A + 2[I_1 I_A]^\frac{1}{2} |\mathcal{M}_A| \cos(2kdx/z + \phi_A) \]  \hspace{1cm} (47)

If \(I_1 = I_A = I\), Eq. (47) would reduce to

\[ I_R(x) = 2I[1 + |\mathcal{M}_A| \cos(2kdx/z + \phi_A)] \]  \hspace{1cm} (48)

and Eq. (48) would be the general case (valid regardless of the degree of coherence of the optical field) of Eq. (31), given on page 12.

The usual way to define fringe visibility, when \(I_R(x)\) is given by Eq. (48), is

\[ V = (I_{\text{max}} - I_{\text{min}})/(I_{\text{max}} + I_{\text{min}}) = |\mathcal{M}_A|^2 \]  \hspace{1cm} (49)

where

\[ I_{\text{max}} = 2I[1 + |\mathcal{M}_A|^2] \]  \hspace{1cm} (50)

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The visibility is a measure of the modulus of the complex degree of coherence of the two beams (assuming $I_r = I_x = I$). One can then measure the degree of coherence of a field by measuring the fringe visibility between two points.

### Spatial and Temporal Coherence

The effects of partial coherence are governed by the complex degree of coherence, $\gamma (\tau)$, in Eq. (39). The complex degree of coherence is a function of both spatial and temporal components. It is useful to separate the complex degree of coherence into separate spatial and temporal parts. The spatial effects would be governed by $\gamma_s(0)$. It results primarily from angular source size. Temporal effects would be described by $\gamma_t(\tau)$. Temporal coherence, or coherence length, results primarily from the finite spectral width of the radiation.

### Formation of a hologram

I will now consider the case of the noise free formation of a hologram. For this development, I will assume that the optical field is described by the mutual coherence function defined as (see Partial Coherence):

$$\gamma_s(x, x', t) = \langle V_s(x) \exp(i \omega_0 t) V_s^*(x', t) \rangle.$$
If the following quasi-monochromatic approximations are valid

\[ \Delta \psi \ll \psi' \quad \text{(53)} \]

\[ \Delta I \ll c/\Delta \psi \quad \text{(54)} \]

and if the radiation is coherent, \( \sum_{\Delta} (x, x, \tau) \) can be shown to assume the form[14]

\[ \sum_{\Delta} (\tau) = \sum_{\Delta}(x, x, \tau) = \psi(x, x) \psi^*(x) \exp(2\pi i \nu' \tau) \quad \text{(55)} \]

where \( \psi(x) \) is the solution to the Helmholtz equation

\[ \left[ \nabla^2 + k_f^2 \right] \psi(x) = 0 \quad \text{(56)} \]

in which \( k_f' \) is the mean wave number in the formation process and \( \nu' \) the mean frequency.

To better understand the physics behind the problem, I will first describe the problem for planar objects. If the object transmission function is represented by \( D(\xi) \) and the object illumination is described by \( \psi^0(\xi) \), the diffracted field, \( \psi(\overline{x}) \), at some plane removed from the object is given by

\[ \psi(\overline{x}) = \int \psi^0(\xi) D(\xi) dG(\xi, \overline{x}) / \partial \overline{x} d\xi \quad \text{(57)} \]

Here \( \overline{\xi} \) is a position vector in the object plane defined by \( \overline{\xi} = \xi_i + i\eta; \) \( d\overline{\xi} = d\xi d\eta \); \( \overline{x} \) is a position vector in the hologram plane defined by \( \overline{x} = \xi_i + j\eta; \) and \( G(\overline{\xi}, \overline{x}) \) is the appropriate Green's function for the Helmholtz equation satisfying the boundary condition \( G(\overline{\xi}, \overline{x}) = 0 \) for \( z = 0 \) and \( \partial G/\partial n \) is its derivative along the normal to the wave front. The Green's function is

\[ G(\overline{\xi}, \overline{x}) = \exp[ik_r \overline{r}]/4\pi r - \exp[ik_{r'} \overline{r}']/4\pi r' \quad \text{(58)} \]
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where \( r \) and \( r' \) are the distances shown in Figure 8.

If we use Eq. (58) to solve Eq. (57), it can be shown that Eq. (57) reduces to

\[
\tilde{\psi}(\tilde{x}) = C \int \tilde{\psi}(\tilde{s}) D(\tilde{s}) \exp(ik' r(\tilde{s}, \tilde{x})) d\tilde{s}
\]  

(59)

where \( C = \sqrt{1 - ik' z} \cos \theta / 2 \imath z \); \( r \) is the distance from a typical point on the object plane \( \tilde{s} \) to a typical point in the observation plane \( \tilde{x} \), that is

\[
r = \sqrt{(\tilde{s} - x)^2 + (\tilde{s} - y)^2 + z^2};
\]  

(60)

\( z \) is the distance from the object plane to the hologram plane; and \( \cos \theta = z / r \geq 1 \).

If both the source and the point of observation lie near the optical axis (the paraxial approximation) \( r \) may

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**Figure 8.**
Geometry and notation for the calculation of the Green's function for the Helmholtz Equation.

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be expanded as

$$r \approx z_i \left[ 1 + \frac{i \gamma^4}{2z_i^4} + \frac{\gamma}{2z_i} - \frac{\gamma}{z_i} + \ldots \right].$$

(61)

Thus, the field can be expressed in the form

$$\psi(\vec{x}) = C \exp[i k z] \int \psi_i(\vec{\xi}) D(\vec{\xi}) \exp[ik \frac{\vec{x} - \vec{\xi}}{2z} d\vec{\xi},$$

(62)

This shows that the diffracted field from the plane is just the Fresnel transformation of the object transmittance. Depending on the relative size of $|\vec{\gamma}|_{\text{max}}^2$ and $z$, the quadratic phase term $|\vec{\gamma}|_{\text{max}}^2/2z$, may or may not be significant. If $|\vec{\gamma}|_{\text{max}}^2/2z, << 1$ (63)

the resulting hologram is referred to as a Fraunhofer hologram. If equation (63) is not satisfied, the resulting hologram is referred to a a Fresnel hologram.

I will now consider these general results as applied to specific hologram processes, Fresnel and Fraunhofer Holography. A detailed discussion of the reconstruction process will be included which will enable one to see that a hologram truly does recreate the original wavefield.

I D) Fresnel Hologram Process[15]

ID1) Formation

Again I will assume that the object is a plane, semi-transparent diffracting object whose geometry is described by $D(\vec{\xi})$ where $\vec{\xi}$ is the position vector in the object plane.
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A coherent, quasi-monochromatic plane wave is incident on the object.

The incident field is assumed to be constant (K) over an area which is large as compared to the area of the object. This gives us a boundary-value problem to solve, where the boundary condition is

\[ \Psi(\vec{z}) = K - D(\vec{z}) \quad (64) \]

where K is the amplitude of the incident field. If the direction of propagation is along the z-axis, the solution to our general field equation, Eq. (59), may be written as

\[ \Psi(\vec{x}) = \int_{\vec{z} = 0}^{\infty} C[K - D(\vec{z})] \exp[ik, r(\vec{z}, \vec{x})] d\vec{z} \quad (65) \]

where

\[ C = (1 - ik) \cos \theta / 2 \pi r \tilde{z} = -ik, \cos \theta / 2 \pi \tilde{r} \quad (66) \]

Since quasi-monochromatic light is used, we have replaced \( k' \) with \( k \). The term \( r(\vec{z}, \vec{x}) \) is the distance from a point \( \vec{x} \) in the observation plane to a point \( \vec{z} \) in the object plane, as given in Eq. (60). If we use the form of \( r(\vec{z}, \vec{x}) \) as given by Eq. (61), assuming the paraxial approximation, and ignoring terms of order \( 1/z^2 \) and higher, Eq. (65) becomes

\[ \Psi(\vec{x}) = \exp(ik, z) \{ Kf(\vec{x}) - [\exp(ik, |x|^2/2z) - \exp(i\eta x)]d\eta d\xi \}, \quad (67) \]

where \( |x|^2 = x^2 + y^2 \) and

\[ f(\vec{x}) = f(x, y) = \int_{\vec{z} = 0}^{\infty} \exp(ik, \frac{(|\xi, \eta|^2 + (\eta - y)^2}{2z}) d\xi d\eta \]. \quad (68) \]

The intensity can be found in the plane at \( z \), to be

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\[
I(\vec{r}) = |Kf(\vec{r})|^2 + \int D(\vec{r}) \exp[ik_0 r - \frac{\vec{k}_0 \cdot \vec{r}}{2}] d\vec{r} d\vec{k}_0
\]

\[
X \int \left[ -ik |f(\vec{r})|^2 \right] d\vec{r} d\vec{k}_0
\]

\[
- \int D(\vec{r}) \exp[-ik_0 r - \frac{\vec{k}_0 \cdot \vec{r}}{2}] d\vec{r} d\vec{k}_0
\]

\[
+ \int \left[ -ik_0 f(\vec{r}) \exp(-ik_0 r - \frac{\vec{k}_0 \cdot \vec{r}}{2}) \right] d\vec{r} d\vec{k}_0
\]

and the notation \( i|C| = C \) has been used. By controlling the amplitude of the incident field \( K \), we can make the third term in Eq. (69) small, thus reducing it to

\[
I(\vec{r}) = |Kf(\vec{r})|^2 + \int D(\vec{r}) \exp[ik_0 r - \frac{\vec{k}_0 \cdot \vec{r}}{2}] d\vec{r} d\vec{k}_0
\]

\[
- \int D(\vec{r}) \exp[-ik_0 r - \frac{\vec{k}_0 \cdot \vec{r}}{2}] d\vec{r} d\vec{k}_0
\]

in which

\[
\mathcal{L}(\vec{r}, \vec{\gamma}) = \frac{i \vec{k}_0 \cdot \vec{\gamma}}{2} + \frac{\vec{k}_0 \cdot \vec{r}}{2}
\]

The intensity distribution in Eq. (70) is called the hologram of the process, and equations 65-71 describe the formation of the hologram.

\[\text{ID2) Reconstruction}\]

If we prepare a transparency whose transmission \( T(x) \) is proportional to \( I(x) \) given by Eq. (70), we can use the amplitude transmittance of the film as a boundary condition to solve another propagation problem as we did with Eq. (64) and Eq. (65). It can be shown [16] that \( f(x) \) in Eq. (68)

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is just a plane wave and can be set equal to one to simplify the math. If we use film to record the intensity given by Eq. (70), the amplitude transmittance of the film when placed in a coherent beam is

$$T(x) = K^4 + i(-J/2)K^4 + C \exp(ik_{1} |x|^{4} /2z_{1}) \int_{D_x} D(x) \exp[ik_{1} \mathcal{L}(x, \tau)] d\tau$$

$$- iK(-J/2)C \exp(-ik_{1} |x|^{4} /2z_{1}) \int_{D_{r0}} D^{*}(x) \exp[-ik_{1} \mathcal{L}(x, \tau)] d\tau$$

where $\lambda$ is the wavelength of light used to form the hologram and $J$ is the slope of the $H$- and $D$- curve of the photographic process.

When we solve the propagation problem we find the amplitude distribution in the observation plane ($\times$-plane) a distance $z_{2}$ from the transparency (film) illuminated with light of wavelength $\lambda_{2}$ is

$$\Psi(x) = K^4 \exp(ik_{1} \mathcal{L}_{2} x_{2}) + K^4 (-J/2)C \exp(ik_{1} |x|^{4} /2z_{1}) \int_{D_{x2}} D(x) \exp[ik_{1} \mathcal{L}(x, \tau)] d\tau$$

$$- K^4 C \exp[-ik_{1} \mathcal{L}_{2} x_{2}] \int_{D_{r0}} D^{*}(x) \exp[-ik_{1} \mathcal{L}(x, \tau)] d\tau$$

$$\times \exp[ik_{1} \mathcal{L}_{2} x_{2}] d\tau$$

where $C$ is given by Eq. (59) and $C'$ by

$$C' = (1 - i k_{1} z_{2} \lambda_{2} \cos \theta/2 \pi z_{2}^2) \quad (74)$$

If we expand the exponents in Eq. (73) and use the focusing condition

$$k_{1}/z_{1} = k_{2}/z_{2} \quad (75)$$

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to remove the quadratic phase factor in $x$ in the third term of Eq. (73), upon integration we obtain the amplitude of the reconstructed image

$$\Phi(z) = \exp(ik_4z_4)[|K|^2 - K^*F|C^*C'|/2$$

$$\times \exp(ik_4z_4^2/2z_4) \mathcal{A}(x) + K^*F|C^*C'|/2\mathcal{D}(x)]$$

where $\mathcal{D}(x)$ represents the real image because of the condition given by Eq. (75), and

$$\mathcal{A}(x) = \int\int D(y) \exp(ik_1\bar{z}_1^2/2z_1) \exp[i(\bar{z}_1^2/2)(k_1/z_1 + k_4/z_4)]$$

$$\times \exp[i\bar{z}_1(z_1^2 + \bar{z}_1^2)]dxdy$$

We see that the third term in Eq. (76) represents the real image due to the boundary condition of Eq. (75) and this is the wave field from the object in the plane of the hologram. Thus, the hologram has recreated the exact wavefront, with some added background noise! It is important to note that while the location of the image plane varies with a change in wavelength between construction and reconstruction, as given in Eq. (75), the scale of the image does not. More will be said on this under magnification. The second term represents an out-of-focus virtual image $z_4$ units behind the transparency, which appears as background when the real image is focused on. Interference between real and virtual images will result and when the real image is focused on, the virtual image appears as unwanted background noise. If we go back to Eq. (73) and use the condition that $k_1/z_1 = -k_4/z_4$ to observe the virtual image, the results

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would be the same with the out-of-focus real image as background noise to the virtual image. This noise causes deterioration of the reconstructed image, whether it be real or virtual.

\[ \text{IF} \] Fraunhofer (Far-Field) Hologram Process[17]

To reduce the effect the conjugate image has in Fresnel holograms, one can form the hologram in the Fraunhofer (far-field) zone of the object.

The intensity distribution in the reconstructed plane of a hologram formed in the far-field of an object can be found from Eq. (76) to be

\[
I(\overline{z}) = \left| \Phi(\overline{z}) \right|^2 = |K|^2 |\phi|^2 |C|^2 |C'|^2 / 4
\]

\[
\times \left[ |K|^2 |\phi|^2 |C|^2 |C'|^2 / 4 \right] \times \left[ \text{Re}(K) \right] - \text{Re}[K^2 \Phi(\overline{z}) \exp(ik_\lambda \overline{z}^n / 2z_\lambda)] \exp(k_\lambda \lambda / 2z_\lambda)] (78)
\]

It is obvious from the form of this equation that the quality of the reconstructed image is degraded by the interference between the two conjugate images. Although the two images should have equal energy, because the real image is focused on, the conjugate image (virtual image) appears to be an out-of-focus image. Thus, the real image should have a greater energy density than that of the virtual image. That is \( \Phi(\overline{z}) \) should be small compared to \( D(\overline{z}) \). I will now show this.

If the background is adjusted such that \( |K|^2 |\phi|^2 |C|^2 |C'|^2 / 4 \)
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is small relative to \(|K|\), Eq. (78), which would only be valid for semi-transparent objects, reduces to

\[
I(\vec{x}) = |K|^q + |K|^4 / C! \{ \text{Re}[KD(\vec{z})] \}
- \text{Re}[K^* A(\vec{z}) \exp(ik_1 |\vec{z}|^2 / 2z_\lambda)]
\]  

(79)

If \(A(\vec{z})\) in the last term of the equation is small, then we have the reconstructed image of the object superimposed upon a background. This will be the case with Fraunhofer holograms, because of the far-field condition.

Under this approach, Eq. (77) may be written as

\[
A(\vec{\eta}) = \int_{\vec{x} = 0} \exp[i|\vec{x}|^2 / 2(k_\parallel / z_\lambda + k_\perp / z,)]
\exp[-ik_\parallel (\vec{x} \cdot \vec{\eta}) / z_\lambda] [F(\vec{x})] d\vec{x}
\]  

(80)

where

\[
F(\vec{x}) = \int D(\vec{\eta}) \exp(ik_\parallel |\vec{\eta}|^2 / 2z,) \exp[-ik_\parallel / z, (\vec{x} \cdot \vec{\eta})] d\vec{\eta}
\]  

(81)

For simplicity we will assume that \(D(\vec{\eta})\) can be written as a product \(D(\vec{\eta})D(\vec{\xi})\). (Experimental results support this assumption.) [18] Equation (81) then reduces to a product of two integrals, each of which take on the form of

\[
F(x) = \int D(\vec{\eta}) \exp(ik_\parallel \vec{\eta}^2 / 2z,) \exp[-ik_\parallel / z, (x \cdot \vec{\eta})] d\vec{\eta}
\]  

(82)

Assuming that \(D(\vec{\eta})\) is a rectangular function of width 2b, one can complete the square of the exponential terms obtaining
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\[ F(x) = \int_{-b}^{b} \exp\left\{ ik_{1} / 2z_{1} (\frac{x}{2} - x') \right\} d\frac{x'}{2} \] 
\[ \times \exp\left\{ -ik_{1} / 2z_{1} (x') \right\} \]

(83)

It can be shown\[19\] that this integral can be rewritten

\[ F(x) = \frac{1}{2z_{1}} / k_{1} \exp\left\{ -ik_{1} / 2z_{1} (x') \right\} \int_{-\sqrt{k_{1} / 2z_{1}}\left( b - x' \right)}^{\sqrt{k_{1} / 2z_{1}}\left( b + x' \right)} \exp(iy') dy'. \]

(84)

which is a form of the Fresnel Integral. If we demand that

\[ \sqrt{k_{1} / 2z_{1}}\left( b - x + (b + x) \right) << 1, \]

(85)
equation (84), and thus Eq. (80), become negligibly small. Equation (85) can be written as

\[ 4\pi b^{2} / \lambda, << z, \]

(86)

which is a form of the far-field condition for Fraunhofer diffraction.

Thus, the effect of the out-of-focus virtual image appearing in Eq. (79) can be ignored. If \( K = 1 \), Eq. (79) gives a reconstructed image intensity of

\[ I(\tilde{J}) \approx 1 + |C|^{2} |C' | Re\{D(\tilde{\omega})\} \]

(87)

and thus the focused image is seen to be erect. A similar analysis would show that the virtual image would appear undeteriorated and erect also.

If) Side-Band Fresnel Hologram Process\[20\]

With side-band Fresnel holography, the reference wave is introduced at some angle to the plane of the hologram, see Figure 9. This type of holography relies on the coherent addition of two fields in the plane of the

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hologram; (1) the object field which is reflected or transmitted by the object, and (2) a reference field from a known source. We shall first consider the case in Fig. 9, because the object is being transilluminated, as were the cases before. The diffracted field will consist of the Fresnel diffraction pattern, and this will be combined with a reference field that is a plane wave.

The intensity distribution from the addition of these two fields in the plane of the hologram is given by

\[ I(x) = |K\exp(ik_0 \cdot \vec{r}') + R(\vec{x})|^2, \quad (88) \]

where

\[ \vec{k} \cdot \vec{r}' = k_0 (x \sin \phi + y \cos \phi \cos \theta + z \cos \phi \sin \theta), \]
\[ \vec{r}' = \hat{x} + \hat{y} + \hat{k}_z, \]
\[ \vec{k}_r = \hat{x}k_x + \hat{y}k_y + \hat{k}_z, \]
\[ k = |k| = 2\pi / \lambda. \]

and \( \phi \) is the angle between the propagation vector \( \vec{k} \), and its projection into the \( y,z \) plane, and \( \theta \) is the angle in the plane measured from the \( y \)-axis.

\( R(\vec{x}) \) denotes the diffracted wave from the object, and this is given by the second term in Eq. (67), which is

\[ R(\vec{x}) = K' \exp(ik_0(z)\exp(ik_0(\vec{x}^2/2z)), \]

\[ \chi \int_{\vec{r} > 0} D(\vec{r}) \exp(ik_0(\vec{r}^2/2\zeta) - \vec{x} \cdot \vec{r}/\zeta) d\gamma, \quad (89) \]

where \( D(\vec{r}) \) is the amplitude transmittance of the object and \( K' \) is an appropriate constant. Substituting Eq. (89) into Eq. (88) gives
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Figure 2
Schematic of system for formation and reconstruction of side-band holograms.

\[ I(\mathbf{x}) = |K|^2 + |K'|^2 |G|^2 |\mathcal{A}(\mathbf{x})|^2 \]
\[ + KK'G \exp(ik, z_1) \exp(ik, |\mathbf{x}|^2 / 2z_1) \mathcal{A}(\mathbf{x}) \exp(-ik, \cdot r') \]
\[ + KK'G \exp(-ik, z_1) \exp(-ik, |\mathbf{x}|^2 / 2z_1) \]
\[ \times \mathcal{A}(\mathbf{x}) \exp(ik, \cdot r'), \quad (90) \]

where
\[ \mathcal{A}(\mathbf{x}) = \int_{\mathcal{D}} \mathcal{D}(\mathbf{x}, \mathbf{q}) \exp(ik, |\mathbf{x}|^2 / 2z_1 - \mathbf{x} \cdot \mathbf{q} / 2z_1) d\mathbf{q}. \quad (91) \]

To view this hologram, a film having a distribution given by Eq. (90) is prepared and placed in a coherent beam.
of light as in Fig. 9. If one makes the background large, $K > K'$, we can neglect the second term in Eq. (90). It can be shown that the resulting amplitude transmittance of the hologram is then

$$T(x) \approx \frac{K}{K'} \left( \sqrt{\frac{\lambda}{2}} \right)^4 \exp \left( -i \frac{\pi}{2} \right) \exp \left( i \frac{\lambda}{2} \right) \exp \left( -i \frac{\pi}{2} \right)$$

The first term generates a diffraction pattern characteristic of the hologram size centered on the optical axis in the image plane. The other two terms in Eq. (92) represent the two conjugate images. We shall first look at the condition that the real image is focused on.

If we solve another propagation problem with only the third term in Eq. (92), the amplitude in the image plane is given by

$$\psi(x) = \left( -\frac{i}{2} \right) K' \left( \frac{\lambda}{2} \right)^4 \exp \left( -i \frac{\pi}{2} \right) \exp \left( i \frac{\lambda}{2} \right)$$

It can be shown for one-dimensional problems ($\ell = \frac{\pi}{2}$) and if $\sin(\omega_0) = \omega_0$, Eq. (93) becomes

$$\psi(x) = \frac{1}{2} \left( -\frac{i}{2} \right) K' \left( \frac{\lambda}{2} \right)^4 \exp \left( -i \frac{\pi}{2} \right) \exp \left( i \frac{\lambda}{2} \right)$$

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where

$$A'(\Delta) = -(\pi/2)K^2KC'/(\lambda_z z_1)\exp(ik_z z_2)$$

$$\chi\exp(ik_x \xi/2z_4)$$

(95)

and

$$k_z z_4/k_z z_1 = m = 1$$

(96)

is the linear magnification of the system.

If we consider the virtual term in Eq. (90), and view the virtual term in the plane of the focused real image, it can be shown

$$\psi_{\text{vir.im}}(\Delta) = A'[\Delta(\xi)]f(\xi + \delta z + \xi/m)d\xi,$$

(97)

where

$$f(\xi + \delta z + \xi/m) = \exp(ikx\xi/z_1)$$

$$\chi\exp(-ikx(\xi + \delta z + \xi/m))dx.$$

Equation (97) is an unrecognizable distribution that appears in the real image plane due to the virtual image. It is centered $2\delta z$ units from the real image. Thus the real image term yields an in focus real image $\delta z$ units off the optical axis, $z_4$ units in front of the hologram. If we had focused on the virtual image, it would be located $\delta z$ units off the optical axis, $z_4$ units behind the hologram.

The result of folding in the reference beam, i.e., introducing a carrier to store the desired information, creates a focused image off axis where the image will not be deteriorated by either the diffraction terms or conjugate.
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images if the carrier frequency, $\omega_c$, is large enough. This technique does remove the background noise, but it does result in a loss of system resolution compared to the in-line Fresnel Holography.

IG) Holographic Magnification [21]

With plane wave illumination during construction and reconstruction, no magnification will take place. The focusing condition, $\lambda_z = \lambda_2 z_4$, implies that the magnification, which is $m = \lambda z_2 / \lambda z_1$, is equal to one when the image is in focus. The equation does show that the location of the object will change, in the ratio of the wavelength used to view the hologram, to that wavelength used to expose the hologram. For spherical wave illumination, either during exposure or reconstruction, magnification will take place. I will only consider the results of spherical wave illumination of a holographic scene to present the properties of holographic magnification.

IG1) Magnification Obtained with Fresnel and Fraunhofer Holograms

It can be shown that for in-line holography

$$m = \left[ \frac{R_i}{R_i + z_i} - k_i z_i / k R_i \right]^{-1}$$

Equation (98) describes the magnification in terms of
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the parameters that one has control over in the holographic process, i.e., wavelength of illumination light \((k_1, k_A)\), and radius of spherical wave \((R, R_\lambda)\) for construction, \(R_\lambda\) for reconstruction. We can now consider different limiting cases (as \(R, R_\lambda\) go to zero or infinity) and examine the results.

If a plane wave \((R\) approaches infinity) is used during exposure and reconstruction, the second term in Eq. (98) vanishes, and the magnification is equal to one. The magnification is independent of wavelength, as was put forth before.

If the hologram is illuminated with a plane wave during exposure, \(R_\lambda\) = infinity, and reconstructed with a spherical wave \(R_\lambda\), Eq. (98) becomes

\[
m = k_1 / z_1 (k_1 / z_1 - k_A / R_\lambda)
\]

This can result in a large magnification if

\[
k_1 / z_1 \neq k_A / R_\lambda \tag{100}
\]

A form of the focusing condition is

\[
k_A / R_\lambda - k_1 R_\lambda / [z_1 (R_\lambda + z_1)] + k_A / z_\lambda = 0 \tag{101}
\]

and if Eq. (100) is used in Eq. (101), we obtain

\[
k_A / z_\lambda \neq 0 \tag{102}
\]

That is, the image plane at a distance \(z\) approaches infinity. Thus, the advantage of obtaining a large magnification is offset by the fact that the object becomes infinitely far from the plane of the hologram.

If the hologram is formed with a spherical wave \(R_\lambda\), and viewed with a plane wave \((R_\lambda\) equal infinity), Eq. (98)
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reduces to

$$m = 1 + \frac{z_i}{R_i}. \quad (103)$$

One can obtain large magnifications as $R_i$ goes to zero. But as $R_i$ goes to zero, the object approaches the point source and only one point on the object is illuminated. As before, the focusing condition of Eq. (101) as $R_i$ goes to zero implies Eq. (102) is true, with the same consequences as before. Also, the assumption was made for in-line holography that the wavefield illuminating the object during construction is large enough such that the wavefield both illuminates the object and provides a background field. This puts a further limitation on the size of $R_i$.

If both $R_i$ and $R_\lambda$ are finite, very large magnifications are obtained from Eq. (98) when

$$k_1 R_i / \left[ z_i (R_i + z_i) \right] \approx k_\lambda / R_\lambda. \quad (104)$$

Again it can be shown that Eq. (102) holds, thus negating the effect of the large magnification.

This analysis was done for planar objects and assumed the wavelength of reconstruction is in the visible range because only optical (film) detection has been considered. Since planar objects were considered, longitudinal magnifications have been ignored. If three dimensional objects were considered, no inconsistent results would be obtained.

**1G2) Magnification Obtained with Side-Band Fresnel Holograms**

It can be shown that for side-band Fresnel holography
Equation (105) describes the magnification in terms of the parameters that one has control over in the holographic process, i.e. wavelength of light and radius of spherical waves. We can now consider the different limiting cases and examine the results.

If a plane wave is used during both exposure and reconstruction, the second and third terms in Eq. (105) vanish, and the magnification is equal to one. The magnification is independent of wavelength, as was put forth before.

If the hologram is illuminated with a plane wave during exposure, and reconstructed with a spherical wave, Eq. (105) becomes

\[ m = \left( 1 - \frac{\lambda z_i}{\lambda_0 R_1} \right)^{-1}. \]  \hspace{1cm} (106)

This can result in a large magnification if

\[ \lambda_0 R_1 \approx \lambda z_i. \]  \hspace{1cm} (107)

A form of the focusing condition which must also be simultaneously satisfied for this problem is

\[ -k_1/z_i + k_i/R_i + k_4/z_4 + k_4/R_4 = 0. \]  \hspace{1cm} (108)

If we use Eq. (107) in Eq. (108), Eq. (108) becomes

\[ k_4/z_4 \geq 0. \]  \hspace{1cm} (109)

That is, the image plane located at a distance \( z_4 \) approaches infinity. Thus, the advantage of obtaining a large magnification is offset by the fact that the object becomes infinitely far from the plane of the hologram.

If the hologram is formed with a spherical wave \( R_1 \) and viewed with a plane wave, Eq. (105) reduces to
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\[ m = \left( 1 - \frac{z_1}{R_1} \right)^{-1}. \quad (110) \]

One can obtain large magnifications as \( \frac{z_1}{R_1} \equiv 1 \). But when \( \frac{z_1}{R_1} \equiv R \), the focusing condition, Eq. (108), once again reduces to Eq. (109), \( k_1/z_1 \equiv 0 \).

If both \( R_1 \) and \( R_\delta \) are finite, very large magnifications are obtained from Eq. (105) when

\[ \frac{z_1}{R_1} + \lambda_\delta \frac{z_1}{R_\delta} = 1 \quad (111) \]

which is equivalent to

\[ k_1/R_1 + k_\delta /R_\delta = k_1/z_1. \quad (112) \]

If one substitutes Eq. (112) in the focusing constraint of Eq. (108), it once again reduces to Eq. (109), and \( z_\delta \) goes to infinity as rapidly as \( m \) goes to infinity. The highest resolvable magnification obtained to date has been a magnification of 120 times.

This analysis was done for planar objects and assumed the wavelength of reconstruction is in the visible range because only optical detection has been considered. The only restriction on the wavelength of construction, and its associated \( k \), are the focusing conditions. If three-dimensional objects were considered, it could be shown that the longitudinal magnification is

\[ m_{\text{Long}} = \left( \lambda_1 /\lambda_\delta \right) m_{\text{Lat}}. \quad (113) \]

This means a distortion of the image will result if the magnification of a three-dimensional object is not equal to one. In principle, the distortion can be removed if \( m_{\text{Lat}} = \lambda_\delta /\lambda_1 \), with the result being that

\[ m_{\text{Lat}} = m_{\text{Long}}. \quad (114) \]
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A further constraint required such that the reconstructed three dimensional image be undistorted is that $m(\text{Lat})$ should not depend on $z_i$. 
REFERENCES

[4] Caulfield, page 33 Figure 2.
[6] Caulfield, page 34 Figure 4.
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II) Experimental Holography

IIIA) Introduction

In this section I will attempt to describe, generally, the holography process that I have worked with and developed, and also describe the optics lab and what equipment is available for holography. I will begin by describing what equipment is used in making a hologram. On some items, the optical table for instance, I will give a brief background on how it was built and why it was built this way. The equipment report will be broken down into three main categories: the optical table, optical equipment, and finally the lasers. Some of the equipment I will describe will be easy to find, such as the optical table itself. Other pieces of equipment, such as the neutral density filters, may not be as easy to find. One rule to remember when using the optics lab: never assume that the physics department does not have something. Assume that the department does and look! One will be amazed at what one finds if one digs around long enough. After this introduction to Colby's equipment, I will describe the general set-up to make a transmission hologram. I will describe the actual geometrical set-up of the apparatus and various tricks that I have discovered that facilitate the making of these holograms.

After this introduction to general holography, I will briefly describe other types of holography in which one can...
use most of the techniques put forward in the discussion of the general results. The different types of holography will include Dual Object Beam holography, 360 degree Holograms, Multiplexed Holograms, and Holographic Interferometry. After these holograms I will describe white-light (or reflection) holography and closely related color (red/blue) holography.

The last section will be entitled 'The Darkroom.' As the title suggests I will describe the use of the darkroom and what equipment the Colby Physics department has to offer. Also, I will describe specifics about the various holographic film that Colby presently has.

With these three sections anyone should be able to make any of the holograms that I have made over the years, and easily expand on this base. Good luck!
IIB) Equipment for Holography

IIB1) The optics Lab

No discussion of equipment for holography would be complete without a brief description of the optics lab itself. The lab is supposed to be light-tight. To this end, the door frame is lined with soft foam and a mechanism is provided that seals to the floor when the door is closed. The force with which this mechanism pushes the seal to the floor is adjusted by a screw which protrudes from the right-end of the mechanism. When the door closes this screw pushes against the door frame and, in turn, pushes the seal to the floor. It is a good practice when one does not need the room to be light-tight for extended periods of time, to turn the tension adjustment screw all the way in. This will prevent the seal from being pushed against the floor and will extend the life of the seal.

The false ceiling tiles along the back wall of the lab cover up the skylight that was part of the design of the building. The skylight itself is covered up by individual tiles that are sealed with caulking compound to make the skylight light-tight. The only other source of light into the room is through the ventilation duct above the optical table. On bright days, sun shines in through the window of the Modern Physics Lab and reflects into the Optics Lab. Generally this light is not enough to fog the film, but I sometimes cover the vent with dark paper to ensure that no...
stray light enters the lab. This vent sucks air out of the room, and this suction can easily support the weight of the dark paper without the need of extra tape. Since this vent does remove air from the lab, one should not leave this vent blocked for extended periods of time, especially since the dark room does not have an independent exhaust fan.

IIIB2) The Optics Table

I am describing the optical table and its construction because stability is the major factor in obtaining quality holograms. If one has the correct geometrical set-up, which is easy to obtain, the only potentially uncontrollable variable is motion. To obtain a hologram, all the components used in exposing the film must stay within one-quarter of a wavelength relative to one another. The optical table was designed to accomplish this, and does so remarkably well.

Colby's optical table attempts to isolate the surface of the table from the surrounding environment by "floating" a massive box on innertubes slightly inflated with air. The basic theory behind this isolation system is that the resonant frequency $f$ is proportional to $\sqrt{k/m}$, where $k$ is the effective spring constant of the system and $m$ is the mass. One would like to have the resonant frequency of the table as low as possible in an attempt to get the resonant frequency below any natural frequencies generated by the environment (i.e., building ventilation motors, people walking, etc...). Thus, regardless of the spring constant $k$, the
more massive the system, the lower the resonant frequency of the system will be.

To obtain this mass I used white sand, actually the sand that companies use in ash-trays, because sand dampens vibrations well, is easy to use (to pour in and make flat), and is cheap. Since the table's base and the box itself must support the mass of this "dampening factor," special techniques were used to ensure the longevity of the table. The base is built out of six 8 x 8's that support a 1 and 1/2" thick plywood panel which is the platform that the tubes will rest on. The box has two 3/4" plywood panels for its floor and single 3/4" panels for the sides. To ensure rigidity of the box, the box is reinforced with a network of 2 x 8's screwed and glued into the bottom, as seen in Figure 1a. The box contains approximately 1,200-1,400 pounds of the white sand. I used a wooden "trowel" that fits across the box, with notches cut out to slide on the side of the box, to level the sand. I tried to compact the sand slightly to minimize settling effects.

With the mass of the optical table provided, one must now mount optical equipment on the table in some manner that provides rigid set-up of optical systems. One option considered was to mount the various optical instruments directly into the sand, on posts. This had the advantage of versatility (one can set the posts anywhere within the box) and is a good way to make sure stray vibrations are a minimum. I decided against this approach because it seemed
messy (sand all over the place) and I thought that the components might settle or list on their own accord. What was decided was to use optical benches on some sort of surface and to affix this surface to the vibration dampening sand. The optical benches enable very rigid positioning of optical components, and the table top eliminates the mess due to the sand. We used a piece of 1/4" steel plate (weight approximately 200 lbs.) for the surface. We mated the steel plate to the surface of the sand by using a 1 and 1/2" thick wood platform to raise the steel plate above the edge of the box (this wood platform is behind the door in Room 327.) A problem that we encountered with this set-up was that the wooden
platform warped with time. This partially negated the effect of our isolation system, because after the wood warped, the steel plate was essentially an independent plate supported at various points on a very massive table. The plate itself was free to vibrate in various modes even though the box was moving rectilinearly, as a whole body. The box can move all it wants to rectilinearly as long as the optical components on the table do not change more than 1/4 of a wavelength relative to one another. For example, the box could be rocking back and forth in a plane, but with the steel plate supported only at various points and not uniformly, this rocking could excite the vibrational modes of the steel plate and wash-out the hologram. We decided to use styrofoam insulation as the platform instead of wood, because the styrofoam has less rigidity than wood. One must be careful to make sure that the styrofoam insulation is supported evenly by the sand, or one can run into a similar situation as with the warping of the wood.

To actually mount an optical assembly on this table, I started by using optical benches. These benches proved to be too restrictive on the various geometrical set-ups that could be accomplished on the table. I decided to make individual optical bases to support each piece of equipment separately (construction of these bases is described under optical equipment.) These bases have worked well and allow one to create a variety of set-ups on the optical table.

The box and table top are separated from the supporting
base by a set of eight innertubes. The innertubes are connected to a manifold system that allows one to inflate the tires equally (on an unloaded table.) If one has weight on the table that is not uniform, the table will not rise evenly. Each tire can be sealed off from the manifold to prevent the entire table from going down if one tube gets a flat, or to differentially inflate any tube(s) if desired. If a flat does occur, one must inflate the remaining good tubes to get room to work with between the base and the box. Unsolder the copper tube from the manifold and replace/repair the tube. It is a good idea to keep the 2 x 4 blocks between the base and the box at all time. If a flat develops, the wood blocks will help support the box so the box will not have the tendency to warp. Also, when not using the optical table for an extended amount of time, deflate all the tires and put supports between each tire and, very importantly, in the middle of the table too. See figure 1b. Otherwise the entire weight of the table would only be supported on the sides and the results could be disastrous. As an aside, if one is having problems with the stability of the table, it would be a good idea to check to see if these blocks have been removed (from the inside of the table) and if not, whether they are touching the box. For best stability it seems best to keep the air pressure in the tires as low as possible, so that the box just clears the support blocks.

To determine whether the table is actually "stable,"
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the Michelson interferometer is used. This interferometer splits the laser beam and recombines it, causing the beams to interfere. If the components move relative to one another for any reason, the interference pattern will wash out (note that if one yells loudly at the table top, the interference pattern will wash out—the table was not designed to eliminate acoustical vibrations.) To set up the Michelson interferometer (see Fig. 2) one will need two front-surfaced mirrors, either a 30R/30T or a 40R/60T beam splitter (the R refers to percent light reflected, and the T to percent light transmitted), a lens to diverge the beam and a ground glass screen to display the image. Position the mirrors such that they are approximately the same distance from the beam splitter (note that one can determine the coherence length of the laser one is using by starting with the mirrors the same distance away from the beam splitter, and the gradually moving one mirror away from the beam splitter, until the fringe pattern is no longer present. The distance the mirror moved is one-half the coherence length of the laser.) Adjust one mirror so that the laser beam reflects directly back on itself (this is most easily accomplished if one does not put the second mirror in place so that the mirror reflects another spot onto the beam splitter.) Now adjust the second mirror in the same way. Pass these recombined beams through the lens and project the beam onto the screen. Make fine adjustments in the angle of one mirror until the fringe pattern is

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One can also 'drive' the supporting base in sinusodial motion induced with a vibrator (driven with an appropriate frequency sine wave.) If one sweeps the frequency one can get a rough idea of what frequencies pass through the isolation system. One can also vary the air pressure in the tires until an optimum setting that dampens the most fre-

Figure 2.
Set-up of Michelson Interferometer.

maximized. Stamp on the floor, yell, or try to touch the table top without disturbing the interference pattern; you will discover how sensitive a device the interferometer is.
quencies is found. I observed that the interferometer did not wash out until about 20 Hz. Below this point the interferometer washed frequently.

IIB3) Optical Components

In this section I will describe the use and design of various equipment that best comes under the heading optical equipment. For some items (the support bases) I will also describe how they were made.

IIB3a) Support Bases

The purpose of the support bases is to provide one with a means to rigidly set up equipment on the optics table. They are lead filled to give them enough mass so that they will stay in place when one, for instance, makes an adjustment on a mirror. They are small and can be positioned anywhere on the optical table, which, as mentioned before, increases the versatility of the optical table. One of the bases is larger than the others and this one was designed to support the film/plate holder. The film/plate holder is heavy (compared to the other optical components) and its weight is not centered over the support rod. It needs the increased area of the base to give it added stability. There is one special support base for combined use of the film/plate holder and the rotating table (this base is just two lead bricks.) This base is used when one is making
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multiplexed holograms. The rotating table (a machinest dividing head) is bolted onto the two lead bricks, which are tapped for this purpose. This holds the bricks together to provide one rigid platform for the film/plate holder and the dividing head. More on this will be described in the section on multiplexed holograms.

The way in which the regular mounts are made is straightforward. I took a piece of brass rod 3/4 of an inch in diameter and drilled a 3/8" hole down the center of the rod on the lathe. Then I cut an appropriate height cylinder from 2 and 3/4" brass pipe stock. Centering the drilled rod in the middle of the tube, I poured in molten lead. I ribbed the inside of the brass pipes to ensure that the lead would not slip out after the base cooled (I found that this was the case if I did not. One could also slightly pound on the casing after the base is cool to prevent this slipping.) After the lead and the base are cooled, I drilled and tapped the hole to be used for the locking set screw. I cut off the head of a 1/4-20 screw and soldered a wing nut to the screw for convenience in locking in the rod. I sprayed the entire base flat-black and attached a piece of felt to the bottom to prevent the base form scratching the optical table's top.

IIR3b) Two-Axis Mirror Positioners

If one has looked in the optics lab one will notice
that the department has one commercial positioner and two home-made positioners. The motivation for making one's own optical equipment is that commercially available equipment is extremely expensive. For nearly all applications in holography one can easily get satisfactory results using equipment made in the department's machine shop, and at a drastically reduced cost. The mirror positioners I made can be reproduced simply by studying the one in the lab. I opted to use push-out springs to provide the tension v.s. a spring that pulls in to provide the tension, as in the commercial model, because it seemed easier to accomplish in the machine shop. I made little platforms to mount the first-surfaced mirrors on.

I could have used some type of bonding cement, such as is needed with the commercial positioner, to affix the mirrors, but I decided against this method for various reasons. First, no bonding cement was readily available that anyone knew anything about. Second, one could be changing mirrors quite regularly depending on what one wished to accomplish in the optical set-up. It was not clear to me whether available bonding cement would provide this easy exchange of mirrors. And last, a couple of the mirrors are quite large and, again, it was not clear to me whether this bonding cement would support this weight. There are drawbacks using the design I opted for. The most obvious is that one has to contact the first surface of the mirror in order to support it. This really was not a large concern to me because if
one uses a piece of felt cloth between the mounting screw and the first surface mirror, any effects will be small. Also, the beam will never hit that close to the edge of the mirror to really be concerned about small imperfections there, but it is a good idea to try to keep first-surface mirrors in as perfect condition as one can. The drawback that I was more concerned with, but still unconfirmed, was that this support system provided support at only one point. I am worried that since the mirror is not evenly supported by the positioner it will tend to vibrate more easily, especially due to acoustical vibrations (this is much the same idea as what could happen when the steel table top is only supported in a few places.) I lived with this system, and obtained good results, but it is an area for improvement. There is one first-surfaced mirror that is permanently affixed to a positioner. This positioner does not work as smoothly as the other positioners so I tend to use it primarily for the reference beam in which angular adjustments are usually less critical.

IIB3c) Mirrors

I will just mention briefly that all mirrors used in holography should be first-surfaced mirrors. First-surfaced mirrors prevent any unwanted reflection from the uncoated first surface of a second-surface mirror. Because they are first-surface mirrors, they must be handled with great care.
Whenever a first-surfaced mirror is not in use, it should be covered to protect the mirror from dust and other stray particles and do not touch the surface.

II.B.3d) Beam Splitters

The department has a variety of beam splitters, but the beam splitter that can generally be used is a simple piece of flat glass. A small percent of the incident light will be reflected off the glass plate due to the change in the index of refraction from air to the glass. This amount of light is generally enough to provide a reference beam (more on reference beams under General Procedures.) Flat glass is very convenient to use as a beam splitter because glass is easy to clean and is cheap to replace if broken. The department also has 30R/30T and 40R/60T partially silvered reflectors (R = percent light reflected and T = percent light transmitted.) These are used, if needed, to help match object to reference beam ratios (more on beam ratios under General Procedures.) The 40R/60T beam splitter was cut from a larger piece of stock that is stored in the optics lab. Both partially silvered beam splitters and also the flat glass beam splitter can be mounted in the spring loaded slide holder. When using these beam splitters one will get a beam reflected from each of the surfaces. For the case of the partially silvered beam splitters, the beam reflected off the coated surface will be much brighter. The
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Secondary reflection must be blocked with a small block. When using partially silvered beam splitters, the same care must be given to these surfaces as to first-surfaced mirrors. There is one 40R/40T pellicle beam splitter that has to be very carefully handled. The pellicle surface must not be touched in any way, and also must be kept free of dust and dirt. I built a special holder for the pellicle beam splitter to be mounted on. Since the pellicle beam splitter is so thin, there is no secondary reflected beam. This eliminates the necessity to block the secondary beam as was necessary with the glass plate beam splitters. Two beams are actually reflected, but at an angle of 45 degrees their separation is only about 7 microns, making them indistinguishable. When not in use, store the pellicle beam splitter bolted down in its special plastic case. Note that the pellicle beam splitter splits the beam 40R/40R only when the beam is incident on one side. If the beam is incident on the incorrect surface, the pellicle beam splitter will split the beam approximately 8R/92T.

IIB3e) Laser Beam Aligner

The laser beam aligner allows one to move a laser beam in three angular directions, and also raise or lower the laser beam parallel to itself. It was obtained to facilitate the alignment of the helium-cadmium and helium-neon laser beams for color holography. The mirrors used on this
device are first-surfaced mirrors and should be treated as such.

IIB3f) Neutral Density Filters

The department had two neutral density filters for use in holography (the filters are designed such that they can be attached to a 35-mm camera.) They reduce the beam intensity by a factor of two or a factor of four, or when used together, by a factor of eight. They are used primarily to help one obtain the correct ratio between object reference beams (which will be described later.) The neutral density filters are not as delicate as first-surfaced mirrors, but, as with all optical equipment, always store them in their cases when not in use to protect them from dust and dirt.

IIB3g) Lenses

The use of lenses in holography is to spread the beam out. Either a negative or positive lens can be used to accomplish this. There are two fairly nice (positive) microscope objectives that I use (5x and 10x.) I generally use the 10x because it will spread the beam further in a shorter distance. The microscope objectives have a special mount that they screw into which enable them to be placed in the support bases. There are two negative lenses that are permanently mounted to a post which fits into the support base. Since the negative lenses are of lesser quality than
the positive lenses. I generally use the negative lenses for the object beam (since this beam is diffusely reflected off the object onto the film, the effects of any lens aberration are reduced.) The better quality positive lenses I use for the reference beam. I would like to note here that I have never used any spatial filters. A spatial filter consists of positive lens and a small pinhole (10 inch) at the focal point. The effect of this spatial filtering is to remove any light that is not parallel to the optical axis (due to dust, lens imperfections, etc.). This spatial filtering results in better-quality display holograms. I think it is something that should be instituted into the holographic setup.

**II B3h) Lasers**

Colby has two types of lasers for holography. They are Helium-Neon (HeNe) gas lasers and a Helium-Cadmium (HeCd) metal-vapour laser. The HeNe lasers lase at 632.8nm (red) and the HeCd laser lases at 457.9nm (blue-violet.)

The department has various weak (<1mW) HeNe lasers. These are the lasers that I started out with, but because of the small power output, I was limited in the size and type of object that I could make a hologram of. The department acquired a new, and much more powerful (5mW nominal, class IIIb), laser in the summer of 1981. This new HeNe laser allowed me to easily make 4 x 5" holograms without hypersen-
sizing the film. The more powerful 5mW HeNe laser can harm one's eye if the undiverged beam enters into the eye. I did not have special safety goggles (goggles that reduce a specific wavelength by a large amount, but otherwise permit one to see unobstructed) for HeNe 632.8nm. The goggles should be obtained for one's safety.

The low power HeNe lasers are self contained (power supply and laser head in one housing) and are light tight. The more powerful 5mW HeNe laser has an independent laser head and power supply. The power supply has a 3.5 second delay after the pilot-light comes on before the power supply passes the power into the laser head, as required by the Bureau of Radiological Health (BRH). The power supply is turned on by the use of a removable key. The laser head on the 5mW laser gets quite warm; this is normal. Both the 0.95mW and the 5mW HeNe lasers are light tight, so they lend themselves well for use in holography.

The department also has one HeCd laser. When it was new, it could reach beam intensities of 12-19mW. It is a fairly old laser now, and it is losing some of its power. As with the 5mW HeNe laser, it has a laser head separate from the power supply. This power supply allows the operator to control the laser tube current. The power supply is designed to give a "high" current output for the first few minutes of operation, then automatically cut the power down to the running current. This is to "warm up" the metal vapour. The laser will not lase instantaneously, but could.
take several minutes, depending on when it was last used and on the tube current. The laser is getting old so it takes more and more current to get the same power output. Be gentle with it! I usually start with the current at about 750mA. It will fall back down, automatically, to about 500mA. At this point turn the current up slowly until it starts to lase. Once it starts to lase it will take a good five minutes for the power output to settle down to be stable enough to make holograms. One can easily get 5mW from this laser without pushing the laser too hard. I have had it up to 9mW, but I have never needed this much power. Whatever you do, do not over-drive the power supply. The laser head produces a lot of heat, and it is air-cooled. Because of this, the laser head is not light tight. This is very much an inconvenience in making holograms. For this reason I do not use the HeCd laser unless I am experimenting with color (red/blue) holograms, or if I have a particularly blue object. If I need to use the HeCd laser I set up a thick black cloth barrier between the HeCd laser and the holographic film holder. There is a small hole in which I pass the laser beam through. To support the cloth off the table (because of vibrations) I use the various optical rails and bases to form a skeleton structure supported from the floor. I try to cover above the laser also because the ceiling in the optics lab is white. As a closing note, the effectively variable power available from the HeCd laser is nice combined with the fixed output of the HeNe lasers, for Senior Scholars 1982
color holography. In making two color holograms one can use the HeNe lasers fixed power output and vary the output of the HeCd laser (by varying the tube current) to obtain the appropriate power mix to match the sensitivity of the film or the human eye. This eliminates the need to "waste" power from either the lasers by obtaining this match by using neutral density filters.

IIB3i) Laser Power Meter

The laser power meter enables one to measure, in watts, the power incident on the hologram plane. With this knowledge, and knowing what exposure (in ergs/cm²) one wants to obtain a certain resultant density on the film (this knowledge is obtained from the technical data supplied with the film) one can set the digital shutter (next topic) to the appropriate time to obtain a good hologram. This eliminates the need of making a "test strip" to determine the appropriate time.

The laser power meter is calibrated for HeNe 632.8nm. It is supposed to be within 10% for wavelengths between 400-700nm, so it can be used for the HeCd laser, too. To calibrate the meter, cover the aperture of the photosensor and set the meter to the most sensitive scale (20μW.) Adjust the "Calibrate" knob until the meter reads 00.0, and the meter is calibrated. The photosensor is very critical to the angle of incidence, so try to point the sensor in the
direction of the light one is trying to measure (e.g. the reference or object beam.)

**II83i) Electronic Digital Shutter**

As mentioned above, the digital shutter, when combined with the laser power meter, provides a tool that greatly facilitates the making of holograms. When the correct time is determined, one simply turns the counters on the shutter to the appropriate time (from 10 ms to 1000 seconds.) The shutter has a time position, where the shutter stays open for only as long as what has been preset, and a manual position. In the manual position the shutter can be left open indefinitely to aid in the alignment of the experiment. In the timed position one has the option of having an eight second delay before the shutter opens (from the time the switch is tripped) to allow the table to settle down. The shutter is separately mounted from the timing electronics. It is connected via cable that must run from the back of the control electronics to the table top (as with the power cables for the lasers that have separate power supplies.) One should attempt to make sure that these cables do not vibrate, thus perhaps spoiling a hologram. It should suffice if one tapes the cable to the optical table's top, and also on the table where the electronics are located.
Holographic Procedures

Off-axis Transmission Holograms

The basic idea behind off-axis holography is to record the interference between an object field and a reference wave, when the reference wave is introduced at some angle to the plane of the film. A more detailed analysis was put forth in the technical part of this report. Here I will only describe a procedure for making holograms.

Equipment Required

In order to make simple off axis transmission holograms, one will need the following equipment: a laser, a beam splitter, two first surfaced mirrors, and two lenses, either positive or negative, to diverge the laser beam.

Geometrical Set-up

There are various geometrical set-ups available that enable one to project the reference beam onto the film at an angle to the object beam. I use the set-up shown in Figure 3. The set-up uses a minimum number of optical components and from this basic set-up it is easy to measure the optical path lengths. I have used this set-up for off-axis angles between 30 and 60 degrees with good results.
IIC1(c) Exposure Procedures

IIC1(c)i) Path Length

The difference in path traveled from the beam splitter to the film via the reference beam, and the path from the beam splitter, off the object, onto the film, must not exceed the coherence length of the laser one is using. The coherence length of the laser is essentially how far apart (in meters) one can be along the path of the laser beam and still maintain a definite phase relationship between the two points. If the difference in path length exceeds the
coherence length of the laser, a hologram of the given object will not be formed. To maximize the coherence volume, essentially the depth of field of a holographic scene, it is best to make the object and reference beam path lengths as close to the same as possible. One does not have to obtain path differences within millimeters, but the greater the difference between the paths of the two beams, the less depth of field will be available in the holographic scene. Path lengths can easily be measured with a string cut to the desired path length. (Path length from the beam splitter should be approximately twice the length of the resonant cavity of the laser, for the highest degree of coherency at the plane of the film. The coherency of the laser beam is a periodic function of path length, with the period being twice the length of the laser resonance tube).

IIIC1ci1) Beam Ratios

The next step is to ensure that the ratio between the intensities of the reference beam and the object beam are correct. This is accomplished using the laser power meter described previously. Since the reference beam recreates the object field during reconstruction, one wants to ensure that the reference beam characteristics are properly encoded. Because of this, one wants the reference beam to be two to five times more intense than the object beam. Generally, if one has a white object or highly reflective object, a reference beam to object beam ratio of two-to-one...
is appropriate. If one has a dark or highly contrasted object, a ratio of five-to-one is better. For one's own knowledge, one should make several holograms of the same object, but vary the beam ratios from, say, two-to-one to a beam ratio of five-to-one. Both the resolution and object brightness will be affected.

To obtain the desired beam ratios for a set-up, one thing to keep in mind is not to waste laser power. One only has 5mW available to start with, which is more than enough for small holograms, but the greater percentage of power one wastes from this 5mW, the longer the exposure time required. By laser power wasted, I mean power that does not go to expose the film, but instead is lost in neutral density filters or beam that is not reflected off the object onto the film. When the exposure time increases, the likelihood that an unwanted vibration will penetrate the isolation system will also increase, thus ruining the hologram. Before using neutral density filters to adjust beam ratios, first attempt to adjust beam ratios using power conserving techniques. This is especially important if one is using the low power lasers. These power conserving techniques include changing the beam-splitter one is using to split the laser beam. For most bright objects and reasonable film size (less than 3X5") a piece of flat glass works the best to obtain the correct beam ratios while conserving the laser power. The small percent of reflected light should be used as the reference beam and let the majority of the beam to
pass through as the object beam. Even though one wants the reference beam to be two-to-five times as intense as the object beam, the inherent low efficiency of the object beam reflection to the film usually permits this small percent of reflected light to be sufficient to provide the reference beam desired. The low efficiency of the reflection of the object beam to the film can easily be imagined for dark objects, since only a small fraction of the light incident on the object will reflect off the object at all. But also, to illuminate an object uniformly, the object beam must be spread out to cover more area than the object, thus creating waste at this point too. Perhaps the major loss in the object beam is due to the fact that the light reflected off the object fills all space, and is not focused onto the plane of the film (this is why one can see a three-dimensional image).

If one uses the flat glass beam splitter and finds that the object beam is too intense, first change to a different ratio of beam splitter: do not use a neutral density filter to reduce the intensity of the object beam. One must remember, though, that changing to a partially silvered mirror beam splitter will not only increase the intensity of the reference beam, but it will also decrease the intensity of the object beam fairly substantially. The first partially silvered mirror to use would be the 40R/60T. The reference beam now would be much more intense than previously, while the object beam intensity is reduced. Clearly
the most convenient power conserving beam splitter would be a variable density, partially silvered mirror. These beam splitters are usually circular mirrors that reflect and transmit differently depending on the angular location of the mirror. The ratios run from about 2R/98T to 98R/2T. This gradual change in beam transmission would eliminate large jumps in transmission encountered when changing actual beam splitters. (If one were to do a project in holography it would be my recommendation that a variable density beam splitter be the first piece of new apparatus purchased over any other item).

I suggest that one uses the 40R/60T beam splitter first when attempting to balance beam ratios because the other beam splitters (30R/30T and 40R/40T) have an inherent lose (40% and 20% respectively). Since over 90% of the beam passes through the flat glass beam splitter to form the object beam, if one were to use the smallest neutral density filter, the filter would reduce this 90% by a factor of two. One would still have a savings of beam power if one could use a different beam splitter to obtain the correct beam ratios instead of a neutral density filter. A possibly quicker and easier way to reduce the object beam intensity would be to over expand the object beam before it strikes the object. In this method one would have more fine control over the intensity of the object beam alone, compared to the predetermined changes in both the object and reference beam intensities using partially silvered mirrors. This method
of overexpanding would not use the power of the laser most efficiently, but sometimes this method is most convenient.

For such a seemingly simple request, to have one beam a given amount more intense than another, in practice it can provide many difficulties and be the source of many headaches. Yet, besides the path length requirement—which is easy to meet—beam ratios are the single most important factor in determining the quality of a resulting hologram.

When positioning the reference beam, the reference beam should not "just cover" the holographic film. The film should be exposed as uniformly as possible over the entire surface area of the film. With smaller holograms this can be accomplished using either a collimated beam produced with lenses (expanding the beam) or by a spherical wave produced by a single lens. For larger holograms (4X5") it will be hard to use a collimated reference beam (parallel light beam) because in order to cover the hologram uniformly one will need a five inch diameter lens. The focal length of a five inch lens would not normally be within the path length for most holographic set-ups, unless a special lens is obtained. The easiest way to provide a reference beam for large holograms is to over-expand the reference beam (by using either a positive or negative lens) so that the film appears uniformly illuminated when viewed with the reference beam alone. A good way to qualitatively determine the coverage of the reference beam is to place a piece of white paper the size of the desired hologram where the film will
be during exposure. Usually everything, including the film holder, is flat black and it is difficult to see the (red) laser beam on these surfaces. The red (or blue) laser beam will beam highly reflective on the white paper and thus much easier to adjust the beams position. To view one beam separately, either to measure the actual beam intensities or to judge the degree of film coverage by the beams, I used dark paper boxes that slip over the final lens of the beam I wish not to view. One caution here: I have many times, after painstakingly adjusting the beam ratios correctly, expose a hologram only to discover that I have left one of these boxes on one of the final lenses. Amazing things can happen in total darkness!

In measuring the actual beam ratios remember to have the detector in the plane of the hologram. Also remember that the detector for the laser power meter is very sensitive to the angle of incidence of the incoming light. To measure the intensity of the reference beam point the photosensor of the laser power meter at the reference beam, in the plane of the hologram. To measure the intensity of the object beam, place the photosensor in the plane of the hologram and point the detector at the object. Remember to block the beam you are not measuring. Because of the angular sensitivity of the laser power meter's detector, to determine total power in the plane of the hologram I usually simply add the results of the separate beam measurements. Since the meter on the laser power meter is not illuminated,
one must somehow illuminate the read-out (with a flashlight covered except for a small hole) while insuring that no stray light from this source influences the power readings. This usually presents no problems. Mount the detector on a "wand" (a rod with a 1/4" - 20 tapped end) to ease placing the detector in the desired location. One has to develop a steady hand to hold the detector in the desired place and at the same time illuminate and read the laser power meter.

IIC(iii) Film Holders

To hold the film in place during exposure, one must consider stability, convenience, and non-restrictive geometries. The film holder must ensure that the film remains motionless during exposure or else the interference pattern will be washed out. The film must be flat to ensure good reconstruction. Actually the film can be any shape one desires, but the film must be returned to this shape to obtain quality images during reconstruction. The film holder must be convenient to use so that the holder does not present a major undertaking when one attempts to prepare a plate for exposure. Finally, since the hologram will act as a window through which one can view an object on the other side, the film holder must not restrict one's field of view of an object. I accomplished the above needs not by buying expensive film/plate holders but primarily through the use of double sticky tape. It may not seem truly professional but it meets the convenience criterion very well, keeps the

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film flat, and allows an unrestricted film holder to be used. Emulsion coated on glass plates is the easiest to handle, use, and develop. Glass plates however, do not allow one the versatility of film in geometrical set-ups (for 360 degree holograms for instance). For small holograms (from 4X5” glass plate cut into quarters) I mounted, with double sticky tape, the glass plate inside a 2.25” film holder from an old format camera. A quarter of a 4X5” glass plate just fits into one side. The format camera film holder enables one to load several separate pieces of film in the darkroom, close the light tight slide on the film holder, and then position the film holder in normal ambient light. These holders are convenient if one wants to make several holograms of the object, for instance if one wishes to determine the effect of varying the beam ratios as suggested earlier. To do this with the format film holders, have film ready in both sides of the holder and after one exposes the first side to the initial scene, simply flip the holder over, change beam intensities, and one is ready for the second situation. The holders have a small space available to write pertinent information on either side, whether it be what type of film is on that side, or the beam ratios used on that one piece of film. Once the film is taken out of these holders for development, one will have to remember on his own which film is which. The film holder itself is simply taped to the large right angle object-film holder support base.

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With film (emulsion coated on flexible plastic—what most people would consider normal film) the same technique used for glass plates can be utilized. It is a bit more subtle a problem because one must try to mount the film flat without touching the emulsion too much.

For larger holograms, using either plates or film, the problem becomes more complicated along several lines. First, I have failed to discover any film holder which would enable me to load the film in the darkness and then would allow me to set up the film under normal light, as I could using the format film holder with small holograms. For 4×5" plates for instance, one must set up the experiment on the optics table in such a way that the film plate can be positioned accurately in total darkness, without disrupting any of the components on the table. I took small blocks to define a 90 degree angle with which one corner of my film plate was to mate. I could feel the blocks in the dark and carefully slide the plate in place. Again I used double sticky tape to mount the plate directly onto the stand. When using tape to secure the plate in place, it is easy, in the dark, to get the plate stuck on the stand at some inappropriate angle. I am sure that a better device can be made to hold these larger plates, but keep in mind stability and ease of use, especially in total darkness, when designing one.

When positioning the film plate, if one happens to knock over the object or move anything else a tiny bit, put
If one has the proper geometrical set-up and the film in place, one is ready to expose the film to the scene. The only critical parameter here is time. The correct exposure time can be determined primarily by two methods. The first, less precise method, is to make a "test strip". This
is done by making an educated guess of an exposure time (which comes from the experience of working with the various films—one should always record the beam intensities and exposure times for later reference and making these educated guesses). To make this test strip, expose slices of a strip of film for various times, centered around, or bracketing, the educated guess. This bracketing is most easily accomplished by exposing the entire film to the least desired time, and then covering up a small section of the film, and expose the remaining film for another interval of time. Continue this process until the bracketing is completed. The test strip is most easily interpreted if all the intervals are of equal time. For example, if one wanted an exposure time of approximately 40 milliseconds (ms), one could bracket this educated guess by making exposures of 20, 30, 40, 50, and 60ms. This could be accomplished by exposing the entire piece of film for 20 ms. Cover a portion of the film up and expose the film for another 10 ms, etc. The major drawback of using this test strip procedure (besides wasting film) is that one has to make two holograms for each final hologram desired of an object. One has to go through the relatively long developing process just to determine the correct exposure time. This exposure time is then only as accurate as approximately one-half the interval of time used. A better method is to calculate the exposure time using a knowledge of the light intensity at the plane of the film.
With the technical data supplied with the film, a graph is provided that one uses to determine what exposure is needed, in ergs/cm, at a particular wavelength, to yield a given film density. Since the collection area of the detector for the laser power meter is equivalent to one square centimeter, the reading of the power meter can be read directly as watts per centimeter (W/cm). This can then be converted into ergs/cm-sec. If we divide the desired exposure (in ergs/cm) by this converted meter reading, we obtain the desired exposure time, in seconds.

I will give specific information on this process in the Darkroom section. With the exposure determined one can set the digital shutter appropriately, and expose the film. Now one is ready to go into the darkroom.
### Table One

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* Exposed with HeNe laser at 632.8nm. Developed for five minutes (not six minutes as suggested in this report). Holograms bleached using dry Bromine method.

** Exposure time unknown. Data included to provide one with an idea of what effect beam ratios have on the quality of a hologram.

*** These holograms were interferograms, so each scene (before and after object deformation) was exposed for one-half this total time.
IIC2) White-Light Reflection Holograms

I am presenting this section on reflection holograms to be complete. My concentration has been with transmission holography, and accordingly I have had limited experience with actual lab setups for reflection holograms. They are a simple extension of side-band holography, when the angle between the object and reference beams approaches 180 degrees. More will be said on this under the geometrical setup section.

IIC2a) Equipment Required

In order to make simple white-light reflection holograms, one will need the following equipment: a laser, and a lens to diverge the laser beam. Note that one does not need additional beam splitters or first surfaced mirrors for simple reflection holograms. More complicated setups can require additional mirrors and beam splitters [1], but we will only consider the simple in-line case here.

IIC2b) Geometrical Set up

The simplest setup for reflection holograms is shown in Figure 4. In this setup the reference wave is diverged onto the film, perpendicularly. A portion of the reference wave will pass through the hologram (film), reflect back off the object, and this back reflection will constitute the object beam.

The basic theory behind reflection holography is that
when the object and reference waves are traveling in opposite directions and allowed to interfere, the hologram
(film) will record an intensity which is similar to that shown in Figure 5. Figure 5a depicts two point sources equally distant from the center of the plane of the hologram (film). The concentric circles represent the location of maxima of each standing wave field. Where one line intersects another, a region of maximum intensity will be formed. If these two points of maximum intensity are connected, a set of hyperbolas will be formed, representing lines (surfaces in a three-dimensional analysis) of maximum intensity. These surfaces are commonly referred to as Bragg planes. Figure 5b shows what the hologram (film) would actually record.

The theory behind reconstructing images with reflection
a) Interference of two point sources equally distance from the plane of the hologram, and lines of maximum intensity.
b) Depiction of what hologram would actually record.

holograms will be presented in section IIE2.

IIE2c) Exposure Procedures

The exposure procedures for reflection holography are much more simple than for transmission holography. Since the object beam is determined by the amount of light transmitted through the hologram and reflected back off the object, nothing can be done to alter the ratios of the two beams. In this geometrical setup, this fact does restrict the class of objects that a hologram could be successfully made of.

The desired film density for reflection holograms must be greater than the desired film density for transmission holograms. This should be intuitively obvious. With a
transmission hologram the hologram bends the light that passes through it (transmitted); thus, the hologram cannot be opaque. For a reflection hologram, however, one wishes to cause the incident reference beam to be reflected back in the direction it came from, thus one desires a high film density to obtain this.

Because the beam must pass through the film to reflect off the object, conventional film holders will not work. I used the department's sliding spring holders to hold small (a quarter of a plate) hologram. I have not thought of a way to support larger plates. Since white-light holograms have an even more strict requirement on motion than do transmission holograms, the film support must attempt to support the film uniformly.

I ID) The Darkroom

There are two types of film currently available in the darkroom for use in holography. The first is Kodak SO-253 film, which is used for transmission holograms. A transmission hologram is formed when both the object and reference wave are incident on the same side of the film. Because of this, most film for transmission holography has some type of coating that reduces reflections or exposure from one side. This backing is called an anti-halo backing (AH). There are also KODAK type 649-F plates for reflection holograms. In

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reflection holograms, or white-light holograms, the object
wave and reference wave are incident on opposite sides of
the film. Because of this requirement, film for this type
of holography must not contain any type of anti-halo back-
ing. Thus the name non-anti-halo (NAH). The 649-F plates
can be used for transmission holograms if desired, but
because the plates are NAH, stray reflections will not be
reduced and this will tend to fog the film. On the other
hand, since the SO-253 film contains a dyed gelatin pelloid
on the polyester support, it cannot be used for reflection
holograms, since this AH backing would remove either the
object or reference beam. The SO-253 AH film is provided on
a 120 foot, 35mm roll. The 649-F NAH emulsion is provided
on 4X5" glass plates. I will first describe in detail the
SO-253 AH film for transmission holograms.

I1D1) KODAK High Speed Holographic Film SO-253 (ESTAR Base)
[2]

As mentioned before, this film is provided on a roll of
120 feet by 35millimeters. The desired quantity is cut off,
in total darkness, and the roll returned to total darkness.
The film comes with perforated edges to fit a standard 35mm
film roll. I did not desire this feature and have no real
use for these perforations (it is along these holes that I
touch the emulsion if I have to, to flatten the film, etc.).
Both types of film were ordered from JODON Engineering Asso-
ciates, 145 Enterprise Dr., Ann Arbor, MI 48103. Their
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telephone number is 313-761-4044. One should ask to speak to Mr. John Gillespie. Type SO-253 film was designed to be most sensitive at 632.8 nanometers (nm), being some five times faster than "conventional" holographic film at this wavelength. This high speed makes this film a very good candidate for large size holograms (using multiple strips of film on a glass plate) or when one uses a low power HeNe laser, because the film does not require a high amount of power to obtain a desired film density. I should note here that although this film is termed high speed, it is only fast compared to holographic film. This, and all holographic film, is extremely slow by conventional standards (it does not even have an ASA number). Specifically, at 632.8 nm, an exposure of 5 ergs/cm² will yield a film density of one, when developed in D-19 developer for six minutes. This density is the best for transmission holograms. The high speed of this film can be seen when one looks at exposures required to obtain the same density on other holographic film. Type 649-F film for instance requires almost 1,000 ergs/cm² exposure (at 632.8 nm) to obtain a density of one. For AGFA-GEVAERT film type 8E75, an exposure of 100 ergs/cm² is required to obtain a density of one. Even KODAK SO-253 is less sensitive at other wavelengths. At 460.0 nm, SO-253 requires an exposure of 110 ergs/cm² to obtain a density of one (see Figure 6 and Figure 7 for specific graphs on SO-253).

Larger holograms using several strips of SO-253 on a

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glass plate, can take some practice to prepare the plates correctly in the dark. To make a larger hologram, for instance 3x5", first take the double sticky tape and space the tape at appropriate intervals on the glass plate such that the tape secures the edges of the film. Make sure that the extreme top and bottom of the glass have tape on them, no matter how close a seam comes to the top (or bottom). Cut only one piece of the film off the roll at a time, because more than one precut piece could get misplaced in the dark. To aide in cutting the desired lengths of the film in total darkness, cut out construction paper 35mm wide and the correct length of the desired piece of film. Place this template against the non-emulsion side of the film (when the film is on the roll, the emulsion is on the inside surface of the film). Use the end of this paper as a guide as to where to cut the film. Start from the bottom (or top) of the glass and use the edge of the glass to align the first piece of film. Take the next piece of film and lightly slide it, parallel to the bottom edge of the glass, until you hear the film "snap" down from the top of the previous piece of film onto the tape on the glass. This method insures that the strips of film will be joined without any unwanted spaces or overlap. The emulsion on this side of the film will scratch if overly abused, but do not let this scare you unnecessarily. The emulsion is pretty hardy, and even if slightly scratched, the scratch will not effect the holographic image significantly. Any point on the hologram
will recreate the entire scene, so the hologram will "for­
give" one if it is missing a few points!

IID1a) Developing SO-253 Film

The developing procedure for SO-253 film is as fol­
lows:

- 6 minutes D-19 developer
- 30 seconds Stop bath
- 5 minutes Kodak Rapid Fix
- 1 minute Rinse in water with moderate agitation
- 4 minutes Rinse in solution of KODAK Hypo Clearing Agent with agitation
- 3 minutes Rinse in water with moderate agitation
- 5 minutes Rinse in 75% Methanol
- 5 minutes Rinse with moderate agitation in running water
- 30 seconds Rinse in Photoflo solution
- Dry in dust free atmosphere, slowly at room temperature.

(Keep all the baths the same temperature of the developer)

As with other holographic films, if one increases the developing time to eight or ten minutes, an increase in the speed of the film and diffraction efficiency will result, but only at the expense of a reduced signal-to-noise ratio. The one minute rinse after the fixing bath is to remove the
Experimental Section

CHARACTERISTIC CURVES

Exposure @ 633 nm

Process: KODAK Developer D-19
5 and 8 minutes
68°F (20°C)
Cont. Agitation

SPECTRAL SENSITIVITY CURVE

Density = 1.0

Process: KODAK Developer D-19
5 minutes at 68°F (20°C)
Continuous Agitation
excess hypo (to prolong the life of the Hypo Clearing Agent—which can be reused). The fixer can also be reused, its life being checked with "Hypo Check". I usually use small amounts of D-19 developer and discard after use, especially if dark brown. Stop bath is usually discarded because it is so cheap. The 75% methanol bath is needed to remove the AH backing from the film. This backing is the blue dye one sees when looking at the film after it is developed. This blue dye would greatly reduce the visibility of any reconstructed object at 632.8nm. After the film is dry, one can view the hologram; see the section on reconstruction.

Over the range 1 to 10 seconds SO-253 shows virtually no reciprocity effects. The law of reciprocity for photographic emulsion states that image density is a function only of the total exposure (Ixt) and is independent of the magnitude of either I or t. Because of the mechanism and kinetics of latent image formation, the reciprocity law does not hold for high irradiance (short exposure) or for exposure of low irradiance (long duration). For exposures of 10 to 100 seconds the exposure should be approximately 25% greater than those calculated from trial exposures of 1 second or less duration.

As a last note on development, most films with extremely fine grain, such as SO-253, exhibit significant latent image fading during the hours just after exposure. The latent image is stored in stable four-atom (or greater) aggregates, until these silver atoms are reduced to metallic.
silver by the developer. In between the formation of the latent image (by exposing the film to the laser light) and development, the latent image can relax and thus yield a reduced density upon development. For example, an exposure sufficient to yield a density of 1.0 when the film is exposed and processed immediately, will result in a density of 0.8 if development is deferred for one hour. It is a good practice when determining an optimum exposure level for a given holographic setup, to develop the film as soon after exposure as possible, provided that the elapsed time can be maintained for all subsequent operations with the same setup.

IID1b) Phase Holograms (or Bleaching Procedures) [3]

Image brightness can be increased if one bleaches the amplitude hologram, making it a "phase" hologram. The bleaching process lightens the interference fringes and allows more light to pass through the hologram. One can use a liquid bleach, but bleaching with "dry" bromine vapour produces phase holograms that have a higher signal to noise ratio and better first order diffraction efficiency.

Bromine is poisonous and must be used under a fume hood. Wear goggles, rubber gloves, and a protective coat when working with all holographic bleaches. To neutralize any spilled bromine use either dilute NH OH, or Na CO. Sodium carbonate is better to use on liquid bromine spills because the reaction between sodium carbonate and bromine is not
violent, whereas NH OH does react violently with bromine. In cleaning up a bromine spill, it is a good idea to have present a partial pressure of NH OH (leaving the NH OH bottle open or having several small beakers slightly filled with NH OH will provide this partial pressure of NH OH). When using the sodium carbonate on liquid bromine, cover the liquid bromine with dry sodium carbonate. Slowly add water. This mixture should be white when the reaction is complete and the substance is safe to touch and one can safely wash the white mixture down the drain. When using liquid bromine, always have a small amount of water running so that one can obtain water quickly for this purpose when needed.

Bromine has a high vapour pressure, so only a small amount of liquid bromine is required to establish a sufficient partial pressure; the less liquid bromine the better. Use the bromine in the bottle marked "Bromine Water" before using the bromine in the reagent bottle. The bromine in the "Bromine Water" bottle has been used for the bleaching process before, but it is still perfectly good to use again. Never return any bromine liquid to the reagent bottle. For small holograms, place a very small amount of liquid bromine in the bottom of a flat bowl (this and other necessary glass apparatus can be located in the department's chem-lab). Place the hologram to be bleached in a small watch-glass, and set this watch glass into the flat bowl. Cover the flat bowl with a large watch-glass (this will concentrate the bromine vapour more closely to the film). Place this entire
assembly in the casserole bowl, and place the casserole bowl's cover on tightly. The cover has strip caulk around the seal to make an air tight seal. One will notice a small amount of reddish vapour leaking from the small flat bowl and gathering inside the casserole bowl. Watch the film and remove the film when it becomes uniformly clear. The time that this takes depends on the bromine vapour pressure, but in generally takes between five and fifteen minutes (fifteen minutes for the equivalent of 3X5" of film). When putting the film on the watch-glass, place it emulsion side up, so that the emulsion does not come in contact with the watch-glass. Also try to get the film as flat as possible. The bromine vapour tends to stay low, so if the film was hanging vertically, the bottom of the film would bleach more quickly than the top. The bromine vapour will eventually soften the polyester base so try to keep the film in the bromine vapour for the shortest amount of time possible. When removing the film, be careful not to get any liquid bromine on the film (if some bromine does get on the film, rinse the film with warm water for at least five minutes). Pour the remaining liquid bromine into the "Bromine Water" bottle via a glass funnel. Have this funnel set-up ready, except for having the the bromine water bottle unstoppered, before you open the system up so the returning of the liquid bromine can be accomplished quickly. When venting the bromine vapour, try to vent the vapour slowly, as not to overload the fumehood's capabilities. The film will come out of
this bleaching process with a slight yellow stain. This stain should go away if left in the fumehood overnight. This stain can also be removed if the hologram is rinsed in a water bath, but this rinsing negates the effect of a dry bleach.

Bromine smells very much like chlorine (people would say "bleach") but it is much more dangerous. Be conscious of what is happening in the building. If people say that the stairwell or the fourth floor smells like bleach, it is probably due to the bromine. The hood has leaked in the past on the positive pressure side of the exhaust pump. One is safe in the chem-lab itself because the ducts are all under negative pressure.

Miscellaneous Notes on SO-253

When working with the entire roll of film, no safelight is "safe". Always be in total darkness. Make sure the roll is always put away before any light is turned on. A U.V. filter over an incandescent bulb seems not to fog the film too much, and can be used to illuminate the holographic table when one cannot work in darkness. More film fogging tests should be conducted to determine the filters exact effect.

When making larger plates using SO-253 film, take off all double-sticky tape before developing. The double-sticky tape in some undetermined way impedes the development process.

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Distilled water for the D-19 developer, stop bath, and fixer can be obtained from the Chemistry Department.

REMEMBER: always put the roll of film away before any light is turned on!

IID2) KODAK Type 649-F Holographic Plates

As mentioned before these plates are NAH. Because of this they are used primarily for reflection holography. Development of these plates can follow along the same lines as described for SO-253 film. It must be remembered that one wishes to obtain a greater film density than was desired for transmission holography. I have no specific information on the exact film density one should hope to obtain for reflection holograms, in terms of the desired exposure in ergs/cm², but I have included a graph of the films spectral sensitivity (for a density of one), to help in determining the desired exposure, see Figure 8. Experimenting in the lab is the best way to determine desired exposure, but remember to record beam intensities, etc., for future use.

Remember that during development, the spacing of the Bragg planes can change. If this takes place, the reconstructed image will be seen as a different color than it was exposed in. If one is viewing a hologram is white light, this generally presents no problems. However, if reconstruction is desired with the same laser light used during exposure, this fact will have to be kept in mind. The move-
Experimental Section 53

ment of the Bragg planes can be minimized if the fixing step in development is skipped. The hologram will tend to darken, but the Bragg planes will remain closer to their original position.

II E) Holographic Reconstruction

II E1) Transmission Holograms

To view a hologram, place the hologram back into the exact geometrical set-up in which it was exposed, minus the object beam. Replace the beam splitter by a first surfaced...

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**SPECTRAL SENSITIVITY**

<table>
<thead>
<tr>
<th>KODAK Holographic Plate, Type 120-02, and</th>
<th>KODAK Spectroscopic Film, Type 649-F</th>
</tr>
</thead>
<tbody>
<tr>
<td>KODAK Holographic Film (Extra Base) SO-173</td>
<td></td>
</tr>
</tbody>
</table>

Effective Exposure: 24 sec
KODAK Developer D-19: 8 min
at 20 C (68F) with continuous agitation

Sensitivity is defined as the reciprocal of exposure, in erg/cm², required to produce a density (D) above gross fog when the material is processed as recommended.

Figure 8

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Mirror to make the reconstructed image brighter. Look through the film from the opposite side the reference beam is incident on, and one will see the object in the same position as during exposure. Be sure to remove the "real" object to view the holographic image. The image one sees through the hologram is the virtual image of the object (it takes additional lenses—one’s eye—to view the object). The hologram acts as a window looking onto the scene. When looking out a window, if one pulls a shade half way down over the window, the world outside does not disappear; everything on the other side of the window is still able to be seen, but one has a more restrictive view of the outside (one must move one’s head around more, and be closer to the window, to see everything one could see before). The same effect happens with a hologram. If one covers up any portion of a hologram, the entire object can be viewed from the remaining uncovered portion of the hologram, but one’s field-of-view is reduced. This process of covering up the hologram can be theoretically continued down to a single point (a single point on the hologram reconstructing a three-dimensional image) but as the size of the hologram recreating an object field decreases, so does the resolution of the hologram.

To view the real (focused) image created by the hologram, illuminate the hologram with the reference beam rotated by 180 degrees from the original direction of the reference beam. This illumination will place the real
object on the opposite side (from illumination) of the hologram. To view the real image a screen is needed. The object will be located in the same location as it was during exposure if the same geometrical set-up and laser wavelength is used during reconstruction as was used during formation. If one moves the screen towards and away from the hologram "through" the object, one will see, essentially, changing cross-sections of the object.

To view large holograms made by placing several pieces of SO-253 film next to each other on a glass plate during exposure, one must recreate this exposure set-up in order to view the object. Since the different film strips were removed from the glass plates during development, one must now reposition the film strips the way they were previously. To do this one must first determine the order of the film strips, if no numbering of the film strips was used. Since each film strip acts as an independent hologram of the scene, the only difference between the various film strips is the point of view the hologram has of the object. Thus, it can be readily determined which hologram should be placed first on the plate, etc. After placing the first (bottom) hologram on the glass (using double-sticky tape) position the next hologram in front of the glass, but not touching the tape. I usually tape the film to the glass plate using the non-emulsion side of the film. Though the emulsion is not protected by the glass as it would be if the emulsion were sandwiched between the the plate and the polyester
backing of the film, the emulsion will not be damaged in subsequent removal of the film from the glass if the removal of the film becomes necessary. When one has a fairly good match up of the object on the two holograms, press the hologram (flat) against the tape. This procedure is much like focusing a 35mm camera that has a split field focusing system. This procedure will not provide a perfect hologram, but it can be more than adequate for display holograms. Large holograms are quiet impressive because they allow a larger field of view, and one does not have to be as near the film to observe the three-dimensional effects.

Be especially careful during reconstruction of a hologram not to accidently steer the undiverged laser beam into the eye, since the entire power of the laser is in the reference beam.

**IIIE2) Holographic Reconstruction: Reflection Holograms.**

White light can be used to view a reflection hologram. This is because the hologram not only acts as a reflector such that one's eye thinks it sees a three-dimensional image, but also as a wavelength filter. That is, the hologram recreates a three-dimensional scene while at the same time it recreates this scene with only one particular wavelength of the multiple-wavelength white-light. This is because of the reflecting Bragg planes that are encoded in the hologram. They have a specific spacing such that, at a
given angle \( \theta \) of incidence, only one wavelength will be constructively reflected by these Bragg planes. This can be seen if one remembers that the spacings of these planes at a path an angle \( \theta \) with respect to the normal of the surface, is \( \lambda/2 \). Thus, only the one wavelength, at a given angle \( \theta \), will constructively interfere (add in phase) from every given Bragg plane. All other wavelengths will either be deflected or transmitted. It should be mentioned here that the wavelength (color) of reconstruction is dependent on the spacing of these Bragg planes, which can move during development. If the spacing of these planes change during the development process, the hologram will be seen in a different color. Also, it is possible that at some other angle of incidence, \( \theta' \), and different wavelength \( \lambda' \), could combine to constructively recreate the hologram. To actually view a reflection hologram then, one simply positions the hologram in a beam of white-light (sun light) at the same angle it was exposed in (as one would do with a transmission hologram, except the beam of light would be coherent monochromatic light). As a last note, there are different methods available that control the shrinkage of the hologram, and thus insure that the hologram recreates a scene in the correct color. This is especially important for work in color holograms (more than one wavelength used to expose the hologram), to maintain the correct color relationship.
IIIF Variations of Transmission Holograms

IIIF1) Dual Object Beam Holography

Dual object beam holograms are a simple extension of single object beam holograms. For some objects, one can obtain adequate object illumination using only a single object beam. Other objects, either because of size of geometry, need two object beams to illuminate properly to remove shadows or dark spots. When using two object beams, a single object beam is split in half. The 40R/40T pellicle beam splitter is ideal for this purpose. If half of the object beam is incident on the object at an angle $\phi$ with respect to the plane of the hologram, the other half of the object beam should be incident on the object at approximately $(180 - 2\phi)$ degrees relative to the first beam. See Figure 9. One must be careful now that all path lengths remain within the coherence length of the laser. This means (assuming that the previous single object beam path and the reference beam path were equal) that the path of the second object beam must be equal to that of the unsplit object beam path. The initial object beam can be split anywhere along its path, as long as the second path is equal to the path length used in the set-up.

One can expand dual object beam holography easily to n-object beam holography analogously. An interesting application of n-object beam holography uses several object beams to expand the coherence volume of a holographic scene. [4]
Figure 2
Position of the object beams in dual object beam holography.

One such set-up is shown in Figure 10. As can be seen in
this figure, the beam path from the first beam splitter (the
object/reference beam splitter) to the film is the same no
matter which object beam path we chose to follow. Thus,
this set-up has enlarged the coherence volume. This is not
easy to accomplish in real life given a finite distribution
of beam splitters. The perfect set-up, to obtain an even
light intensity in the entire coherence volume, would
require a specific sequence of beam splitter ratios as fol-
lows (this sequence would distribute 10% of the incident
object beam throughout the coherence volume): Beam Splitter
1: 10R/90T; Beam Splitter 2: 11R/89T; Beam Splitter 3:
13R/87T; Beam Splitter 4: 14R/86T;...50R/50T

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IIIF2) 360 Degree Holography

As the name implies, this is the making of a circular hologram that surrounds the object. This type of hologram can be very impressive when viewing because one can "walk around" an object. The only difference in this type of holography and the normal transmission holography is the geometrical set-up.

To obtain a reference beam, the division of amplitude approach is used. That is, the reference beam is obtained by reflecting some of the object beam onto the film as the reference wave. First diverge the beam onto the object. Position a (spherical) mirror such that the mirror intercepts part or all of the beam that misses the object. This (spherical) mirror reflects the diverged beam to the film as
the reference wave. In this approach there are no reference-to-object beam ratios to determine. When a reference beam is derived by the division of amplitude approach, the hologram will yield greater resolution, at the expense of depth of field. The geometrical set-up is shown in Figure 11. (Figure 11 is an edge on view of the optical table).

To obtain a circular piece of film, I support the film with some sort of cylindrical tube, preferably with the inside diameter that of the spherical mirror to be used. To remove the necessity of rigidly securing an object to the spherical mirror, I let gravity hold the object in place.

![Diagram of set-up for 360 Degree Holography]

**Figure 11**
Set-up for 360 Degree Holography
and present the diverging beam to the scene from the top. In doing this a structure is created that is very susceptible to the pick-up of vibrations. Use the large support base to support this structure. A small metal pole clamp can also be found that enables two 3/8" rods to be mounted mutually perpendicular to each another. Position the mirrors and the single diverging lens as shown in Fig. 11. To adjust the divergent beam on the scene, first steer the beam such that the beam is incident on the center of the object. Determine the correct length that the single diverging lens must be to enable the lens to be positioned in the laser beam such that this lens diverges the beam uniformly on the object. Once the length of the support rod for this lens is determined, secure the lens in place at that length. The final adjustment is to determine the angular placement of the diverging lens that again centers the diverged beam evenly on the object. Since one parameter, the length of the support rod for the lens, is already fixed, determining the correct angular placement of the lens is fairly easy. Slowly rotate the lens about its axis of rotation until the beam is centered on the object. Secure this parameter. From here small adjustments can be made with either mirror positioner.

As was necessary with large plate holograms, one must prepare the film for this set-up in the darkroom and then bring this film out and set it up on the optical table in the dark. No effective cylindrical film holder has been
designed for this type of set-up that would be light tight, and I believe that such a film holder would be very difficult to make. Instead, one must secure the film to the inside of the support used by hand in the dark. Place two small pieces of double-sticky tape a small distance apart inside the support. Secure one end of the film to one piece of tape. Slowly unroll the film inside the support pressing the film tightly against the tube, until one reaches the other piece of tape. If the piece of film is cut correctly, there should be little if any overlap.

This geometry is a good example of the benefit in using the laser power meter to determine exposure times. Attempting to make an accurate test strip with this set-up is very difficult, but measuring the overall light intensity in the plane of the film is a relatively simple task.

**IIIF3) Multiplexed Holography**

Multiplexed holograms enable one to see a 360 degree view of an object, while viewing the object with a plane hologram (v.s. a circular hologram mentioned above). A multiplexed hologram is viewed by moving from left to right in front of the hologram, and the object appears to rotate 360 degrees. This allows all sides of an object to be displayed. As with other types of holograms, multiplexed holograms provide a three dimensional image as well. A planar hologram enables one to see a three dimensional image, but only in a restrictive sense. By this I mean that
even though the point of view of an object changes when the viewing position changes on a planar hologram, depending on the size of a hologram, the field of view can still be fairly restrictive. No matter how large the hologram is, the viewer can never see behind the object. The film being a plane is the ultimate limit on the field of view for a planar hologram.

With a multiplexed hologram, however, the situation is different. Two viewers observing the virtual image created with a multiplexed hologram are able to see two distinct views of an object (with a die for instance perhaps the one and the six). With a planar hologram the two viewers would see the same side of the die, but with a slightly different perspective. One can also obtain a view of all sides of a three-dimensional object using the technique described under 360 degree holography. Those holograms have perhaps the restriction that the viewer must walk around the object to obtain this 360 degree view. With multiplexed holograms all sides of an object can be seen while the hologram remains in a plane. This characteristic of multiplexed holograms makes them an ideal candidate to display a 360 degree view of an object on a two-dimensional plane (in a page of a book or report for example).

A multiplexed hologram is formed by making several separate holograms of an object, each hologram exposed to a slightly different view of an object. These independently exposed holograms are then placed next to each other. When
the viewer moves his head from left to right, the object appears to rotate. This is how the term holographic movies came about.

The easiest way to make a multiplexed hologram is to expose a single piece of film separately to the changing view of the object. It would be very difficult to actually make separate holograms of each view and after development, piece these holograms together. To accomplish this exposure procedure the film must be masked except for one small slit. This slit must then be sequentially moved along the film and, at the same time, the mask is kept over both the non-exposed film and the previously exposed film. One more (important) requirement is that the following slits leading edge must line up with the previous slits trailing edge. If the slits are not perfectly adjacent, one will either have an unexposed slit of film, or two views of an object superimposed on one another; either result would degrade the desired effect of this procedure. The amount that the object rotates between each adjacent hologram must be small to prevent the object from jerking, instead of smoothly rotating, when viewed. When determining object rotation slit width ratios, it must be remembered that the hologram will be viewed with two eyes separated by a finite distance. This factor requires that the scene in the holograms located some finite distance away from each other cannot be significantly different. If the image that each eye sees in each of these independent holograms is significantly

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different. one's mind will become confused. To this end, it is better to view multiplexed holograms with the eyes as far away from the hologram as is convenient. The further the eyes are from the hologram the fewer the number of slits that the eyes are separated by, and thus less difference in the scene. See Figure 12.

The advantage of being distant from the hologram can be seen by examining a geometrical argument when one is at the limiting case of one's eyes in the plane of the hologram, and then some finite distance away. If one's eyes are separated by a distance d, in the plane of the film, the eyes would see two views of the object that are rotated by (d/slit width)X(amount of each rotation). For the following argument I assume that the object is a point source located

\[ \tan \theta = \frac{d}{(2w_0)} \]

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{hologram_diagram.png}
\caption{Multiplexed Hologram}
\end{figure}
Experimental Section

at a distance \( c \) behind the hologram. If the eyes are removed to a distance \( x \) perpendicular to the hologram and the point source, from Figure 12, \( \tan \Theta \) can be seen to be \( d/2(x + c) \). The small triangle is isomorphic to the larger triangle so the angle \( \Theta \) is the same. With \( c \) known, the new distance between slits (\( d' \)) becomes:

\[
d' = 2\left[ \frac{c}{\tan \Theta} \right] = \frac{2c}{\left( \frac{d}{2(x + c)} \right)} = \frac{cd}{x + c}.
\]

\( d' < d \)

number of slits for \( d' < \) number for \( d \) and the number of slits in \( d' \) goes to zero (one) as \( x \) goes to infinity.

This analysis assumes a point source, and also eyes that receive as point receptors, i.e., the only light that the eye receives from the object (point source) is light that has traveled (one) straight line between the object and the eye. For a three-dimensional case, the analysis would be similar, but more complex.

I accomplished the requirements for multiplexed holograms using a fairly crude system of multiple slits. Each slit, about 2mm in width, was cut out of a separate 4x5" cardboard stock. I progressively moved the slit over, 2mm at a time, on subsequent cards. I attempted to ensure that these slits were mutually adjacent by using the right edge of the previously cut slit as a guide to cut the left edge of the current slit, and so on. Using paper stock and knives to cut with, only a certain degree of accuracy can hoped to be achieved. I found the accuracies of the adjacent cuts not to be the major problem with the procedure I
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developed, as I will explain later.

To obtain a 360 degree view of an object, rotating five degrees between each successive exposure, puts certain limits on film size. Since a five degree rotating sequence requires a sequence of 72 slits, each slit being approximately 2mm in width, implies that the minimum length of film required is \( 72 \times 2\text{mm} = 144\text{mm} \), or about 14.5 cm, which is quite long. The film must be attached to a special plate this length, and there must also be some mechanism to support the sequence of cards. It is important that this supporting system be simple to use, because the changing of the cards must be accomplished in total darkness. I located the film by securing small blocks on the film platform and sliding the film into the blocks (the blocks define a 90 degree angle as before). Again I taped this plate (with the 14.5 cm film strip secured to it) to the film holder. One must remove the floor of this special platform in order to use this film support in the special base provided (the floor simply unscrews from behind). On these blocks which I support the film, I also rest the sequence of cards, securing the cards in place with small amounts of double-sticky tape. As mentioned previously, a special base is used with this procedure to ensure that the film/plate holder and the dividing head do not move when changing cards or rotating the object.

The rotation of the object is greatly facilitated (in total darkness) by the use of a machinist's dividing head.

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It turns out that one rotation of the handle of this table corresponds to a rotation of the object of five degrees (this is one very important reason why I choose a rotation of five degrees). Both the dividing head and the film holder are secured in two lead bricks that are themselves secured together. I used two lead bricks to provide enough mass to ensure that this entire assembly did not move during the adjustment procedure. I choose to mount both the film/plate holder and the dividing head together in one fixed base to ensure that these components could not move relative to one another, in the darkness. As a final note here, one should securely position the object to the dividing head so that in no way could the object fall over or move slightly if accidently bumped. Remember, one has to repeat this procedure over seventy times, so I attempted to design a system that was simple to use in the darkness as possible and also one that was very forgiving (could take slight bumps and jars without destroying the holographic set-up).

The results of this procedure were not as I had hoped they would be. As one moves from right to left, the object does tend to rotate. The problems start with over-lapping or non-adjacent slits. The non-adjacent slits develop into dark lines on the hologram that interrupt the smooth rotation of the object. One advantage the dark slits did have was to enable me to align the three separate film strips, that composed a 3X5" hologram, very easily. The overlapping
slits produced blurry images. There also were several slits that were simply "fogged" over, diffracting a meaningless constant intensity wavefront. I can only set forth a few theories as to the cause of these constant intensity slits.

The first, and I feel most likely reason for these fogged slits, is that the cards themselves moved slightly during exposure, thus washing out any interference pattern. The cards are simply taped to the film, not uniformly, but only at a few points. Air currents or gravity could easily cause unperceived motion of the card. You only have to attempt to touch the surface of the optical table (let alone a mirror or optical component) and watch the Michelson interferometer, to realize that not much force is required to wash out the interference pattern. The second thought I had was the since the multiplexed hologram was a sequence of seventy separate recordings, stray vibrations could have penetrated the isolation system during a few of these independent recordings. I do not put much faith into this thought because I have never experienced a hologram washing out due to a lack of stability of the optical table.

I feel some type of mechanically controlled slit can be designed to slide the slit across the film very precisely, and with great stability. If one wishes to seriously work with multiplexed holograms such a device should be built.

Holographic Interferometry

Holographic interferometry is a nondestructive technique.
measurement of the effects that various deformations have on an object. The basic idea behind holographic interferometry is the use of the hologram as a storage device, to store certain information about an object, and compare this stored information with new information generated at a later time. The information being stored in the hologram is the wavefield produced by the object at a given time. If later the wavefield of the object were changed due to very small geometrical changes in the object, the stored wavefield and the newly created wavefield would interfere with each another at every place the two wavefields were different. The object, when viewed through the hologram, would display diffraction patterns where the two wavefields were different. The comparison of these two wavefields can be accomplished in primarily two methods. The first wavefield comparison technique that I will describe will be real-time interferometry, and the second technique will be double-exposure holography.

Real-time holographic interferometry is much more versatile than double exposure holographic interferometry, but real-time interferometry is much more difficult to carry out because it requires strict adherence to very high tolerances. The idea behind real-time interferometry is that a person can record the original wavefield coming from an undeformed object just once. This stored wavefield will then be the norm to which later states are compared to (this is why one would generally choose an unexcited state, a Senior Scholars 1982
state that would be considered normal, for this stored image). To compare this stored wavefield to a new deformation of the object, the hologram is placed back exactly to the same place that it was in during exposure (to less than \( \frac{1}{10} \lambda \)). One can now deform the object in any way, and see the effect by viewing the object through the hologram. Any difference in the two fields will be seen by the diffraction pattern created. Since the first wavefield stored in the hologram acts as the norm to which all later wavefields will be compared to, the second wavefield can change continually with time and the effect will be seen when viewed through the hologram. The difficulty with real-time holographic interferometry is the repositioning of the hologram to its original position to such high tolerances. To meet these high tolerances required, the hologram is developed "in situ". For in situ development the film is emerged in some liquid (water) during the exposure process. This liquid is then drained from the tank and the developing chemicals are circulated through the tank for the appropriate intervals of time. After development the hologram is re-emerged in the liquid present during exposure. The liquid being present both at exposure and reconstruction allows the emulsion to expand to the same size during exposure and reconstruction. Since the hologram was never moved, the hologram is in the exact place it was during exposure, and now one can compare the wavefield stored in the hologram to any new wavefield coming from the object; even one changing in time. Because

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of the difficulty of repositioning the hologram to such high tolerances. I never tried real time interferometry, but worked only with double-exposure interferometry.

Double-exposure interferometry, though less versatile than real-time holographic interferometry, is much easier to accomplish in the lab (given the current apparatus available). For double-exposure holographic interferometry one makes a hologram of an object in its undeformed state. One then deforms the object in some manner and exposes a second hologram on the same piece of film as the first. When this composite hologram is developed and viewed, the two permanently stored wavefronts will interfere at any points the two wavefields differ, as the wavefields did in real-time. The only difference between the two methods is that with real-time one can continuously deform the object and view the result, whereas with double-exposure, the two wavefields being compared are fixed. The exposure time required for each scene in double-exposure interferometry is one-half the time required to obtain a desired film density by a single exposure.

To deform the object in double-exposure holographic interferometry, I use the property of thermal expansion. When using aluminum-beverage-cans or other metal objects one can make the first hologram of the can at one temperature (room temperature), then heat (or cool) the can and make the second exposure. Heating using electrical resistance is the most convenient method. Electrical resistance is a source.
of a predetermined amount of power, and can be applied without touching the object in any way (which could move the object).

For the aluminum-beverage-can I ran a piece of nichrome wire inside the can. Nichrome wire is nice to use because the wire has a given resistivity per inch, so it is simple to obtain a predetermined amount of resistance. I exposed the first hologram to the aluminum-beverage-can at room temperature. I then turned on a current for a given amount of time, and then exposed the second hologram. One must be careful not to pass too much current through the wire, or the wire will begin to glow, and this would fog the film. To ensure that the wire would not come in contact with the aluminum-beverage-can I used ceramic beads to insulate the wire. The beads will easily take the heat produced, and also remove the wire from coming in contact with the can. After development, the hologram show a circular interference pattern characteristic of how the aluminum-beverage-can expanded.

Holographic interferometry can be used to measure the effect of almost any type of deformation and most any objects. It is a very sensitive (1X10^-6") measurement, and nondestructive.
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