Chapter 8
HOLOGRAPHY

[Reading Assignment, Hecht 13.3. For additional material, see Introduction to Fourier Optics, by J. Goodman, 2nd ed., Chapter 9.

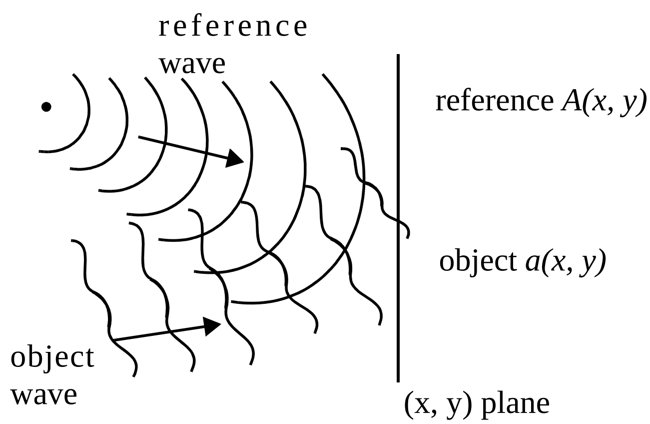
Virtually all recording devices for light respond to light intensity.

Problem: How to record, and then later reconstruct both the amplitude and phase of an optical wave. The same issue can also be raised for acoustic and seismic waves.

The challenge is to figure out how to convert phase information to intensity.

Interferometry

Create a second wavefront with known amplitude and phase that is coherent with the wave to be recorded (the object wave). Add this to the object wave.



The intensity of the sum contains the interference pattern

let

$$I_s(x, y) = |A|^2 + |a|^2 + A^*a + Aa^*$$
$$= |A(x, y)|^2 + |a(x, y)|^2 + 2|A(x, y)||a(x, y)|\cos[\psi(x, y) - \phi(x, y)]$$

A recording of this interference pattern is a hologram.

The recording medium for holography is typically some type of film emulsion. The transmission of the developed film can be linear in absorbed energy over a limited dynamic range.

Under these conditions, the transmittance of film can be written

Where we assume that $|A|^2$ is constant and uniform, which gives the bias t_b. β' is the sensitivity parameter of the film.

<u>Reconstruction:</u> illuminate transparency by reconstruction wave $B(x, y)$.

Transmitted light is: $B(x, y)t_A(x, y)$

$$= Bt_B + \beta'|a|^2 B + \beta' A^* Ba + \beta' ABa^*$$

If B is a duplicate of A, $B = A$.

Then $U_3 = \beta'\left|A^2\right|a$. If $|A|^2$ is uniform, then U_3 is a duplication of a.

We could also arrange that $B = A^*$. Then

$U_4 = \beta'|A|^2 a^*$ the conjugate of the original wavefront

This process is a two dimensional analog of amplitude modulation.

Here we have three extraneous signals which lead to unwanted interference. If we want a or a^*, we have to filter out the other components.

Real and virtual images

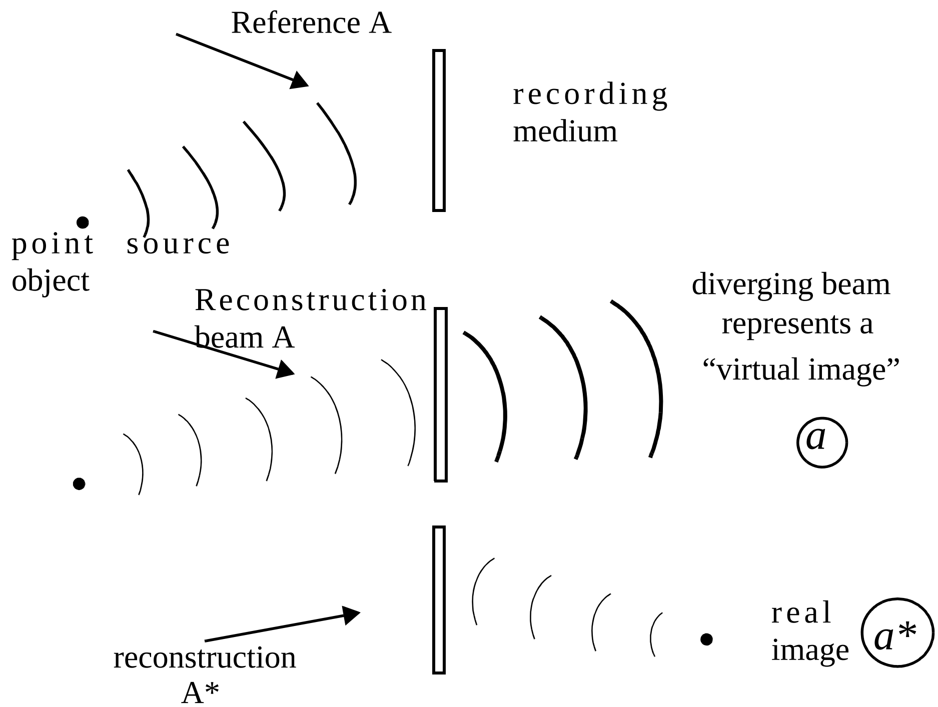
A general principle in holography is linearity. A useful construct is to consider a point object. The behavior of a complex object can be found by superposition.

The point source object is $a(\vec{r}) = \dfrac{a_o e^{jk(\vec{r} - \vec{r}_o)}}{|\vec{r} - \vec{r}_o|}$ r_o: position of the point source

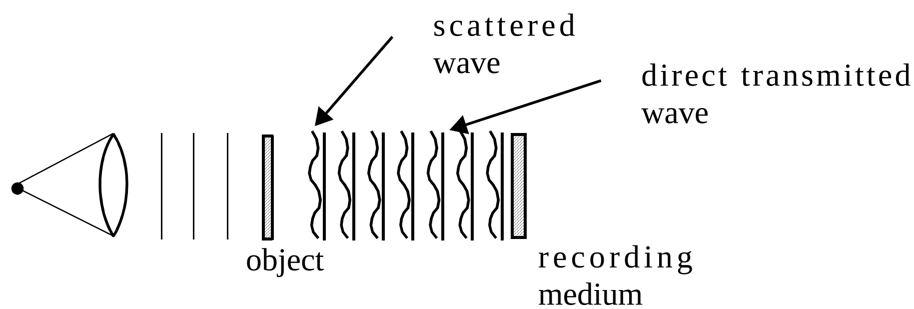
When the A* reconstruction wave is used:

$$U_4(\vec{r}) = \beta'|A|^2 a^*(\vec{r}) = \beta'|A|^2 \frac{a_o^* e^{-jk(\vec{r} - \vec{r}_o)}}{|\overrightarrow{r - r_o}|}$$

We get a converging spherical wave toward point $(-\vec{r}_o)$. But we still have not specified how to exclude the three unwanted components.



Original Gabor Hologram (1948)



recording

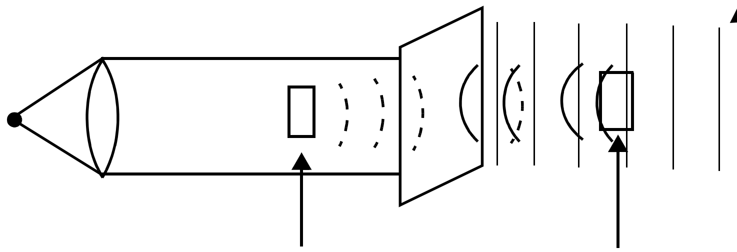
object must be highly transmissive

The reference wave is a plane wave which comes from the t_o component of the object itself.

The object wave is scattered by the variations $\Delta t(x_o, y_o)$

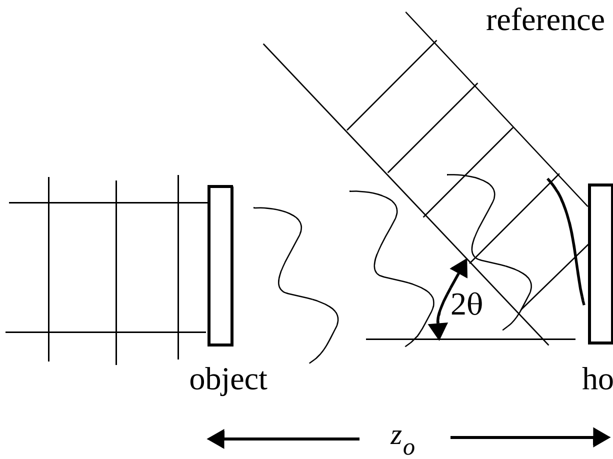
The scattered wave is weak compared to the reference plane wave

Thus we can neglect the U_2 term.



In a Gabor hologram there are three overlapping components, the real image, the virtual image, and the background.

Leith-Upatnieks (offset reference) hologram (1962)



The reference beam is tilted. This is a real "hero" experiment without a laser. Holography was made practical after the invention of the laser.

Now the field at the recording plate consists of a scattered wave from the object $a(x, y)$ plus the reference plane wave.

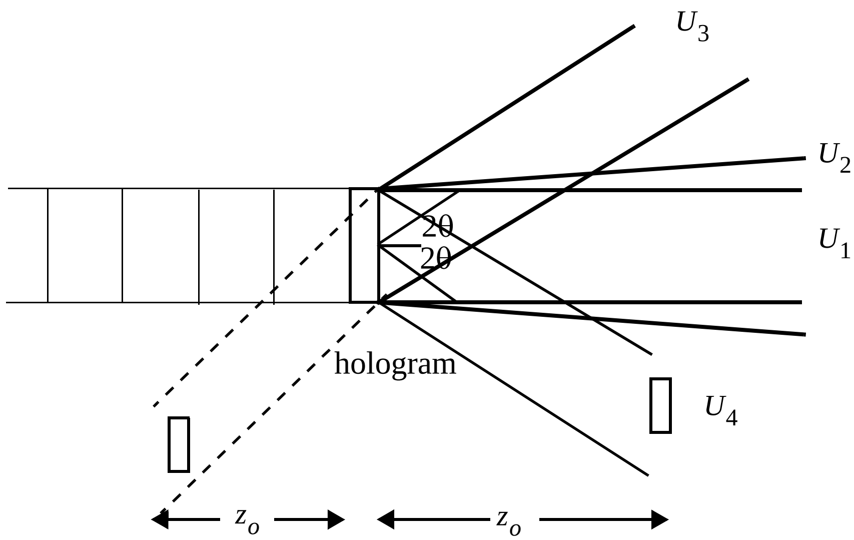
The intensity at the plate is

$$I(x, y) = |A^2| + |a(x, y)|^2 + A^*a(x, y)\exp(jky\sin 2\theta) + Aa^*(x, y)\exp(-jky\sin 2\theta)$$

The developed film transmittance has four terms:

$$t_A = t_b + \beta'[|a(x, y)|^2 + \beta'A^*a(x, y)\exp(jky\sin 2\theta) + \beta'Aa^*(x, y)\exp(-jky\sin 2\theta)]$$

Reconstruction:



The reconstruction beam is a plane wave at normal incidence, with amplitude B.

Four components in the transmitted wave:

$$U_1 = Bt_B \qquad U_2 = \beta' B|a(x,y)|^2$$

$$U_3 = \beta' BA^* a(x,y)\exp(jky\sin 2\theta)$$

$$U_4 = \beta' BAa^*(x,y)\exp(-jky\sin 2\theta)$$

U_1: attenuated version of the reconstruction beam

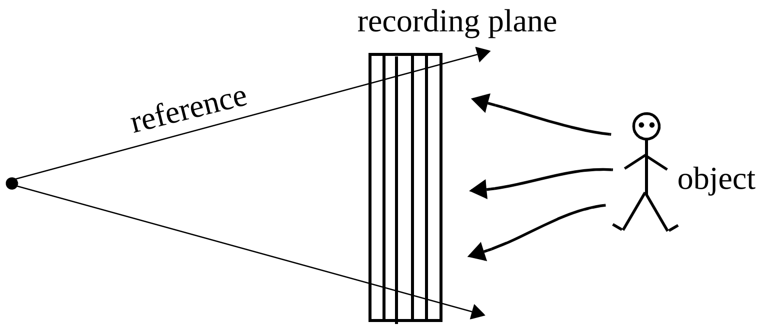
U_2: scattered wave by object $|a(x,y)|^2$. It stays close to the axis.

U_3: original wave a, modulated by the exponential phase factor. This modulation causes deflection by the angle 2θ. Proportionality to a causes the virtual image to be formed at the distance -z_o.

U_4: a^* is modulated. By a similar argument, we get the real image deflected by -2θ at the distance z_o.

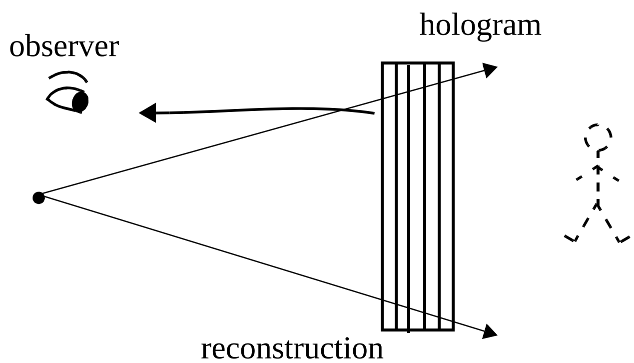
The twin images (real and virtual) are now angularly separated from each other as well as from the background components of U_1 and U_2.

Reflection holograms



Interference fringes form standing waves in emulsion. The period is about $\lambda/2$ and this is parallel to the surface.

The reference and object waves come from opposite sides of the recording medium.



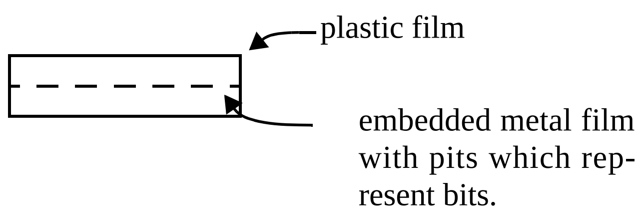
The virtual image is formed by the light Bragg reflected by the hologram

This can be viewed in white light since the Bragg condition is wavelength selective. More on this later.

<u>Holographic Data Storage</u>

A current CD-ROM stores 640 megabytes. A dramatic improvement in CD-ROM technology is possible with holographic techniques:

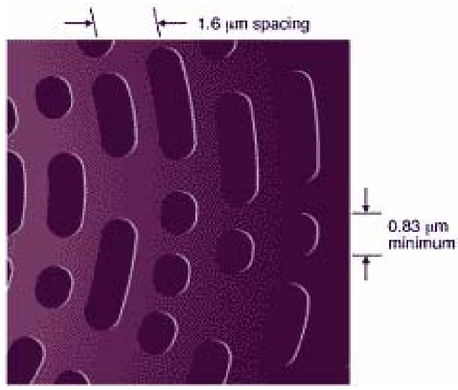
<u>current scheme</u>



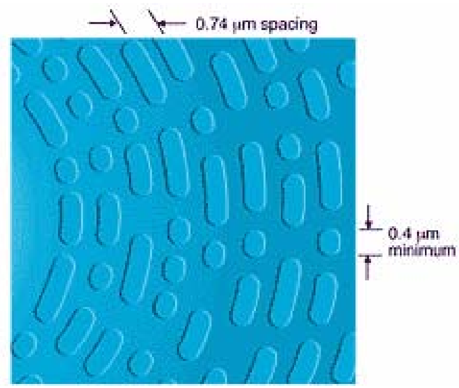
The λ~850 nm laser is focused using a high NA lens to read the pits.

Rayleigh resolution: $0.6\lambda/NA$ 1 μm $\lambda = 850nm$ $NA = 0.5$

With a shorter $\lambda \sim 650nm$, and using a higher $NA \sim 0.80$ lens, we reach a resolution of 490nm. With improved coding, DVDs reach a storage density of 4.7 Gbytes.



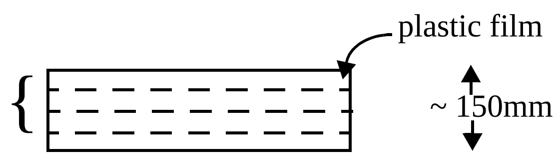
CDROM



DVD

multiple levels

several storage levels



We use a small DOF to focus in on only one level at a time. Another factor of 3 - 5 is possible. The DVD standard allows for using 2 levels, with recording on both sides of the disk, which makes it possible to store up to 17 Gbytes.

Holographic storage targets:

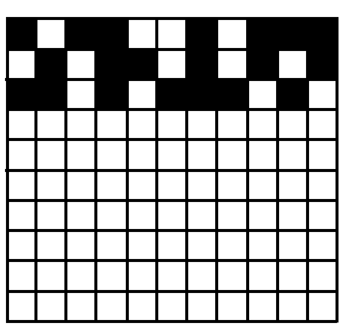
Hundreds of Gbytes, in about 1 cm^3, or possibly a disk format.

About a 100 Mbyte/sec data transfer rate [4 x CD: 640 Kilobyte/sec]

This technology has come very close to commercialization, but problems remain.

Basics

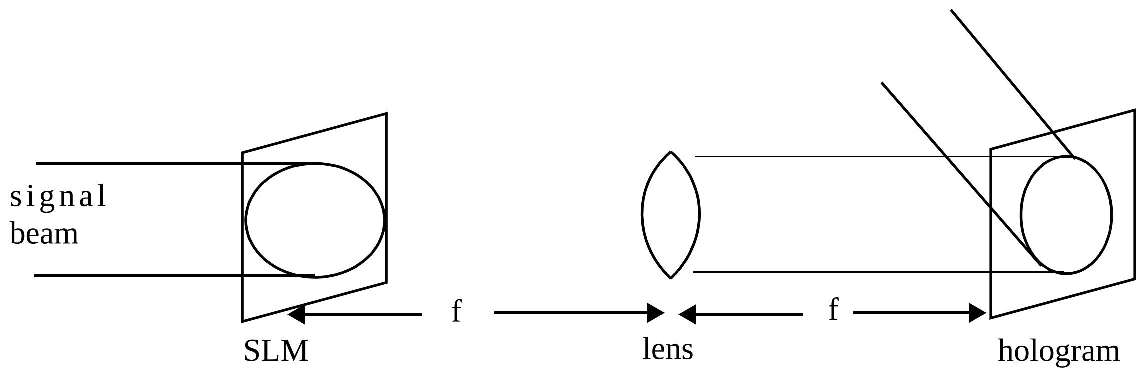
Data encoding: 2 dimensional “page” format



1 bit = 1 pixel

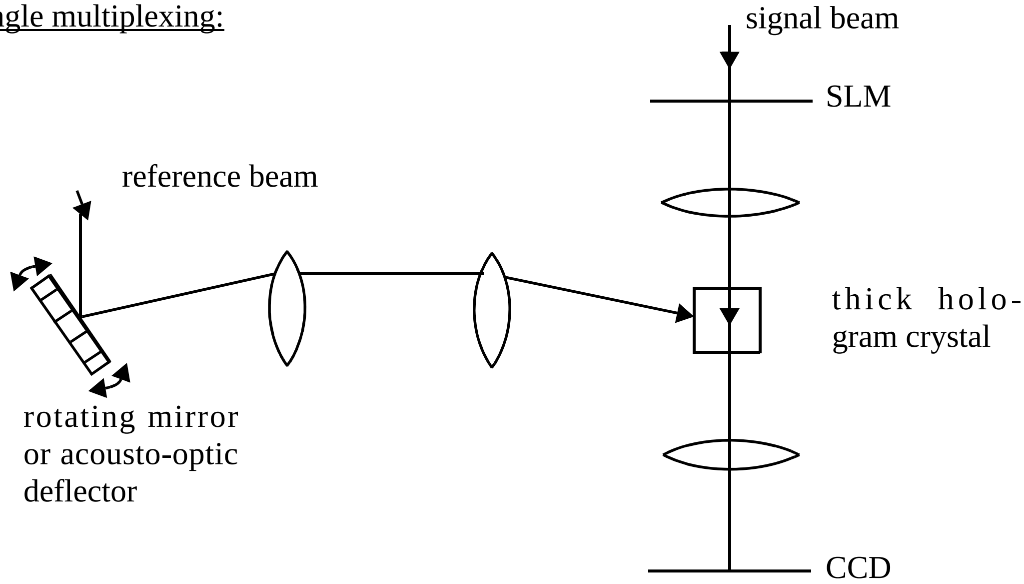
To convert random digital data into such an image representation, spatial light modulator (SLM) technology is used. SLM: liquid crystal technology for video projection. This is commercially available for common video formats, e.g. $640 \times 480 \cong 300$ Kbits/page.

simplest scheme:



A big improvement is obtained using Bragg selectivity of thick holograms.

Angle multiplexing:



We could get $\sim 10^4$ holograms in one area, with 1-10 gigabits.