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Second Training College on Physics and Technology of Lasers and Optical Fibres

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Modern Aspects of Holography

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MODERN ASPECTS OF HOLOGRAPHY

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Contents

Display, Computer generation, Optical elements
HNDT, Information processing, Imaging and Imaging through distorting media.
Storage, memory and interconnecting.

6. Tutorial Problems

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INTRODUCTION

1. Light as a carrier: Information (light, sound or heat) reaches us as waves (electromagnetic and elastic) by modulation of amplitude (intensity), phase, frequency or polarization.

   Particular interest in image formation is Spatial Information i.e., amplitude and phase variation of radiation field in the object scene.

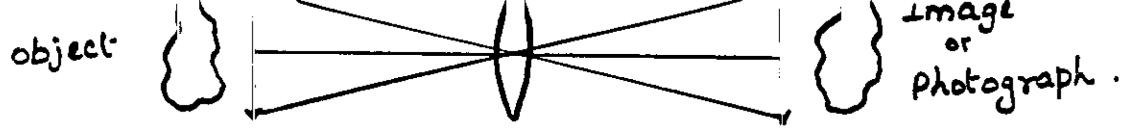
2. Perception: An object is perceived when the wavefront from object reaches the eye.

   Storing or freezing the waves in time (i.e., store the spatial information as samples in time) enables recall of object at a later time.

3. Photography.

   classical method of information recording (Picture or image) on photosensitive surface using lens or pinhole

   <u>Partial record</u>: only intensity distribution is recorded.
   each object point is converted into a corresponding image point.



4. Limitation :

Photograph is 2-D record of 3-D scene. A true scene has 'depth' and 'Parallex' .i.e., amplitude and phase variations. Photography respond only to amplitude. What is the way out for "whole" record?

5. Holography :

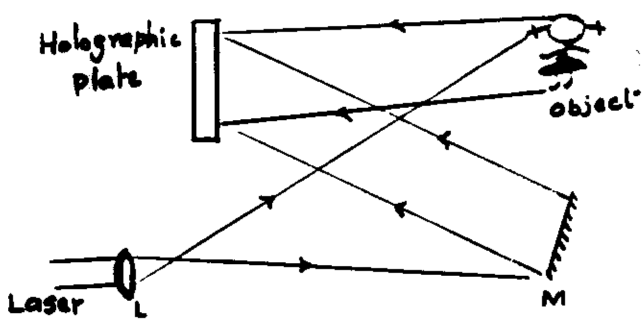
Dennis Gabor (1948) suggested the addition of a background (reference) to the object wave. This way recording of both amplitude and phase can take place.

Phase information is converted into intensity variation.

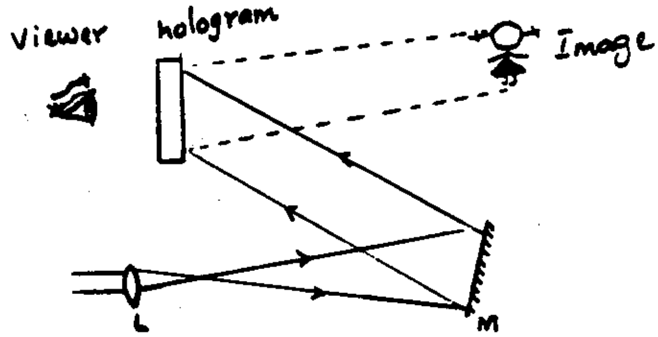
Intensity at any point depends on amplitude and phase of object.

Recording is complete ("whole")

Reconstruction by reference wave alone.



a. recording



b. reconstruction.

6. Features :

Two step process, recording and reconstruction.

Communication point of view : Modulation and demodulation
Coding and decoding.

Interference and diffraction play key role.

Many ~~differences~~ between photography and holography.

Gabor solved the problem with background waves and encoded phase as intensity variations. The pattern of the object is imprinted on to hologram and can be regenerated at any later tim

observer will seem to see the object as if it is still there uninterrupted – full 3-D and normal parallex.

Fascination for both Scientist and Laymen alike!

Image looks like a solid object floating in space. Hologram is recorded in 2-D (flat) surface but produces a 3-D image

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HISTORICAL DEVELOPMENT

1. Bragg x-ray microscope is the basis for holography. Structure (1939)
   x-ray reconstruction of crystal
   Centrosymmetric crystal with heavy atom at centre of unit cell.
   The diffraction pattern is purely real. The weaker scattered amplitudes add to or subtract from amplitude from heavy atom.

   New mask – transmittance at any point is proportional to amplitude in the diffraction pattern.
   Illuminate with collimated light (second FT) to reconstruct the crysta

2. Gabor aimed to improve resolution of e^- microscopy (1948)
   aberration correction of e^- lens was difficult
   He proposed to record scattered light due to electron and reconstruction with visible light.

   Gabor succeeded in optical holography
   twin images – undesirable.

3. [illegible]

Leith and Upataniek's work on SAR imagery

Recording at Long wavelength ; Reconstruction at Optical wavelength

we can use diffusely reflecting objects ; arrival of lasers

need for high coherence source and high recording resolution.

Volume hologram : Denisuk (1962-65)
basis for colour and white light holograms.

holographic Interferometry : several independent groups.

Powell, Stetson : (1965) – time average

Brooks et al : (1965) – double exposure, real time
use of relatively rough Surface

Vander Lugt : (1965) – character recognition

Kogelnik : (1965) – Imaging thro' diffusing and aberrating media.

Lohmann : (1967) – Computer Generated hologram

Lu : (1968) – Multiple imaging

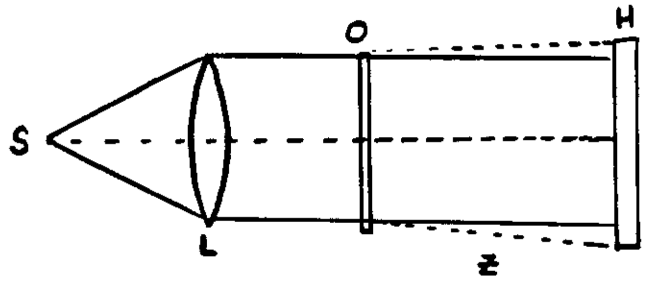
Benton : (1969) – Rainbow hologram.

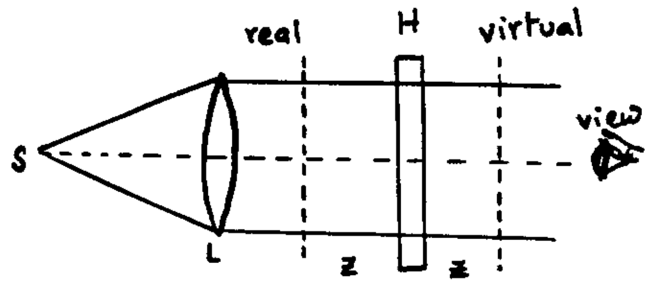
4. Other developments :

Synthetic (multiplexed) hologram ; Photorefractive crystals and optical phase conjugation ; holographic optical elements ; diode laser and fiber holography ; associative memory and neural computing ; optical interconnects.

In-line or Gabor hologram :

Transparent object and opaque details





The collimated light after passing transparency results in strong uniform plane wave and weak scattered object wave.

Amplitude and phase of reference wave does not vary and hence is a real constant, a.

Resultant intensity at recording plane is

$$I(x,y) = |a + O(x,y)|^2 \qquad \ldots(1)$$
$$= a^2 + |O(x,y)|^2 + a\,O(x,y) + a\,O^*(x,y)$$

After proper exposing and processing

$$t(x,y) = t_0 + \beta\tau\, I(x,y) \qquad \ldots(2)$$

Reconstructed wave field of the developed hologram is

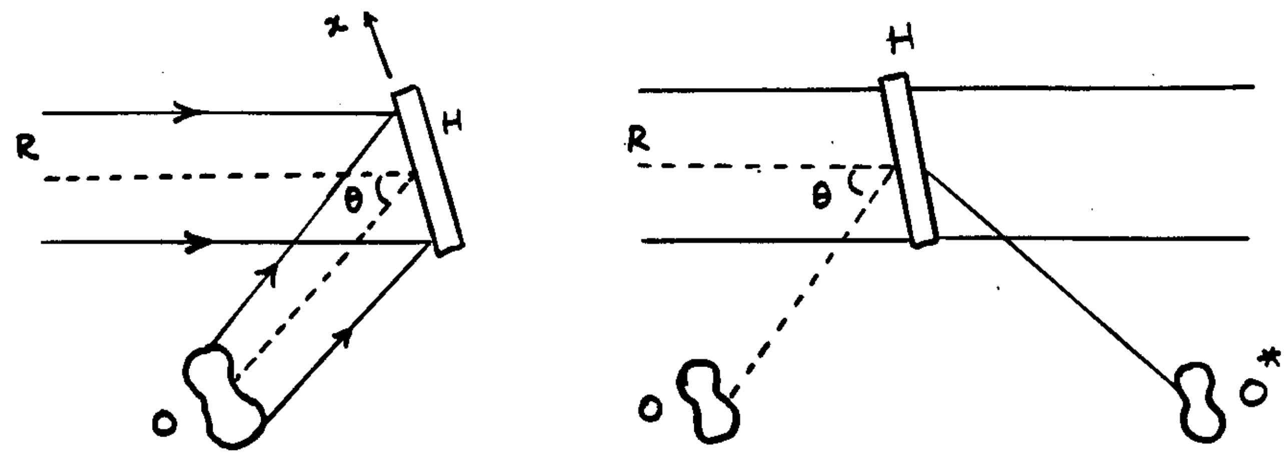
$$r_c(x,y) = a\,t(x,y)$$
$$= a(t_0 + a^2\beta\tau) + a\beta\tau\,|O(x,y)|^2$$
$$+ a^2\beta\tau\,O(x,y) + a^2\beta\tau\,O^*(x,y) \qquad \ldots(3)$$

Thus object wave and its complex conjugate are recreated

Limitations : 1. Presence of twin image

2. need for strong reference while recording.

Off-Axis or Leith-Upatnieks Hologram



Instead of single beam, two beams - reference and object beams are used here.

Both derived from same source and made to interfere with an off-set angle θ.

Let the object distribution be

$$O(x,y) = |O(x,y)| \exp\{-i\phi(x,y)\}$$

and a uniform intensity reference wave with phase variation $\xi_r = \frac{\sin\theta}{\lambda}$ along x direction be

$$r(x,y) = r \exp\{i 2\pi \xi_r x\}$$

Resultant intensity at recording plane is

$$I(x,y) = |r(x,y) + O(x,y)|^2$$
$$= r^2 + |O(x,y)|^2 + 2r|O(x,y)| \cos\left[2\pi\xi_r x + \phi(x,y)\right]$$

Above eqn implies that the amplitude and phase of object wave are encoded onto a spatial carrier frequency ($= \xi$) as amplitude and phase modulation respectively.

After exposure ... a linear transmittance is achieved.

Reconstruction with the same reference beam lead again to 4 terms as follows,

$$U(x,y) = t_0 r \exp(i2\pi \xi_r x) + \beta \tau r |O(x,y)|^2 \exp(i2\pi \xi_r x)$$
$$+ \beta \tau r^2 O(x,y) + \beta \tau r^2 O^*(x,y) \exp(i4\pi \xi_r x)$$

a directly transmitted beam (attenuated reference plane wave)

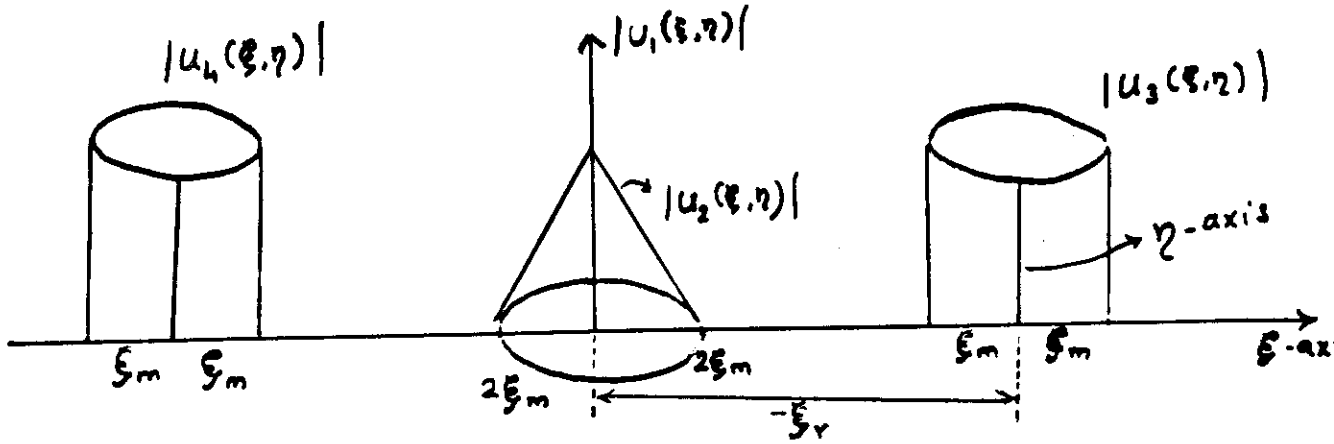
a halo surrounding it whose spatial extent is determined by the object,

a original object wave which makes an angle θ with the reference wave

and a conjugate object wave which is now seperated both from the object and reference wave.

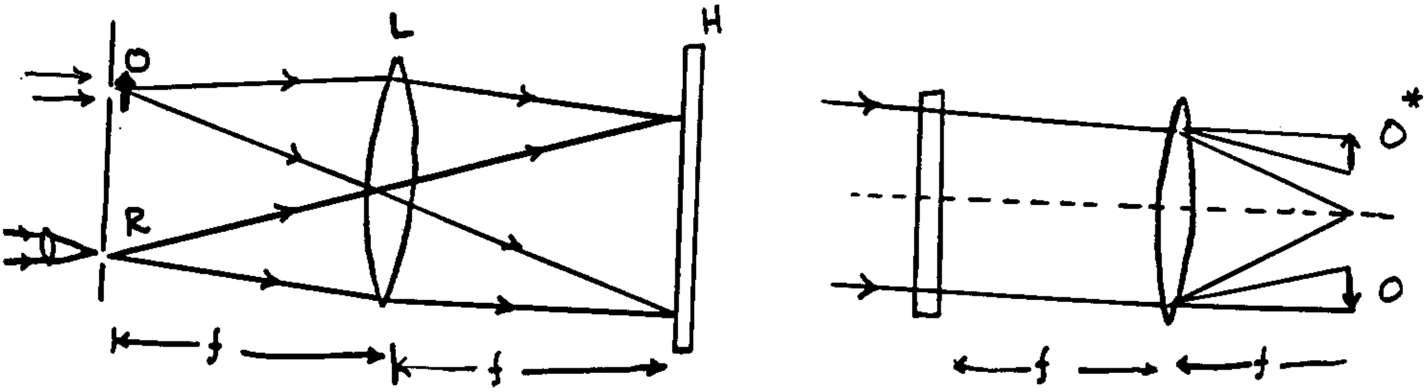
To get an idea of minimum off-set angle to avoid overlap, F.T of the above terms can be taken and fix ξ_r accordingly.

The spatial spectra is shown below



Evidently if $\xi_r \geq 3\xi_m$, there will be no overlap.

Fourier Transform Holograms:



Hologram is recorded by the interference of Fourier transform of the object and reference waves.

$$O(\xi,\eta) = FT\{O(x,y)\}$$

$R(\xi,\eta) = \exp(-i\,2\pi\xi b)$, for a point source, $\delta(x+b,y)$

$$I(\xi,\eta) = 1 + |O(\xi,\eta)|^2 + O(\xi,\eta)\exp\{i2\pi\xi b\} + O^*(\xi,\eta)\exp\{-i2\pi\xi b\}$$

Hologram is reconstructed with a collimated beam

Diffracted light is inverse transformed

Both images are real but one is inverted.

Lensless Fourier Transform hologram:

If reference wave is produced in the plane of the object F.T hologram can be obtained without the help of a lens.

Image Plane hologram: Recorded with a real image of the object instead of the object itself.

There are many other types

IMAGE RECONSTRUCTION

Images are obtained from holograms upon reconstruction with appropriate light.

The characteristics of obtaind images depend on factors such as geometry, source coherence, wavelength etc.

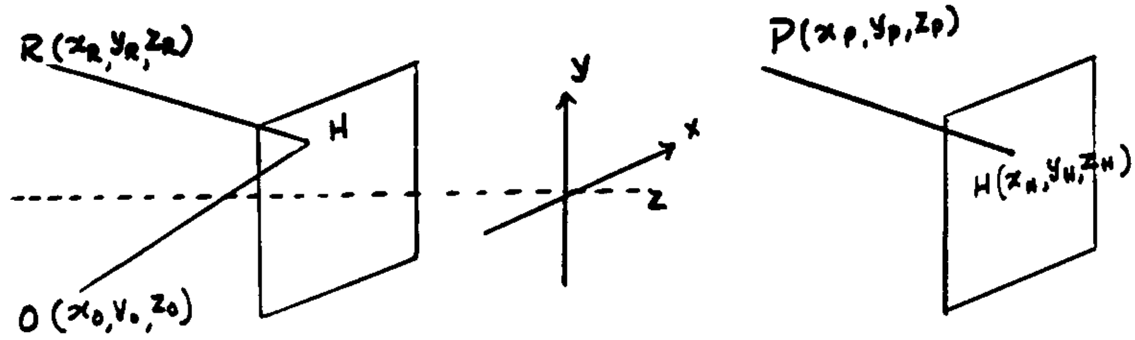
Exact image formation - without aberrations and change of magnification or distorsion is possible only when the wavelength, direction and shape of reconstructing wave is an exact replica of the reference wave.

Let a hologram be formed by a point object $O(x_o, y_o, z_o)$ and a point reference $R(x_R, y_R, z_R)$.

Let the Hologram plane be $H(x_H, y_H, z_H)$

and reconstructing point source $P(x_p, y_p, z_p)$

Ratio of reconstructing to recording wavelength, $\mu = \frac{\lambda_2}{\lambda_1}$



The image coordinates are

$$x_i = \frac{x_p z_o z_R + \mu x_o z_p z_R - \mu x_R z_p z_o}{z_o z_R + \mu z_p z_R - \mu z_p z_o}$$

$$y_i = \frac{y_p z_o z_R + \mu y_o z_p z_R - \mu y_R z_p z_o}{z_o z_R + \mu z_p z_R - \mu z_p z_o}$$

$$z_i = \frac{z_p z_o z_R}{z_o z_R + \mu z_p z_R - \mu z_p z_o}$$

Lateral magnification : $M = \left[1 + z_o\left(\frac{1}{\mu z_p} - \frac{1}{z_R}\right)\right]^{-1}$

Angular magnification : $U = \mu$

Longitudinal magnification : $V = M^2/\mu$

THIN AND THICK HOLOGRAMS :

Thin or plane hologram is formed when the thickness of recording material is small compared to average fringe spacing.

The thickness should be comparable with wavelength of light and

$$t(x,y) = |t(x,y)| \exp[-i\phi(x,y)]$$

One can define amplitude and phase Holograms.

In thin amplitude (absorption) hologram, the amplitude transmittance at best can be

$$t = \frac{1}{2} - \frac{1}{4}\exp(2\pi i \xi x) - \frac{1}{4}\exp(-2\pi i \xi x)$$

The diffraction efficiency is at best : $\left(\frac{1}{4}\right)^2 = 6.25\ \%$

Volume hologram is formed when the thickness
of the medium is much large compared to fringe spacing.

ex. fringe spacing may be of the order of 1 μm

medium thickness can be ~ 1 mm

Diffraction amplitude is maximum only when Bragg condition is satisfied.

Diffraction efficiency of volume phase hologram: close to 100%

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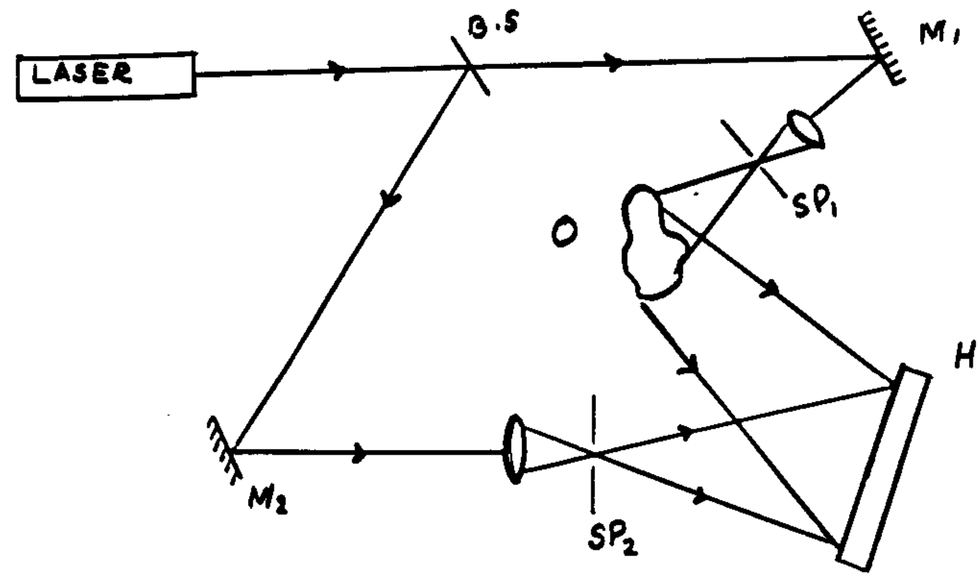
SYSTEM REQUIREMENTS

The layout, components selection and the system requirements for holography vary depending on application and available budget.

A general purpose optical system for recording a transmission type hologram is shown.



Laser light is divided into two beams: one serving as reference and the other illuminating the object.

Both are combined at the hologram plane.

1. Source :

Holography involves interference phenomena so source coherence properties are important. CW gas lasers with TEM_{00} output are often used. For short exposure time (recording transient events) high power pulsed laser is used.

Good fringe visibility needs linearly polarised light.

2. Optical Components :

Beam divider, reflecting mirrors

lens - pinhole - spatial filter-cum-expander

a shutter and a plate/film holder : the minimum required components.

3. Vibration Isolation :

Fringe movement (due to vibration or thermal/air current drift) during exposure reduces hologram efficiency.

It can even wipe out the recording. So layout must be placed on vibration isolation platform.

There are many techniques to minimize the effect of object motion and fringe displacements.

4. Recording Material :

Photographic emulsion is commonly used.

Others include : Dichromated gelatin, thermoplastics photoresists, photochromics and many others (Table 2)

Resolution, sensitivity, cyclic use are some of the important ~~properties to be~~ considered.

Table I : Classification of Holograms

S.No	Type of Hologram	Features/Description
1a	Fresnel hologram	Object is close to the hologram;sometime a lens is used to project an image onto the hologram (image plane)
1b	Fraunhofer hologram	Object is far enough or small in size so that the hologram is in the far field of the object.
1c	Fourier transform hologram	A point reference source is used; A lens Fourier transforms a point source as also the object distribution; a special case of this is the lensless Fourier transform.
2a	Extended reference hologram	These are special holograms wherein the size and nature of the reference beam is unique.
2b	Local reference hologram	The reference wave originates from the object wave. Source coherence and object distance can be related
2c	Speckle reference hologram	A focused spot on the object provides a speckle reference; cab be used to compensate for phase distortions of the medium.
3a	Incoherent hologram	Usually the temporal coherence of the source used is poor
3b	White light hologram	Recording with coherent light but readout with white light; colour holograms, rainbow hologram etc are the variants of this
3c	Multiple exposure holograms	Incoherent superposition of several holograms on the same emulsion but recorded with coherent light
4a	Phase only hologram	Only phase information is preserved; computer generated hologram, kinoform are other variants of this type
4b	Amplitude only hologram	Similar to above but amplitude only is preserved
4c	Thin hologram	Recording/storage occurs at or near the surface of the medium. Reconstruction efficiency is low
4d	Thick hologram	Volume recording as against recording in a plane; high efficiency and wavelength selective
4e	Reflection or transmission hologram	Reconstruction light either bounces off or passes through the medium

Following the revival of holography (1962-64) an explosive growth of activity took place.

Holographic images are striking, realistic and fascinating.

Holography is no longer a novelty.

It is an invaluable tool and a technique par excellence.

Offers solutions which are unique and in some cases indispensible.

Many and varied applications have been demonstrated and made practical later.

They Include:

Holography for displays

Holography in measurement and testing.

Computer generated holograms and their applications

Holographic optical elements

Applications in imaging and image processing

Optical Storage, memory and interconnects

Microscopy

Non-optical holography.

Display Holography:

Photographic emulsion coated on glass to sizes 1.5 X 1 m are available: so large displays are feasible.

Conventional holograms have some drawbacks: limited angle of viewing, low image brightness and the need to use laser/monochromatic light.

Desirable display hologram characteristics :

High resolution and brightness, colour combination, white light illumination, easy copying and mass production.

A number of techniques were developed for this.

Envisage a 3D airport approach and departure display or bigger than life 3D advertising!

1. 360° hologram : made using either four or more plates or a cylinder of film.

2. Colour holography : Combination of He-Ne and Ar^+ laser wavelengths are used to make transmission or reflection type multicolour holograms.

   Volume holograms are highly wavelength selective : so reconstruction with white light is feasible.

3. Rainbow Holograms :

   Enable reconstruction of a bright, sharp, monochromatic image when illuminated by white light.

   Benton's discovery of this technique is responsible for the popularity of holography amoung artists.

   Rainbow holograms sacrifice vertical parallex to solve the problem of colour smearing.

4. Synthetic holograms :

   Adjacent holographic strips constructed from a sequence of still scenes.

5. Replication, embossing : Help in mass production

   – master holograms, metalization, electroplating, ...

HUD is used to project a CRT display into a Pilot's line of sight.

Holographic HUD have wide-angle, improved brightness and single element advantages.

More recently motor car HUD is also developed (navigational aid, vision enhancement, dash board information)

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TEST AND MEASUREMENT – INTERFEROMETRY

Optical interferometers are the best known test and measurement system.

All forms of classical interferometers have their counterparts in holography – in this atleast one of the interfering beams is created by holography.

Arbitrary shape, lower optical quality, stored wavefront, comparison of wavefronts due to different wavelengths, non-contact measurement etc., are the advantages.

Applications :

Non-destructive testing – Structural weakness, crack detection, poor bonding, medical research, aerodynamics, heat transfer, plasma diagnostics ....

Real-time :

Hologram is replaced after processing in exactly the same position. The holographic image matches exactly the object.

If now the object changes slightly there is interference between the virtual image and the new object wavefront.

$$\{ \phi'(x,y) - \phi(x,y) \} = 2n\pi \quad (\text{dark fringe})$$

Double-exposure :

A hologram of the object in its initial condition and a second hologram of the stressed object are made on the same plate.

$$I(x,y) = |O(x,y)|^2 \{ 1 + \cos[\phi(x,y) - \phi'(x,y)] \}$$

Time-average :

Hologram of vibrating object recorded with exposure time large compared to period of vibration.

Contouring :

Holographically constructed image is modulated by fringes corresponding to contours of constant elevation :

Two-wavelength, two-refractive index ...

Introduction of laser diodes and optical fibers make the system compact and access inaccessible parts.

Holograms of wavefronts that are defined only mathematically.

Binary de-tour phase : Phase shifts introduced to the light diffracted from an aperture in a sample cell.

Kinoform : These are phase-only holograms; high efficiency.

Applications : Pattern recognition, neural computing, wavefront transformation, aberration compensation, generation of optical elements (multi-functionality, multi-facet)

Holographic Optical Elements

HOE can be used to transform optical wavefronts in the same manner as COE

Thin substrates, relatively light and large aperture.

HOE can be computer generated ; several holograms can be superimposed.

Unique system configuration and multifunction capability.

Difficulty is in terms of efficiency and aberration.

Applications:

Head-up display, multiple imaging, Fiber optic and optical waveguide components, laser scanners, signal processing elements, plane and curved diffraction gratings.

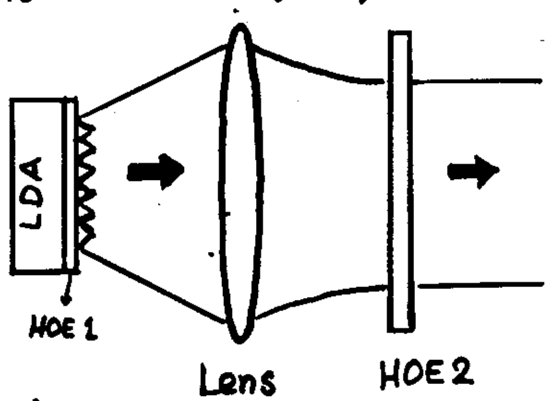
Beam Shapping : LDA

Poor quality beam makes it difficult by COE.

Multi lobed super mode → single lobed Gaussian

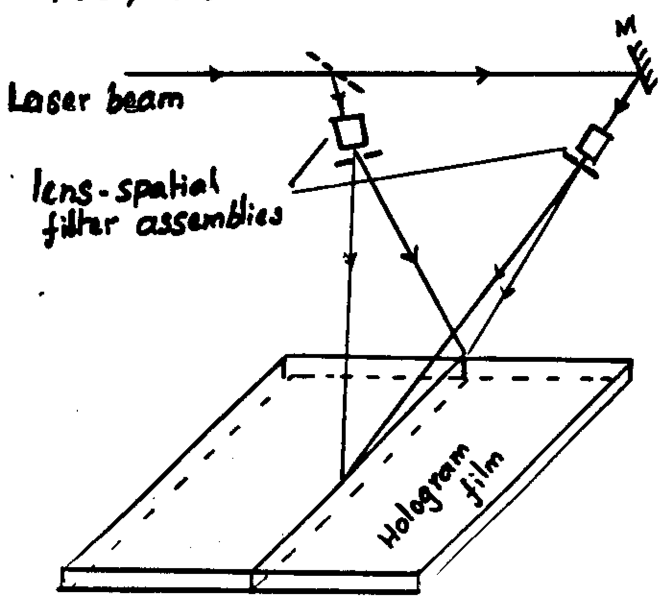
HOE-1 acts on the phases in the nearfield (Phase plate).

HOE-2 flattens in the far field.

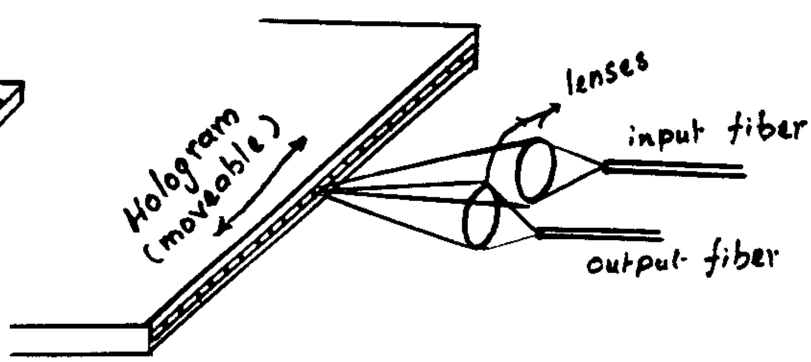


Edge addressed holograms

Realization of volume hologram in thin transmission hologram; FOC; WDM.



Exposure system for tuneable filter - dual beam



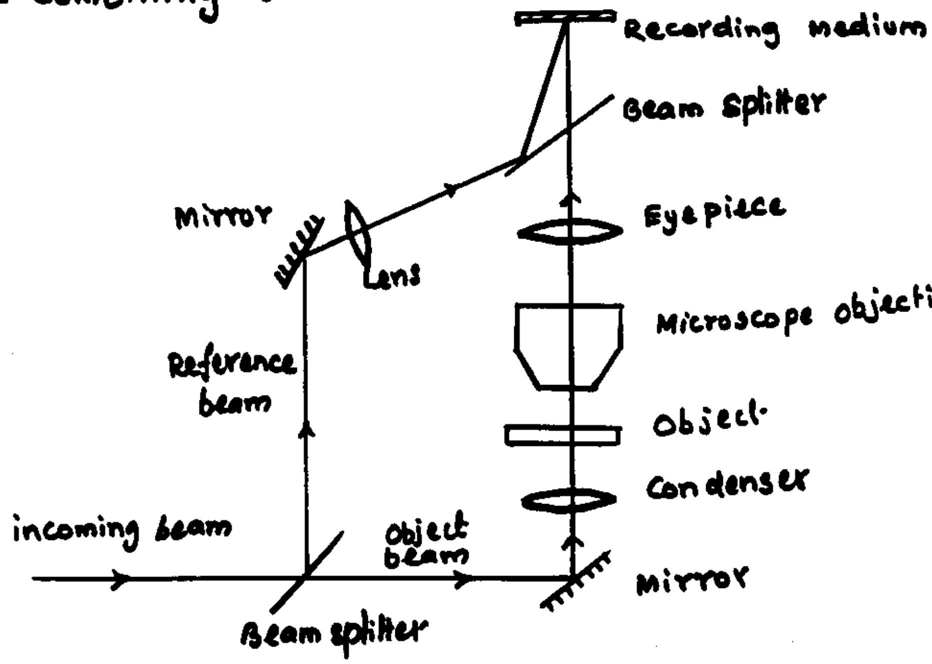
Device configuration - tuneable filter.

Large format display images ; portraiture ;

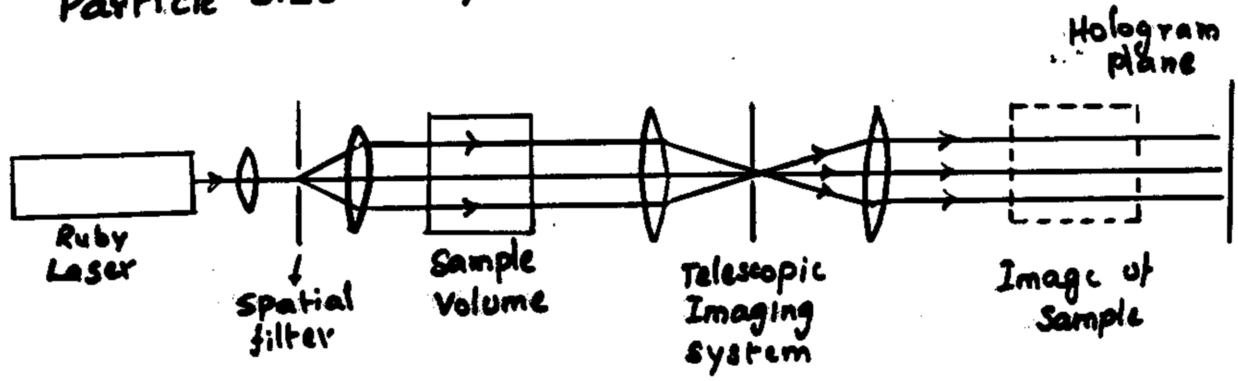
Multiple image generation (Production of integrated circuits)

Microscopy (wavelength change , curvature) - not very successful

- Combining with conventional microscopy.



Particle Size analysis



Non-optical holography : microwave , acoustical ...

Image Processing, Signal Processing – Pattern Recognition.

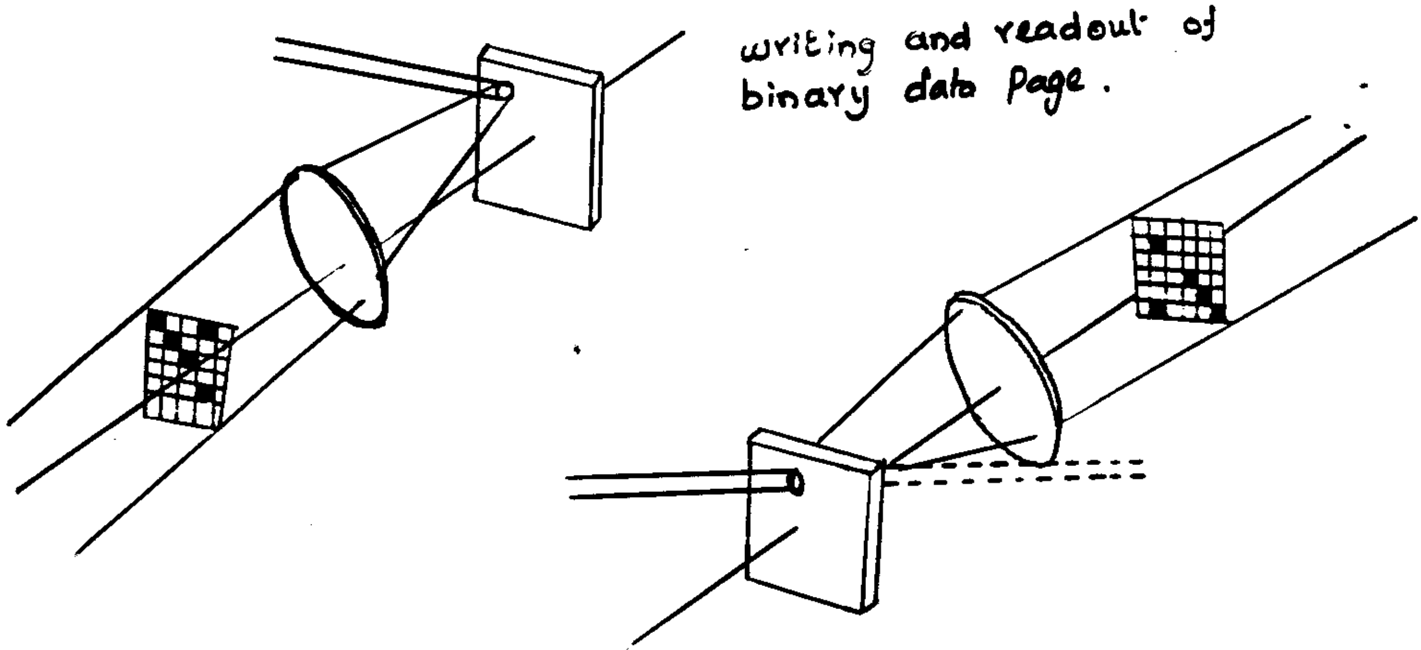
Application of Communication theory to optics (complex filters, image enhancement, restoration)

Imaging through distorting media (image processing)

Mathematical operations, character recognition.

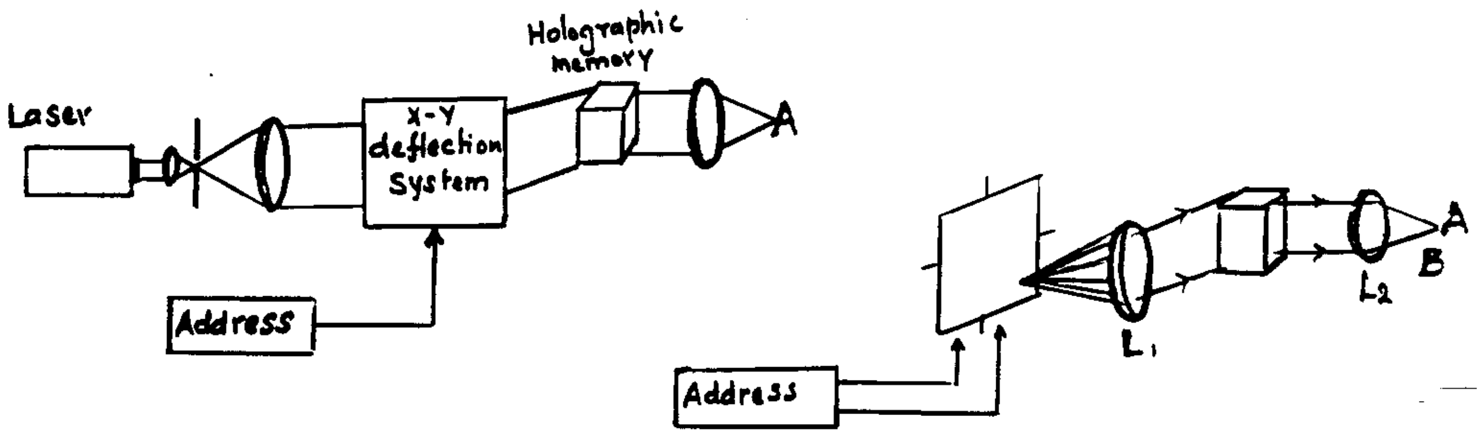
Storage, Memory, Phase Conjugation, interconnects

Memory: Page-organized format, binary code, thick phase holograms, non-mechanical addressing.



writing and readout of binary data page.

Memory readout systems.



Types of Page Composers*

Page composer concept	Materials	Addressing techniques
Polarization rotation by induced birefringence (electrooptic effects)	PLZT (ceramic), $Bi_4Ti_3O_{12}$, KDP, KD*P, ADP	Electrode matrix, electron beam, light beam (with photoconductor)
Phase changes by formation of surface relief pattern	Thermoplastics, photoplastics, thin metalized membranes	Electron beam, electrode matrix plus charge
Phase disturbances by piezoelectric excitation of reflecting surfaces	Mirrored piezoelectric crystals	Individual switches to an rf driver
Optical density change by induced absorption	Photochromics, cathodochromics	Light beam (uv) plus flood illumination for erase, electron beam plus flood illumination for erase
Optical scattering change by electrical agitation	Liquid crystals	Electrode matrix, light beam (with photoconductor)
Polarization rotation by magnetooptic effects	MnBi, EuO:Fe, Ni–Fe, $FeBO_3$, FeF_3	Light beam (absorption), conductor matrix
Traveling phase changes by acoustooptic interaction (Debye–Sears and Bragg effects)	Water (and other liquids), fused quartz (and other amorphous solids), $PbMoO_4$ (and other crystals)	Transverse interaction of coherent light and traveling acoustic waves
Thermally induced shift in absorption band edge	CdS, CdSe, As_2S_3	Electrode matrix for heating and heat sink substrate for cooling
Optical scattering by poled and unpoled regions of a ferroelectric	PLZT (ceramic)	Electrode matrix
Phase changes by variation of optical path length	Electrostrictive materials, PLZT (ceramic)	Electrode matrix, double hologram recording method
Reflection changes from thin, deformable membrane mirror elements	Metal films over a substrate support structure	Electrode feedthrough from transistor on back of substrate

* Modified version of table from Roberts (1972).

Some Commercial Optical Memory Milestones

Company	Model	Utilizes laser	Utilizes holography	Nonmechanical system	Date introduced
IBM	1360 photodigital mass storage system	No	No	No	1966
Precision Instruments	690-212 Unicon laser mass memory	Yes	No	No	1971
Optical Data Systems	Holoscan	Yes	Yes	No	1972
3M Company	Megafetch data processor	Yes	Yes	Yes	1974

Photorefractive crystals ($BaTiO_3$, SBN, BSO) :

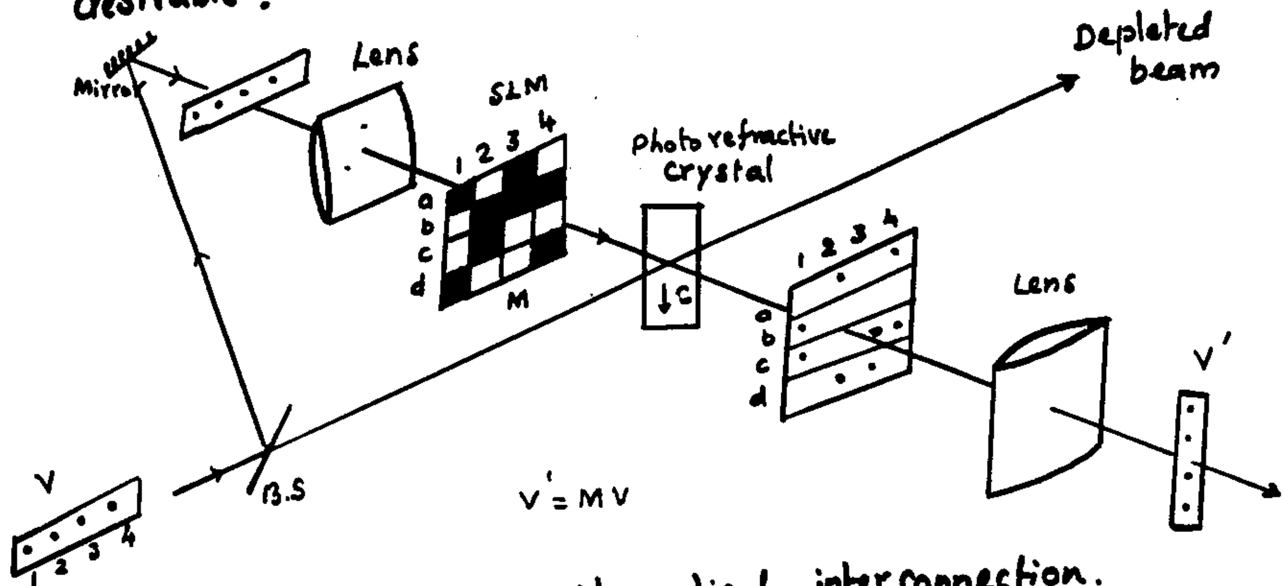
Dynamic holography – real time interferometry, optically controlled light deflector, associative memory ...

Phase Conjugation :

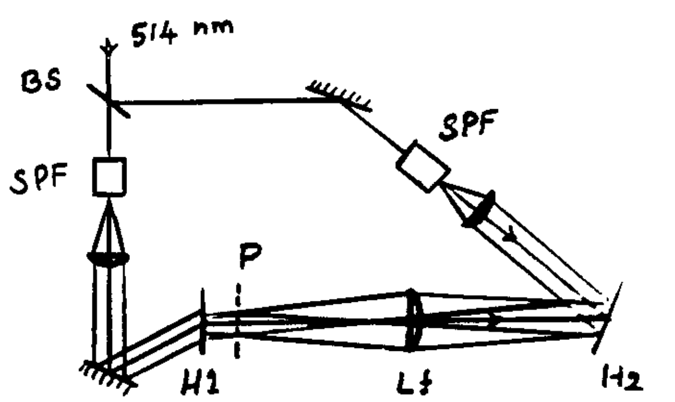
degenerate four wave mixing, computing, image processing and other applications.

Optical Interconnects :

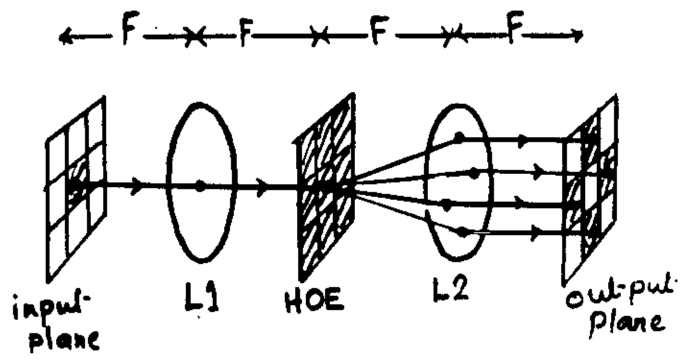
play an important role in computing, reconfigurability, high speed, widebandwidth, energy efficiency ... etc desirable.



Reconfigurable optical interconnection.



Recording of interconnect hologram.



Edge-extractor interconnect hologram