Chapter 2

Holographic Methods

This chapter introduces fundamentals, optical components, recording materials and applications of holography in particular and theory of holograms in general, as it is necessary to introduce the problem of dissertation.

2.1 Fundamentals of Holography

Holography is the science of recording whole information content of a wave. The word hologram is derived from the Greek words ‘holos’ meaning whole or complete and ‘gram’ mean information. Optical holography records the intensity and phase information of the light field emanating from or
scattered by an object. The recording is generally done in a two dimensional light sensitive medium and on reconstruction, the original light field is reproduced and thereby the object or the scene appears with very high visual reality. The reconstructed image exhibits complete parallax and depth of field. The image floats in space, either behind, in front of, or straddling the recording medium. Parallax allows the viewer to move back and forth, up and down and see different perspectives.

![Hologram Recording Diagram](image)

**Figure 2.1 Principle of hologram recording**

By definition, “A hologram is a recording of the optical interference pattern that forms at the intersection of two coherent optical beams in a holographic medium [3]”.
The principle of hologram recording is described as follows. Coherent light from a laser is split into two beams, object beam and reference beam. The object beam carries information and the reference beam is a mutually coherent beam. The two beams are allowed to overlap in the holographic medium and the interference pattern between the two beams is recorded as shown in Figure 2.1. When the reference beam illuminates the recorded hologram, the object beam is reproduced. The microstructure recorded in the hologram diffracts the illuminating beam, resulting in the production of the object beam, as shown in Figure 2.2.

Figure 2.2 Principle of hologram reconstruction
2.2 Difference between Photography and Holography

Photography is a point-to-point recording of the intensity of light rays reflected from an object. Each point on the photograph records the intensity of light rays that illuminates the particular point of object. In color photographs, intensity and wavelength are recorded. A real scene is characterized by intensity, wavelength and phase. In a photograph, the phase of the light from the original scene is not recorded and so it lacks parallax and depth. In a hologram, both the intensity and phase are recorded and reconstructed. To record the phase of the light wave at each point of an object, holography uses the coherent reference beam in conjunction with the mutually coherent beam from the object. Optical interference between the reference beam and the object beam produces intensity variations that can be recorded on a photosensitive medium.

In a hologram, each point does not directly represent the corresponding point in the scene. A small portion of the hologram’s surface contains enough information to reconstruct the entire original scene. During holographic recording, each point on the surface of the recording material is affected by light waves reflected from all points in the scene, rather than from just one point. Hence, when a hologram is cutout and a small section is viewed, the entire scene or object becomes visible.
2.3 Invention of Holography

Holography was invented by Dennis Gabor (1900-1979), a Hungarian Physicist in 1947. Gabor, popularly known as “Father of Holography”, received Nobel Prize for this invention in 1971 [1]. The terms hologram and holography were coined by him. Gabor’s efforts were originally intended to increase the resolving power of Electron Microscopes and the research work was carried out at the British Thomson-Houston Company in Rugby, England. Gabor proved his theory not with an electron beam but with a light beam and the result was the first hologram. However, holography did not advance until the development of Laser in 1960 [8].

In 1963, University of Michigan researchers Emmett N. Leith and Juris Upatnicks created the first three-dimensional holographic images [9, 10]. Yuri N. Denisyuk in the Soviet Union created holograms viewable using ordinary white light [11, 12].

2.4 Common types of Holograms

According to the method of creation, physical and functional properties, holograms can be classified into different categories, though all contain diffractive microstructures created by various means. They all use different optical set ups and therefore have separate advantages and applications. Most common types are transmission holograms, reflection holograms, rainbow holograms, thick and thin holograms, amplitude and phase holograms etc [3].
2.4.1 Transmission holograms

Transmission hologram is one of the first made and most commonly used hologram. It is recorded when light from the object and reference beam fall on the same side of the recording material [2]. It forms an image from the light that passes through the holographic emulsion. Transmission holograms are illuminated from the rear or back and light bends as it passes through the hologram to our eyes to form the holographic image. The schematic of experimental setup for recording transmission holograms is shown in Figure 2.3.

Coherent light from a laser is split into two by using a beam splitter and both beams are passed through spatial filters to avoid noise. One of the beams, the object beam, illuminates the object and the reflected light from the object carries information about the object. The other beam, the reference beam is a mutually coherent wave without information. The object and the reference beams are allowed to interfere from the same side of the holographic emulsion and the interference pattern is recorded. After recording, the film is developed and fixed. The entire setup is arranged on a vibration isolation table to have perfect and stable interference fringes during exposure.
If $\lambda$ is the wavelength of light, $d$ is the spacing between the planes and $\theta$ is the angle between incident and scattering planes and $n$ is an integer determining order, Bragg's law states that for constructive interference [13]

$$n\lambda = 2d \sin \theta \ldots \quad (2.1)$$

When an interference pattern is recorded in a holographic plate, the fringe separation $d$ in transmission hologram is

$$d = \frac{\lambda}{2 \sin (\alpha/2)} \ldots \quad (2.2)$$

where $\lambda$ is the wavelength of the laser beam and $\alpha$ is the angle between the object and the reference beams, at the point of intersection, on the holographic plate. It is shown in Figure 2.4.
During reconstruction, the hologram has to be illuminated with the reference beam, as shown in Figure 2.5, and the beam is diffracted from the hologram, facilitating recreation of the whole light field emanated from the object. Upon looking along the object beam, we see a replica of the object and by shifting the viewpoints, different perspectives of the object are seen.
In addition to the virtual image, a real image is formed when light passes through the hologram. The real image can be caught on a screen placed in the plane. The real image is pseudoscopic [3].

Important properties of transmission holograms:

i) They are viewed by shining laser beam through the hologram

ii) Only less resolving power of material is needed

iii) Depth of scene is possible.

Applications of transmission holograms are in Non Destructive Testing (NDT) [14, 15, 16], Holographic Optical Elements (HOEs) [17], commercial displays [18] etc.

2.4.2 Reflection type holograms

Reflection holograms are recorded by allowing the object and the reference beams to fall from the opposite sides of the recording material [2]. Basic difference between transmission and reflection hologram is that, reflection hologram can be seen when it is illuminated from the front, while a transmission hologram can be seen only when it is illuminated from the backside. Reflection holograms are commonly used in galleries. Schematic experimental setup for recording reflection holograms is shown in Figure 2.6.

Light from a laser source is split into object beam and reference beam. The two beams are allowed to interfere from opposite sides of the holographic plate and the interference fringes are recorded. Typically the thickness of the emulsion is between 6 µm and 15 µm, and the interference fringes are
recorded as layers within it, about half a wavelength apart. Diffraction efficiency of reflection holograms are generally very high, compared to transmission holograms. Sometimes the diffraction efficiency of reflection holograms can even approach 100%.

![Schematic of reflection hologram recording setup](image)

**Figure 2.6 Schematic of reflection hologram recording setup**

If the beams are interfering in exactly opposite direction, the fringe separation

$$d = \frac{\lambda}{2} \quad \text{(2.3)}$$

where $\lambda$ is the wave length of laser beam and the fringes in reflection holograms are closer than that in transmission holograms. The formation of
fringes is parallel to the surface of the recording medium. The interference of object and reference beam on a holographic plate in exactly opposite directions is shown in Figure 2.7.

![Figure 2.7. Interference of object and reference beams in a reflection hologram](image)

In order to reconstruct the object beam, the hologram is placed in white light. The reconstruction beam comes from the same side of the hologram as the viewer, as shown in Figure 2.8. Some parts of the incident light are reflected, depending on the interference pattern. The interference fringes are generally parallel to the surface of the hologram and are formed in the volume of the emulsion. These closely spaced fringes selectively reflect light, based on the Bragg condition. If a white light is located on the viewer's side of the hologram, a three-dimensional image is formed.
Important properties of reflection holograms:

i) These holograms can be viewed in ordinary light.

ii) The finished reflection hologram is monochromatic, i.e. each hologram has a single colour for each laser colour used.

iii) Colours of reflection holograms can be shifted by pre-or-post shrink/expansion of recording material.

Application of reflection holograms are found commonly in displays, image archiving [3], holographic optical elements etc.

2.4.3 Rainbow Holograms

Rainbow holograms, also known as Benton holograms, named after its inventor Stephen A. Benton, are transfer transmission holograms [2, 3]. A rainbow hologram is generally a hologram of a hologram. In rainbow holograms, images are reconstructed by white light. They distribute wavelengths of white light into different directions. Viewer can see only one...
wavelength and the actual wavelength is determined by the viewpoint. Since colour of the hologram changes according to the viewing angle, it is called ‘rainbow hologram’.

A popular application of rainbow hologram is that in credit cards. The schematic of the experimental setup for recording rainbow holograms is shown in Figure 2.9. Rainbow holograms are generally recorded by using a double holographic process. A transmission hologram is used as the object and the reflected light from this hologram is passed through a horizontal slit, which limits the vertical perspective of first image. Thus there is no vertical parallax in the resultant rainbow hologram.

![Figure 2.9 Schematic of rainbow hologram recording setup](image)
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The reconstruction of rainbow hologram is shown in Figure 2.10. Upon illumination with white light, the rainbow hologram separates out different wavelengths of white light and sends them in different directions. The hologram contains a plane diffraction grating, which diffracts light into vertical spectrum with red on the top and violet at the bottom. In the horizontal plane, the image has full parallax and appears in three dimensions as any other type of hologram.

Advantages of rainbow holograms:

i) Easy viewing and High brightness

ii) Multicolor images

iii) Vivid dimensionality

iii) Ease of replication

Applications of rainbow holograms include displays, decorative and product packaging, promotional labels, protection of documents, protection of branded goods, gift wraps, greeting cards, stickers, displays, in advertising, magazines and other high volume projects etc.
2.4.4 Thick and Thin Holograms

A hologram is termed as thick hologram, if the thickness of the recording medium is greater than the spacing between the interference fringes; otherwise the hologram is termed as thin hologram or plane hologram [3]. Thick holograms are also referred as volume holograms. The distance between interference fringes depends on the wavelength of light used. Thin holograms provide little depth to the reconstructed objects. Example of this is embossed holograms such as the images on bankcards.

In a thin hologram, the emulsion thickness is much less than the fringe spacing and they produce several orders: zero order or directly transmitted laser beam, the first order diffraction producing virtual image, the minus first
order diffraction equal in intensity to the first order producing conjugate images and higher orders of decreasing intensity.

A volume or thick hologram can be considered as a superposition of 3D gratings recorded in the depth of the emulsion, satisfying Bragg's law. The grating planes produce maximum change in refractive index or absorption index. The volume hologram reconstructs the virtual image at the original position of the object, if the reconstruction beam exactly coincides with the reference beam. However the conjugate image and higher order diffractions are absent.

2.4.5 Amplitude and phase Holograms

Amplitude holograms are absorption type and produce changes in the amplitudes of the reconstruction beam. Phase holograms produce phase changes in the reconstruction beam due to variations in the refractive index or thickness of the medium [3]. Phase holograms offer no energy dissipation within the holographic medium and the diffraction efficiency is higher compared to amplitude holograms.

2.5 Optical components

The commonly used optical components in a holographic set up are described below:
2.5.1 Laser

Laser is a coherent source required to produce high quality holograms [19, 20, 21]. Full coherent lasers are both spatially and temporally coherent. Laser emits light in a very narrow beam and is spatially coherent. A laser also emits light of a single colour or wavelength and is temporally coherent. Helium-Neon (He-Ne), Helium-Cadmium (He-Cd), Argon-ion (Ar⁺), Krypton-ion (Kr⁺), Diode and Diode Pumped Solid State Lasers (DPSS) lasers are commonly used to produce holograms. The essential characteristics of a laser used in holography are:

1) good stability and freedom from vibrations.
2) low number of modes.
3) good beam quality and low noise
4) high coherence length

The three main parts of a laser are an optical resonator, an active or amplifying medium in the resonator and an energy source for activating the medium [19]. The basic structure is shown in Figure 2.11.

The active medium consists of a collection of atoms, molecules or ions, which act as an amplifier for light waves. Under normal conditions, the number of atoms in the lower energy state is always larger than the number in the excited energy state. So a light wave passing through such a collection of atoms would cause more absorption than emission and so the wave will be attenuated. Thus for light amplification, there must be large number of atoms
in the higher energy state than in the lower energy state. This phenomenon is called population inversion.

When light passes through atoms in the state of population inversion, light will induce more emissions and become amplified. The pump is the source of energy, which maintains the medium on population-inverted state. The optical resonator consists of a pair of mirrors facing each other and provides optical feedback to the amplifier so that it can act as a source of radiation.

![Figure 2.11 Basic elements of a laser](image)

**He-Ne laser**

He-Ne is the commonly used gas laser. In gas lasers since the atoms are characterized by sharp energy levels, generally electrical discharge is used to pump the atoms. The He-Ne laser consists of a long and narrow discharge
tube with diameter 2 to 8mm and length 10 to 100cm. The tube is filled with helium at a pressure of 1 torr and neon at a pressure of 0.1 torr. The lasing atoms are neon atoms and helium is used for selective pumping of the upper laser level of neon. The laser resonator consists of either internal or external mirrors.

Energy levels of helium and neon taking part in the lasing action are shown in Figure 2.12. When an electrical discharge is passed through the gas, the electrons that are accelerated down the tube collide with helium and neon atoms and excite them to higher energy levels. The helium atoms tend to accumulate at levels F$_2$ and F$_3$ due to their longer lifetimes. Energy levels E$_4$ and E$_6$ of neon atoms have almost same energy as F$_2$ and F$_3$ and so the excited helium atoms colliding with neon atoms in the ground state can excite the neon atoms to E$_4$ and E$_6$. Since the pressure of He is 10 times that of Ne, the levels E$_4$ and E$_6$ of neon are selectively populated as compared to other levels of neon.

The transition of neon atoms between E$_6$ and E$_3$ produces the 6328Å line of the He-Ne laser. Neon atoms de-excite through spontaneous emission from E$_3$ to E$_2$. Since this time is shorter than the lifetime of level E$_6$, steady state population inversion can be achieved between E$_6$ and E$_3$. E$_2$ is a metastable state and it is possible for the atoms in this level to absorb the spontaneously emitted radiation in the E$_3$ to E$_2$ transition to be re-excited to E$_3$. This has the effect of reducing the inversion.
The other wavelengths from the He-Ne laser are 1.15\(\mu\)m, corresponding to \(E_4\) to \(E_3\) transitions and 3.39\(\mu\)m corresponding to \(E_6\) to \(E_5\) transitions. Both 3.39\(\mu\)m and 6328\(\text{A}^\circ\) transitions occur at the same upper laser level. Since 3.39\(\mu\)m transition corresponds to a much lower frequency than the 6328\(\text{A}^\circ\) line, Doppler broadening is small and since gain is inversely proportional to \(\gamma^2\), the gain at 3.39\(\mu\)m is much higher than at 6328\(\text{A}^\circ\). Due to very large gain, oscillations will normally tend to occur at 3.39\(\mu\)m and further build up of population in \(E_6\) is not possible. The laser can be made to oscillate at 6328\(\text{A}^\circ\) by either using optical elements in the path that strongly absorb the 3.39\(\mu\)m wavelength.
Typical He-Ne laser [19] with external mirrors is shown in Figure 2.13.
The resonator mirrors are placed outside the discharge tube. Then reflections
from the ends of the discharge tube can be avoided by placing the windows at
Brewster angle (37°). The beam polarized in the plane of incidence (p-
polarized) suffers no reflection at the windows but the perpendicular
polarization (s-polarized) suffers reflection losses. A laser with Brewster angle
windows has a lower output than its randomly polarized equivalent but it has
a completely stable plane of polarization (p-polarized).

Figure 2.13 *He-Ne laser with external mirrors and ends of discharge tube
fitted with Brewster windows*

He-Ne lasers, operating at a wavelength of 632.8nm with power
ranging from 0.5mW to 100mW, are widely used for holography applications.
The laser power output should be at least 5mW otherwise exposure time will
be long and potential table vibrations may destroy the image. The laser must be polarized linearly 500:1, as opposed to randomly polarized type. The Transverse Electromagnetic Mode (TEM) mode should be single.

2.5.2 Electronic Shutter

The purpose of electronic shutter is to control the exposure time during recording process. When the shutter is open, light passes through it and illuminates the recording plate. When the shutter is closed, the laser beam is blocked and there is no illumination of the film plate. Both manual and electronic shutters are available for exposure control. Electronic shutters provide much more control over exposure than manual shutters but they are more expensive. The shutter shouldn't introduce any vibration on the optical table [2].

2.5.3 Beam splitter

Beam splitter is an optical component that splits incident beam into reflected and transmitted beam as shown in Figure 2.14. They can also be used to combine beams. In holography, beam splitter is used to divide laser beam into two separate beams: object beam and reference beam [22].

It consists of a partially transparent mirror, which reflects part of the laser beam and transmits the remaining beam. Usually a half silvered mirror is used. It is a plate of glass with a thin coating of aluminium, usually deposited from aluminium vapour. By varying the thickness of coating,
desired transmission to reflection ratio can be achieved. Typical ratios are 50:50, 40:60, 30:70, 20:80 etc. and are selected according to application.

![Figure 2.14 Beam splitter](image)

### 2.5.4 Spatial Filter

The spatial filter consists of a microscope lens and a pinhole [2]. The spatial filter expands the laser beam. It is a device that improves the spatial coherence of the laser beam by effectively removing the background noise. Background noise refers to irregular intensity variations in a raw beam, producing a non-uniform, near Gaussian, energy distribution [23, 24]. The background noise occurs due to dust particles and material surface imperfections in optical systems, which scatter light in unwanted directions [25].
The principle of operation of a spatial filter is shown in Figure 2.15. The pinhole is placed at the focus of the microscope objective. The spatial filtering means blocking the higher frequencies with a pinhole so that only the desired smooth intensity profile is transmitted. The objective is selected according to the amount of beam expansion required. A pinhole is selected to provide the necessary frequency cut off for a given beam diameter.

Figure 2.15  _Principle of spatial filter_

### 2.5.5 Mirrors

Mirrors are used to reflect light beam in the desired directions [22]. In reflecting light, the angle of incidence equals the angle of reflection. The reflected light remains in the plane of incidence. For the mirror, incident angle $\alpha_i = \alpha_r$, reflecting angle as shown in Figure 2.16.
A mirror means a piece of black glass or a finely polished metal surface. Vacuum evaporated coating of aluminium on highly polished substrates is the widely accepted standard for quality of mirrors. Over aluminium coating, protective coatings of silicon monoxide or magnesium fluoride are often layered.

The mirror should be front surface reflecting type and of good quality so as not to introduce additional diffraction pattern into the wave front. With rear surface reflecting type mirror, due to interference between the wave front reflected by the front and rear surfaces, the hologram will be overlaid with grid of parallel lines.

![Diagram of incident and reflected beams](image)

Figure 2.16 Mirror

2.5.6 Lenses

Optical lenses are light refracting devices that have curved surfaces rather than flat. These devices redirect light and in photography lenses are
used to focus an image on the film. In holography lenses are used to widen the laser beam to illuminate the entire object, which is to be recorded holographically. In Fourier optics [48, 58], lenses are used to converge the object beam to the film plate as shown in Figure 2.17. Usually biconvex lenses are used. The convergent lenses are thicker in the middle; whereas divergent lenses are thinner in the middle [22].

**Figure 2.17 Biconvex lenses**
2.5.7 Vibration Isolation Table

The optical set up is mounted on a vibration isolation table and without this it is impossible to record good quality holograms [2]. A slight movement during the recording of the hologram can result in a shift in the microscopic fringes and will damage the image quality. Since hologram is a recording of the interference pattern, the relative motion between the holographic apparatus should not exceed quarter wavelength after they are mounted. If the relative phase $\Delta\phi$ between the object and reference beam changes by an amount $\pi$ during the exposure, the interference pattern will be destroyed. The value of $\pi$ in relative phase is equivalent to a path difference of $\lambda/2$.

There are two types of vibrations: high frequency vibrations caused by materials like wood, sand etc. and low frequency vibrations caused by isolation of the table from the environment by use of inner tubes, pneumatic hydraulic isolation system etc. The vibrations are overcome by using tables of high mass on resilient mountings with low spring constant to achieve a very low natural frequency and thus filtering out most vibrations [26].

2.6 Holographic recording materials

Many types of recording media are available. The most important requirement for selecting a recording medium is high resolution and it should be of the order of above 2000 lines/mm. It is determined by the wavelength of laser light and the half angle $\theta$ between object and reference waves. The required resolution in lines/mm is expressed as
\[ R = \frac{2 \sin(\theta/2)}{\lambda} \quad \text{(2.4)} \]

For eg: He-Ne laser, \( \lambda = 632.8 \text{nm} = 6328 \text{Å} \), resolution \( 60 \leq R \leq 1500 \) lines/mm for \( 2^\circ \leq \theta \leq 50^\circ \). Emulsion providing sufficient resolutions are available on rigid glass substrate and on flexible acetate film substrate. Glass plates provide more stability, but are more costly.

Good recording media must have very high resolving power, since the dimensions of the structure of interference pattern to be recorded are of the order of magnitude of wavelength of light used for exposure. The photosensitivity of a material depends on the size of the grains. Smaller the grain size, higher the resolution, but lesser the spectral sensitivity. On the other hand, smaller the grain size, more fringes are accommodated in the small area leading to better resolution of the image.

Good recording media must have high optical quality, large refractive index change, thickness (> 500 microns), high sensitivity, fixability, long shelf life, inert and cheap. High optical quality and low scatter are required to ensure that the signal wave front is not adversely distorted and the noise level from scattered light is manageable. A large refractive index change ensures that there is sufficient dynamic range to multiplex many holograms.

High recording sensitivity allows high speed at reasonable laser powers. High speed is required for low exposure time. High speed implies high sensitivity to light, for that the grain size of the emulsion must be big and resolution must be low. High resolving power and high speed are incompatible
properties, which gives highest possible efficiency. A good recording medium should record holograms with high diffraction efficiency.

Principal materials for holographic recording are:

i) Silver-halide materials
ii) Dichromated gelatin
iii) Photoresists
iv) Photothermoplastics
v) Photochromatic materials
vi) Photorefractive crystals
vii) Photopolymer
viii) Bacteriorhodopsin

2.6.1 Silver-halide materials

Silver-halide was the first material used for recording holograms [27, 28, 29]. It has high sensitivity compared to other alternative materials. It can be coated on both film and glass and can record both amplitude and phase holograms. It has high resolving power and is easily available.

Drawbacks of the material are 1. It is absorptive, 2. It has inherent noise and a limited linear response, 3. It is irreversible and 4. It needs wet processing.

A silver-halide recording material is based on one or a combination of silver-halide crystals embedded in a gelatin layer. It is commonly known as photographic emulsion. The emulsion is usually coated on a flexible or stable
substrate. There are three types of silver-halides: silver chloride (AgCl), silver bromide (AgBr) and silver iodide (AgI). Silver chloride is used for low sensitivity emulsions. Chloride/bromide emulsions have high light sensitivity, but bromide/iodide emulsions have even higher sensitivity. Silver iodide is used in a mixer with silver bromide. Silver-halide crystals are cubical in shape and in each crystal a silver ion (Ag\(^+\)) is surrounded by six halide ions. The crystal normally contains an excess of halide ions originating from the manufacturing process. Emulsion grain size varies from nanometers to micrometers and it is 10-30nm for ultra-fine-grained emulsion, 30-50nm for fine-grained emulsion, 50-100nm for fast holographic emulsion and so on.

Silver chloride is sensitive only to violet and UV light. Silver bromide absorbs light up to about 490nm. If silver iodide is added to silver bromide, the sensitivity extends up to 520nm. Sensitizers or dyes are added to the emulsion to make it sensitive to other parts of the spectrum.

Technical specifications of silver-halide materials are as follows: holographic plates have emulsion coated on the surface with typical thickness of approximately 2.4mm. Hologram film has emulsion coated on triacetate substrate with typical thickness of 180 microns. Companies like AGFA, KODAK, SLAVICH etc. are marketing Silver-halide films/plates. The SLAVICH company products are:

1. PFG 01: Fine grained red sensitive holographic plates and film designed for transmission and reflection hologram recording. Average grain size 40nm, resolving power more than 3000lines/mm, spectral
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sensitivity range 600-680nm and emulsion thickness varies from 7-8μm.

2. **PFG 03M**: Ultra fine-grained red sensitive plates and film specially designed for reflection hologram recording. Average grain size 8-12nm, resolving power more than 5000 lines/mm, spectral sensitivity range includes 633nm, 647nm and emulsion thickness 6-7μm.

3. **PFG 03C**: Ultra fine-grained panchromatic (full color) holographic plates designed for colour reflection hologram recording. Average grain size 8nm, resolving power more than 5000 lines/mm, spectral sensitivity range up to 700nm (457nm, 514nm, 633nm) and emulsion thickness 9-10μm.

### 2.6.2 Dichromated gelatin

Dichromated gelatin (DCG) is widely used for making display holograms [3, 28]. It produces high resolution, relatively bright and easily viewable holograms. DCG offers excellent holographic properties such as low scattering, high index of modulation etc. It is usually sensitive only to UV and blue light. Nowadays it is possible to make red sensitive DCG but exposure time will be long. DCG has low sensitivity of about 100mJ/ sq.cm. The drawbacks include the raw material's variability, complex wet processing, poor shelf life and environmental instability.

Technical specifications of the SLAVICH company DCG product is:
1. PFG 04: Long life Dichromated gelatin holographic plates designed for phase reflection hologram recording with blue or green laser. It is a grainless emulsion with resolving power greater than 5000 lines/mm, spectral sensitivity range up to 514nm (457nm, 488nm, 514nm) and emulsion thickness 16-17μm.

2.6.3 Photoresists

Photoresists [3] are organic materials for producing thin surface relief phase holograms. They are employed mainly for the production of master plates for embossed holograms and for manufacturing holographic gratings. In negative working photoresists, the unexposed areas are dissolved away in the development. While in positive working photoresist, the exposed areas are dissolved away in the developer. The photoresist process can be used for making transmission holograms only. If an embossed hologram is mirror backed by using an aluminium coating, it can be utilized in reflection construction mode also. A typical photoresist for holography has a sensitivity of about 10mJ/sq.cm. The most widely used photoresist is Shipley Micro Posit 1350, which is a positive working resist. The sensitivity of photoresist is highest in UV. It has sufficient sensitivity at 458nm of Argon iron laser and good sensitivity at 442 nm of He-Cd laser. The sensitivity at 488nm is very poor.

The material is coated on a glass substrate by spin method to a layer of thickness 1-2 μm. It is then baked at 75 °C for 15 minutes.
2.6.4 Photothermoplastics

Photothermoplastics [3] are used for producing surface relief thin phase holograms. The thermoplastic material repeatedly softens and hardens when heated and cooled. The material has a multilayer structure on a substrate of glass or film. It consists of three thin layers: doped Tin or Indium oxide (a transparent conductor), polyvinyl carbazole sensitized with tri-nitro-9-fluorenone (photoconductive origin polymer) and staybelite Ester 10 (thermoplastic substrate a resin). The material has high sensitivity over the whole visible spectrum.

The thermoplastic resin is first positively charged in the dark by a corona discharge device that uniformly moves over the thermoplastic plate at a constant distance. A uniform negative charge is thus induced on the photoconductive coating on the surface. The plate is then exposed to interference pattern that periodically alters the conductivity of the conducting layer. Electrons travel through the conductive layer and are attracted to the positively charged plate, but cannot pass through the photoconductor.

The electrostatic field is further increased by recharging the surface once again by the corona discharge as in the first step. The charge pattern creates a spatially periodic static electric field of 1-10V/sq. cm. The film is developed by passing current through the conductive layer, heating the plate and softening the thermoplastic film. The softened film deforms under the static electric field becoming thicker in the unexposed areas and thinner in the
illuminated areas. As the film cools to the room temperature, the thickness variation gets frozen in.

The complete charging, exposing and developing cycle takes less than a minute. The plate can be erased by illuminating it with light and by passing a current pulse through the conductive layer. Thermoplastic layer heats up and resoftens. Before the next exposure, the plate has to be blasted with compressed air or dry nitrogen in order to cool the thermoplastic to room temperature.

The material is optically inert when not charged, so there is no degradation from exposure to heat and active radiation. The stability of the developed thermoplastic hologram is excellent. The main disadvantage of the material is the requirement of a complex apparatus for controlled charging and development. Photothermoplastics can be recycled several hundred times and are most suitable for holographic non-destructive testing of materials.

2.6.5 Photochromatic materials

Photochromics are real-time recyclable materials [30]. They require no processing for development and can be erased and reused. The hologram can be read out immediately after recording and this property is used for holographic interferometry. There is no inherent resolution limit since they are essentially grain free and operate on atomic or molecular scale. Since storage occurs within the volume of the material, the storage capacity is very high.
The transmission spectrum of photochromatic materials changes according to exposure with particular wavelength of light. The material becomes dark when exposed to short wave visible or UV radiation. They are bleached by exposure to long-wave visible or infrared radiation. Holograms are recorded by selective optical erasing or bleaching of material. This creates an absorption hologram. To erase the hologram, it has to be illuminated by the switching light, which darkens the crystal uniformly.

The disadvantages are: 1) low sensitivity, low efficiency and less storage time. 2) The reconstruction beam usually degrades the stored information.

### 2.6.6 Photo refractive crystals

Photorefractive crystals are used for recording real time volume phase holograms [3, 31]. These materials have excellent resolution, efficiency, storage capacity, sensitivity and reversibility. The widely used crystals are Lithium Niobate (LiNbO3), Lithium Tantalite (LiTaO3), Barium Titanate (BaTiO3), Potassium Tantalate Niobate (KTN), Barium Sodium Niobate (BSN), Bismuth Silicon Oxide (BSO), Bismuth Germanium Oxide (BGO), Gallium Arsenide (GaAs), and Indium Phosphide (InP).

The photorefractive materials contain localized centers with trapped electrons and they can be excited to conduction band by the action of light. Due to the property of dark conductivity, the charges can be frozen in place. The dark storage time depends on crystal type and typically for LiNbO3 it is a few years. When the material is exposed to an interference pattern, the electric
charges from interference maxima drifts and is collected at the interference minima. The space charge pattern creates a strong spatially periodic field. Due to this field crystal deformation takes place and causes a refractive index modulation to produce the hologram. The recorded holograms are immediately visible and can be erased by exposure to a uniform beam of light. The trapped electrons are released and the crystals return back to its original condition with uniform distribution of trapped electrons. The disadvantage of photorefractive crystal is that continuous readout of a hologram will erase it.

The holograms can be fixed by converting the charge patterns to ionic patterns by thermal process. The LiNbO$_3$ crystal is heated during or after recording to temperature above 100 °C and then cooled to room temperature. Now the hologram is fixed and can be readout without eraser. Heating them to the fixing temperature and then exposing to uniform light can erase the fixed holograms in LiNbO$_3$. Diffraction efficiency of 100% is possible in 1cm thick LiNbO$_3$ crystal. Diffraction efficiency of 95% is achieved in BGO crystal.

2.6.7 Photopolymers

Photopolymers [3, 32, 33] are based on organic molecules that are based on photo-initiated polymerization for recording volume holograms. Due to ease of storing information and dry process, this material is gaining greater attention. They are promising materials for holographic data storage, display holograms, holographic optical elements, holographic diffraction gratings etc. The ease of use and simple processing methods make these materials suitable
for mass production of holographic optical elements and display holograms. Characteristics such as good sensitivity, large dynamic range, good optical quality and relatively low cost make Photopolymers the best material to be used in write-once, read many (WORM) holographic data storage application.

The general composition of Photopolymer material consists of polymeric binders, monomers and plasticizers, along with photo initiators, chain transfer agents, sensitizing dyes etc. The binder acts as the support matrix containing the other film components. The monomers serve as refractive index carrier. The monomers and binders determine the physical properties of the system and also the magnitude of index modulation recorded in the film. The sensitizing dyes absorb light and interact with the photo-initiators to begin photopolymerization of monomers.

For recording holograms, the Photopolymer film is exposed to interference pattern. The interference pattern consists of a sinusoidal variation of bright and dark fringes due to constructive and destructive interference. The sensitizing dye absorbs light from the bright fringes, interacts with the initiators and creates free radicals. Then monomers combine with radicals and polymerization takes place. In the region of polymerization, fresh monomers diffuse in from surrounding dark region to set concentration and density gradients and results in refractive index modulation.

During the exposure and polymerization process, the initial highly viscous composition gel hardens, suppresses diffusion and further increase in the index of modulation of the recorded hologram is arrested. The recorded
hologram is easily viewable. The holographic image consists of polymer-rich regions with monomers diffused into and binder-rich regions with monomers diffused away from, along with some residual un-reacted monomers distributed throughout. After exposure, the film is subjected to a UV cure to fix the image.

The Photopolymer can record holograms up to 100% diffraction efficiency [34, 35]. Other advantages offered by Photopolymers are extended shelf life before and after imaging, high photo speed, higher index of modulation and broader spectral sensitivity. The Photopolymer microholograms are insensitive to humidity and temperature. They can be conveniently mounted on to paper, glass or plastic.

2.6.8 Bacteriorhodopsin

Bacteriorhodopsin is a purple coloured protein found in microbes that live in salt marshes and salt lakes, where the temperature can reach +150°C. Its colour changes from purple to yellow as it absorbs light and provides chemical energy to microbes called halobacterium halobium.

Bacteriorhodopsin can store digital data (logic 0 or 1). A photocycle makes these molecules an ideal logical storing element or a type of switch from one condition to another. The bR-state (logic 0) and Q-state (logic 1) are intermediate states of molecule and can remain stable for almost five years. Another important feature of bacteriorhodopsin is that both states have different absorption spectra. The current state of the molecule can be easily
defined with the help of a Laser. It is a promising material for holographic recording.

Bacteriorhodopsin has drawn the attention of scientists interested in using biological materials to perform technological functions. It is an attractive material for all optical light computers because of its two stable protein forms, one purple and one yellow. Shining two lasers of different wavelengths alternatively on the protein, flips it back and forth between two colours. Several researchers are using bacteriorhodopsin as computer memory.

2.7 Theory of holograms

The basic theory of hologram recording and reconstruction processes is explained as follows. The equations governing the two processes are described very briefly.

2.7.1 Recording process

A hologram is formed by the interference of object wave and reference wave on a holographic film plate, as shown in Figure 2.18.
Chapter 2: Holographic Methods

Figure 2.18 Recording process

Let object beam be $O = A_o e^{i\phi_o}$

Reference beam $R = A_r e^{i\phi_r}$

where $A$ – amplitude of the wave and $\phi$ - phase angle of the wave.

Equations for intensity of hologram are [2, 3]

$$I = (O + R) (O^* + R^*)$$

$$= (A_o e^{i\phi_o} + A_r e^{i\phi_r}) (A_o e^{-i\phi_o} + A_r e^{-i\phi_r})$$

$$= A_o^2 + A_o A_r e^{i\phi_o} e^{-i\phi_r} + A_r A_o e^{i\phi_r} e^{-i\phi_o} + A_r^2$$

$$= A_o^2 + A_r^2 + A_o A_r e^{i(\phi_o - \phi_r)} + A_o A_r e^{-i(\phi_o - \phi_r)} \quad \ldots \quad (2.5)$$

The last two terms contain phase information. That is, hologram records information about phase also while ordinary photograph records only the intensity variation on the object. Thus the whole information of the object wave is recorded in a hologram.

During recording, the holographic film / plate is exposed and the transmittance of the film / plate, $T$ is given by

$$T = T_0 - \beta I t \quad \ldots \quad (2.6)$$
where $T_o$ – transmission constant of the plate

$\beta$ - film factor

$I$ – exposure intensity

$t$ – exposure time

Substituting (2.5) in (2.4)

$$T = T_o - \beta \left( A_o^2 + A_r^2 + A_o A_r e^{i(\phi_o + \phi_r)} + A_o A_r e^{-i(\phi_o + \phi_r)} \right) t$$

$$= T_o - \beta t \left( A_o^2 + A_r^2 \right) - \beta t A_o A_r \left(e^{i(\phi_o + \phi_r)} + e^{-i(\phi_o + \phi_r)}\right)$$

This is the equation of transmission distribution of a hologram.

### 2.7.2 Reconstruction process

For the reconstruction of the hologram, we have to illuminate the holographic plate with the reference beam, as shown in Figure 2.19.

The reconstruction beam can be

$$R = A_r e^{i\phi_r} T$$

where $R$ – is the reconstruction reference beam

$A_r$ – amplitude of reference beam

$T$ - transmission distribution

$\phi_r$ – phase angle of reconstruction beam
Figure 2.19 Reconstruction process

\[ R = A_r e^{i\phi_r} \left[ T_o - \beta t (A_o^2 + A_r^2) \right] - \beta t A_o A_r \left( e^{i(\phi_o - \phi_r)} + e^{-i(\phi_o - \phi_r)} \right) \]

\[ = A_r e^{i\phi_r} T_o - A_r e^{i\phi_r} \beta t (A_o^2 + A_r^2) \]

\[ - A_r e^{i\phi_r} \beta t A_o A_r \left( e^{i(\phi_o - \phi_r)} + e^{-i(\phi_o - \phi_r)} \right) \]

\[ = -\beta t A_r A_o^2 e^{i\phi_r} + A_r e^{i\phi_r} (T_o - \beta t A_r^2) - \beta t A_o A_r^2 e^{i\phi_o} \]

\[ - \beta t A_o A_r^2 e^{i(-\phi_o + 2\phi_r)} \]

The first term represents a wave that travels in the same direction as the reference beam. The second term represents the virtual image. The third term represents the real image. The real image and virtual image can be seen at the same time only for small \( \phi_r \) angles. Phase of the object wave \( \phi_o \) is positive for real image and negative for virtual image. Real and virtual images occur on opposite sides of the holographic plate.
2.8 Applications of holography

Holography finds immense applications in Science and Technology. Holograms are widely used as displays [18]. They are also used for security purposes to prevent forgery and are widely used in credit cards, on tickets, on original covers of software CDs etc. for proper authentication [2]. Holography finds applications in barcode readers in shops, warehouses, libraries etc. Holographic technique is used to make holographic optical elements (HOE) such as diffraction gratings, lenses, mirrors etc. The holographic lenses are lighter than conventional lenses [17].

An area having high impact of holography is the holographic interferometry [14, 15, 16]. This technique is used for the non-destructive testing of objects. In double exposure holographic interferometry, by quantitatively examining the fringe pattern produced on the object, the distribution of strain in the body can be studied. Holographic microscopy is another important area. A conventional microscope has small depth of field and biological specimen is generally suspended in a fluid and move to become in and out of focus of microscope. These movements can be freezed in a hologram taken through the microscope. The reconstructed three-dimensional images can then be studied elaborately [3].

Acoustic holography is also an important area. The principle of holography can be used to study the image formed by sound. In medical field, due to the invention of X-ray holography, three dimensional views of live intact cells and the microscopic structures within the cell can be recorded.
Military application of holography includes target recognition. The use of head-up displays (HUD) in aircraft is another application of holography. HUD helps the pilots in such a way that they do not look down on to the instrument panel, but they are projected on to the wind screen with the help of holographic technology, thus flying become easier.

Holographic data storage [36, 37, 38, 39] is one of the most significant areas of application. This technology is poised to become the next generation data storage for computers [56, 59]. Here information can be stored at high density within the volume of the material and the data transfer rate is very high [40]. Theoretically, all of the information available in the Library of Congress could be stored on a holographic medium of about of the size of sugar cube!

2.9 Concluding remarks

This chapter has presented an overview of holographic methods. Several types of recording materials are available today but here it is highlighted that Photopolymer is one of the best materials for producing security holograms using holographic variable data storage system. In order to implement a cost effective holographic data storage system, low cost spatial light modulator is also required. In the next chapter, an overview of commercial spatial light modulators and commercial security holograms are described.