Hence,

$$\frac{N_2}{N_1} = e^{-h\nu/k_B T}$$

$$= e^{-\left[\frac{31.114 \times 10^{-20}}{4.14 \times 10^{-21}}\right]}$$

$$= e^{-(75.1)}$$

$$= 2.29$$

2. Power = Energy per unit time

$$= \frac{\textbf{Energy}}{\textbf{Time}}$$

Given, Power = 100W = 100 (J/s)

Time = 10ms = 10×10^{-3} (s)

Energy = Power × Time

= 100 (J/s) x 10 x 10^{-3} (s)

= 1J.

∴ Energy delivered to the weld is 1 joule.

UNIT 14 HOLOGRAPHY

Structure

14.1 INTRODUCTION

In the previous Unit, we pointed out that one of the revolutionary applications of lasers is in the development of a novel technique of photography, known as holography. This word is the combination of two Greek words - holos (complete) and **graphos** (writing). That is, holography is the technique of obtaining complete picture (as true as the object itself) of an object or a scene. In other words, it is a three- dimensional recording of an object or a scene. Well, you may be wondering as to what **essentially** differentiates this technique from the normal photography! In **normal** photography, a two-dimensional image of a three-dimensional object is recorded on a photosensitive surface. The photosensitive surface records the intensity distribution of light falling on it after reflection from the object. As a consequence, we obtain a permanent record of the intensity distribution that existed at the plane occupied by the photographic plate when it was exposed. Since the photosensitive surface is sensitive only to the intensity variation, the phase distribution existing in the plane of the photographic plate is completely lost and is responsible for the absence of the three-dimensional character in it. Holography is that technique of photography where not only the amplitude (and hence the intensity) but also the phase distribution can be recorded. As a **result,** pictures obtained by holographic technique possess three-dimensional form and are visually rich.

Holography was introduced by Dennis **Gabor** in **1948.** He showed that one could indeed record both the amplitude and the phase of a wave by using interferometric principles. In **Sec. 14.2,** you **will** learn the basic concepts involved in the holographic technique. You will be able to appreciate the similarity between the hologram and the diffraction grating. The process of holography **i.e.** how to obtain a hologram, how to obtain images from the hologram etc. has been explained in **Sec.** 14.3. Due to high cost of lasers, (an essential **requirement** for holography) this technique is not being used extensively. The technique, however, has tremendous potential and some of the important applications have been explained in **Sec. 14.4.**

Objectives

After going through this unit, you should be able to

- differentiate between normal photography and holography
- explain the basic principle of holography
- describe how holograms are obtained, and
- state some of the applications of holography.

14.2 HOLOGRAPHY: THE BASIC PRINCIPLE

Reference wave is the light wave falling directly on the photosensitive plate.

Object wave is the light wave reflected from the object and received at the photosensitive surface at the time of recording the **hologram.**

Holography is the process of recording the interference pattern produced by light waves reflected by an object and reference waves. This interference pattern of the object is unique and is called **hologram** (total recording). If you look at a hologram, you will realise that it does not even remotely resemble the object. However, when this recorded pattern is illuminated by a suitably chosen reconstruction *wave,* out of the many component waves emerging from the hologram, one wave completely resembles the object wave in both amplitude and phase. Thus, when you look at this wave, you perceive the object still being in position even though the object may not be present there. Since during reconstruction (that is, image production), the object wave itself is emerging from the hologram, the image has all the effects of three-dimensionality. You can indeed shift your viewing position and "look behind the objects.

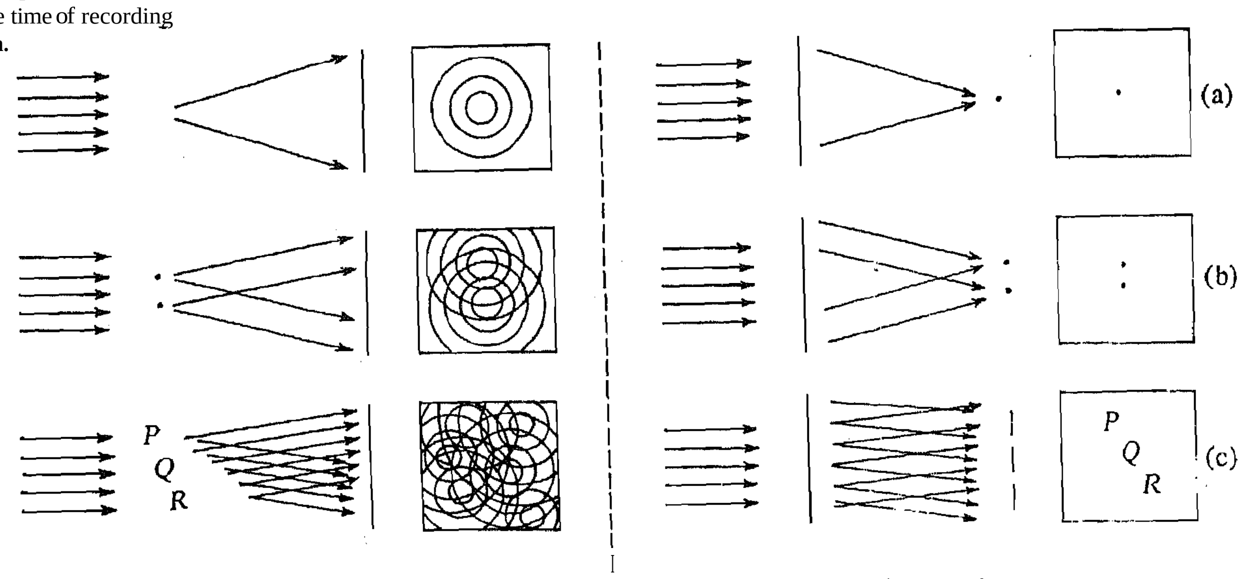

Fig. 14.1: The principle of holography: (a) Point object forming concentric diffraction rings as In zone plate; reconstruction of zone plate gives point image (top right). For two points and a more complex object, these features are shown in (b) and (c) respectively.

Let us understand the basic concept involved in holography with the help of a simple example. Incident light, shown in Fig. 14.1 (a), is diffracted by a point object. It gives rise to a series of bright and dark concentric rings. The pattern is recorded photographically and made into a transparency. This pattern, called a Gabor zone plnte, is similar to a Fresnel zone plate. In the second step (top right) light is incident on the ring pattern (i.e. the Gabor zone plate) and focussed by it into a point, as focussed by a zone-plate.

Now, refer to Fig. 14.1(b) in which the object consists of two points (pixels). The diffraction pattern then consists of two sets of concentric rings. When the pattern is illuminated, each of the two sets focus, and the image consists of two points. As the object is an aggregate of many pixels, its diffraction pattern is shown in Fig. 14.1(c). The intermediate recording is a continuum of superposed zone plates- an unrecognizable multiplicity of lines and rings. Each pixel in the object forms its own set of fringes. Within each set, the light interfers but between sets, there is no fixed phase relationship and hence no interference. In order to make the different signals compatible in phase, another wave called reference is added. Refer to Fig. 14.2 where the effect of adding a sufficiently strong reference beam to the random - phase signal is shown. As a result, the phase of the resultant of reference and the signal becomes similar to that of the reference alone. Thus contributions from different pixels produce an interference fringe pattern.

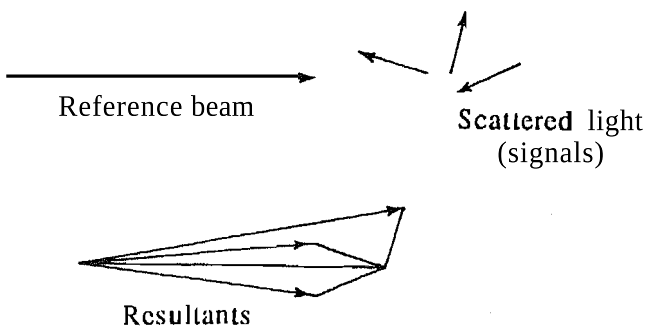

Fig. 14.2: **Addition of a strong coherent reference beam (top left) with random-phase signals (top right) gives similar resultant (bottom).**

The essence of holography is that the process of image formation is being interrupted and splitted into two. In the first step, the object is transformed into a photographic record, called the hologram and in the second step called reconstruction, the hologram is transformed into image. No lens is needed in either step. You may now like to answer an SAQ.

SAQ 1

Spend 3 min

Using the size of the amplitude vectors drawn in Fig. 14.2 calculate

(a) the ratio of-intensities, and (b) the contrast resulting from these intensities.

At this stage, you may say that in photography, what we essentially record is the light reflected from the object and not its **diffraction** pattern. Well, it is **easy** to extend the basic idea of holography, explained above in terms of **Gabor's zone-** plate, to the actual photography situations. Reflected light waves, like other waves, are described by their amplitude (or intensity) and their phase (or frequency). To capture the wave pattern completely (that is, to obtain the hologram) both the amplitude and the phase of the wave must be recorded at each point on the recording surface. As you are aware, recording of the amplitude portion of the wave is achieved in normal photography by converting it to corresponding variation in the opacity of the photographic emulsion. The photographic emulsion is, however, insensitive to phase relations. In holography (also known as wave-front reconstruction), the phase relations are rendered visible to the photographic plate through the **technique** of interferometry. You may recall from block-2 of this course that interferometry converts phase relations into corresponding amplitude relations.

When two plane waves derived from a common source impinge at different angles on a screen, they produce a set of uniform, parallel interference fringes. The spacing of the fringes depends solely on the angle between the impinging waves (that is, on the path **difference** between them). **A** photographic recording of such a fringe pattern results in a grating-like structure. In case of holography, one of these waves is the one reflected from the object (called the object wave) and hence need not be a plane wave. The wavefront of the reflected wave will be highly irregular because of the unevenness of the object surface. When this irregular reflected wave pattern interferes with the reference **wave,** the resulting interference pattern will not be uniform. Rather, it will have irregular interference pattern– the irregularity of the impinging wave fronts. At places where the signal bearing waves (the object wave) have maximum amplitude, the interference fringes have the greatest contrast and vice-versa. Thus, variations in the amplitude of the object wave menifest as the variation in contrast of the recorded fringe pattern. Can you recall the implications of the spacing of the interference fringes? It is related to the path difference (and hence the phase difference) between the two interfering waves. And the path difference, in turn, depends on the angle between them. Larger the angle between the two interfering waves, more closely spaced will be the fringes and vice-versa. Therefore, variations in the phase of the object wave menifest as the variations in the spacing of the fringes on the photographic record (the hologram). Thus, in a hologram, both the amplitude and the phase of the signal-bearing wave (the object wave) are preserved as variations in the contrast and spacing of the recorded interference fringes respectively. The hologram obtained in this manner has many properties similar to the diffraction grating about which we will discuss in the next section. When this hologram is illuminated by light of appropriate wavelength, a three- dimensional image of the object can be obtained.

14.3 HOLOGRAPHY: THE PROCESS

As mentioned earlier, the process of image formation by holography is a two step process. In the first step, the waves reflected from the object are recorded in such a way that complete information regarding the amplitude and phase variations is preserved. This recording of wave-front is called the hologram. The second step involves the reconstruction of an image of the object by illuminating the hologram by light wave called reconstruction wave (which is identical to the reference wave). In the following, we discuss these two steps and also mention some of the practical considerations about the holographic technique.

14.3.1 Production of a Hologram

Holograms can be produced in several ways depending upon the relative orientation of the reflected (or scattered) and the reference waves. For example, Gabor's zone-plate, which is nothing but a hologram, is the record of interference between the two waves travelling more-or-less in the same direction. This is easily done with objects that have enough open spaces between them, such as a wire mesh or opaque letters on a clear background (Fig. 14.1c). Signal and reference, in other words, travel in the same direction. Such a hologram is called Gabor hologram or in-line hologram. It was only after the invention of laser that this novel technique of photography became truly practical. With the help of lasers, N. Leith and Juris Upatnicks' produced what is known as off-axis hologram. In the off-axis hologram, the reference beam and the object beam arrive at the recording plate from substantially different directions. This made possible holography of solid three dimensional objects. Now, the question arises: How holograms are recorded? To understand this, refer to Fig. 14.3. A beam of coherent laser light (in which all points on the wavefront are in phase) is split into two beams. One beam illuminates the object to be recorded and the light reflected from this object falls on a photographic plate. The other beam, called the reference beam, is reflected from a mirror to the same photographic plate. Due to superposition of wavefronts of these two beams, an interference pattern is recorded on the photographic plate. The record on the photographic plate (hologram) is simply a pattern of interfering wavefronts and shows no resernblence to the recorded object. The hologram, however, contains "all the information" about the object.

Ordinarily, these interference fringes are very closely spaced and cannot be seen by unaided eye. Hence the hologram appears to be uniformly gray. When seen by

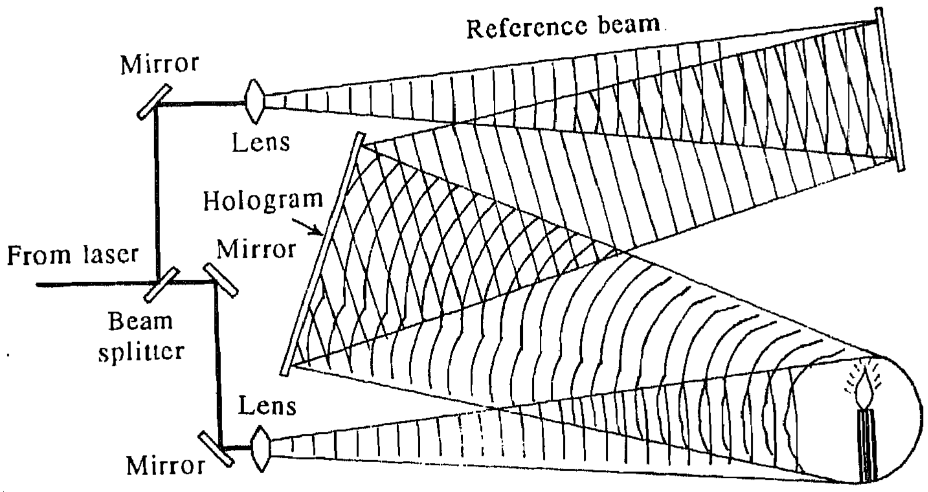

Fig. 14.3: Recording the hologram; mleroscope lenses brondens both beams without affecting their coherence.

microscope, however, a hologram is found to consist myriad of tiny "cells", each cell containing a series of fringes of various lengths and spacing. Further, a laser is needed for holography, merely because its coherence length exceeds the path difference due to unevenness of the object.

Now, having learnt how holograms are recorded, let us pause for a moment and think about the fundamental difference-in terms of technique as well as characteristics-of a hologram and a conventional photograph. This is the subject matter of TQ 1.

14.3.2 Reconstruction of Image

As mentioned above, hologram of an object is the recording of the interference pattern, on a photographic plate, produced by the object and the rekrcnce waves. The hologram, when viewed with unaided eye, does not even remotely resemble the object photographed. The process of obtaining image of the object is known as **reconstruction.** In the reconstruction process, as shown in Fig. **14.4,** the hologram is illuminated by the light beam (which is similar to reference beam) alone and the reconstructed wavefronts appear to diverge From the image of the object. Let us investigate the process analytically.

Let us represent the wave reflected (or scattered) from the object when it reaches the photographic plate as (**Fig. 14.5)**

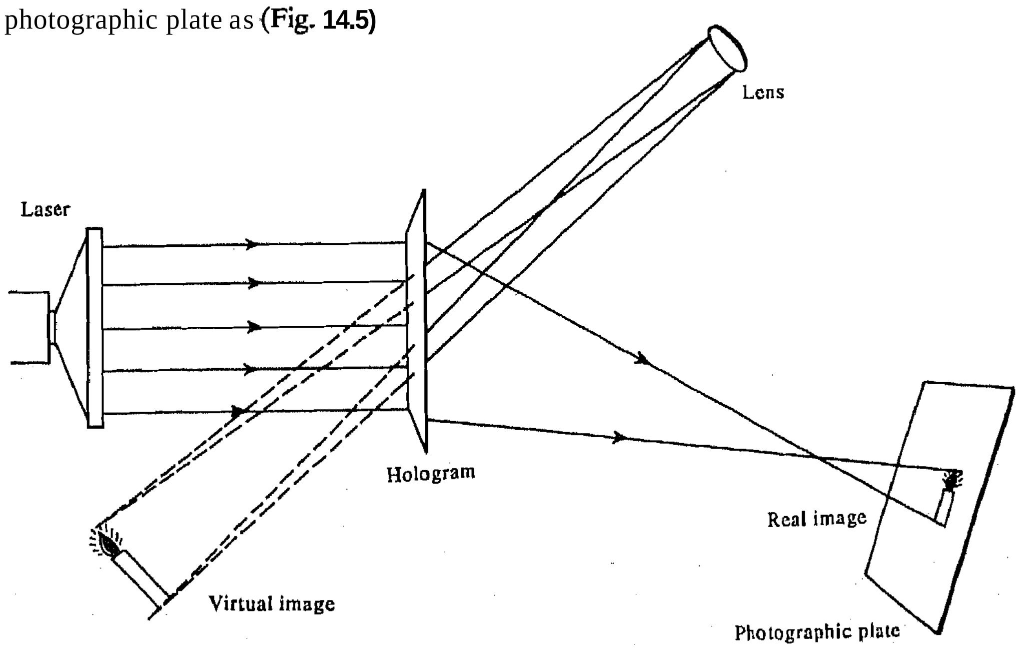

Fig. 14.4: Reconstruction process of an image in holography

$$\psi_1 = A_1(x,y)\cos[\omega t + \phi_1(x,y)] \tag{14.1}$$

and the reference wave as

$$\psi_2 = A_2\cos[\omega t + \phi_2(x,y)] \tag{14.2}$$

You **may** notice that the amplitude of the reference wave is not a function of x or y (the photographic plate is **in xy plane)** indicating, therefore, that it is constant at alt points on the photographic plate, On the other hand, the amplitude of the object **wave, A_1**, is a function of x and y because it will vary from point to point on the photographic plate due to reflection from the object. Similarly, the phase of the reference wave ϕ_2 wilt be constant if it (the reference wave) falls normally on the photographic plate and will be function **of x,y** if the incidence is at some angle. The **phase** of the object wave ϕ_1 **will** be, however, a function of x and y. When these two waves arrive at the photographic plate, the total **field** distribution will be

$$\psi_{total} = \psi_1 + \psi_2$$

$$= A_1(x,y)\cos\left[\omega t + \phi_1(x,y)\right] + A_2\cos\left[\omega t + \phi_2(x,y)\right] \tag{14.3}$$

As you **know,** the photographic plate responds only to the intensity. Thus, to get the intensity distribution on the photographic plate, we must take the time average of $(3_{total})^2$ i.e.

$$I(x,y) = \langle(\psi_{total})^2\rangle$$

$$= \langle\left[A_1(x,y)\cos[\omega t + \phi_1(x,y)] + A_2\cos[\omega t + \phi_2(x,y)]\right]^2\rangle$$

$$= A_1^2\langle\cos^2(\omega t + \phi_1)\rangle + A_2^2\langle\cos^2(\omega t + \phi_2)\rangle$$

$$+ 2A_1A_2\langle\cos(\omega t + \phi_1).\cos(\omega t + \phi_2)\rangle$$

$$= \frac{A_1^2}{2} + \frac{A_2^2}{2} + 2A_1A_2\cdot\frac{1}{2}\langle\cos(2\omega t + \phi_1 + \phi_2) + \cos(\phi_2 - \phi_1)\rangle$$

$$(\because \cos(A + B) + \cos(A - B) = 2\cos A\cos B)$$

$$= \frac{A_1^2}{2} + \frac{A_2^2}{2} + A_1A_2\cos(\phi_2 - \phi_1) \tag{14.4}$$

Eq. **(14.4)** indicates that the phase information of the object wave is also recorded in the intensity pattern on the phorographic plate.

Now, as mentioned earlier, during the reconstruction process, the interference pattern on the photographic plate (called hologram) is illuminated by a reconstruction wave. Let this reconstruction wave, ψ_3 has the same phase as that of the reference wave, ϕ_2. So,

$$\psi_3(x,y) = A_3\cos[\omega t + \phi_2(x,y)] \tag{14.5}$$

What will be the **nature** of the transmitted wave when the reconstruction wave falls on the hologram? Well, the **hologram** is exposed in such a manner that the amplitude transmittance is linearly related to **I (x,y),** the incident intensity at the time of recording. So, we have, the **transmitted wave**

$$\psi_4 \propto \psi_3(x,y)\, I(x,y)$$

$$\psi_4 = \left[\frac{(A_1^2 + A_2^2)}{2}\psi_3 + \frac{A_1 A_2 A_3}{2}\cos(\omega t + \phi_1) + \frac{A_1 A_2 A_3}{2}\cos(\omega t + 2\phi_2 - \phi_1) \right] \quad (14.6)$$

SAQ 2

Spend 5 min

Starting from the relation

$$\psi_4 \propto \psi_3(x,y)\, I(x,y)$$

derive **Eq.(14.6)** using Eqs. *(14.4)* and *(14.5)*

The transmitted wave represented by Eq. *(14.6)* consists of three terms. What do these term signify physically? The first term is the reconstruction wave (ψ_3) with its amplitude modulated by the amplitude of the object wave (A_1). It is so because A_1 is a function of x and y whereas the reference wave amplitude A_2 is a constant. As a result, this part of the transmitted wave will travel, with slight attenuation, in the direction of the reconstruction wave, The second term is identical to the object wave (ψ_1) except for the constant term $(A_2 A_3)/2$. Here lies the beauty of holography. The hologram and the reconstruction wave have generated a wave which is in every way identical to the wave which originated from the real object itself while recording the hologram. This part of the transmitted wave forms a virtual image of the object. The third term which is similar to the object wave forms a real image of the object. As a result, a three-dimensional picture of the object can be obtained by placing a camera in the position of real image. The reconstruction process alongwith various parts of the transmitted wave is shown in Fig. *14.5.* You may note that the object is not present when image is reconstructed. However, one of the evolving beam, resulting due to reconstruction process, is identical to the beam reflected by the object at the time of recording the hologram.

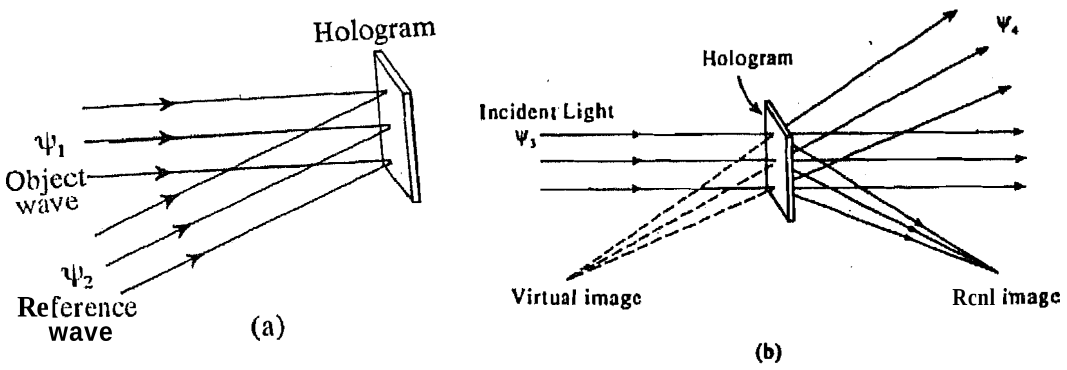

Fig. 14.5: (a) Recording the hologrorn: Wave reflected from an object interferes with the reference wave. (b) Reconstruction: The hologram diffracts the reconstruction wave, resulting In transmitted wave which produces a real and a virtual image.

14.3.3 Practical Considerations

So far we have discussed physical principles and the experimental arrangements of holography. Suppose you are in the actual process of producing holograms and its subsequent reconstruction to obtain a three-dimentional image of the object. What are the important aspects of the process, and components used therein, about which you should be careful? Well, there are several practical considerations in holography which are essentially related to the photographic film, the stability and the coherence condition. Let us have a closer look on these practical considerations.

So far as the photographic film is concerned, hologram must be recorded on films of high resolvance. Look again at Fig. **14.3.** You may notice that the reference wave, (the light reflected by the mirror), and the signal (the light reflected by the object) subtend certain angle at the photographic plate. If this angle is too large, more than a few degrees, the fringes formed between the signal and reference are very closely spaced and even the best emulsion cannot resolve them. To obtain high resolution, extremely fine-grain film has to be used. But fine-grain films are very slow and hence require larger exposure time (a few minutes). And, if during this exposure time object moves, the recording of hologram will not be proper. What is the way out of this problem? The way out of this situation is to use high power laser beam to compensate for the exposure time.

Further, the whole system of recording the hologram should be highly stable i.e. it should be completely free from vibration. Can you say why? It is because the density of the fringes on the photographic film is extremely high. For example, if the angle between the signal and the reference wave is 30° (Refer Fig. 14.3) and the wavelength of the laser light is 633nm, the fringe frequency (Refer to Block-2)

$$= 1/d \text{ ; where d is fringe width}$$

$$= \frac{\sin\theta}{\lambda} = \frac{\sin 30}{633 \times 10^{-9}} \text{ lines per meter}$$

$$= 7 \times 10^5 \text{ lines per meter.}$$

Can you imagine the smallness of this seperation! The fringe width will typically be a thousandth **of** a millimeter. Therefore, if any component of the holographic set-up moves during recording, the whole fringe pattern will disappear. To meet this stability requirement, the film exposure time should be kept minimum (by using very high power laser) and the holographic system should be isolated from outside vibrations.

The most important and obvious consideration in holography is to use coherent illumination. The coherence length of the laser used for illuminating the object must be greater than the path difference between the reference wave and the object wave. The practical problem is that as power of laser increases (which we use for minimising the exposure time), its coherence Icngth is reduced. Similarly, the coherence area (spatial coherence) of illumination from a laser must be greater than the transverse size of the object to be photographed.

Having learnt about various aspects of holography, you may now be interested to know about its applications. This is the subject matter of the next section.

14.4 APPLICATIONS OF HOLOGRAPHY

There are many aspects of holography. Its influence on interferometry, photography, microscopy, astronomy, pattern recognition and even art has only begun to bear fruit. We will now discuss these in brief.

Holograaphic Interferometry

You will appreciate that, in most of the cases, one of the first areas to benefit from the new technique was the area that gave rise to it. Similar was the case with holography which introduced a new range of powerful methods to interferometry. Interferometry is generally used for precise measurement and comparison of wavelengths, for measuring very small distances or thicknesses (of the order of wavelengths of light) etc. Testing for stresses, strains and surface deformation is one of the most useful practical applications of holographic interferometry.

In the double-exposure technique of holographic interferometry for measuring deformation in object due to strain, two exposures are made of the object, - one before loading, and the other after (i.e. under strain). The original object and the object after deformation are recorded holographically on the same photographic plate. The hologram thus obtained is a double exposure, with the second pattern of wave fronts superposed on the first. When this hologram is reconstructed by illuminating it with the reference wave, both images are viewed simultaneously. Since they are slightly different due to deformation, the two images interfere. Thus, any distortion of the object will show in the form of fringes. Like other kinds of interferometry, the technique readily detects changes that produce optical-path difference of the order of a fraction of the wavelength of light, And unlike normal interferometry, however, it is possible to perform experiment quite readily with almost any type of material.

Holographic Microscope

Microscopy has been the primary area of application of holography. In fact, Gabor's discovery of this tecnique was the outcome of his attempt to enhance the resolving power of an electron microscope. In contrast to a conventional high power microscope, a holographic microscope has an appreciable depth of field and it need not be focussed at all. To see how a holographic microscope [unctions, refer to Fig. 14.6. The light beam from laser is split into two. One beam is passing through the specimen and through the microscope, and the other beam is led around it. The two beams interfere on the film, producing hologram. The reconstructed image can be viewed in any desired cross-section. The observer merely looks at the cross-section, he or she wishes to see, moving back and forth throughout the depth of the image without the object being present at all.

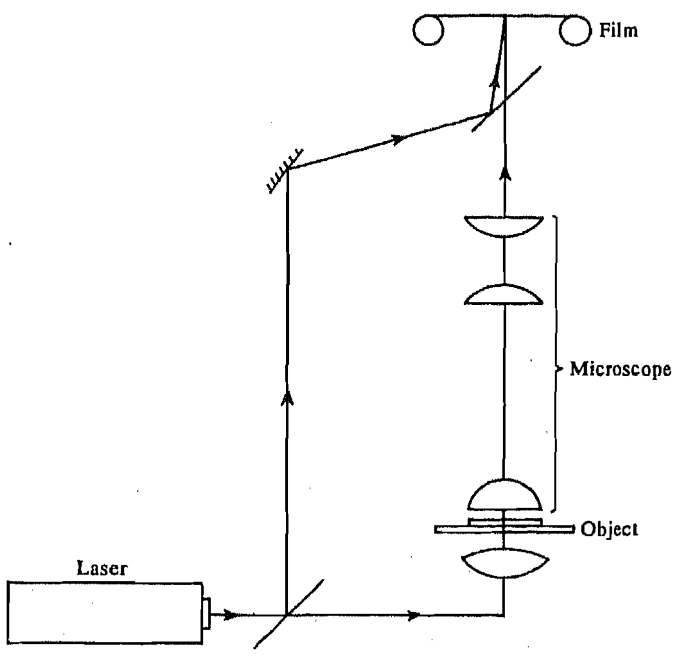

Fig.14.6: Holographic microscope.

Information Storage

Information can be stored and retrieved more efficiently in the form of holograms than in the form of real images. Further, it is the characteristic of the hologram that it will only reconstruct the holographic image if the reconstruction beam is incident on the hologram at the correct angle. Due to this property, several holograms can be recorded on the same holographic plate by using a slightly different angle between the object and the reference beams for each hologram. Thus, on reconstruction, depending upon the angle of incidence of reconstruction beam, a particular holographic image will be visible. Perhaps this is how information is stored in the brain. If that is the case, it would help explain why attempts to locate certain centres in the brain never met with much success and why brain injury often does not lead to predictable circumscribed defects.

Pattern Recognition

One of the most exciting applications of holography is the pattern recognition, also called the character recognition. Early pattern recognition systems, before holography came on the scene, were based on geometrical optics. Consider, for example, that we want to read the letter *A* (Fig. 14.7). *A* set of characters *A*, *B*, *C* ... are printed on a strip of film and this film is moved through the image plane. If the character to be read matches the character on the film, the output from a photo detector is zero, triggering a printer. But, in reality, this does not work. The character and the negative must be aligned perfectly, both in position and size, which is an unrealistic requirement.

Modern pattern recognition systems are based on holography. In place of a mark containing the real imagge of the letter A we may use the hologram of the letter A.

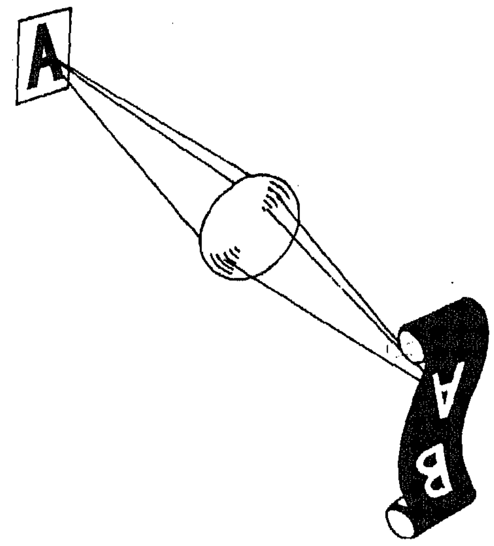

Fig.14.7: Pattern recognition based on geometric optics

As in holography, hologram of the letter *A* is the superposition of two sets of wavefronts, the signal and the reference. The signal is diffracted by an original A and the reference is a beam of collimated light. Subsequently, when the hologram of *A* is illuminated with light from another *A*, plane wavefronts arise that can be focussed into a bright spot (Fig. 14.8 top). The spot can easily be recognised by eye or photoelectrically. On the other hand, if the wavefronts are coming from B or from other characters, they do not transform into perfectly plane wavefronts and do not produce a focussed spot. Instead, a diffuse patch of light (centre) is produced. Hence, we can scan a given matrix of characters and determine whether or not a particular character is present (bottom).

The holograms shown in Fig. 14.8 appear to be amplitude filters. But because they are generated by interference between signal and reference, they in fact represent both amplitude and phase of light. They are called "complex", "matched", or "vander Lugt filters".

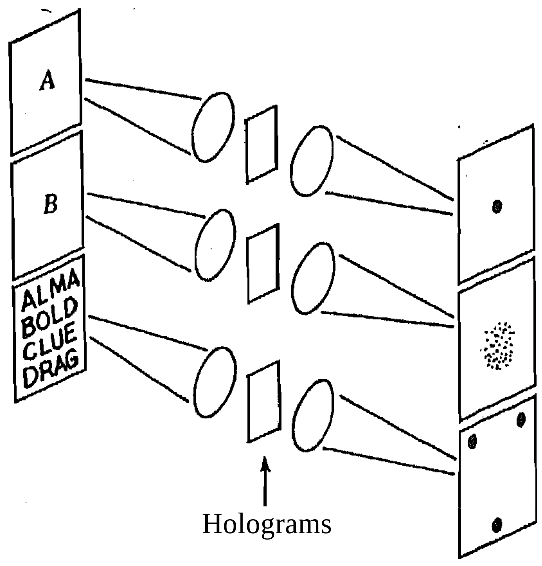

Fig. 14.8: Pattern recognition by holographic vander Lugt filter. (The holograms ere seen between the lenses)

Form reading machine are a distant reality. Some letters and words are "inside" others. For example *F* is inside E, *P* is inside R and B, T, L have the same horizontal and vertical lines and 'arc' is inside 'search'. Clearly, more alike are the two characters, the less will be the power of discrimination. Another problem will be to 'teach' the machine to recognise the "meaning" of a letter set in different typeface. The letter *A* can be written in an infinite number of variations possible when it comes to handwriting. However, pattern-recognition using holographs is being extensively used in developing fingeprints library which stores the fingerprints of individuals with dubious character.

14.5 SUMMARY

- Holography, discovered by **Gabor,** is a novel technique of photography by which a three-dimensional picture of an object or a scene can be obtained. In holography, the **interference** pattern produced by the light reflected from the object and a reference beam is recorded. Such recording on the photographic plate is called the hologram.
- The three-dimensional picture of the object is obtained by **illuminating** the hologram by a reconstruction light beam, which in most cases, is identical to the reference beam. Holography is, therefore, also known as wavefront reconstruction photography.
- Hologram is produced by splitting a beam of **coherent light** from laser into two. One beam is directed, with the help of **mirror(s),** towards the object and the other is made to fall directly on the photographic plate. The light reflected from the object reaches the photographic plate and **interfers** with the reference beam. The recorded interference pattern on the photographic plate is the hologram.

- If $\psi_1 (= A_1 (x,y) \cos [\omega t + \phi_1 (x,y)]$ and $\psi_2 (= A_2 \cos [\omega t + \phi_2 (x,y)$ respectively represents the object wave (wave reflected from the object being photographed) and the reference wave, the intensity distribution on the photographic plate is given as

$$I(x,y) = \frac{A_1^2}{2} + \frac{A_2^2}{2} + A_1 A_2 \cos(\phi_2 - \phi_1)$$

- During reconstruction of image, when the hologram is **illuminated** by the reconstruction wave, $(\psi_3 = A_3 \cos[\omega t + \phi_2 (x,y)]$ the transmitted wave through the hologram is

$$\psi_4 = \left[\frac{(A_1^2 + A_2^2)\psi_3}{2} + \frac{A_1 A_2 A_3}{2} \cos(wt + \phi_1) + \frac{A_1 A_2 A_3}{2} \cos(\omega t + 2\phi_2 - \phi_1) \right]$$

The second term on the right hand side has the same form as the object wave and it represents the three-dimensional virtual image of the object. The third term is also similar to the object wave and represents the real image of the object which can be recorded on a photographic plate.

- In order to obtain a hologram, the photographic plate on which the hologram is to be obtained must be of high resolution. This is required because the density of interference fringes in the hologram is extremely high. Also, the whole arrangement of holography- recording the hologram as well as its subsequent reconstruction-must be highly stable, i.e. it should be free from even a slightest mechanical vibration. And of course, we must use coherent light for recording the hologram as well as reconstructing the image.

- Holography has varied applications. Holographic interferometry is a distinct improvement over normal interferometry because the former can be used for any kind of material. Holographic microscopy has enourmous magnification and it also offers appreciable depth of field. Holography find extensive use in information storage and pattern recognition.

14.6 TERMINAL QUESTIONS

1. (a) How is the process of holography different from ordinary photography?

   (b) Discuss some of the salient features of a hologram?

2. Following **Gabor,** assume that amplitudes of signals and reference are in ratio 1:10. Suppose that the **two** beams when they combine may be completely out of phase or **in** phase. What is the maximum ratio of their intensities?

3. If the angle subtended at the hologram by the signal and the reference beam is 15°, what is the spacing of the fringes provided the wavelength is 492 nm?

14.7 SOLUTIONS AND ANSWERS

SAQs

1. (a) The least possible amplitude (when signal and reference are out of phase, pointing in opposite **direction)** is $4.36 - 1 = 3.36$.

   This is because, measuring the lengths of vectors **Fig.14.2,** we find that the ratio of signal versus reference is **1** : 4.36.

The highest possible amplitude (when signal and reference are in phase) and pointing in same direction is **4.36** + 1 = 5.36. The ratio of the amplitudes = 3.36/5.36. Thus, the ratio of intensities is

$$= (3.36/5.36)^2 = 0.39$$

(b) The contrast is given as

$$\frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

$$\frac{(5.36)^2 - (3.36)^2}{(5.36)^2 + (3.36)^2} = 0.44$$

which is high enough to make the reconstruction visible.

2 The transmitted wave is linearly proportional to **the** incident intensity $I(x, y)$ at the time of recording the hologram and the reconstruction wave, i.e.

$$\psi_4 \, \alpha \, \psi_3 (x,y) I(x,y)$$

$$\alpha \, \psi_3 \left[\frac{A_1^2}{2} + \frac{A_2^2}{2} + A_1 A_2 \cos(\phi_2 - \phi_1) \right]$$

(using egn 14.4)

$$\alpha \frac{(A_1^2 + A_2^2)}{2} \psi_3 + \psi_3 \left[A_1 A_2 \cos(\phi_1 - \phi_1) \right]$$

$$\alpha \frac{(A_1^2 + A_2^2)}{2} \psi_3 + \left[A_3 \cos(\omega t + \phi_2) \right] \left[A_1 A_2 \cos(\phi_2 - \phi_1) \right]$$

(using equaqtion **14.5)**

$$\alpha \frac{(A_1^2 + A_2^2)}{2} \psi_3 + A_1 A_2 A_3 \left[\cos(\omega t + \phi_2) \cos(\phi_2 - \phi_1) \right]$$

$$\alpha \frac{\psi_3 (A_1^2 + A_2^2)}{2} + A_1 A_2 A_3 . 1/2 \left[\cos(\omega t + \phi_2 + \phi_2 - \phi_1) \right.$$

$$\left. + \cos(\omega t + \phi_2 - \phi_2 + \phi_1) \right]$$

$$(\text{using} \cos(A + B) + \cos(A - B) = 2\cos A \cos B)$$

$$\psi_4 = \frac{(A_1^2 + A_2^2)}{2} \psi_3 + \frac{A_1 A_2 A_3}{2} \cos(\omega t + \phi_1) + \frac{A_1 A_2 A_3}{2} \cos(\omega t + 2\phi_2 - \phi_1)$$

which is equation (14.6)

TQs

1. **(a)** The **technique** of holography (photography by wave front reconstruction) **differs** from that of ordinary photography in three aspects. Firstly, in ordinary photography, the light **reflected** from the object is received on the photographic plate with the help of **lenses or** other image forming device. Amplitude of the light wave, reflected from each point of the object, is recorded at corresponding point on the photographic plate. On the other hand, in holography, no lens or other

image forming device is needed and hence, as such, no image is formed on the hologram. What essentially is obtained is the interference pattern due to the light reflected from the object and the reference beam. Secondly, for obtaining hologram, coherent light is used whereas in case of normal photography, no such source of light is needed. The requirement of coherent light is due to the fact that the hologram is an interference pattern. Thirdly, in holography, a set of mirrors is used to render the reference and object beam on the photographic plate.

(b) Hologram has several interesting properties. Some of them are given below:

(i) The image obtained from the hologram has three-dimensional character unlike normal photographs which are two-dimensional. Due to the three-dimensional character of the image obtained in holography, you can observe different perspective of the object by changing the viewing position. Also, if a scene has been recorded, you can focus at different depths.

(ii) We do not obtain negative in holography. Hologram itself, however, can be considered as negative in so far as obtaining the positive is concerned. Otherwise, there is no similarity between the typical negative of the ordinary photographs and the hologram. You may have noticed that when the negative of an ordinary photograph is seen through, we do get a feel of the object or the scene photographed. On the other hand, when we look at a hologram we observe a hodgepodge of speaks, blobs and whorls; it has no resemblance whatsoever with the original object.

2. Let amplitude of the signal (or the object wave) be A_1 and that of the reference wave be A_2, then, as per the problem

$$\frac{A_1}{A_2} = \frac{1}{10}$$

When these two waves are out of phase, their resultant amplitude will be (10 - 1) = 9. On the other hand, when they are in phase, the resultant amplitude will be (10 + 1) = 11. Thus, the ratio of their intensities,

$$\frac{I_{min}}{I_{max}} = \frac{(9)^2}{(11)^2} = 0.67$$

3. The spacing of the fringes is given as

$$d = \frac{A}{\sin\theta}$$

$$= \frac{492 \times 10^{-9}}{\sin 15^{\circ}} \text{ m}$$

$$= 1.8\,\mu\text{m}$$

UNIT 15 FIBRE OPTICS

Structure

15.1 INTRODUCTION

You might have seen advertisement dispalys (made of glass or plastic rods) and illuminated fountains. While looking at these, you might also have noticed that Iight seems to travel along curved path. In the above mcntioncd cases, most of the incoming light is contained within the boundaries of the medium (glass or plastic or water) due to the phenomenon of total internal reflection. And since the medium itself has a curved shape, the light travelling through it appcars to travel along a curved path. Optical fibre, which is made of transparent glass or plastic, also transmit light in a similar fashion. These fibres are thread like structure and a bundle of it can bc used to transmit light around corners and over long distances. Since optical fihrc can transmit light around corners, it is being used for obtaining images of inaccessiblc regions e.g. the interior parts of human body. The real potential of the optical fibrcs was, however, revealed only after the discovery of lasers.

You may recall from Unit 13 of this course that the discovery of lasers- a source of coherent and monochromatic light - raised the hope of rcalising communication at optical frequencies. Since increase in frequcncy of the carrier wave enables it to carry more information, communication at optical frequencies (-10^{15} Hz) has obvious advantages over communication at radio wave (-10^{6} Hz) and microwave (-10^{9} Hz) frequencies. But, early attempts at communication at optical frequencies faced a major problem. When optical radiation travlcs through the Earth's atmosphere, it is attenuated by dust particles, fog, rain etc. Thus, a need for an optical waveguide was felt and the answer was the optical fibres. Optical fibres are an integral part of optical communication – transmission of speech, data, picture or other information – by light. In this unit, you will study about the optical fibres, especially in the context of optical cammunication.

In Sec.15.2, you will learn the physical principles involved in transmission of light through fibres. Types of fibres used in optical communication has also been explained. General considerations about the optical communication through fibres has been discussed in Sec. 15.3. In the same section, you will also learn about the requirements which must be met by optical fibres so that efficient optical communication may take place. The area of optical fibre is relatively new and an exciting Geld of activity. A thorough understanding demands rather sophisticated mathematical background on the part of the student. It has, therefore, been attempted here to keep the mathematical aspects to a bare minimum and the underlying physical principles have been highlighted.