Applied Optics
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Lecture 55
Basic Concepts of Holography - 1

Hello everyone, welcome back to my class. Today we will address the second topic in module number 12, which is basic concepts of holography.

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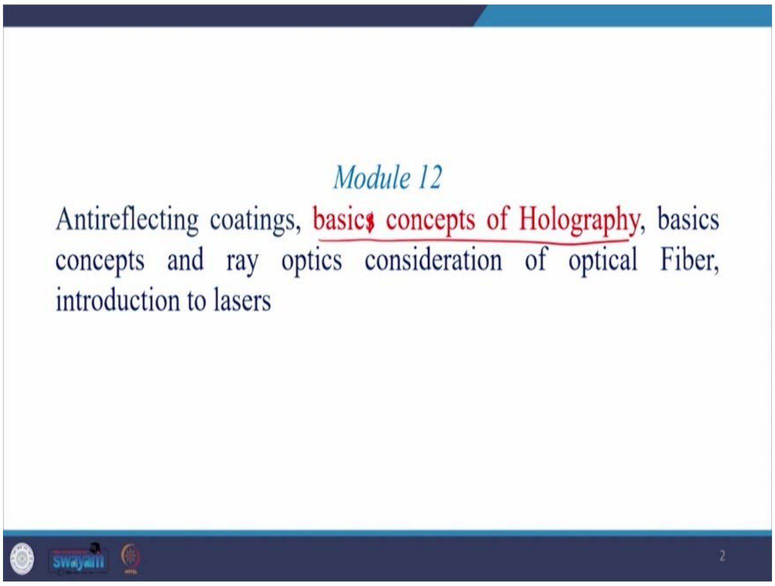

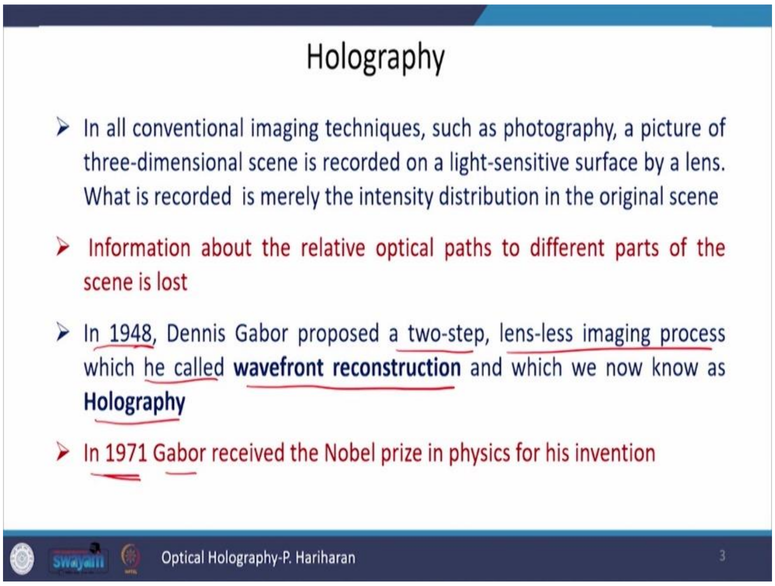

You must have seen 3d Floating images, which if you try to touch then you will see that you are just touching your fingers. It is it floats in the air, but it cannot be touched. In today's lecture, we will learn how to form these images and what is the drawback of usual images, which we shoot using our camera or which we see in the photographic plate?

Now, in all the conventional imaging technique, such as photography, a picture of 3 dimensional scenes is recorded on light sensitive surface via lenses. And whenever we record a 3D surface on a 2D surface, then this 2D information which is just the recording of intensity, it does not hold complete information of the object, what is recorded is merely the intensity distribution in the original scene, we do not record depth.

Suppose, someone is clicking a photograph of mine, then what will be recorded is the intensity pattern if he will be able to see where my nose is where my eyes are, where is my forehead, but he would not be able to clearly say how high my nose is and what is the depth of my eyes from the forehead surface, this left information will be missing.

And also, or alternatively, what we can see is that information about the relative optical paths to different parts of the scene is lost here because rays coming from my nose and rays coming from my eyes, there is a difference in the optical path length. But in 1948, a scientist Dennis Gabor, he realized this and he proposed a two-step lens less imaging process, which is which he called wave front reconstruction and which we now know as holography and in 1971, Gabor received a Nobel Prize in Physics for his invention.

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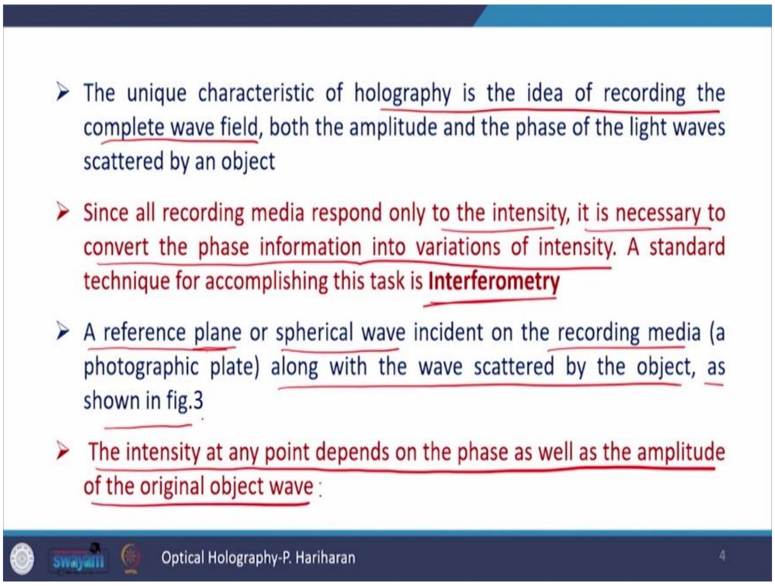

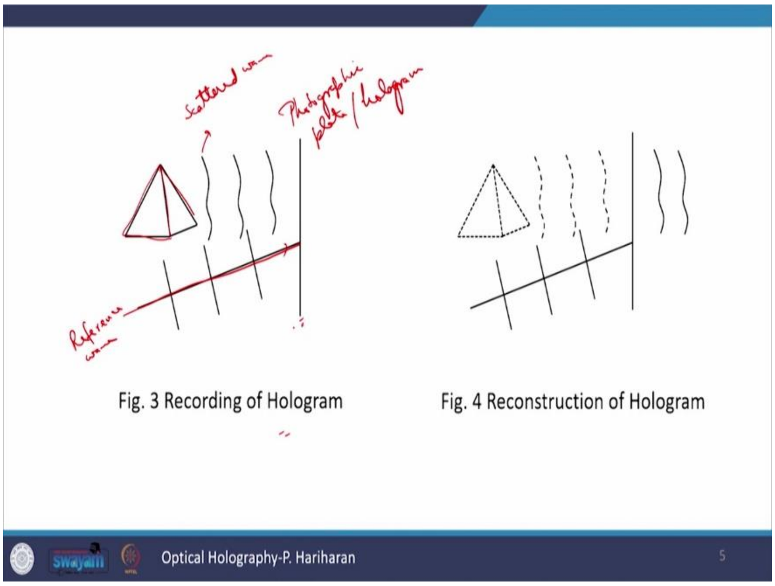

Now, you can realize how important this technique is, the unique characteristic of holography is the idea of recording the complete wave field. Whenever I say complete, it means it is recording both the amplitude and the phase. Now, since all regarding media respond only to intensity, it is necessary to convert the phase information into variation in intensity. Because whenever we record anything, it is just the intensity which you see and record, but the phase information is missing, how to feel the phase the only way is through interferometry, or standard technique for accomplishing this task of changing phase information into intensity fluctuation is interferometry.

And we know that in interferometry, if you change the phase, the light intensity varies and we saw that in interference and diffraction that fringes are formed and this is only due to the change in phase. Now, what does people usually do using this interferometry in Holography or reference plane wave or spherical wave incident on the recording media along with the wave is scattered by the object form or interferometric setup.

I repeat; in an interferometric setup, we have a reference plane or a spherical wave that is made to incident on the recording media along with the wave which gets scattered from the object. And they both fall on some photographic plate, they interfere there and then get recorded. And this is shown here in this figure one recording of a hologram.

This pyramid is the object which we want to record on the hologram and what people do is that the people launch a reference wave on a photographic plate, this is our photographic plate or you can say hologram now, people launch a reference wave and scattered wave from the object. People shine the object and the light after getting scattered from the object and a reference beam they are fall on a photographic plate and they interfere there and this is recorded on this plate and this plate thus becomes a hologram. And this is what is written here, the intensity at any point depends on the phase as well as amplitude of the original object wave.

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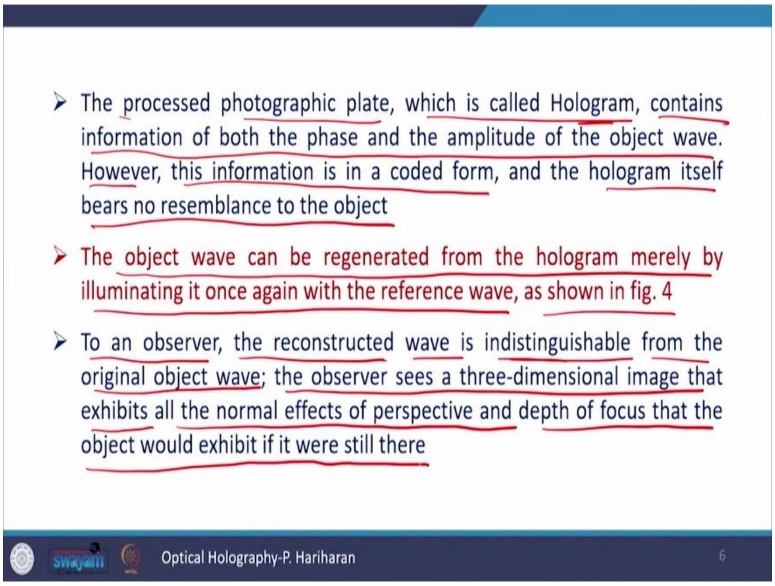

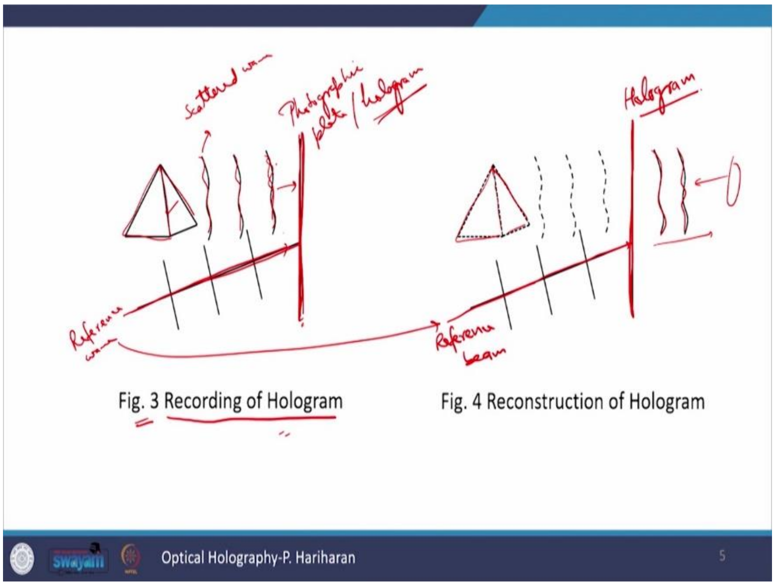

Now, the processed photographic plate which is called hologram contains information of both the phase and the amplitude of the object wave because now it is an interference pattern which is getting recorded therefore, both intensity and phase is being captured by this holographic plate or hologram. However, this information is in coded form, and the hologram itself bears no resemblance to the object. It is not like one to one correspondence between a holographic plate or hologram with the object as we expect in a usable photo.

If a person is standing here and we have the photograph of the person then we can easily match the 2 and say that this photo resembles the object or the person who is standing here, but in case of a hologram, the hologram is coded in such a way that if you see the hologram and the object, then you will see that there is no resemblance the hologram does not correspond to the object. And there are some specific techniques to generate the image of the object from this hologram.

Now, the object wave can be generated from the hologram merely by illuminating it once again with the reference wave as shown in the figure 2. Let us go back to the figure. In figure 3, we understood the recording of hologram, we put a photographic plate here and then we illuminated the object and then the scattered light from the object it falls on the plate apart and as well as a reference beam also falls in this plate these 2 beams they interfere and they create a hologram.

Now, so, this is our hologram and using which we want to reconstruct the object here this is a hologram. Now, to do this we will use the same reference beam this one, we illuminate the hologram with the same reference beam and then after the illumination, some scattered light will pass through this hologram. And if you look from this direction, then you will see that virtual image of object appear here floating in air and this virtual image is a 3d image. It have the perception of depth now, because phase information is also embedded there.

Now, to an observer, the reconstructed wave is indistinguishable from the original object wave. The observer sees a three-dimensional image that exhibits all the normal effects of perspective and depth of focus that the object would exhibit if it were still there, the constructed image of the object would completely resemble the original object and it would be in 3d form it would have the perception of depth it will have all the normal effect of perspective and depth of focus. Now, this is the beauty of holography.

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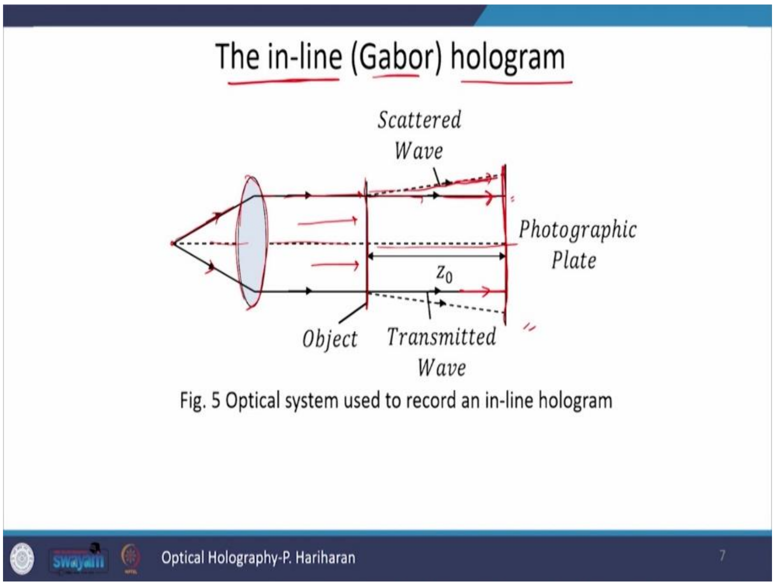

Now, there are several ways of recording and reconstructing the image in holography. Now, one of the wave is in-line hologram. An in-line hologram was proposed by Gabor Here what he did is that he picked some object and he put a photographic plate coaxially with the object and then he illuminated the object with a light source using a lens coaxially and then what happens is that when light falls on this object, then a part of the light get transmitted while a part get scattered why, because in this in-line hologram, the object is choosing to be semitransparent.

Therefore, wherever the light gets hindered, it gets scattered and if there is no obstruction in the path of the light rays, it passes through smoothly, it passes through untouched. And therefore, the direct light which is received on the photographic plate can be treated as reference beam while the light which got disturbed due to the presence of this opaque portion on the object plane, it got scattered.

And therefore, on a photographic plate, this scattered and the reference beam they interfere and far hologram. Now, you see that all these things are coaxially placed in this schematic picture therefore, this type of hologram is called in-line hologram.

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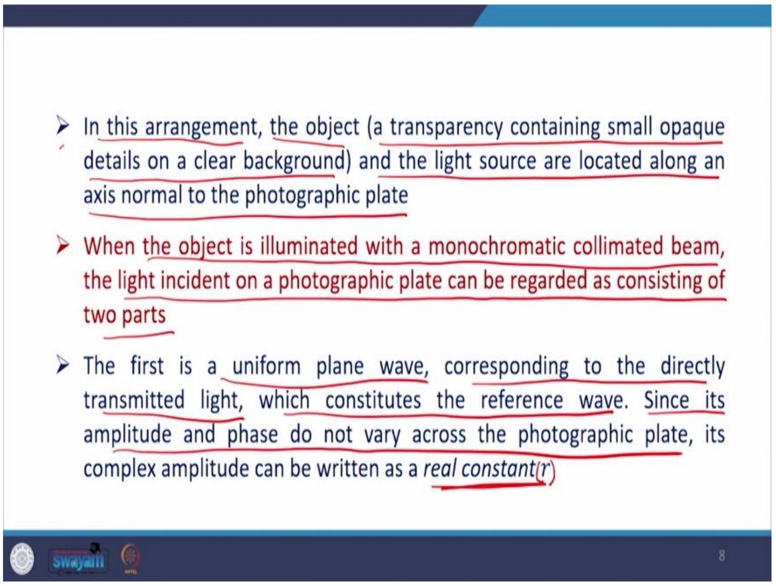

And the explanation of this inline hologram is written here which says that in this arrangement, the object which is a transparency containing a small opaque details on a clear background and the light source are located along an axis normal to the photographic plate when the object is illuminated with a monochromatic collimated beam, the light incident on a photographic plate can be regarded as consisting of two parts. What are those two parts? The first part is a uniform plane wave corresponding to the directly transmitted light which constitutes the reference wave.

Since its amplitude and phase do not vary across photographic plate, it is a complex amplitude can be written as a real constant r. Do remember it the amplitude after un-deviated light or the reference beam is represented by real constant r, it is not complex. While the second part which is the weak scattered wave that is caused by the transmission variation in the object it is complex here.

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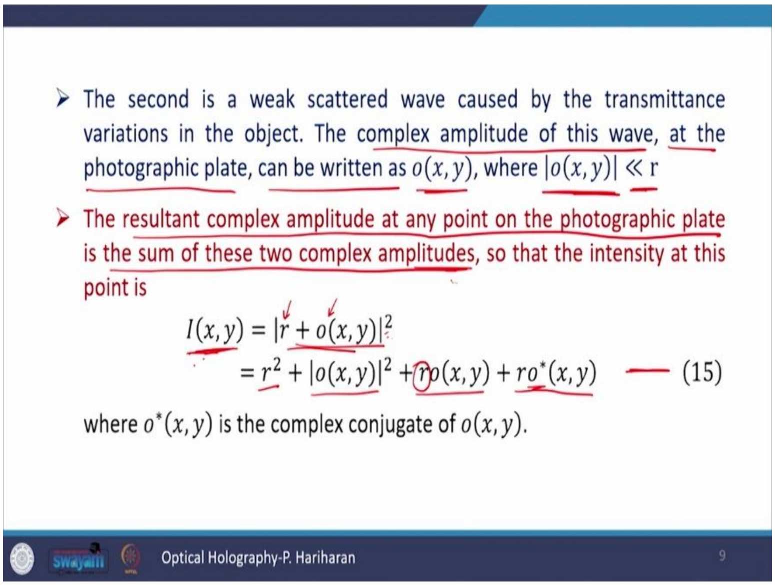

And the complex amplitude of this wave at the photographic plate can be written as o(x,y) because the variation is in the transverse direction in the z direction, it is a propagation happening and since the scattered wave is a weak amplitude $|o(x, y)|$ would always be much-much smaller than r, the contribution from the reference beam. Therefore, the resultant complex amplitude at any point on the photographic plate is sum of these two complex amplitudes the superposition principle is applied here.

Therefore, the intensity at any point on the screen on the photographic plate would be the contribution from the reference wave plus the contribution from the scattered wave added and then squared this would give the intensity. If you expand it, then we will get $r^2 + |o(x, y)|^2 + ro(x, y) + ro^*(x, y)$, since r is a real number, therefore, the complex conjugate of r would be equal to r and therefore, the no star sign is there here on top of r, but o is a complex therefore, there is o^* here in equation number 15. This is the resultant intensity which photographic plate will receive.

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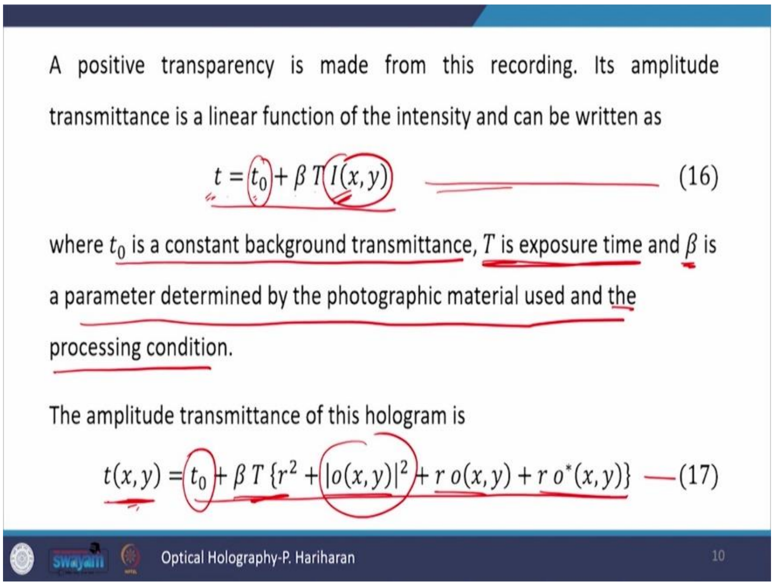

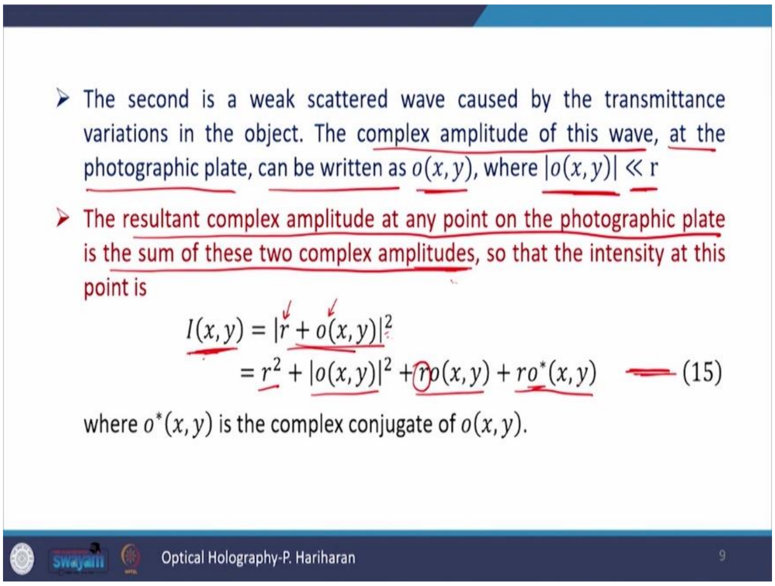

Now, a positive transparency is made from this recording, its amplitude transmit tense is a linear function of intensity and can be written as this, the amplitude transmittance t of this positive transparency will be equal to $t = t_0 + \beta T I(x, y)$, I is the intensity which was received at the at the photographic plate.

Now, we know that in Holography we now launch reference beam on the hologram to reconstruct the image, amplitude transmittance through this hologram is given by equation number 16, where t_0 is a constant background transmittance, T is the exposure time which means how long the photographic plate remains exposed and β is a parameter determined by the photographic material used, because the material also play a role and it also depends upon the processing condition how the photographic plate is processed.

The amplitude transmittance of this hologram. Therefore, be given by this expression where we have just replaced this I which is intensity which is recorded at the photographic plate by equation number 15. We substituted the expression of 15 there, after substitution we get this big expression this is amplitude transmittance of hologram. Now, you see here this t_0 is the background term and then we have this term and the second term third term and fourth term and this term is o^2 term and o is already very small therefore, o^2 will be very-very small which can easily be neglected.

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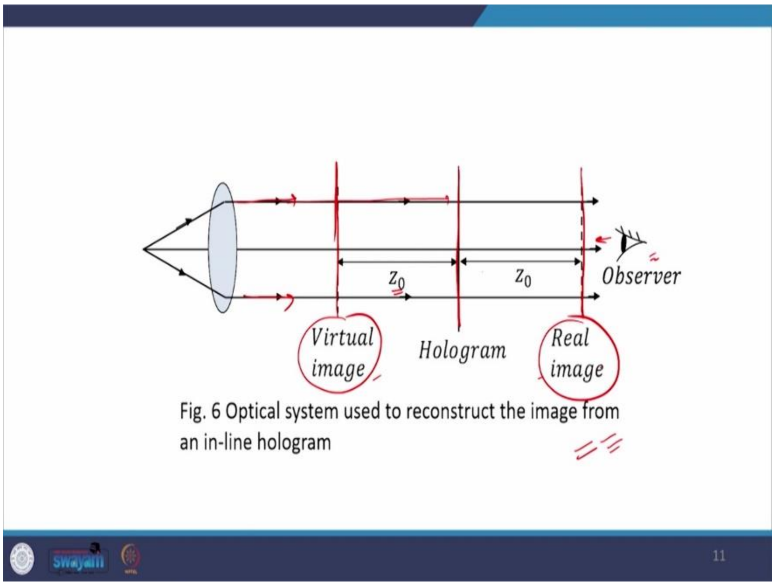

In inline hologram, the reconstruction process is shown here is schematically, here in what we did is that we place hologram here and then we shine the light and everything is coaxial as system name is in line hologram and observer looks into the hologram from this direction. Now, you see that when light falls on the hologram, then one of the image is created here, while the other image is created here, this image which is created the backward direction at z_0 distance is called virtual image while the image which is created in the forward direction which is close to the observer, it is called real image. We will learn about this virtual and real image in the forthcoming slide.

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To view the reconstructed image, the hologram is replaced in the same position as the original photographic plate and is illuminated with the same collimated beam of monochromatic light used to make the original recording.

The complex amplitude transmitted by the hologram can be written as

$$u(x,y) = r\,t(x,y) \qquad (18)$$

$$= r(t_0 + \beta T r^2) + \beta T r|o(x,y)|^2 + \beta T r^2 o(x,y) + \beta T r^2 o^*(x,y) \qquad (19)$$

The complex amplitude of the transmitted wave contains four terms.

- In this arrangement, the object (a transparency containing small opaque details on a clear background) and the light source are located along an axis normal to the photographic plate
- When the object is illuminated with a monochromatic collimated beam, the light incident on a photographic plate can be regarded as consisting of two parts
- The first is a uniform plane wave, corresponding to the directly transmitted light, which constitutes the reference wave. Since its amplitude and phase do not vary across the photographic plate, its complex amplitude can be written as a *real constant* (r)

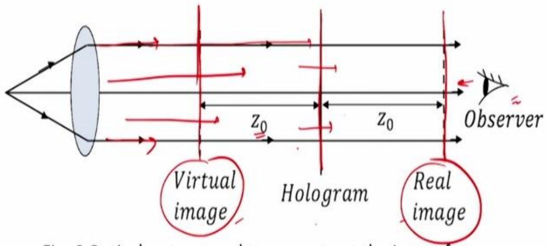

Fig. 6 Optical system used to reconstruct the image from an in-line hologram

Now, to view the reconstructed image, the hologram is replaced in the same position as the original photographic plate the photographic plate now termed as hologram and it is then illuminated with the same collimated beam of monochromatic light that was used to make the original recording, the reference beams should be the same. Now, the complex amplitude transmitted by the hologram it can be given by equation number 18. This is the complex amplitude which is transmitted through the hologram.

T is the amplitude transmittance and then it is multiplied by r. Why r? Let us go back and remember what r is? r is nothing but the complex amplitude of the light which passes through the semitransparent object which remain unaltered.

Now, here too we are signing the hologram with the light and the part of the light will get transmitted, the transmitted part would be given by rt, this is the amplitude of the reference wave and then this amplitude is multiplied by the amplitude transmittance function to get the exact value of the amplitude at the transmission and now we will substitute for t and after substitution we get this big expression.

The complex amplitude of the transmitted wave contains four term, this is our first term, this is our second term, this is the third term and this is the fourth term. Now, in the first term, we see $t_0\beta Tr$, r is also here, but o is not appearing here and o is contribution from the scattered wave. It means object information is not there in the first term

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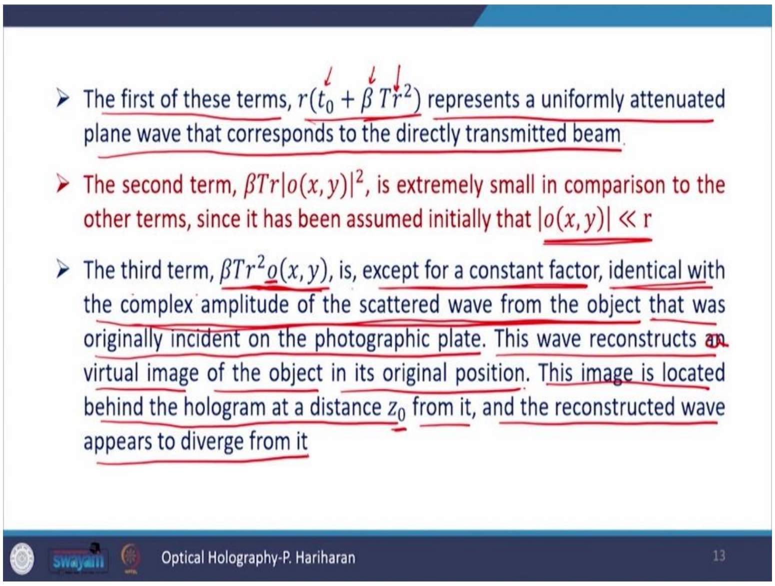

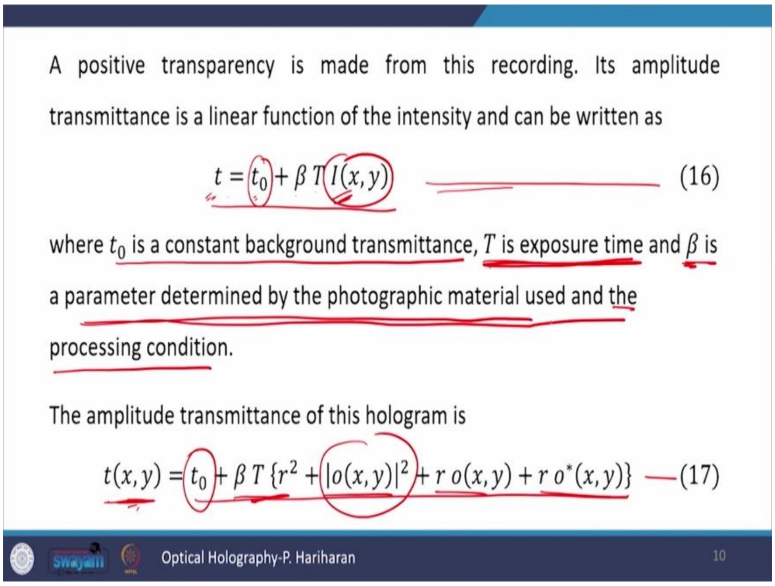

And this is what is written, the first term of these terms which is this this represents a uniformly attenuated plane wave that corresponds to the directly transmitted beam. Beam is coming, it is getting directly transmitted, r is amplitude of the reference wave, t_0 is the background transmittance, T is the exposure time and β is the parameter determined by the holographic material and the processing condition. Therefore, the object information is not here in the first term and therefore, it corresponds to the directly transmitted beam it has nothing to do with the reconstruction.

Now, let us go to the second term. The second term is o^2 term which I said already it is very small therefore, it can safely be neglected because o is already much-much smaller than smaller. The third term $\beta T r^2 o$ is except for a constant factor identical with the complex amplitude of the scattered wave from the object. And that was originally incident on the photographic plate.

Now, this wave reconstructs and a virtual image of the object in its original position and this is the virtual image, which appears here. This image is located behind the hologram at a distance z_0 from it, and the reconstructed wave appears to diverge from it, it diverges. If you move away from the hologram, then the reconstructed image diverges, it becomes bigger and bigger if you move away from the hologram.

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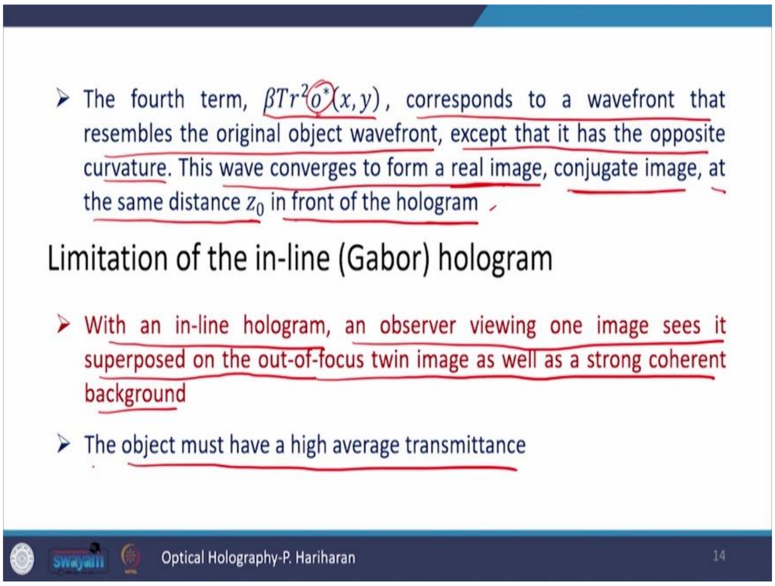

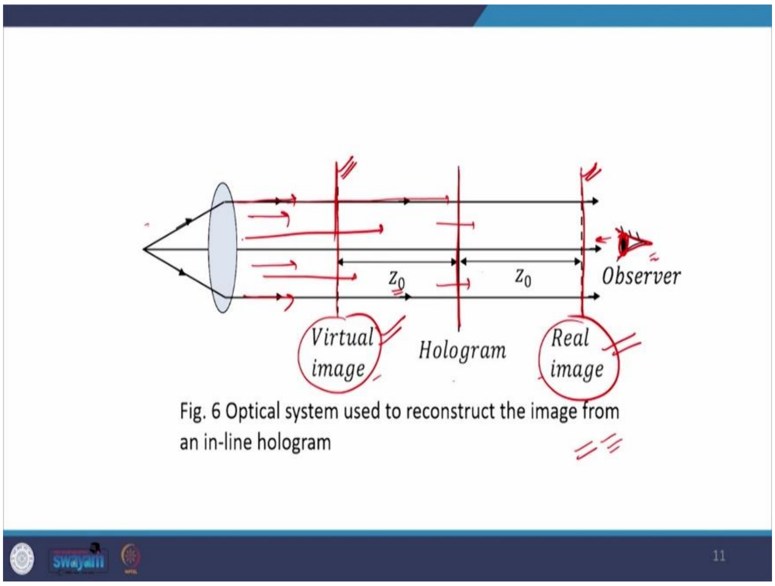

Now, the fourth term is $\beta T r^2 o^*$, it is a complex conjugate of o this corresponds to a wavefront that resembles to the original object wave front, except that it has the opposite curvature because of this complex configuration. The wave converges to form a real image which we also call a conjugate image. And this image is formed at a same distance z_0 in front of the hologram, which we call the real image and which is shown here.

Now, this is how an inline hologram, we get two images, one virtual and one real. But, associated with this in-line hologram or Gabor hologram, there are a few limitations, which is very much obvious. The first limitation is, with an in-line hologram and observer viewing one image sees it superposed on the out of focus twin image as well as a strong coherent background.

Why? Let me repeat it, with an inline hologram and observer viewing on image sees it superimposed on the out of focus twin images as well as a strong coherent background which means that the observer which is viewing from here, it says this image as well as the second image, the 2 images are being simultaneously washed and apart from this, you are also seeing the rays from the source coming to the observer.

Therefore, it is very difficult to make out the image properly because in our field of view, there are several things which are appearing simultaneously. The second thing is that to create a hologram using inline technique, we require an object which must have some transmittance we cannot use an opaque object here, this is the second limitations it is a limited to some semitransparent object.

Then object must have a high average transmittance to enable this technique to form a hologram here. Now, this is all about in-line hologram. And in the next class, we will talk more about holography and we will learn about off axis hologram also, which removes these two limitations which are imposed in inline hologram. With this therefore, I end my today's lecture. And thank you for joining me. See you in the next class.