Applied Optics

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Lecture: 31

Introduction to Diffraction

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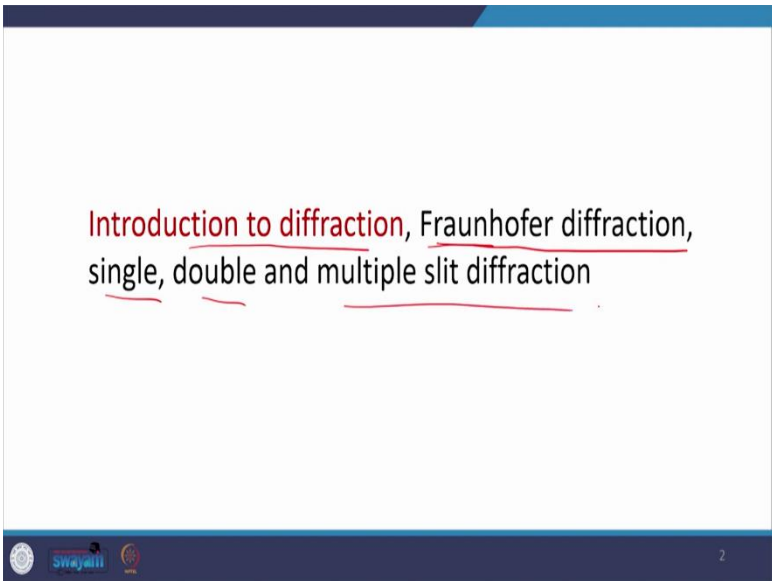

Hello everyone, welcome to my class, in the last class we talked about coherence. Today we will start module 7, wherein we will talk about diffraction, in this class I will introduce diffraction to you. And diffraction is of basically two kinds, the first one is called Fraunhofer diffraction and the second is called Fresnel diffraction.

Then Fraunhofer is diffraction is a simpler kind of diffraction. Therefore, we will cover Fraunhofer diffraction first and then the next module, we will talk about Frensel diffraction. And after from introduction of Fraunhofer diffraction, we will talk about single, double and multiple slit diffraction. Then let us start with the introduction to the diffraction today.

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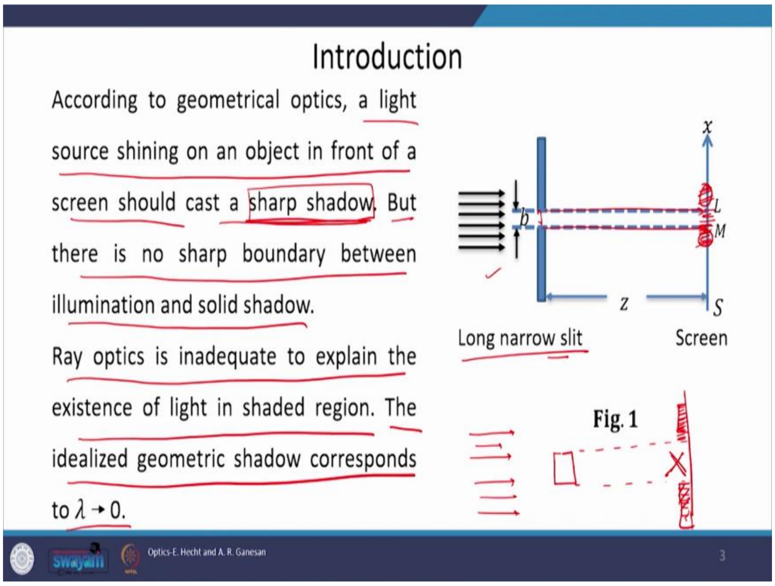

We know that when we launch a parallel beam of light, in this particular case let us talk about ray only. When we launch a parallel beam of ray on a very narrow long slit, then what do we expect? We expect that since the light propagate in a rectilinear path, we expect a very bright image of this slit and no light on this side.

Now this is the conception of geometrical optics and geometrical optic says that a light source shining on an object in front of a screen should cast a sharp shadow. Here this word is very important from geometrical optics perspective, we should not see any light here in this part which is not falling in the straight line path of the light. But there is no sharp boundary between illumination and solid shadow, and this we know.

If we keep decreasing the size of the slit then we see that light start to spread out it start to go into the shadow region, this cannot be explained through geometrical optics or ray optics. Ray optics is inadequate to explain the existence of light in shaded region. Therefore, the idealized geometrical shadow corresponds to λ is equal to 0.

When we talk about shadowing effect, suppose this is an object and we launch a parallel beam of light onto it, then on the screen, in ray optics expect then we will see light here, and here, and no light which is in the area, which is right behind this object here, the light is there in this shaded region but no light is here. This is what geometrical optics or ray optics says but if the size of the object or aperture size is very small then we see that light is also there in the dark region.

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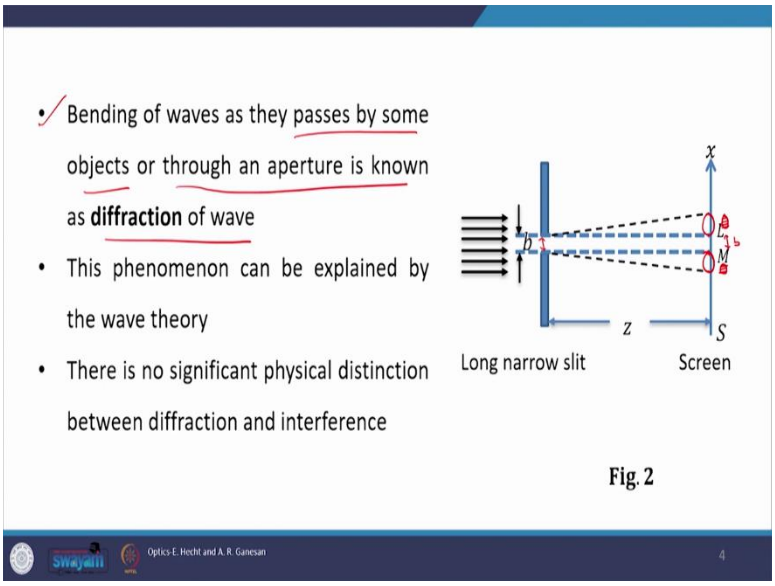

Now conventionally bending of waves as the passes by some object or through an aperture is known as diffraction. We have some aperture and if the light bends in the dark region or shadow region then this phenomena name as diffraction. Now here you see that the opening width is b but light is not only falling on this b region but it is also going in this region which from the geometrical optics point of view should be dark.

This bending we define it as diffraction or diffraction of wave and this phenomena can only be explained by the wave theory. And there is no significant physical distinction between diffraction and interference. People talk about differences between diffraction and interference and you will see that diffraction and interference they are almost the same phenomena.

Conventionally or traditionally when people talk about interference among few sources or few point sources then they call it interference but if this interfering beams or this interfering lights are too many, if the number of sources are too many, then we call them diffraction, then we call the interference between these large number of rays or diffraction.

But alongside we have also studied multiple ray interference in a thin film experiment where we launched only one ray and then out of one ray we produce many number of reflected beams and many number of transmitted beams and all these transmitted and reflected beam they interfere among themselves and we call this interference.

On the other hand, in the coming lectures, we will also learn diffraction grating there to be we will have n number of sources and they interfere among themselves and we call them diffraction therefore this confusion is there. But most often when the number of sources are limited we call it interference when there is a large number of sources we call it diffraction.

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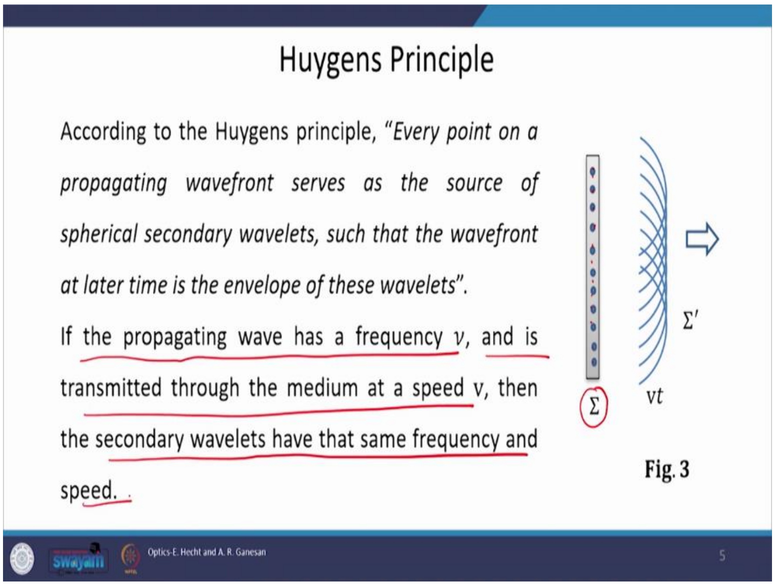

Now moving ahead first principle which described the phenomena of reflection and refraction, total internal reflection is Huygens principle, this we know. And what does Huygens principle say, Huygens principle says that every point on a propagating wave front serves as a source of spherical secondary wavelet, such that the wave front at a later time is the envelope of these wavelets.

Now suppose this is your source plane, the Σ represents your source plane which consists of a large number of point sources. Then from all these point sources spherical wave fronts emit and all the points on this spherical wave front they behave as the source of secondary wave, and they also emit secondary wavelets, and then we draw a common envelope to all these wavelets, and this common envelope represents the next position of the wave front and this is how a wave propagate.

Now if the propagating wave has a frequency υ and is transmitted through the medium at a speed v, then the secondary wavelets have the same frequency and the speed. This is what Huygens principle say.

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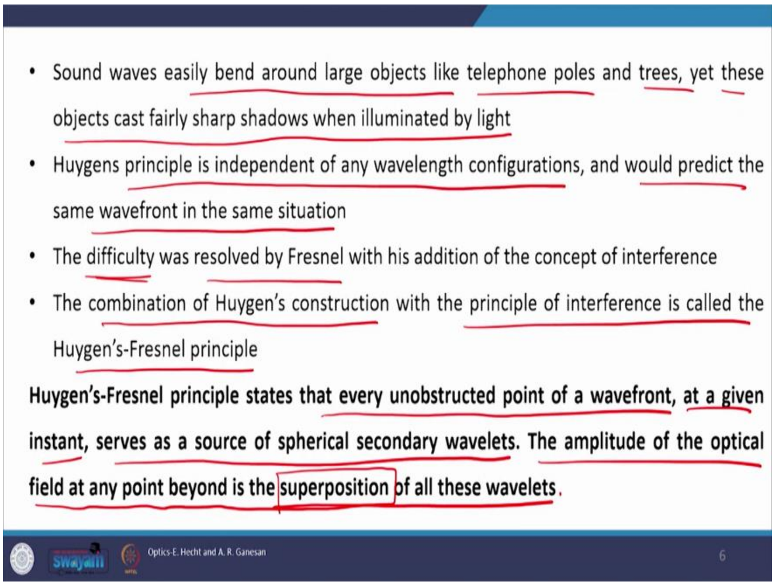

Now we know that the sound wave easily bends around large objects like telephone poles, trees yet these objects cast fairly sharp shadow when illuminated by light. What I mean to say is that the bending is significant when we use sound wave but this bending is not very significant when we illuminate these objects like poles, telephone poles entry with a light wave. Now Huygens principle is independent of any wavelength configuration and would predict the same wave front in the same situation, the wavefront shape should be the same.

But here in the case of sound wave illumination and light wave illumination on a telephone pole or a tree we see that that the two waves behave differently. One is bending in the darker region, which is sound wave. And the light wave is making a shadow which is fairly sharp, then there is a discrepancy which needs a proper solution. This difficulty was resolved by Fresnel and he modified Huygens principle and the modified Huygens principle is known as Huygens-Fresnel principle, we have already talked about this but just to refresh you, I am repeating these things. The combination of Huygens construction with the principle of interference is called Huygens-Fresnel principle.

And what does Huygens-Fresnel principle say? Huygens-Fresnel principle states that every unobstructed point of wave front at a given instant serve as a source of spherical secondary wavelets. This is also the statement of Huygens but what Fresnel added is the following. The amplitude of the optical field at a point beyond is the superposition of all these wavelets, he added this super position of wavelet. This was the Fresnel contribution and due to this addition Huygens-Fresnel principle could successfully explain diffraction and interference, which the Huygens principle alone was not able to.

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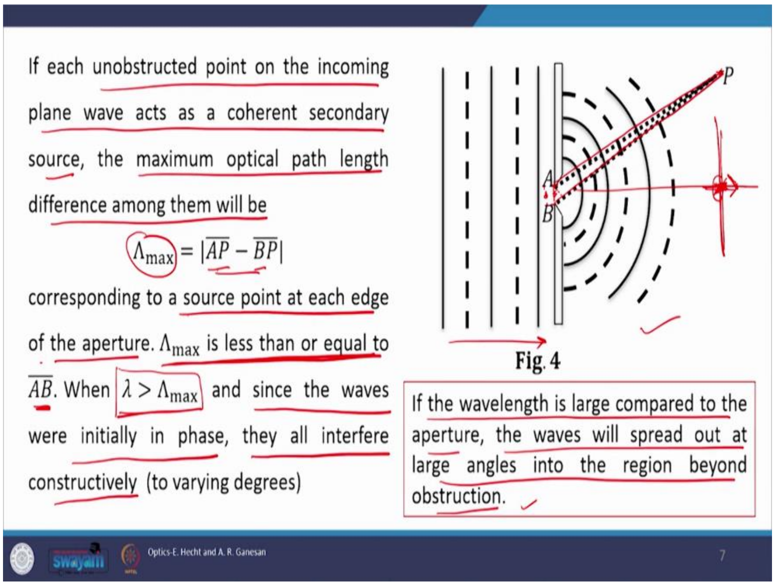

Now let us consider an aperture which is shown here by point A and B, A and B represents the extremities of the aperture and we are launching a plane wave on this aperture. Aperture is small in size and then the spherical wave front would be generated on the other side of the aperture as shown here in this figure. Now let us pick a point of observation P, which is AP distance away from A and BP distance away from B.

If each unobstructed point on the incoming plane wave act as a coherent secondary source, the maximum optical path length difference among them would be AP -BP. The maximum optical path difference between the rays which is originating from point A and point B it would be AP-BP and this path length is represented by Λ_{max} . Now this path difference of course correspond to a source point at each edge of the aperture.

Λ_{max} is less than or equal to AB and this is very much clear because the path difference if you want to calculate then you will have to draw perpendicular from A to B, and if this distance is d then, and if this is theta then d cosθ represents the path difference and d cosθ would always be less than or equal to AB. The maximum value of path difference therefore, therefore will always be either equal to AB or less than AB.

Now consider the case when the wavelength which is illuminating this aperture is larger than path difference, the maximum value of path difference which is kept Λ_{max}. If this is the case and if we also assume that the ways which are emanating from point A and B are coherent therefore they would be initially in phase. And therefore, they all interfere constructively and this constructive interference would vary.

If you are close to integral multiple of λ or if you are close to the central point which is central point of the screen or if you are exactly on the axis, it is a perfectly constructive interference, if you go beyond a bit then it would be constructive interference. But it is not perfectly construct constructive, the intensity would be maximum at the center and it will slowly go down.

And this condition is satisfied as long as λ is larger than Λ_{max}. Now if the wavelength is large compared to the aperture the waves will spread out at large angles into the region beyond the obstruction. This is the list which we can take out from this slide. You will have maxima here and it will slowly decay down. The intensity fades away as you move away from the center from the axis of the symmetry.

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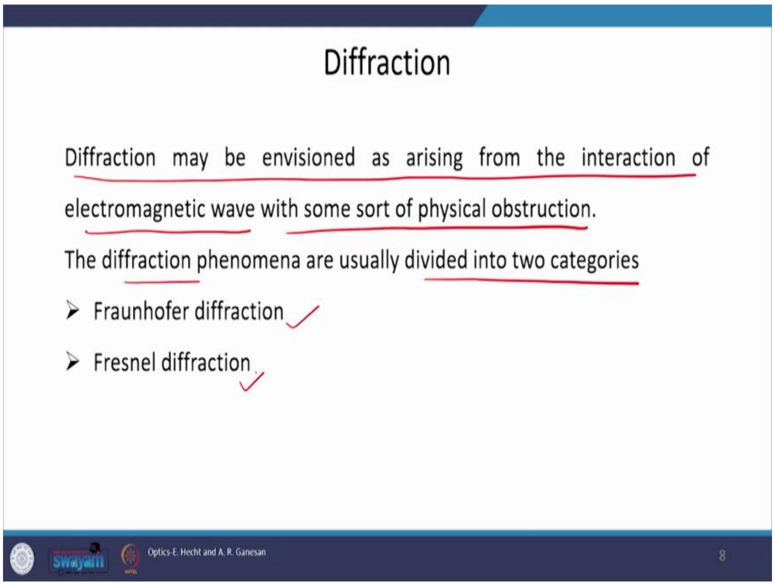

Now coming back to the definition of diffraction, diffraction may be envisioned as arising from the interaction of electromagnetic wave with some sort of physical obstruction. We always talk about bending of wave and the wave bend whenever there is some obstruction. But make it a point, if we want to observe diffraction or if we want to perform some measurement then only we require this bending or then only we require fringes which are introduced due to bending.

Diffraction will occur anyway, if you have multiple sources, the sources will emit radiation and this radiation will interfere and will give you some pattern. The pattern only serves us to measure the some parameter, like wavelength of the light and if there are two very closely spaced wavelength in the source then the separation between the source, this is the applications of the fringe measurement but the phenomena in itself, it is there anyway, irrespective whether we are placing some obstacle in the light path or not.

Now, the diffraction is usually divided in two categories. The first is called Faunhofer diffraction and the second is called Fresnel diffraction. We will talk about Fraunhofer diffraction and Fresnel principle diffraction one by one.

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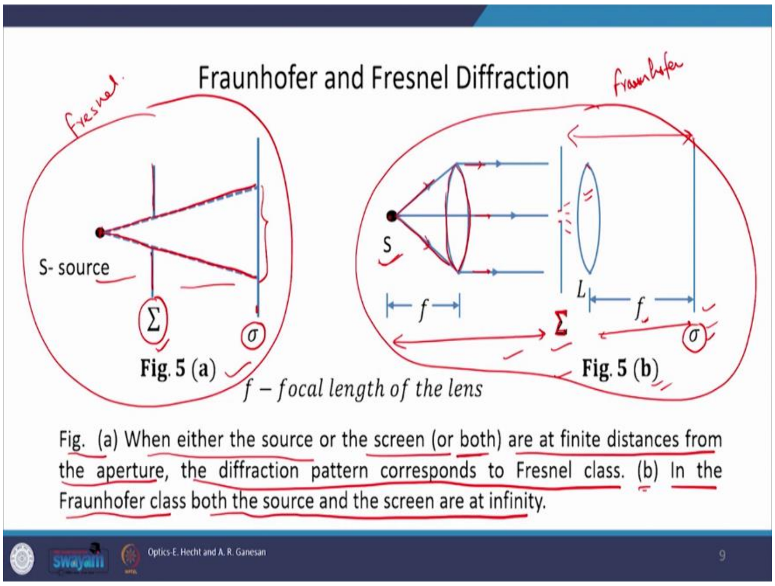

Now, consider that we have an aperture and the aperture plane is designated by this Σ. And we have the screen of observation which is designated by σ. Our source is situated here which is illuminating the aperture and then it is spreading, it is bending and we are seeing some pattern on the screen. This is the first case and in this figure 5 (b), what we see is that, we have a source which is generating some light.

Since it is a point source, it will emit a spherical wavefront and then with the help of a converging lens or a convex lens, we make this wavefront plane or we make these rays parallel. Therefore, parallel light illuminate this aperture, the aperture plane again is designated by Σ and then the diffracted light which is coming out of this aperture is again made parallel or the screen is kept at the focal plane of this second converging lens.

This distance is equal to the focal length of this lens and here again the screen plane is designated by σ. Now in these two cases the major difference is that in figure 5 (b), in the right hand side figure, the incident and the outgoing these two waves are plane waves, there wave front is almost plane. Therefore, what we can assume is that in second case both source and the screen are effectively at infinity.

Source is the separation between source and the screen plane here is almost infinity and the separation between the image plane and this aperture plane or diffracting element plane is also effectively infinity. While here both source and the screen are at a finite distance from the diffracting element or from the aperture plane. Now this left hand side figure, this comes in the domain of Fresnel diffraction, while the second figure it comes in the domain of Fraunhofer diffraction. This is Fraunhofer and this is Fresnel.

Now the definition is written in the figure caption here, when either the source or the screen or both are at finite distances from the aperture the diffraction pattern correspond to Fresnel class, as it is there in figure 5 (a). In figure 5 (b), in the Fraunhofer class, both the source and the screen are at infinity are effectively at infinity if you place a lens then you can use the word effectively at infinity.

Now, I repeat if either the source or screen or both are at finite distance from the aperture plane then such a diffraction falls into the category of Fresnel and if both source and screen planes are effectively at infinity from the aperture plane, then this type of diffraction fall in the category of Fraunhofer diffraction.

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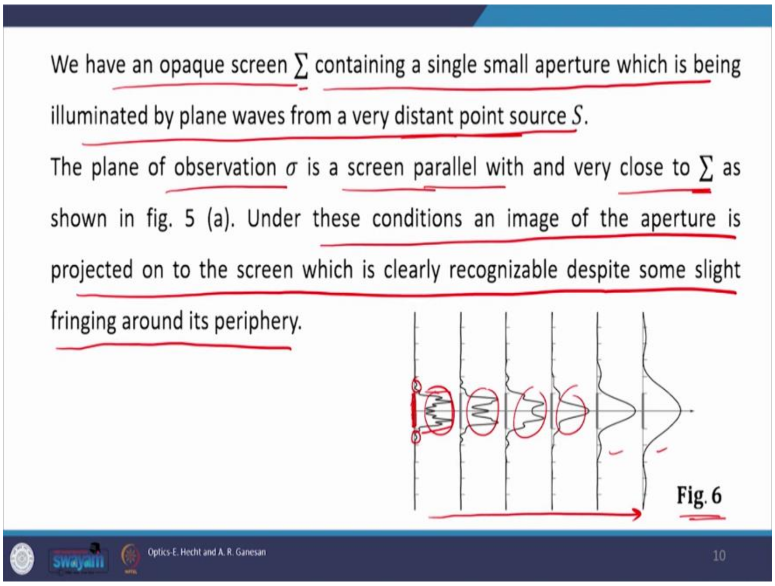

Now, we have an opaque screen Σ containing a single small aperture, which is being illuminated by a plane wave from a very distant point source S. This is what we saw in the last figure. The plane of observation is σ and this screen is parallel with the aperture screen and this is very close to σ in figure 5 (a) of course. Under these conditions as the image of the aperture is projected on the screen, which is clearly recognizable despite some slight fringing around its periphery.

What we expect in figure 5 (a) if we illuminate the aperture with a light, then the image of this aperture will be formed on the screen, if the screen is close to the aperture plane. But what will happen if you keep moving the screen plane away from the aperture plane and this is what is shown in figure 6. You see this is your aperture, this is your opening, and if the screen is very close to the aperture you see almost image of aperture, little patterns are also seen on the other side some light get bent.

But if you slowly move the screen plane away from the aperture then you see that this structure on the screen modifies and then ultimately it takes some stable shape which does not change with the separation, its size changes but shape remain invariant.

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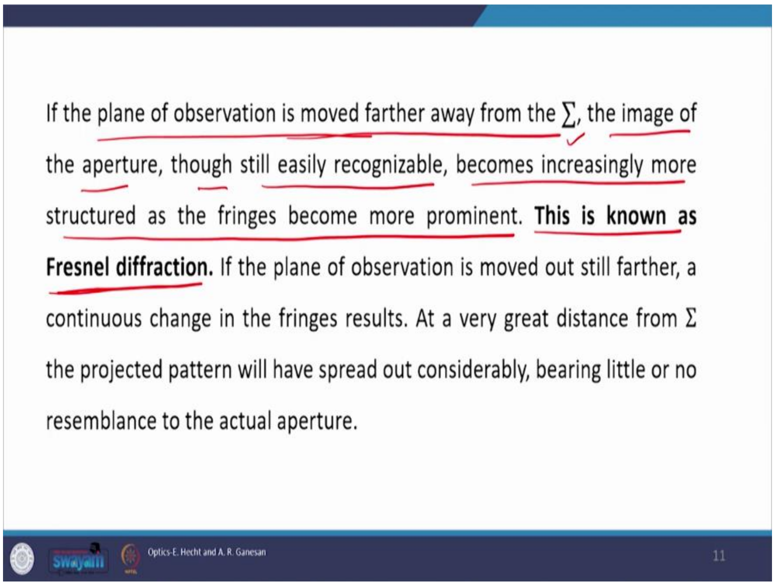

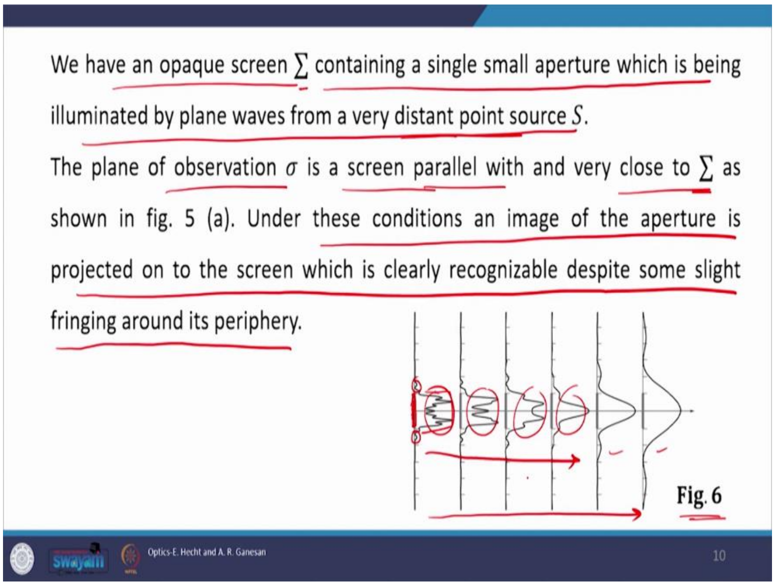

Now if the plane of observation is moved further away from aperture plane, the image of the aperture, though still easily recognizable becomes increasingly more structured as the fringe becomes more prominent. It is visible here in this figure, the fringes became prominent as you move away and this is known as Fresnel diffraction. As you move the screen the structure of the fringe pattern changes.

And if the plane of observation is moved out still further, a continuous change in the fringe results. And at a very great distance from aperture plane the projected pattern will have spread out considerably bearing little or no resemblance to the actual aperture. Now if the distance is very far then the pattern which you see on the screen it will not resemble the aperture. Aperture is of this side but the pattern you see in the screen would be very wide, very big as compared to the aperture, it can never resemble. And if the screens are close to the aperture plane then the structure on the screen resembles with aperture.

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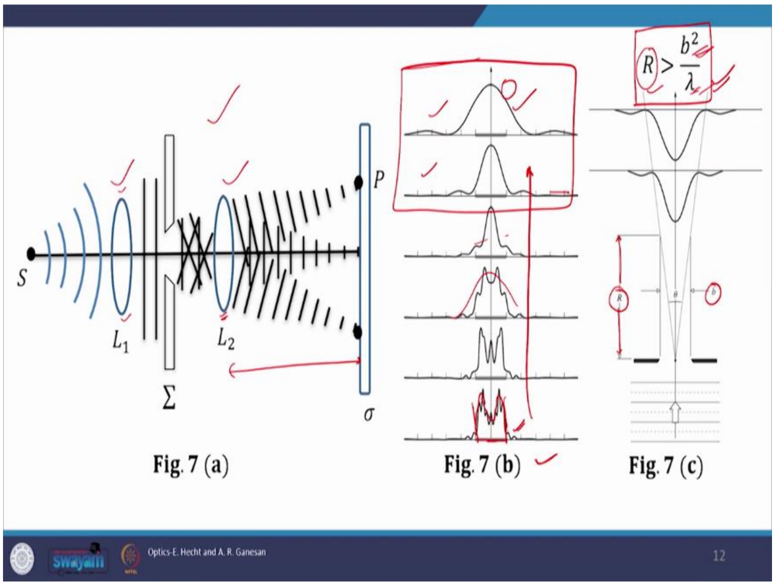

Now, in this figure what you see is that, this is the same figure which we saw in the last, two last slide and you see that there is some intensity pattern which you see here, which is almost resembling the aperture but as you move away from the aperture plane, as you increase the separation between screen plane and aperture plane, and what happens is that this structure is spread out. You are seeing that it is getting bigger and bigger, size is getting bigger and bigger and here it is not resembling with the aperture, this last figure.

Now, as long as with the movement of the screen, with the motion of the screen, the structure on the screen is changing its shape, the region is called Fresnel region and the diffraction which we see there is Fresnel diffraction or near field diffraction. But after certain distance what you see is that particularly in these two upper figures you see that although the size increases but shape remains intact and this only happens after certain separation between the two screens, the aperture plane and screen plane.

If the separation between the two is larger than some distance then only size varies and shape get fixed, this region is called far field region or Fraunhofer region. And there Fraunhofer diffraction takes place. As I said before, in Fraunhofer diffraction we use two lenses, one before the aperture and second after the aperture. What does this lenses do is that, first lens make the incoming rays parallel and the second lens is placed in is such that, that the screen is at its focal plane.

And therefore, both incoming and outgoing waves are effectively, they makes their images effectively at infinity and therefore we can say that both source and screen plane is at infinity and therefore we see Fraunhofer diffraction pattern here. If we are close to the source then we see Fresnel diffraction pattern. Now suppose the region or the distance between the source and aperture plane beyond which we see no change in the shape is represented by R and aperture size is b then the region for which this relation holds defines Fraunhofer region.

Suppose source and screen is at a distance R_1 and R_2 respectively from the aperture plane then we pick R which is larger of the R_1 and R_2, R is larger of the R_1 and R_2 and if this R is larger than b^2/λ then the diffraction is Fraunhofer. b is the aperture size and λ is the wavelength.

If we start reducing the λ then of course b^2/λ will get bigger it means that we are going into the Fresnel design and if we increase the λ then we are going into the Fraunhofer design. Similarly, with b, smaller is the b we are in the more into the Fraunhofer design, larger is the b, we are more into the Fresnel design.

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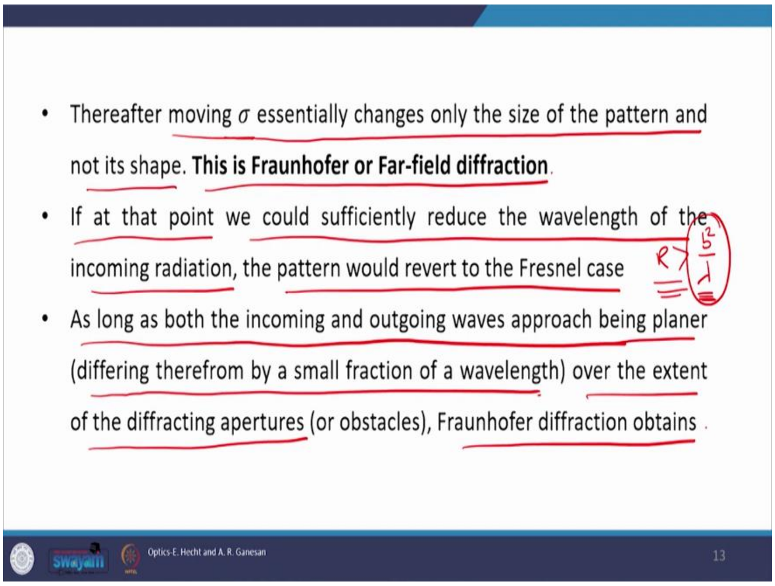

And therefore, continuing from the last slide, moving σ which is your screen plane essentially changes only the size of the pattern and not the shape. And this is Fraunhofer or far-field diffraction. If at that point we could sufficiently reduce the wavelength of the incoming radiation, the pattern would revert back to the Fresnel case.

This is what we discussed in the previous slide, if you reduce λ this quantity will increase and this condition will not hold there, means reducing λ lead to Fresnel design. Now as long as both the incoming and outgoing waves approach being parallel that is differing there from by a small fraction of wavelength over the extent of diffracting aperture, Fraunhofer diffraction obtains. If incoming and outgoing they are parallel wave then of course it is Fraunhofer region.

And this is all for today, this class is prepared only to introduce you the diffraction. I hope that the diffraction is understood properly and probably you know that the diffraction is not very different from interference. The crux or the gist is if we have sources which are small in number then the pattern is called interference pattern. And if large number of sources are involved like in grating, like a broad source if is there and then the interference pattern is called diffraction pattern.

But if we talk about mathematics then there is a operator which is called convolution operator. And if you read about the convolution operator, then I feel that the perfect definition of diffraction is nothing but this convolution, diffraction is nothing but it is a convolution. Now, since this convolution is beyond the scope of this course, therefore, we will not discuss in this course. Thank you for listening me and see you in the next class.