Optical Engineering
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Lecture – 43
Diffractive Optics

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Good morning. So, welcome to this class on Diffractive Optics, in this course we have only a certain amount of time to spend on the different topics and so in diffractive optics we will not cover all the details of the equations, but instead I want to introduce it to you in terms of how it affects optical systems, how we can use it in a good way and give you some overview of the applications that diffractive optics is used for. So, it is an overview and I hope it will help you understand diffractive optics in general.

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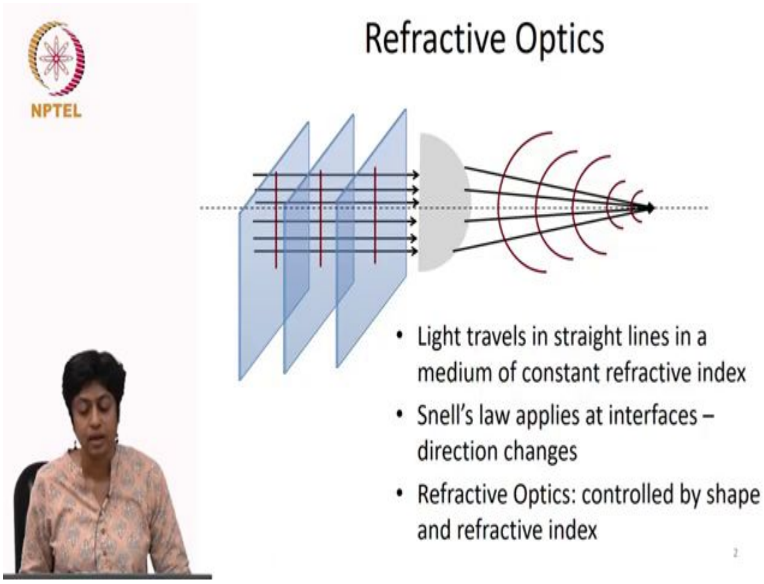

Now, till now in this course, we have actually been looking at refractive optics, lenses or reflective optics like mirrors, how did that work as a refresher let us just see. If we had a wave of light so these blue squares over here indicate the plane the phase front of that light.

If we had a plane wave; so these are the flat planar phase fronts that are coming in an incident on this lens, this is a refractive lens. The shape of this lens is what changed the incident beam and we went from having a planar wave to a wave with curvature, the curvature of course, determined by several parameters, some parameters of course, relating to the shape and refractive index of the lens.

In this way we manipulated the light, we changed the behavior of the light with an optical element and a refractive optical element. What did we look at right at the beginning of the course? We said light travels in straight lines and you can use a material like glass shaped in a certain way to change that direction, and we have so, that is Snell's law is what we applied whenever there was an interface and by shaping the material correctly we could get the required change.

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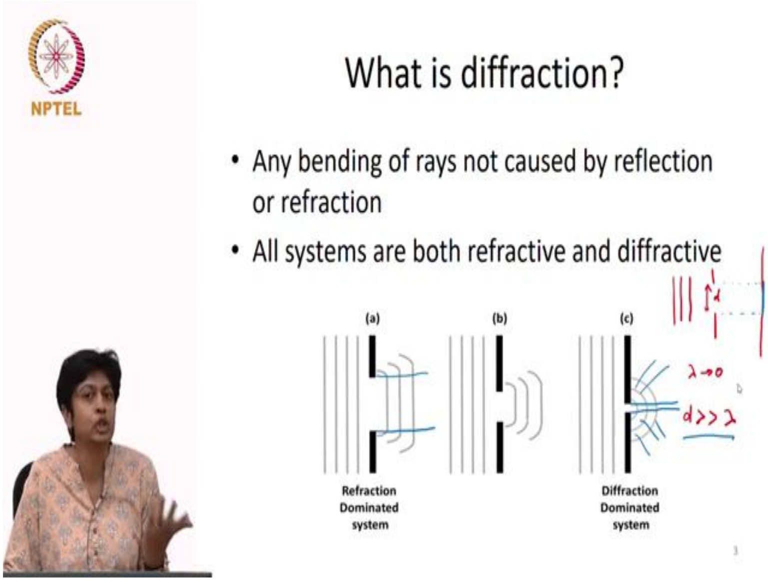

So, what is diffraction? So, if you ask someone whose in school or even people who have come to college and done a little bit of optics, the first answer you might get when you ask what is diffraction, is that it is the bending of light. Now, we just saw that when light hits an interface, you have air and glass light could bend, so that is refraction. So, how do I distinguish this bending of light by diffraction and this bending of light by refraction?

Well the answer really is to go back and see that diffraction is not simply the bending of light. One of the effects of diffraction is that light takes a route or a path that is not intuitive, it takes a path that does not, that is not a straight line path as seen or what one expects from geometric optics. One way of defining diffraction then is to actually define it by what it is not. So, any bending of light caused not by reflection, not by refraction you could think of this is diffraction ok.

Now, while that might be good for a definition, what does it really mean? So, to understand that let us look at three different cases. In all these pictures you have a plane wave that is incident on an aperture, the only difference between these three pictures is that the size of the apertures changes.

Now, what do we expect from a very simple geometric optics picture, is if you have a plane wave of light incident on an aperture. In geometric optics we assume lambda tends to 0 or in other words the size of this aperture d is very very much larger than lambda. In that case what would we expect if we looked on a screen some distance away?

We would expect that in a region corresponding to the opening to the aperture itself you would have a region of light and you would have darkness in the regions next to that. So, in other words you have perfect shadow in the regions next to the lit region and the lit region corresponds exactly to the dimension of the aperture. That is what you expect in geometric optics and if your apertures are very large that is this condition is satisfied that is in fact what you will see.

But the moment that aperture starts getting smaller and smaller and in fact starts approaching the size of the wavelength you start seeing light in regions beyond. So, in this first example most of the light lies in this region there is a little spread beyond, but you can see over here where the apertures become very small most of the light is in the region beyond.

Now, why does this happen? One thing to note is there is light traveling in this region. So, there is always some light that is obeying geometric optics. In other words I can say my systems are always both refractive as well as diffractive. It just can be under certain circumstances one of these phenomena will dominate.

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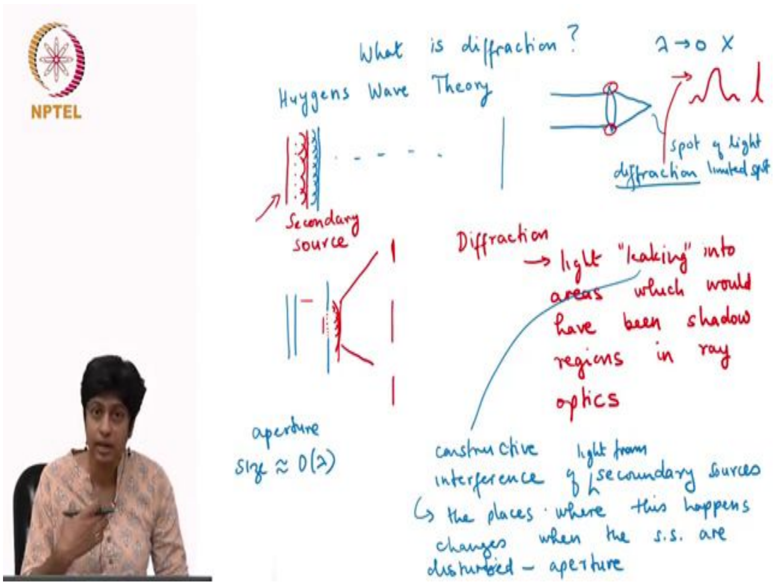

So, let us go back to the question of what diffraction is. We have seen when it occurs, so when you cannot when this condition is not true is when it occurs ok. So, to really understand diffraction one has to go back to a principle called Huygens Wave Theory of wave principle. Now, the scientist Huygen, has come up with this hypothesis that you could think of any wave as being constituted of many sources.

So, I drew this earlier as a plain wave, but you could think of every point every single point on this plane wave acting as a secondary source. So, every point is acting as a secondary source. What does that mean? From each one of these points you get another wave and in fact that is how the plane wave propagates. Now, every point on this will act as a secondary source.

So, every point acts as a secondary source and I get another set of waves from these secondary sources and I have the plane wave and this continues right. But in this ideal picture if I started out with a plane wave as the wave travels at any distance it is going to look very much the same, but what happens when it encounters an aperture? Because that is what we are concerned with.

So, let us say I have a plane wave and now we have an aperture. Up for in this distance whatever we saw here is what is happening so, the wave travels till it reaches the aperture. At the aperture now you have you can consider this region to have sources the rest are blocked, and for all the sources in the middle you can consider these travel onward undisturbed, but for the sources at the edge the wave gets disturbed.

And when the wave gets disturbed in other words that secondary source is disturbed. The region in which the phase matching condition occurs is now no longer this region, but something like this in other words what is happening is light is traveling in another direction. Now, the moment I said you can consider the wave as consisting of a number of secondary sources you could actually think of this as interference.

When we looked at an interferometer we said take a source of light, split it up into two beams and then have them interfere. So, an interferometer had two beams on, in general when we talk about interference we talked about a finite number of beams coming together because of some difference between these beams we see some effect or we exploit and get some up use out of that.

In diffraction you can see every point on the secondary source is act, sending out a wave all those waves are coherently interfering and causing the next phase front. Every point on that phase front acts as a secondary source; they are all coherently interfering and giving us the next phase front, but the moment there is a disturbance. The waves that are interfering have changed slightly and where the interference happens, it does not happen only in the open region somewhere here is where the constructive interference happens.

And that is why light leaks into areas which would otherwise have been shadow regions. So, I can think of diffraction if you want to give it another definition is light. It is because of this leaking I say leaking, but now you should understand that that leaking is actually constructive interference of secondary sources of light from secondary sources.

So, its constructive interference of light from secondary sources and the place or the places where this happens changes; changes when the secondary sources are disturbed and this happens whenever there is an aperture. Especially if the aperture size is in the order of lambda. Now, let me also allow you to remember something that we talked about in the past.

We said look at a system and let us look at the aberration, so you have say an imaging system and you want to create the perfect image, so you have designed your optics in such a way to minimize all the aberrations. If you remember we said the best you can do is to get a diffraction limited spot. So, if I had a beam of light and this single lens here now represents an optical system, if my optical system is perfectly designed and fabricated I would ideally get a spot of light here, but we always say we get a diffraction limited spot.

That is because the spreading of the light nor the leakage of the light of the in constructive interference in regions that you do not want there to be constructive interference of light, all of these different definitions of diffraction. All that they are saying is even if I have the perfect optical system light is going to spread a little bit and that is why the focus spot never looks like a point, the focus spot would always be something like this right, whereas ideally you would just want something like this.

So, this is a diffraction limited spot and you can now understand where it arises from, because light is interacting with the edges here you always have finite sized elements and the diffraction effects come into play and that is why you never get a perfect sized spot. So, that is a very simple way of describing diffraction. Who are the people who brought this theory or gave us more background information into this theory? I will call them the diffractive optics heroes.

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There are four people there of course, many other scientists who are important in this regard, but I have listed up four whose names you will see repeatedly if you are studying diffractive optics in detail. The gentleman over here, so this figure over here is from the 17th century the remaining 3 are well known scientists from the 19th century some of whose names you would have heard.

So, Fraunhofer, Augustine, Jean Fresnel and Gustav Kirchhoff these people are famous; they develop many theories of diffraction and Kirchhoff you would if you are an electrical engineering student you might have heard of Kirchhoff’s laws. So, he also of course, did not work just in optics or study electromagnetic waves, but also how voltages and currents in a circuit could be understood or calculated.

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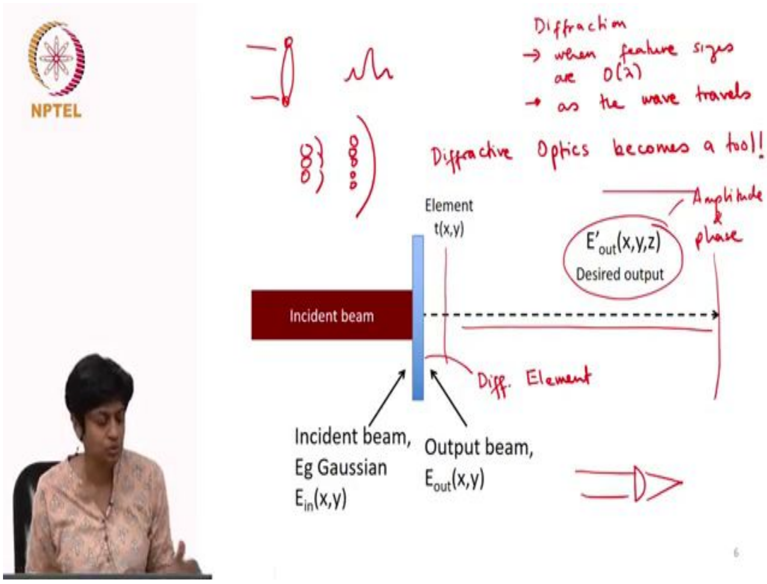

So, what we need to understand now or let us do a quick recap of what I have said about diffraction. Geometric optics, ray optics works fine when you can imagine your feature sizes to be very large or your element sizes to be very large compared to the wave length. In that case we say light travels in a straight line and I go from there and I can use a lot of trigonometry to figure out what happens to the light and I get very clear sharp shadows when I block the light in some way.

We see; however, that in systems with small feature sizes small openings light seems to bend into regions we do not expect it to go and that is, because now the size is effected, but the relationship between the size of that feature and the wavelength of the light is actually causing constructive interference from the secondary sources and that constructive interference takes light into regions that ray optics would not take it.

What you have to understand is I said in the imaging case I do a lens like this and I said you get a diffraction limited spot here. Well you could ask if the lens is large, its centimeters long the wavelength of light is in 100s of nanometers, why do we see the effects of diffraction here? It seems that the size of the object is much larger than the wavelength.

The point is when light sees the regions near the edge that edge is acting like the small aperture of the figure I drew earlier. So, while the bulk of the lens or base this that its dimension is much larger than the wavelength, this energy effect here you cannot ignore that some part of the secondary wavelengths with regard to the edge of the lens they are being blocked and they at that point the dimension being much less than wavelength is no longer true and that is why even apparently large systems do have diffractive effects.

So, we have diffraction clearly, when feature sizes; when feature sizes are of the order of the wavelength, but let us also think of this case. Say you had light coming out of a source, now fairly close to the source the size of that beam propagating is going to be very similar and does not change too much.

But as we saw with a Gaussian beam as the beam propagates it slowly starts growing in size, and we said this is the beam diverging. Why is the beam diverging? Well again it is because of these secondary sources and you are considering the wave from each of them, but as you as the wave propagates this is causing more of a divergence, and this divergence is also a diffractive effect.

So, I can talk about diffraction either because of the feature sizes I can also talk about it as the wave travels. Because we know only in a plane wave do we say that you have a certain set of secondary sources, but for the Gaussian beam you can imagine that the secondary sources now do not exist anymore on a flat surface they are exist on a curved surface and; that means, the directions in which their resultant wave exists is going to spread into other regions.

So, as the wave travels you can consider that as diffraction. So, you have two areas or two ways you can consider diffraction happening, it can be just because of the interaction of light with certain sized elements or it can be just the very travel of the wave that is causing diffraction.

Now, to the early optical engineering diffraction was a problem, you wanted a finite size spot and infinitesimal peak focused peak you did not get because of diffraction that was a problem. You want to resolve two things with a microscope because your spot is now spread and you cannot resolve that it affects the resolution. So, diffraction was a problem, but I can also use diffraction.

Because if you think of it, we use refractive elements to manipulate light in a certain way to carry out a certain function for us. What is diffraction doing? Diffraction is changing the intensity in the phase of the light at some plane away from the structure causing the diffraction. What if I create a structure that causes a specific intensity and phase pattern. I can also use a diffractive element just like a user refractive element and have a desired intensity of phase distribution.

So, diffractive optics diffraction in an imaging system is a problem, but diffractive optics becomes a tool ok. I can think of it as meeting your enemy or friend and using that friend ok. So, think of you have an incident beam you now have a diffractive element. This is the diffractive element, we will see what I mean exactly by the diffractive element.

But, I am now going to design this element in such a way that I control the output, I get a desired field when I say field I mean a desired amplitude as well as phase. And that desired amplitude and phase, it could be very close to the element, it could be very far from the element, it could be along the axis from the element, it depends on the application that I am interested in.

My goal is to use diffraction to create an element that gives a desired behavior that is a desired amplitude and phase in the regions after the element ok. Just like you think you had an incident beam you had a lens and then you focused it. So, it was a refractive element its goal was to focus ok.

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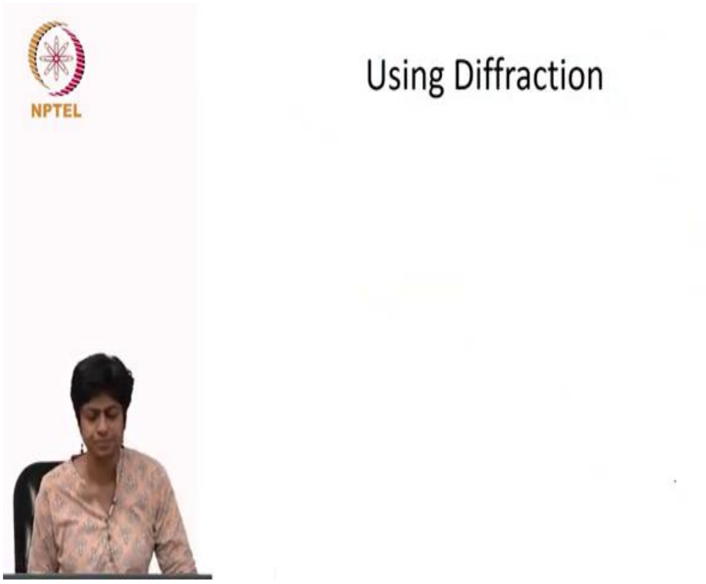

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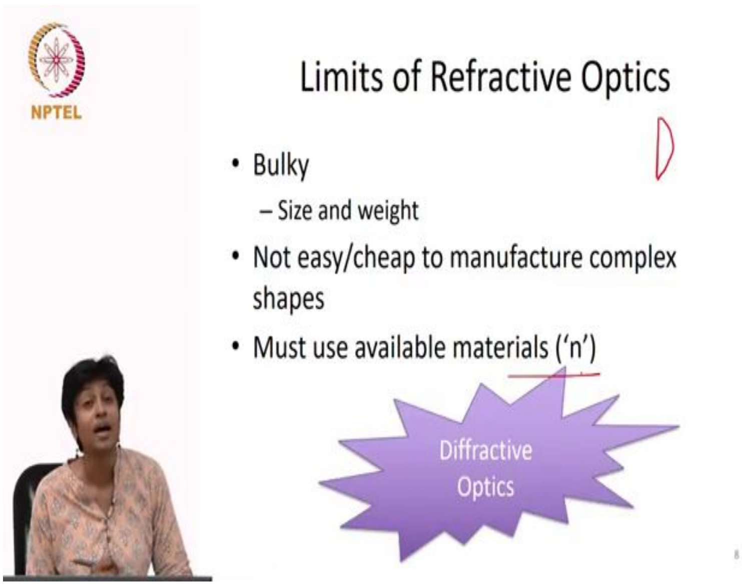

So, you might ask though, why use diffraction, when I can use refraction have these refractive elements why use diffraction? Well let us look at some of the issues with refraction.

Every time we draw a lens, we draw a lens like this right and we might in certain conditions say this is a thin lens, but the fact of the matter is the lens has a finite thickness and is usually made of glass, so its slightly heavy in other words its bulky.

It is not so easy to manufacture complex shapes, yes if I want to manufacture spherical surfaces. In fact, we manufacture spherical lenses even though they are not the best lenses, because that is easy to manufacture. So, even if I just want an aspheric lens it becomes hard to manufacture and if I want to manufacture something which is more complicated, why? Because, I want to create a phase distribution or an intensity distribution that has it is not just simple focusing but creates some exotic pattern, it becomes very hard to do that with refractive optics.

And again for refractive optics I need to pick a certain thickness or shape and refractive index and we do not have a lot of different materials we can use for refractive optics. So, we are very limited in the availability or the variety of n the refractive index. So, there are some of the limitations of refractive optics.

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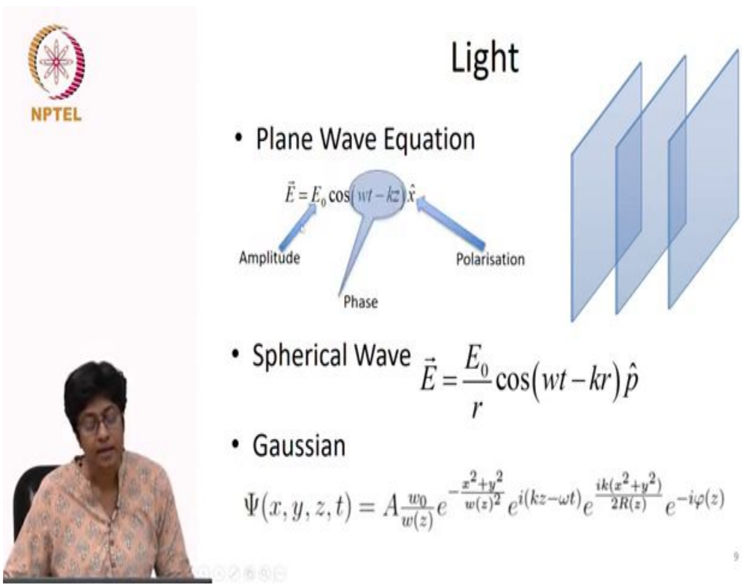

What do we do instead? We switch to diffractive optics. Now, just to remind you so it is a small recap in this course we looked at light, when we went to the wave theory we said you can consider it to be a plane wave a spherical wave a Gaussian. In all cases it meant you were talking about an amplitude, a phase and a polarization, and what is indicated in the figure here is the phase fronts of a plane wave.

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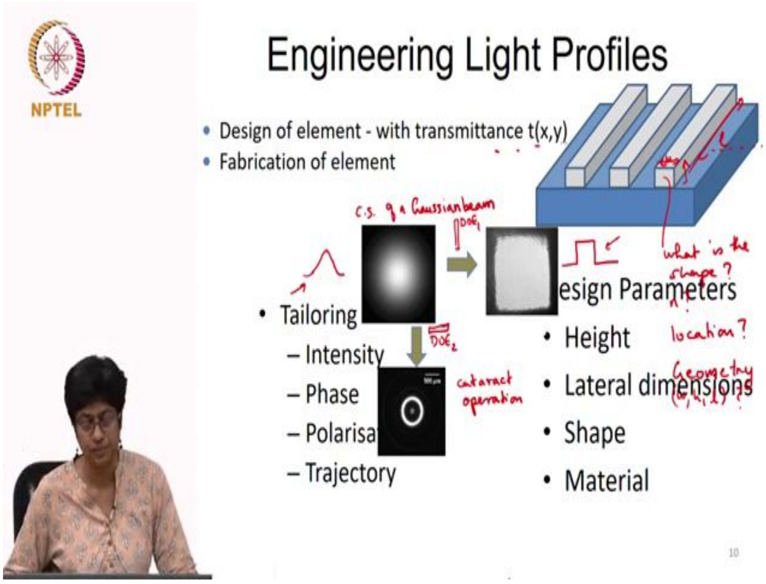

If, I want to engineer a diffractive element, unlike the refractive element I want to now use fine features, small structures to somehow manipulate light and we are going to do this we could play around, so that we affect the amplitude, we can play around that we affect the phase of the incident beam. So, let us take a structure like this. Let us say I had a structure which had these finite cuboids on it.

And, I am just showing you a part of the structure. If this was a diffractive element you there would be many more it is like I have shown you a section of the structure. Designing the element means, what is the shape of these structures? What is the refractive index? What are the location? What is geometry? In other words, what is the height and the width and the length? Right.

So, width height length is required in order to transform an input beam into some other kind of output beam. So, I am going to use this element now to tailor the incident beam's intensity, its phase, its polarization, even the path it takes its trajectory. And as I mentioned, the design parameters can be the lateral dimensions where these features are located: the shape, the height, the material.

Here is an example: this is a cross section of a Gaussian beam. This is if you looked at the cross section of a beam coming out of a laser, it would have this kind of intensity distribution you know that brightest in the middle tapering off towards the size. If I put it on a certain kind of diffractive element that was designed to uniformly spread out the light. So, the intensity of the Gaussian beam is spread like this and the intensity of this beam is spread like this.

So, maybe you are a manufacturer and part of the industrial process requires to uniformly heat up a patch of metal, if you use this beam you are heating up the central region more than the sides whereas, if you use this beam you are uniformly heating it up. What have you done, you have used some diffractive optical element that converts this intensity distribution to this intensity distribution. This is something not easy to do with the refractive element. I could convert this into a ring of light.

For example, if you are doing a cataract operation. The surgeon needs to make a circular incision to remove the lens. Now, why heat up the entire region to make a circular incision? You could just use a ring of light and so you could use another diffractive optical element, that would convert the incident Gaussian beam into a ring of light.

So, you buy these two simple examples should see that diffractive optics gives you the possibility of creating slightly more complex intensity and phase. In this case we are only played around with the intensity. I have not said what is the phase here, but I could also say I have a required phase and I could use a diffractive optical element to give me a desired phase variation.

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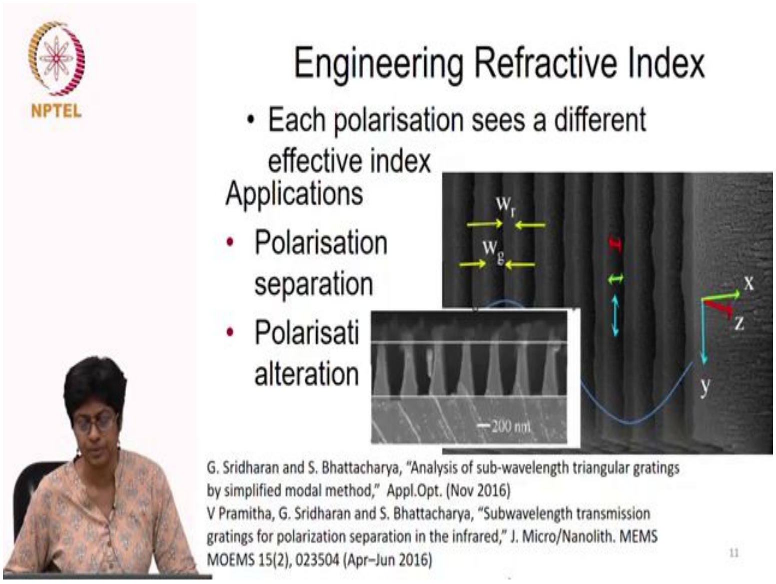

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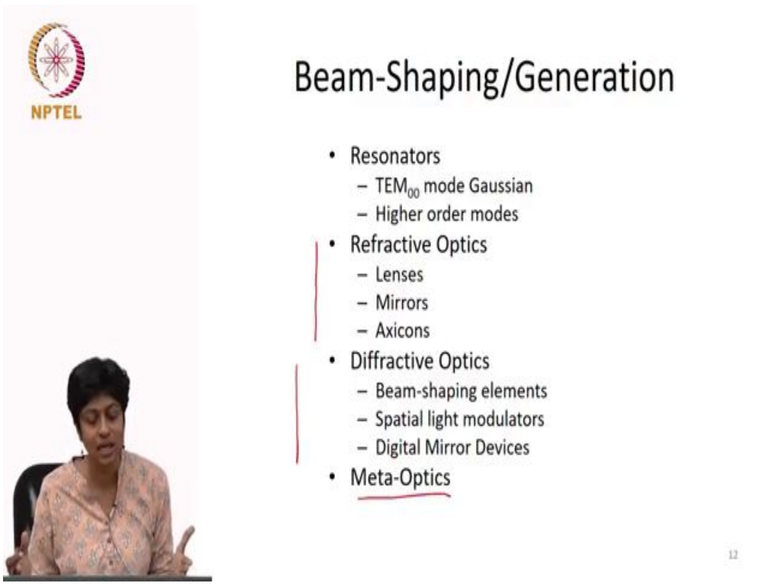

So, we started out by saying what is diffraction defining what is diffraction, we said for an optical engineer diffraction can be a problem because it spreads out the spot or it makes a beam that is traveling through space grow larger. But we can also use it and if we look at all the beam shaping techniques available to us you have seen that the refractive optics is what we have spent most of this course talking about, you also have resonators the way the light comes out.

It comes out Gaussian from a source that is because of the resonator and the laser, so that itself can be thought of as a beam shaping device. And what we will look at a little bit in the next few slides is the diffractive optics, just for the sake of completion I also mentioned meta optics which over the last decade or so has really revolutionized the way one shapes light.

And it has some advantages to diffractive optics, but in even to understand that it is best to go through diffractive optics. So, for the remainder of this class we will look at diffractive optics.

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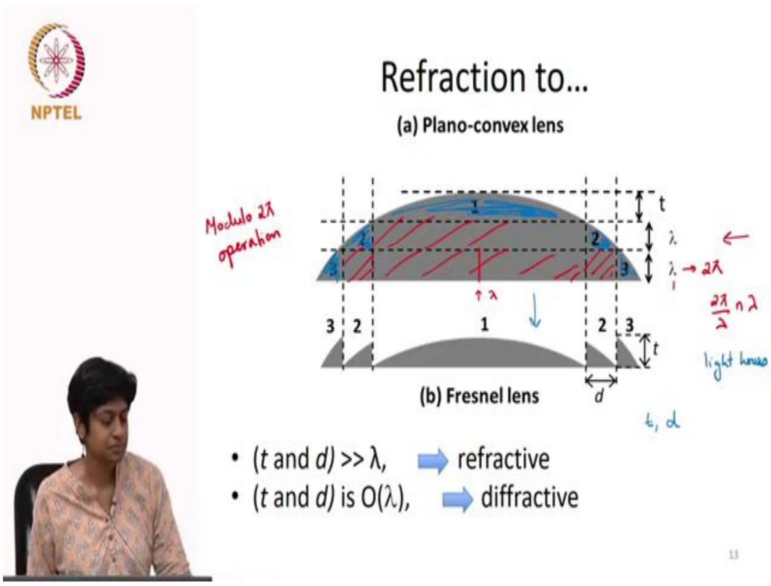

So, the one of the simplest ways of thinking of designing a diffractive optical element is to start with your refractive optical element. So, here you have a Fresnel a plano convex lens that is what is shown here.

Now, if I look at this lens and I consider the thickness of the lens what is the thickness of the lens providing in optical terms? As the wave travels through the lens for a distance corresponding to the; so, let us say you have an incident light of wavelength lambda, as it travels through the lens it has it for every lambda it travels through in other words. The phase is 2 pi by lambda into n lambda. Every lambda therefore, corresponds to a phase change of 2 pi.

And, we know if light undergoes a phase change of 2π you can consider the value of phase identical to the value of phase it started out with. So, that thickness of that lens is not optically actually doing anything for us. So, the diffractive optical element just eliminates these extra thicknesses. So, this is called a Modulo 2 pi operation where you are dividing the phase in terms of 2π levels, and removing all the 2π levels.

So, you draw the lines corresponding to lambda or that is to 2π and this section does not play any role, this section does not play any role. In this region this section does not play, in this section does not play any role and so you just pull out the remaining sections which is this region here, and this region here, and this region here, and this region here, and this region and that is what you get over here.

This is what we call a Fresnel lens. Now it is still not necessarily a diffractive lens because that is determined by the feature sizes t and d, and the very first Fresnel lenses were used in lighthouses, because you can imagine those lenses are huge they are meters in diameter and so the thickness of the glass in the middle was also very much meaning that the weight of those lenses are very large.

So, the very first Fresnel lenses were refractive Fresnel lenses because t and d were still very large, much bigger than the wavelength of light, but you could reduce the bulk of the material. If t and d now start becoming the order of the wavelength, then they become diffractive lenses.

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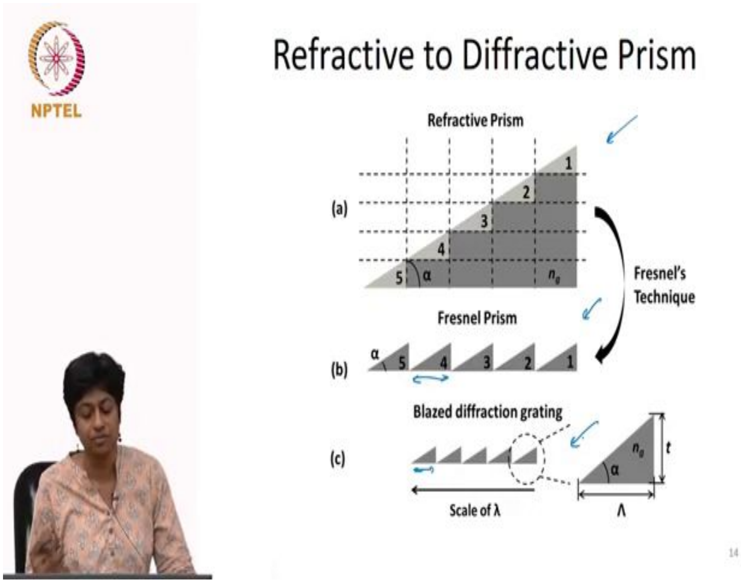

I can use the same technique to convert a refractive prism to a diffractive prism and in fact, we call this a blazed diffraction prism. And you can have a refractive Fresnel prism or a diffractive Fresnel prism depending on these dimensions ok. So, you can immediately see that the amount of material used here in the amount used here or here is far less, which means your element becomes compact and your element becomes less bulky baseless, and that is where some of the users of diffractive optics come from.

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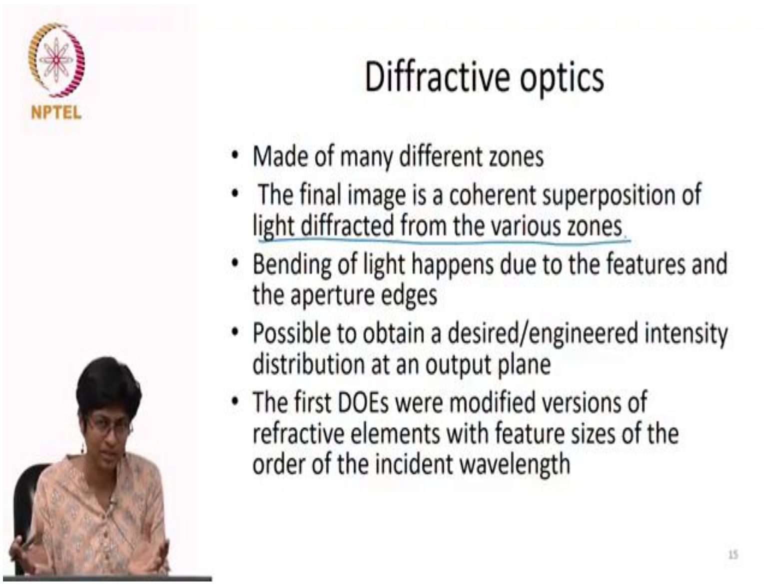

So, to summarize at this point. Diffractive optics works very differently from refractive optics. You are in some sense creating a number of zones in your element and the zones are creating a number of beams. The final image then is a coherent superposition of light diffracted from those various zones. The so called bending happens because of the features and the aperture edges and you can use this now to engineer a desired intensity or phase outputs.

What we have seen in the last two slide's were the first types of diffractive optical elements that were designed and fabricated; they were all based on refractive elements, you took an existing concept of a refractive element and then did this modulo 2π operation and converted it into a diffractive element. But you do not, you can see the power of diffractive optics lies in the fact that I can now create any structure. Even those that I could not ever do in a reflective sense, I can create any structure and therefore, I can manipulate light in ways that are not possible with refractive elements.