Modern Optics
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Lecture - 55
Acousto-optic Modulators and Devices (Contd.)

So, we have discussed Acousto-optic diffraction. We have seen that Raman-Nath type of diffraction and Bragg diffraction. In the case of Raman-Nath diffraction, the width of the acoustic wave required is small. So, we have as a thin phase grating whereas, in the case of Bragg type of diffraction, which is only one order of diffraction requires relatively large acoustic wave width and it behaves as a volume rating. Now, we will discuss the modulators based on this acousto-optic diffraction.

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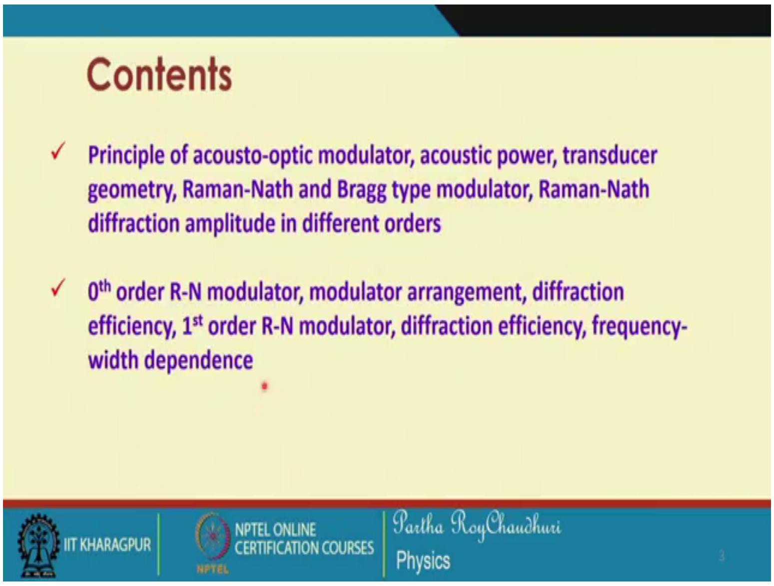

So, first we will consider a Raman-Nath type of diffraction. So, we will be discussing this the basic principle, which is involved with acousto-optic modulation. And how the modulation is related to the acoustic power, geometry of the transducer, then we will look at the difference at the Raman-Nath and Bragg type of modulators, consider Raman-Nath diffraction amplitude at different orders.

Then we will see that it gives rise to two possibilities; one is the modulator; it can be designed with the 0th order diffraction or the 1st order diffraction. And in both the cases, we will compare that diffraction efficiency and the frequency dependence of the width, so that will complete a discussion on an understanding on this Raman-Nath type of acousto-optic modulator.

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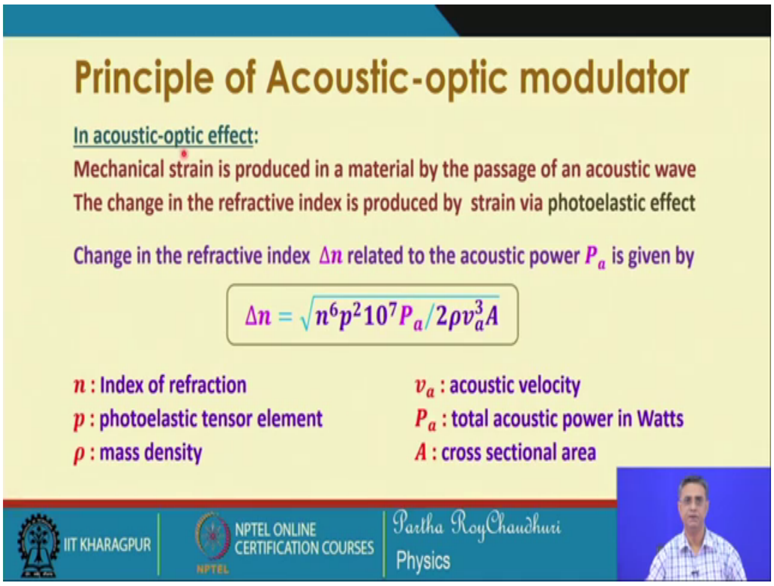

So, the basic principle let us remember that the mechanical strain, which is produced by the passage of an acoustic wave is to create a refractive index modulation, why this photoelastic effect. And the change in the refractive index, the peak change that is the maximum change the modulation depth delta n is related to the acoustic power by this.

We will see how we get this relation, so where but this is the relation, which will be used for designing such modulators knowing the values of this refractive index of the medium, the photo elastic the strain optic tensor coefficient, acoustic power, density, then velocity of the acoustic wave and cross sectional area of the beam that is effective for this for this diffraction. So, n refractive index photoelastic tensor, so by now we know all these terms, which are involved in this. So, this delta n is the peak change in the refractive index on top of the base refractive index, which is given by n that is because of the progression of the acoustic.

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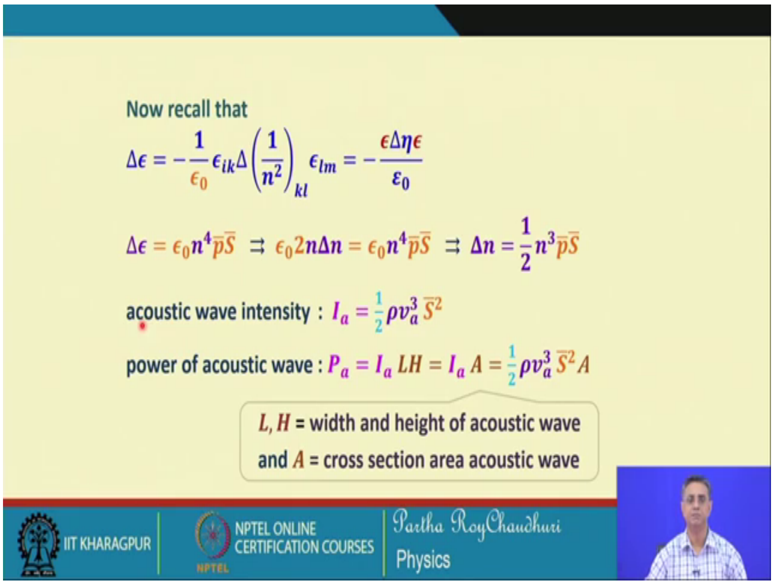

So, this is the basic principle that an acoustic wave propagates. There is a periodic change, there is a modulation of the refractive indices, which is travelling with the velocity of the acoustic wave. And now that optical beam will get diffracted depending on the acoustic wave characteristics, the beam can be optical beam can be modulated.

So, now let us recall this to get this equation, let us recall that the permittivity relation, which is given by this in terms of this impermeability change. And this delta epsilon is equal to n to the power of 4 p S that we have seen. So, this quantity because you have delta n delta eta, so this delta eta gives you delta of 1 by n square, which will give you twice n delta n this n to the power of 4, therefore we get this equation. So, delta n is equal to half n cube p a p into S after doing this, so from here we can get this equation this equation.

And the acoustic wave intensity is given by half rho v a cube S square. Power of the cost in terms of the power, we can write that acoustic intensity acoustic wave intensity multiplied by the cross section that is L into H. So, in terms of the cross section, we can write this equation here.

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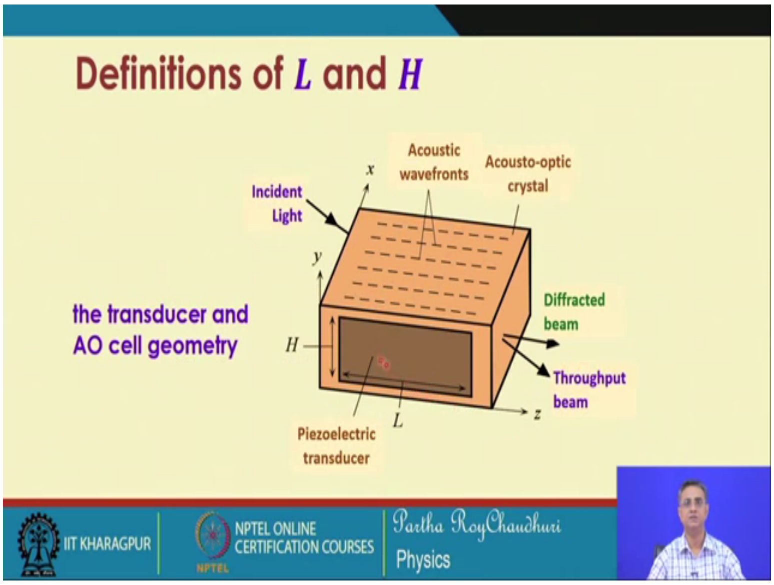

So, L and H width and height of the acoustic wave, we can see this configuration of the transducer. This is your L the length of the piezo transducer piezoelectric transducer. This is H the height and therefore it forms the cross section. So, this is the beam width that is propagating through this medium. So, acoustic wavefronts are given by this acousto-optic crystal is this medium and this is the diffracted beam throughput beam if you have an incident beam, this will be the throughput beam and there will be a diffracted beam.

In the case of Bragg type of diffraction, in the case of Raman-Nath anyway there will be multiple orders. So, this defines the geometry and the cross section of the transducer for this modulator power. This is very useful to understand how this configuration is required.

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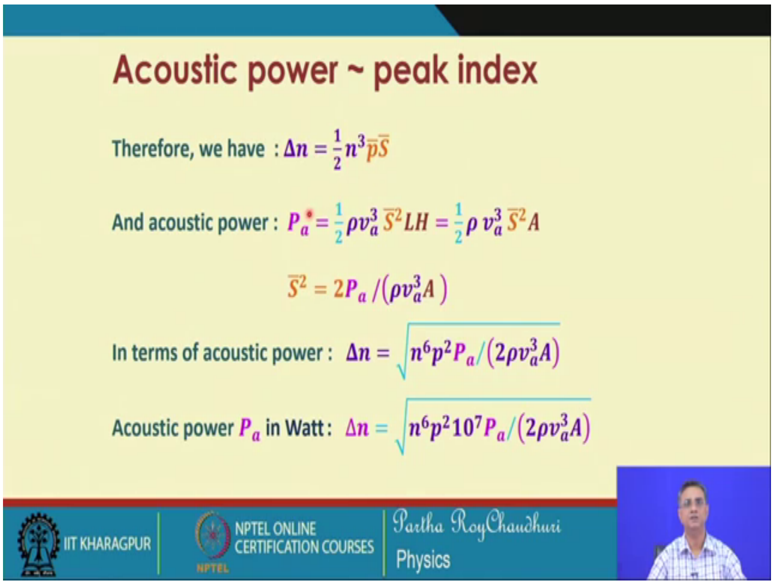

Now, since we have seen that this delta n is equal to half n cube p S, we will use this relation and then acoustic power is given by this equation, this just now we have seen. So, from here we get this relation very straightforward and then, we can get this in terms of acoustic power, this change in the peak change in the refractive index, which will be given by this. And the acoustic power in units of watt will involve 10 to the power of minus 7 in this expression.

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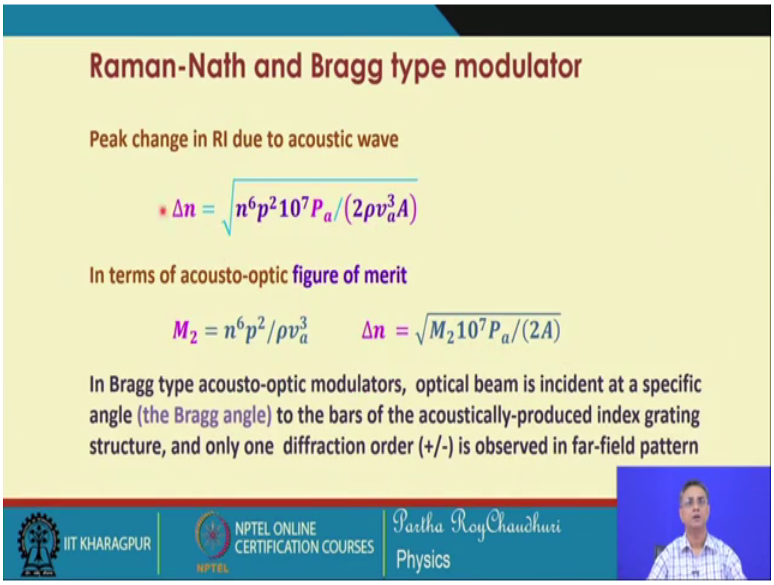

So, peak change in the refractive index is given by this. In terms of the acoustic figure of merit M 2 is equal to this and using this acoustic figure of merit delta n comes out to be equal to this. Expression is again useful for designing and analyzing acousto-optic modulators, because they will appear in common in all the cases. In Bragg type of acousto-optic modulator, the beam is incident at a specific angle, which will satisfy the Bragg condition and the acousto optically produced index grating, then only one diffraction order is observed.

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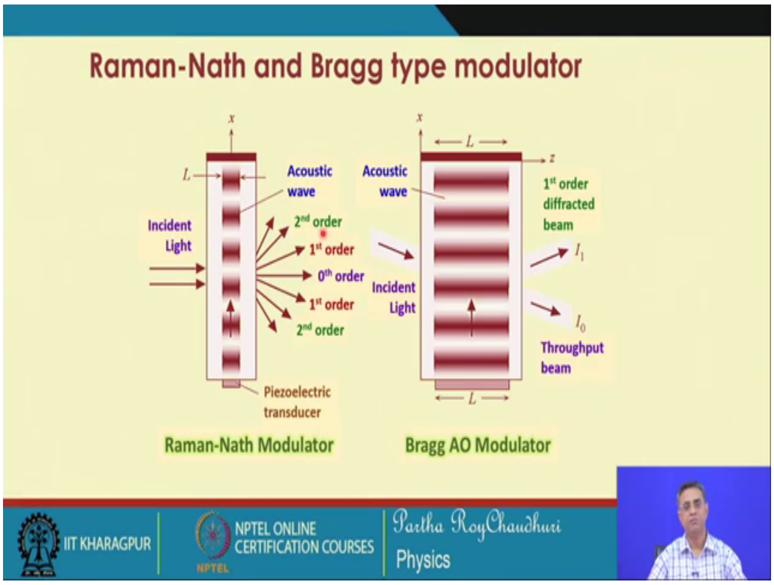

But, in the case of Raman-Nath, it could be a normal incidence and we will get a number of diffraction orders. So, let us recall this Raman-Nath type of diffraction, where the incident beam normally incident on this acoustic cell, Raman-Nath modulator cells. And there will be various orders 0th order, plus order, minus order, 1st order, 2nd order and so on this is the propagation of the acoustic wave. So, this gives a very clear picture and understanding about this.

And you see that the width of the acoustic beam is very thin as compared to a Bragg cell, which has a larger acoustic width. So, therefore, the wave optical beam is incident at a slightly different angle compared to the normal incidence. And you will get the throughput beam, which is along the same direction. And you will get a diffracted beam, which will be coupled from this to this 1st order beam here and this is how this Raman-Nath and Bragg type of difference.

In this case, once you have an incident beam, there will be a modulation periodic exchange of power between these two. But, in this case when there is an incident optical beam, the light from the 0th order will be distributed over all the higher order diffracted beams. So, designing a modulator with these requires a little you know we will see that there will be two possibilities.

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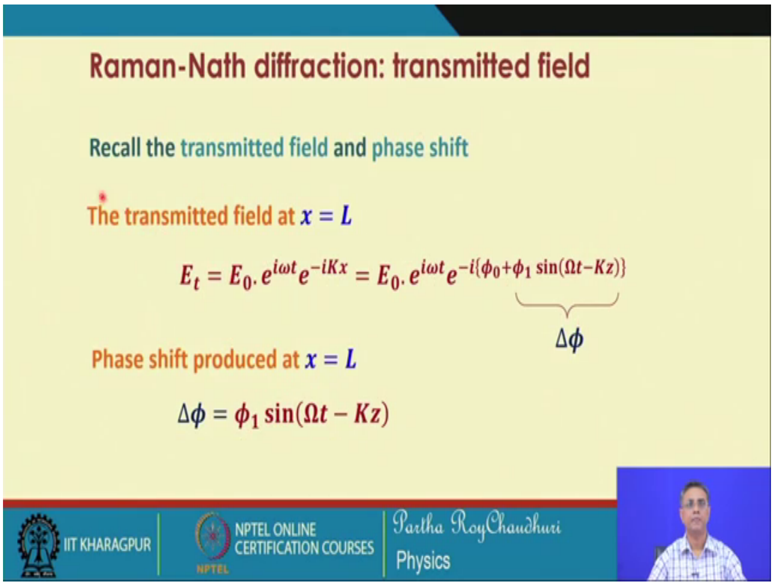

So, let us remember that the transmitted field is given by this, because these are the quantities which we will now require. So, this is the change in the phase, because of the optical wave because of the because of it is travelling through a length of L of the acoustic wave, but this is this will be the change in the change in the phase.

So, this change in the phase peak change in the phase will be equal to delta n, so that we will see which will be equal to phi 1 that we will see. So, the phase shift produced at x equal to L; at x equal to L here at x equal to L, I think we have a we will have a better picture phase shift produced at x equal to L will be given by delta phi is equal to this.

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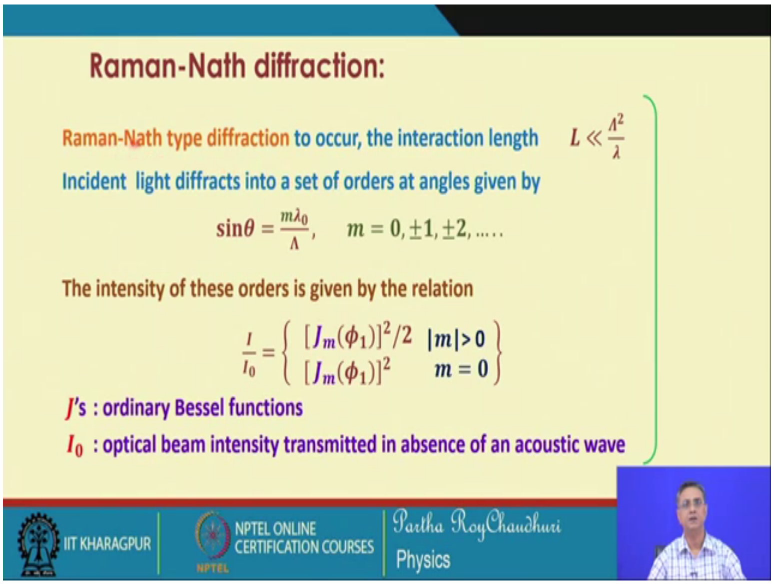

And this then Ram for Raman-Nath type of diffraction to occur the length of interaction this that is condition has to be satisfy. So, L must be smaller than this value that is the acoustic wave length square by the wave length of the optical beam. So, incident light diffracts into a set of orders at different angles, which are given by this we have seen this in details that how this should be sin theta m. So, the sine theta m for m equal to 0 plus minus 1 and 2. We will get the direction of the diffracted beams just by knowing the periodicity of the peach of the acoustic wave the wavelength of the acoustic wave and the wave length of the optical beam.

So, the intensity of these orders are given by the various orders of the Bessel function, and interestingly J 0 will correspond to the 0th order, J 1 will correspond to 1st order, J 2 will correspond to the 2nd order and so on. So, the ratio of the intensities at different orders will come from here I by I 0, when m is greater than 0 will be given by this. But, when m equal to 0 that is 0th order, then it will come from this equation, we will see that later. So, these are the ordinary Bessel function the J 0, J 1, J we have seen that and I 0 is the optical intensity of the optical beam in the absence of any acoustic wave that is the original incident beam.

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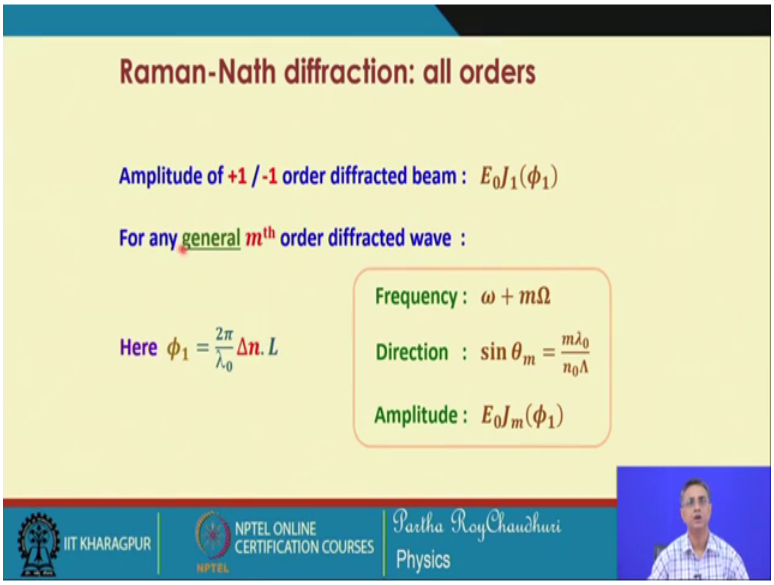

So, amplitude of the 1st and minus plus and minus order diffracted beam will come from here, easy row the intensive amplitude of the incident be multiplied by J 1. For any general mth order diffracted beam, these are the parameters associated with that order of diffraction m equal to 1, 2, 3 will give you the frequency upset or it could be minus also for the frequency down shaped theta will come from here, amplitude will come from we just have to replace this m by the corresponding order number of diffraction.

And this phi 1 is equal to this so, delta phi and phi 1, they are related as delta phi and phi 1 they are related as the peak value of let us say this delta phi will be the this phi 1 is the peak value of this delta phi. So, this is the maximum value of the change in the phase, so that will correspond to the depth of modulation of the phase.

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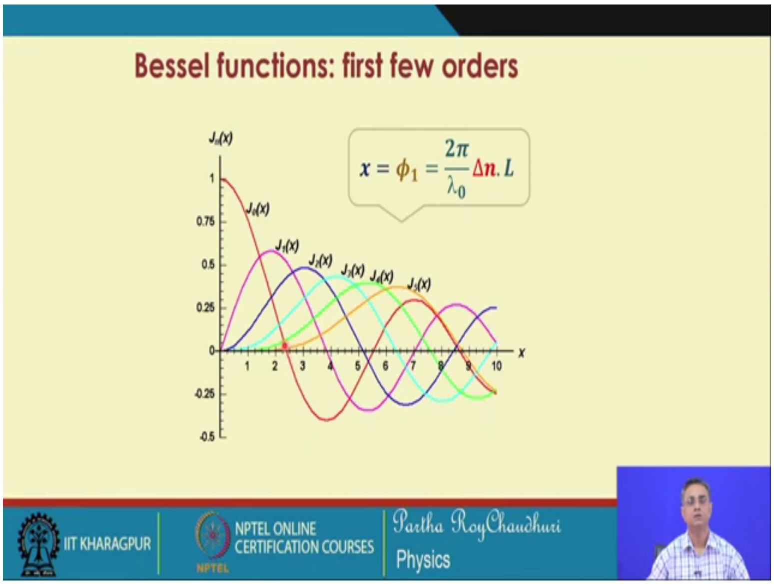

So, therefore, the various orders of Bessel function, we may recall that this is J 0, J 1, J 2 etcetera. So, they have different zero crossings and it is only the J 0, which is maximum at x equal to 0, in this case phi 1 equal to 0.

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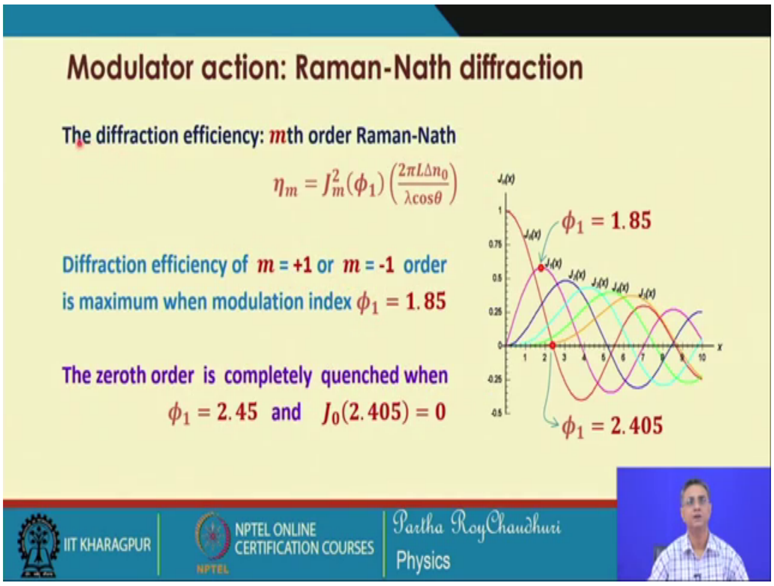

Therefore, the diffraction efficiency in the mth order will come from here J 1 square J J m square phi 1; phi 1 is phase, which will come from here. Now, the diffraction efficiency in the plus minus 1 order is maximum when the modulation index phi 1 is equal to 0, because that is the 0 of the Bessel function J 1. You can see this the this is the

Bessel function J 1, which has a zero crossing at this point, which corresponds to a value of phi 1, because in this axis it is phi 1 this to be represent this x.

So, therefore phi 1 equal to 2.4045 will represent the zero crossing of the Bessel J 0 function that is which will correspond to the 0th order diffraction. But, J 1 this to correspond the plus and minus order of this Raman-Nath diffraction, we will have the peak value at J 1 equal to 1.85. So, these are the two main points, which will guide the modulator design. So, this point at this point the 1st order diffracted beam will have the maximum intensity at this point whereas, the 0th order diffraction beam will have the minimum intensity at this point.

So, this tells us that you can see that the 0th order is completely suppressed completely quenched, when J 1 equal to 2.4048 this value at this value. So, it guides you it provides a guideline that there could be two types of modulator design; one is using the 0th order, another is using the plus or minus order of the diffraction view.

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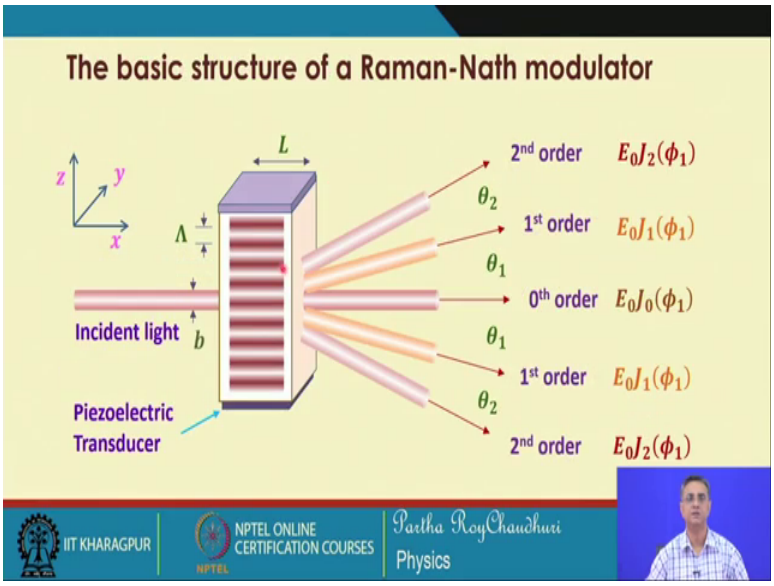

So, we will continue our discussion with this. So, the schematic of this Raman-Nath type of modulator is you have an incident beam, which is incident normally. And this is the beam width, you have this acoustic wave length capital lambda and the beams are diffracted this is the 0th order beam, plus 1 order, plus 2 order, minus 1 order, minus 2 order and so on and so forth.

So, the and you can see that interestingly they correspond to the 2nd order is given by J 2 multiplied by E 0 J 1 multiplied by E 1 to represent 1st order and for 0th order this E 0 J 0. So, knowing all these J 1, J 2 for the value of phi 1, which will be the phase that will be accumulated by the optical wave while traveling this length. We can find the intensities the distribution of intensities at the various diffracted orders.

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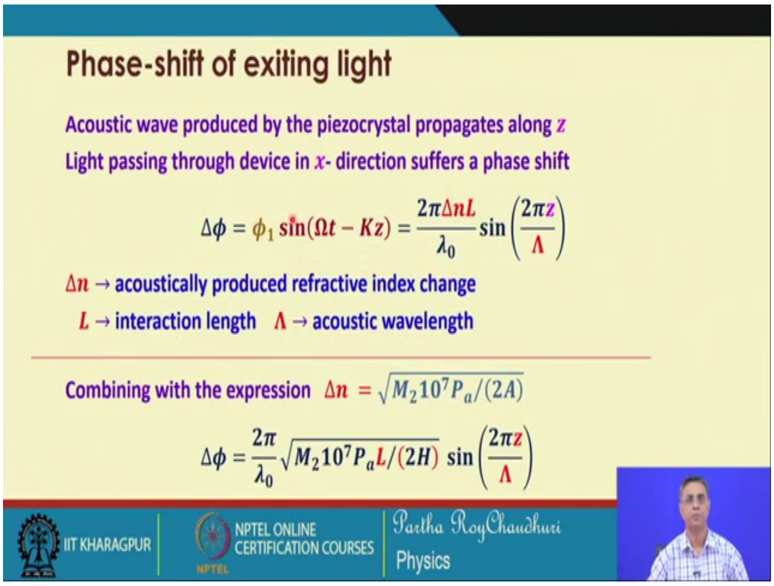

So, del phi d delta phi is equal to phi 1 sine omega t, because this is at a acoustic frequency looking at the standing nature of the grating with respect to the high frequency of the optical beam. So, therefore this delta phi will come which is equal to phi 1 twice pi delta n is the peak change in the refractive index multiplied by L and divided by lambda 0 that is K 0 delta n into L, this is equal to phi 1 and this sin.

So, this phi 1 is the amplitude is being modulated by this acoustic frequency acoustic wavelength. So, length L is the interaction length that is width of the caustic wave through which the optical beam travels and capital lambda is the acoustic wavelength this we have seen. So, now if we combine these into this expression of delta n, which is given by this we have seen earlier that the peak change in the refractive index. In terms of the figure of merit and acoustic power and width of the acoustic wave we can write in this form.

Therefore, this delta phi will be given by this, delta phi involves one more L, in addition to this so this twice pi by lambda, now L goes upstairs and this becomes twice A. So, this is L into H and you have L outside so you get this. So, this is simply I express this quantity in terms of this delta n which is in turn again represented by M 2 an acoustic power. So, this is the expression for the phase change of the optical wave as long as it is traveling through a length of L of the acoustic beam.

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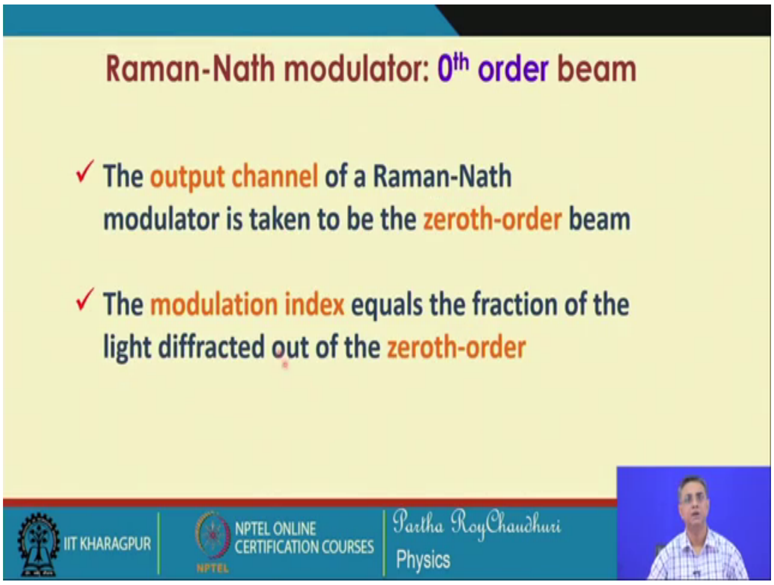

So, the output channel of a Raman-Nath could be 0th-order. If we consider that the 0th-order is the output channel there, the intensity will go from maximum to minimum that will be the modulation. And so therefore the modulation index equals the fraction of the light diffracted out of the 0th-order to the various higher orders.

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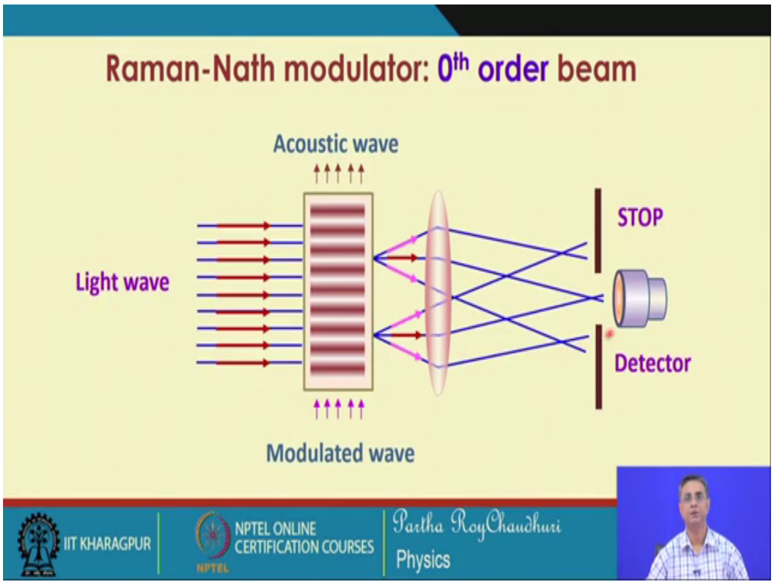

So, we can put the detector at the 0th order, and we stop all the higher orders. So, in the case of we just look at the variation in the intensity in the 0th order. So, this is how the light wave is incident, it passes through this modulator. You have a lens, which will collect the beams at various orders so, this here you will get the 0th order in front of which there will be a detector.

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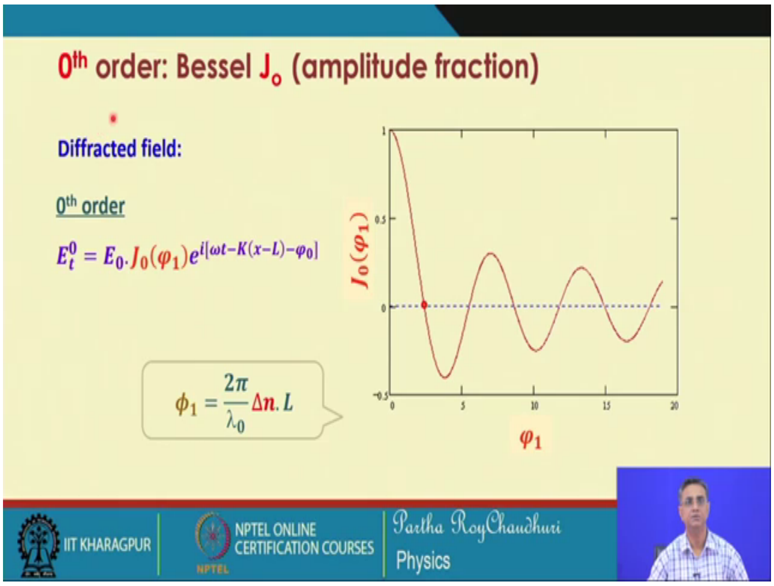

Now, look at this for the 0th order diffracted beam you have this 0 of the Bessel function, which corresponds to 2.4048, 2.4045 at this point. So, this is the flexible, this is the dynamic range for modulation. So, the intensity without any acoustic wave will be here, which is the maximum intensity at the 0th order beam.

And this decreases as the diffraction distributes the optical intensity to various orders. And it comes down to 0, when all the incident beam 0th order diffract 0th order beam intensity is distributed to all the higher orders. Therefore, this is the effective modulation range over which so the phi has to vary from 0 to this 2.4048 phi 1 has to vary from between this, so that will provide the modulation depth so, phi 1 is equal to this. Therefore, knowing this phi so these are the additionally it could happen, here also this is another 0, this is another 0.

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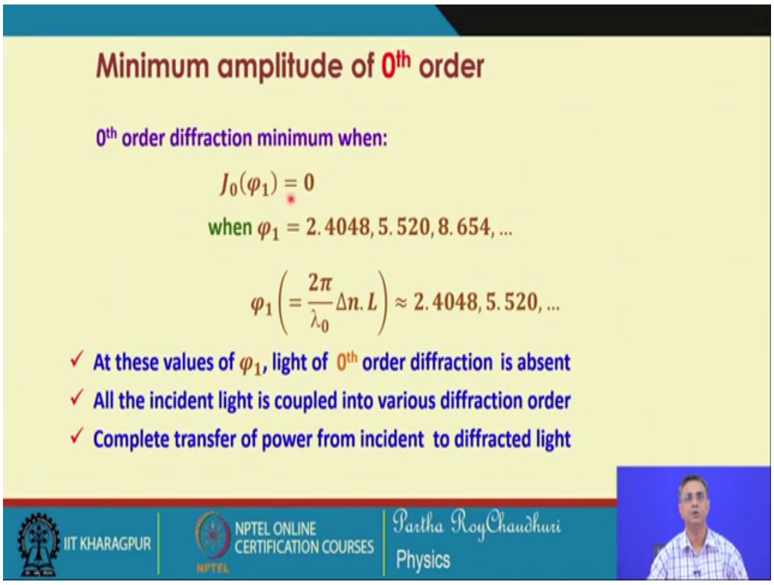

So, these are the 0's of Bessel functions, but the first 0 we will occur here and as a result, we will get this. So, all these values of phi 1, light of 0th order diffraction is absent. So, at this point there is no light in the 0th order all the intensities are distributed in the various higher orders. So, complete transfer of power from the incident to the diffracted wave is possible and we will provide the maximum modulation of the incident light to higher. So, this is the light will be a light will be modulated to 0 between 0 and 1

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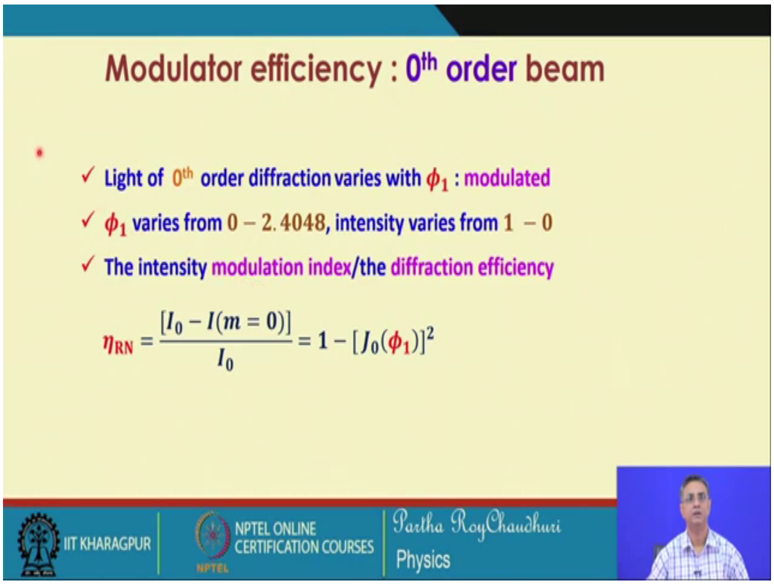

And the diffraction efficiency in this case will be equal to m equal to 0. So, I 0 and for the 0th order this is the incident beam and the intensity of the 0th order beam. So, from here, we can calculate the diffraction efficiency. The intensity modulation index or the diffraction efficiency is given by this equation, which is very straightforward.

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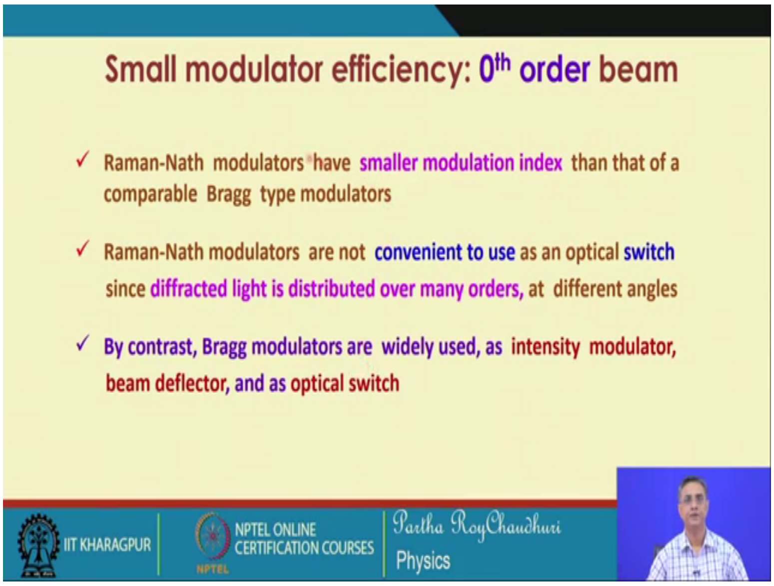

So, small modulator efficiency; the Raman-Nath modulators have smaller modulation index than that of the comparable Bragg type of modulator, Raman-Nath modulators are not convenient to use as an optical switch since the diffracted light is distributed over many orders and that too happens at different angles therefore, it is difficult to track all of them. By contrast, Bragg modulators are widely used for optical modulator, beam deflector and also optical switches.

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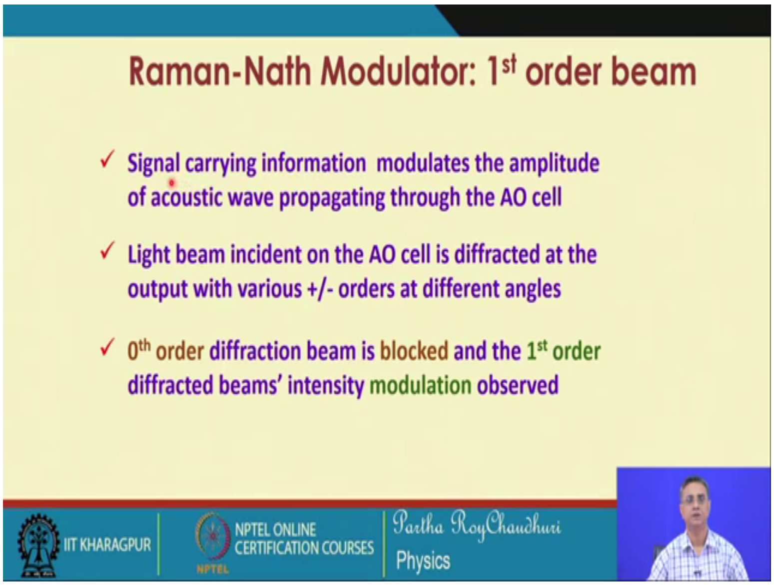

Now, we will see the modulation property. If we employ this 1st order diffraction, signal carrying information modulates the amplitude of the acoustic waves propagating through the acousto-optic cell and that will modulate all the power incident power optical power into various diffracted orders and plus order and minus orders. The 0th order diffracted beam is in this case is blocked. And we look at only the 1st order beam and look at the modulation, because it is not the range only but, you have to see how first it is falling to 0 and what is the diffraction efficiency.

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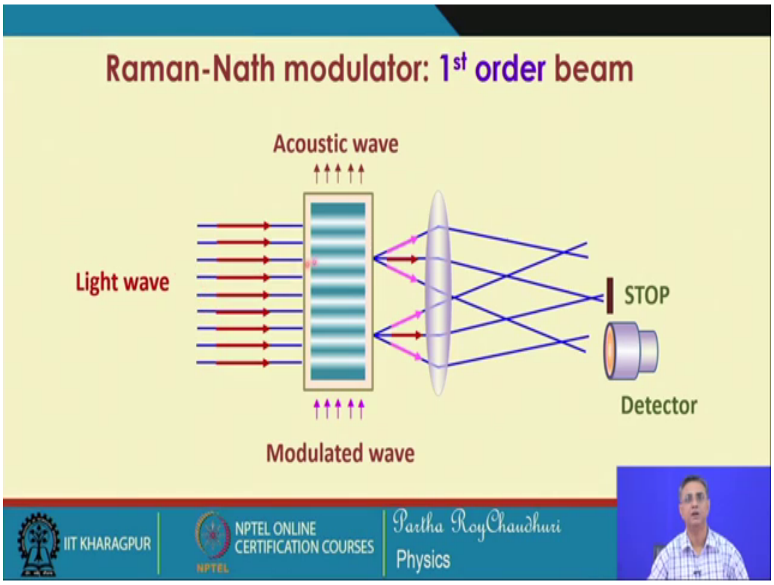

So, in this case, you look at the design of the modulator for the 1st order beam. You have this optical acousto-optic cell and the light beam is incident normally on this cell and various orders various diffraction orders. And now in this case you put a stop at the 0th order, but you put the detector at the 1st order. And take the signal out from this, which will give you the modulated signal the way this acoustic wave will be modulated.

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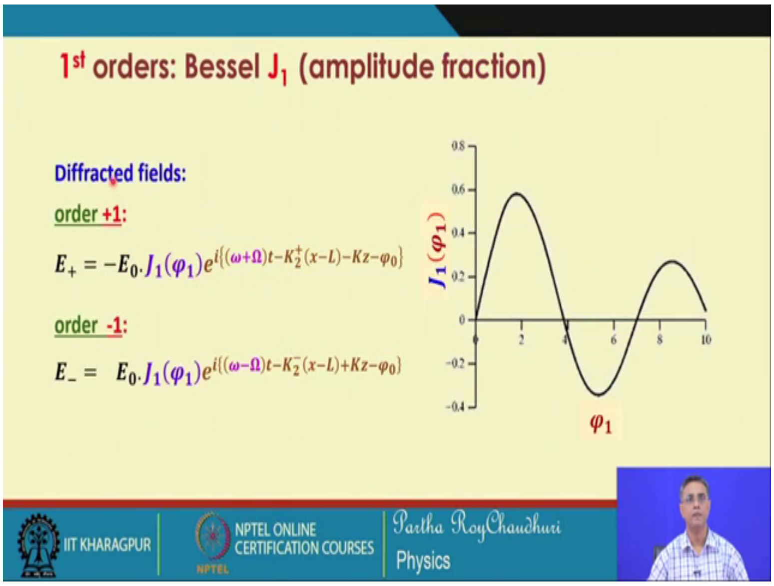

1st order first order Bessel function, if you look at this, you see this is the expression for the amplitude of the light electric field amplitude of the light, which is diffracted in the

1st order and this is the amplitude for the minus 1 order. And you can see that this amplitude, it becomes maximum at this point it becomes maximum at this point, you can see this amplitude becomes.

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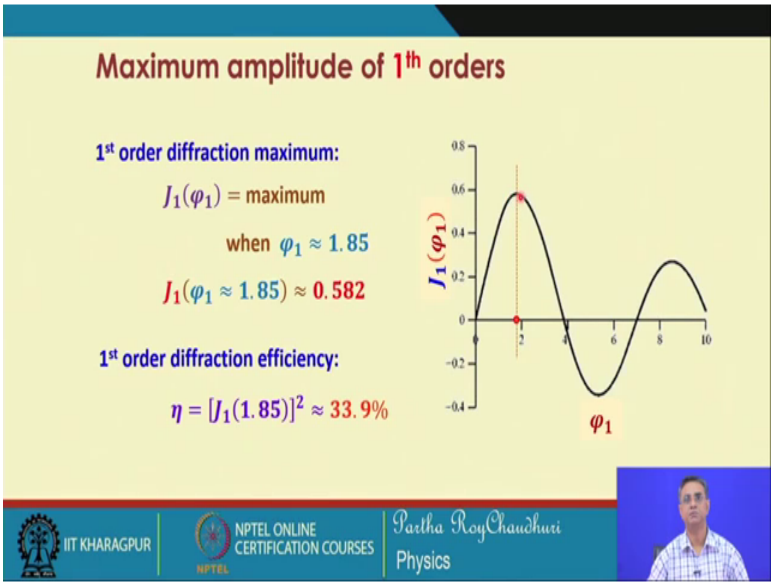

Therefore, starting from 0, so when you have phi 1 equal to 0, you have no light in the 1st order diffracted beam. But, when this phi 1 the phase change phi 1, which will be modulated as delta phi equal to phi 1 sin of omega t or sine of k z periodically along the length of the of the acoustic wave. So, this is the value of phi 1 when it is equal to 1.85 this value, you get that the maximum power in the 1st order diffracted beam. And that gives you the modulation starting from 0 up to this.

And this intensity corresponds to a diffraction efficiency, which comes from this is roughly about 34 percent that we have also seen earlier. So, you get a diffraction efficiency of 34 percent starting from 0 to 1, this amplitude modulation is can be configured using this 1st order diffraction beam.

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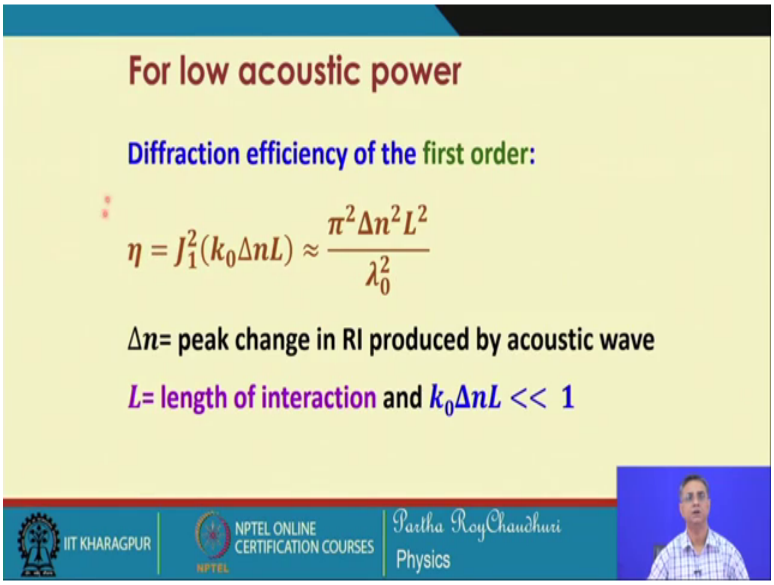

And this is for low acoustic power, we have also seen that. This diffraction efficiency can be simplified in this form pi square delta n square L square by lambda square. As a result, the peak change in the refractive index produced by the acoustic wave. This and this length of the interaction, therefore, this will be less than k 0 delta n and L.

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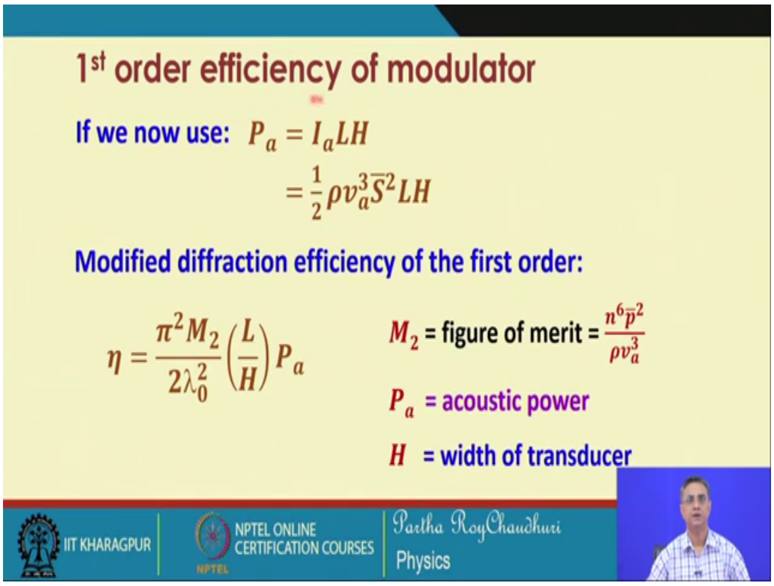

1st order efficiency of the modulator if we now use this relation, that is acoustic power and acoustic intensity relation, which will finally lead to this diffraction efficiency for the 1st order, we can write in this form. A very simple straight forward algebra and M 2 is the figure of merit, which is given by this. And I said this is common and the P a and H are defined as the acoustic power and this.

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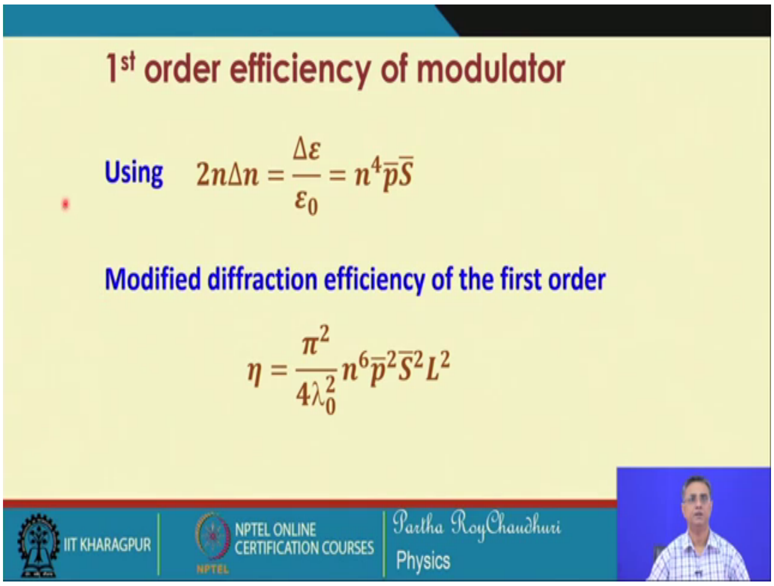

So, now again the one which we have used that n equal to n cube, n cube half n cube p into S. So, if I use that, so delta n will be equal to half n cube p into S will give you the diffraction efficiency in this form. Using this case for this case that is when the acoustic power is low and we have seen how we can approximate the diffraction efficiency as this.

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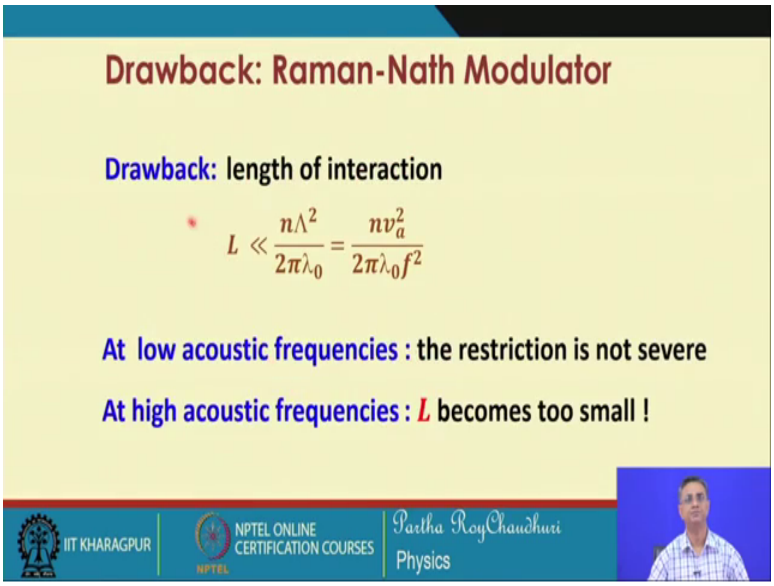

Therefore, the problem with this the drawback using the system that the length of interaction L comes from here at low acoustic frequencies, this restriction is not severe. But, at high acoustic frequencies L becomes very large.

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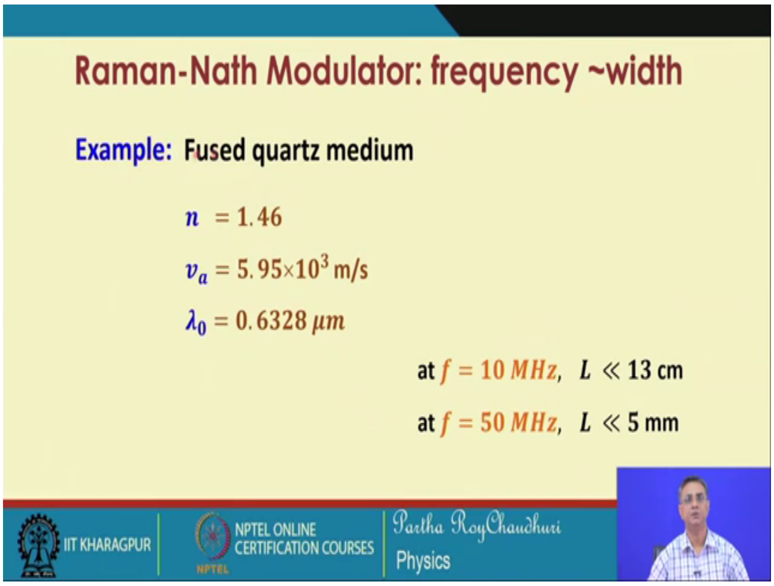

For example, if we take the case of Fused quartz, then n equal to 1.46 for an acoustic wave velocity given by this 5.96. These are the typical values and for a helium neon laser wavelength 0.6328 micrometer. The frequency for 10 megahertz less than 13 and for 50 megahertz if you this.

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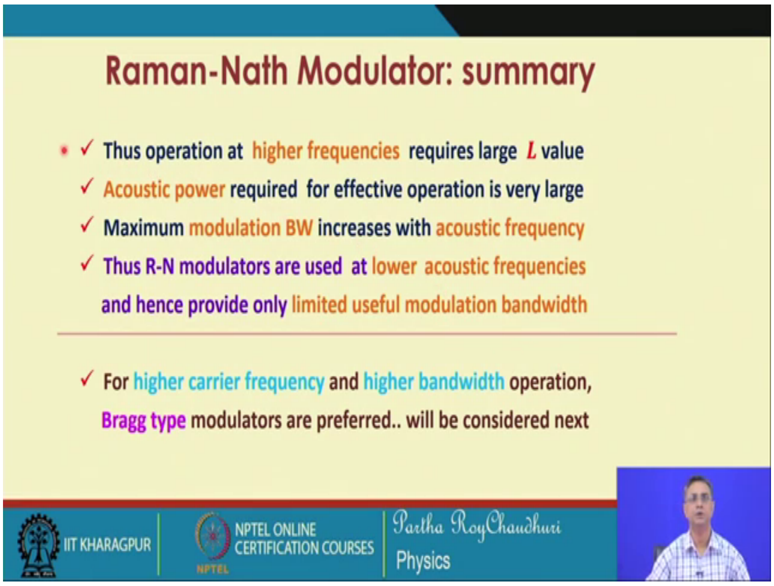

So, therefore that is the operation at higher frequencies, it requires a large L value. And the acoustic power required for effective operation is also very large. So, this is the limitation for this Raman-Nath type of modulators maximum modulation bandwidth increases with the acoustic frequency. If you increase the acoustic frequency, you can get maximum modulation and this Raman-Nath modulators are therefore used at lower acoustic frequencies. And hence provide only limited useful modulation band width for higher carrier frequency and higher bandwidth of operation,

So, with an understanding of this limitations of this Raman-Nath modulators, particularly for higher carrier frequency very high speed modulation and higher bandwidth larger bandwidth of operation, Bragg type of modulators are preferred. And we will discuss this Bragg type of modulators for acousto-optic deflection for beam scanning and various other modulation purpose in the next section.

Thank you very much.