Modern Optics

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Lecture - 40
Electro-optic Modulators and Devices (Contd.)

Good morning. So, far we have studied the principles of electro optic effect. We have studied various electro optic materials in terms of their longitudinal configuration transverse configuration and in terms of the applications. We discussed how the electro optic crystals can be configured for a phase modulation, amplitude modulation.

Both of these are widely used for commercial applications and having known those basic understanding basic properties of the electro optic materials with regard to the applied electric field, we will now discuss the applications in terms of the electro optic devices electro optic modulators. And we will discuss few of them which are very important and commercially available devices

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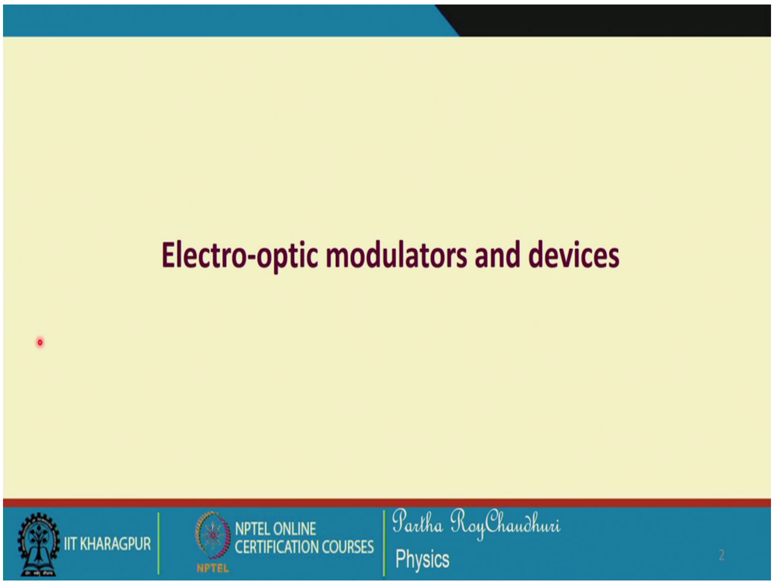

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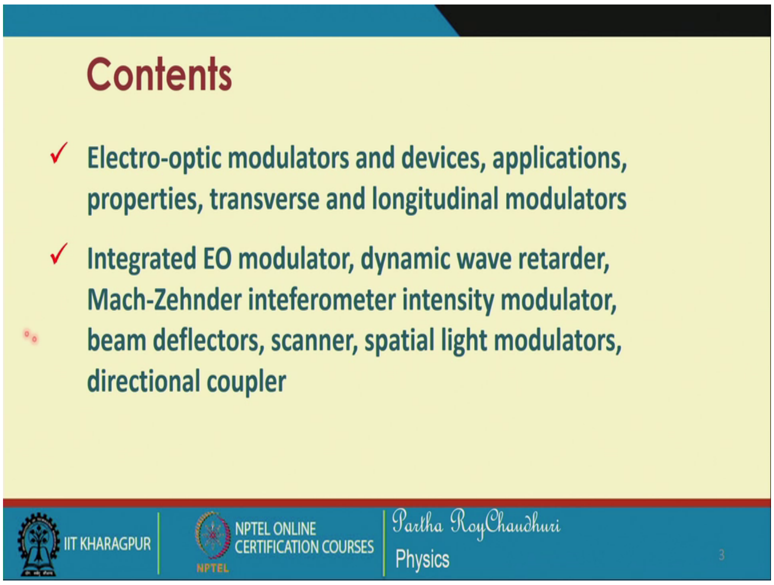

So, we have discussed we are going to discuss this today's discussion under the following heading that is electro optic modulators and devices, look at the applications and the properties and particularly their properties required for transverse and longitudinal modulators application. Then we will discuss few of the a very useful electro optic modulators like integrated optic modulator and a very common and versatile use is a dynamic wave retarder which could be incorporated in any photonic circuits any photonic devices.

Then Mach-Zehnder interferometer intensity modulator, this is a very powerful modulator in terms of this is very widely used in sensing applications also apart from switching of the light signals. Then beam deflectors and scanners, spatial light modulators and another very important use is the use of directional coupler for switching a versatile device for many applications.

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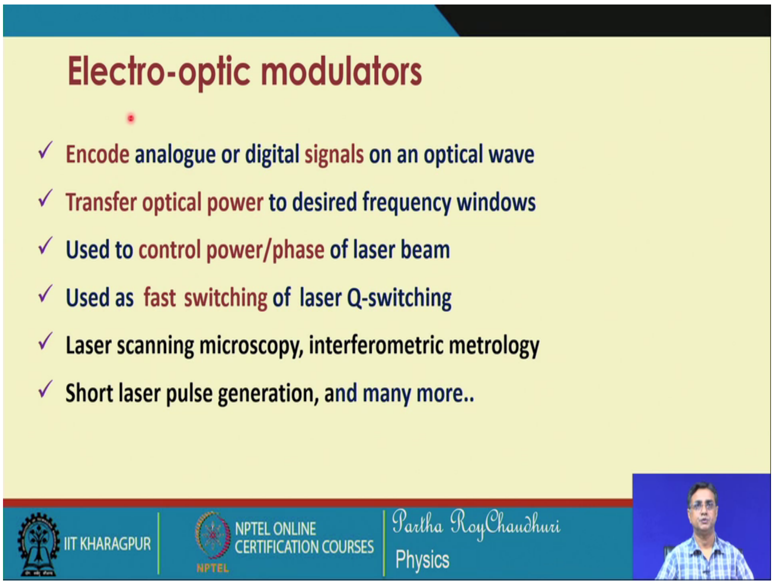

So, for electro optic modulators these are the basic things that that have to be taken care before designing and going for application; this electro optic modulator basically enclode encode analog or digital signals on an optical wave, in the form of phase or amplitude modulator which carries the modulation signal.

Then this transfer optical power to desired frequency windows. This task is also done there are many more applications, of course, modulators electro optic modulators are used to control power and phase which is nothing but the same like if I can control the retardation, the phase delay then under amplitude modulation, it can be used to control the power then the phase can also be controlled by we have discussed that the one has to launch the light into one of the Eigen polarizations of the crystal.

And have to use it as a phase modulator used as a first switching and these are being used for many years for Q switching of laser beam. Laser scanning microscopy, interferometric metrology then modulators are very widely used in laser pulse generation and there are many more to list.

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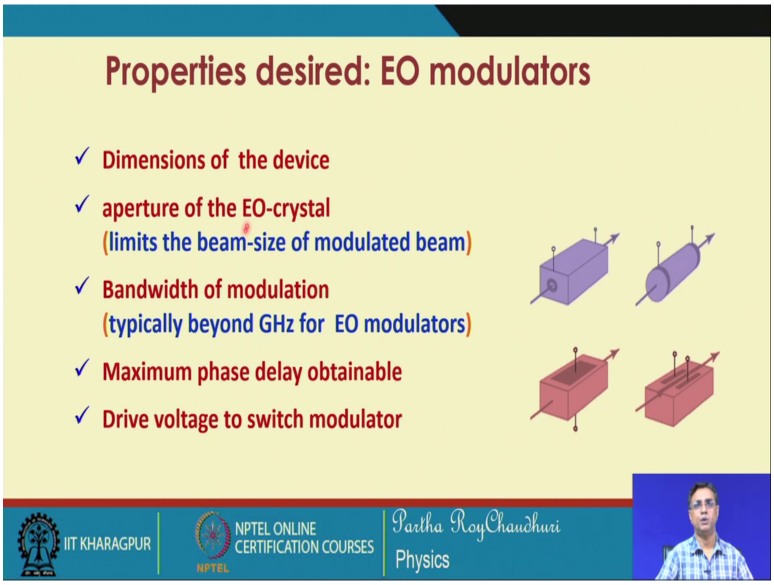

The basic properties that is required are the dimensions of the device. It is important from the design point of view for extracting the best performance of the device. Then aperture of the electro optic crystal that is also very important the designer has to take care of that because it limits the beam size of the modulated beam the spot size of the modulated beam.

The bandwidth of modulation this is typically for electro optic modulation of the order of gigahertz. And one has to look at [the maximum obtainable phase delay with minimum applied voltage that is very high performance device. Then the drive voltage to switch the modulator that is to get a phase delay of pi at the drive voltage should be of the order of because we have seen it can vary from kilo volt to volts.

So, looking at the specific application desired application, one has to take this point as one of the important designing factor.

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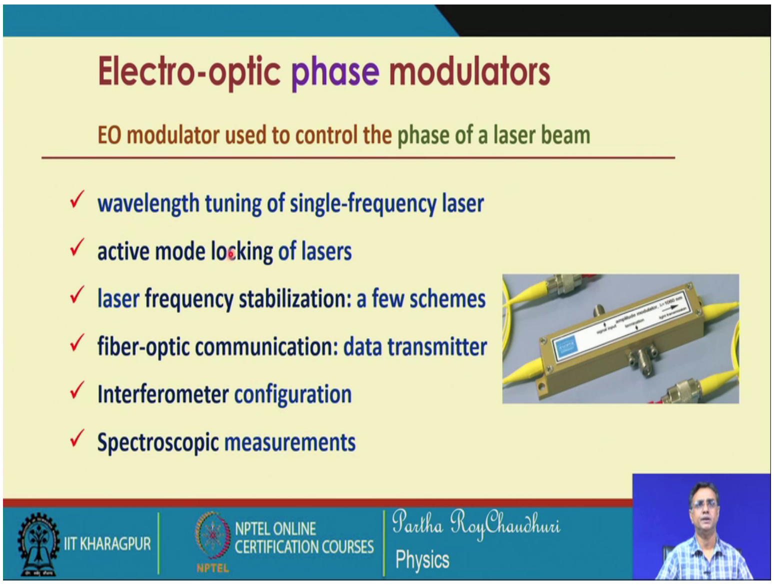

The electro optic modulators when used as a phase modulator then it controls the phase of the laser beam, phase of the electromagnetic wave. Wavelength tuning of and that has directed in application in wavelength tuning of single frequency lasers, active mode locking of the laser beam, laser frequency stabilization there are number of schemes to do that we will not discuss those things, but the basic task is that by using an electro optic modulator the phase can be modulated.

Then widely used in fiber optic data communication used as a data transmitters because the data the information in the form of electrical signal can be impressed on to the light signal, through an electro optic modulator. It could be in the form of phase modulation, it could be in the form of amplitude modulation. Then interferometric configuration several configurations are already well known in the photonic devices, for sensing application, for signal processing and spectroscopic measurements also.

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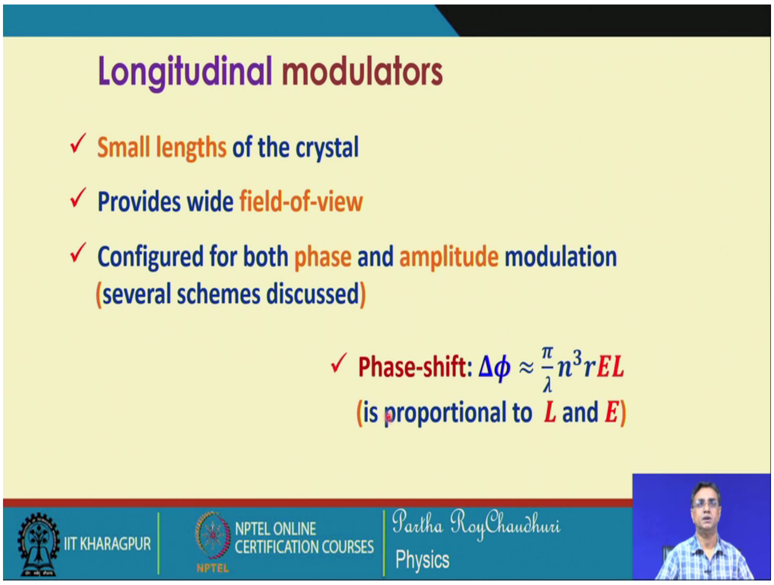

In the case of longitudinal modulators when we devise an electro optic crystal to function as a longitudinal modulator, then it should be of small length and it provides a wide field of view. Then this longitudinal modulator can be configured this we have seen with all the theoretical and basics of understanding, that how it could be implemented as a phase modulator or an amplitude modulator. And that is what we have discussed several schemes of you know orienting the crystal the configuring the crystal with respect to the applied voltage.

And in such longitudinal modulator case, the phase shift that is obtainable is proportional to the length of the crystal is the electric field and this we have seen with many examples. And we see that it is proportional to L and E; applied voltage on the length of the crystal.

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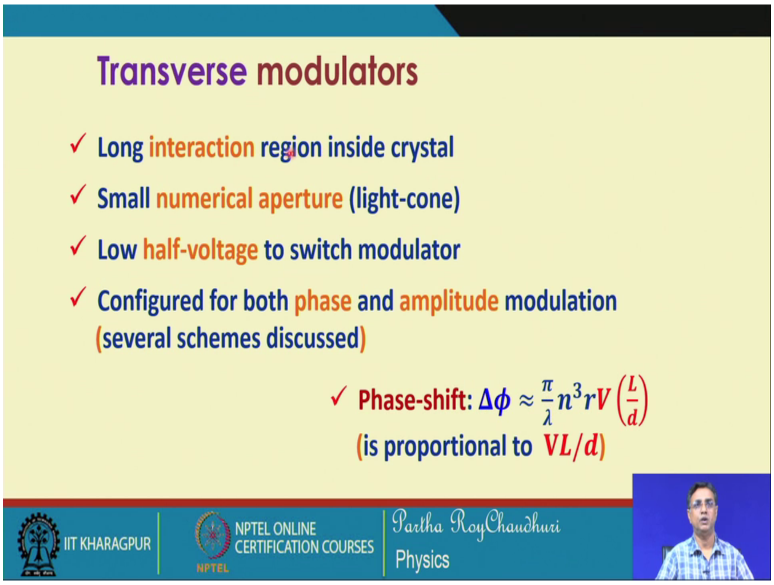

But for transverse modulators, we usually require a long interaction region inside the crystal interaction of the light wave with the crystal and we require a small numerical aperture that is the light cone the acceptance angle of the light from the input side.

This is useful because we have also studies the beam geometry to optimize to maximize the performance of the modulator in the case of transverse modulation, transverse for configuration. Effectively, as a consequence of this it requires much less half voltage to switch the modulator, we have seen examples and with numerical problems also that it really required a requires voltage of the order of volts.

Then again it can be configured this transverse modulations. These examples also you have seen that it could be implemented as a phase modulator, amplitude modulator and but in the case of transverse configuration, the phase shift is proportional to both the voltage and the and inversely proportional to the width of the crystal linearly proportional to the length of the; so, you have a better freedom of 3 parameters, voltage. Voltage of course, is the main control factor to tune the phase delay and length and d L and d can be used to optimize the performance of the device.

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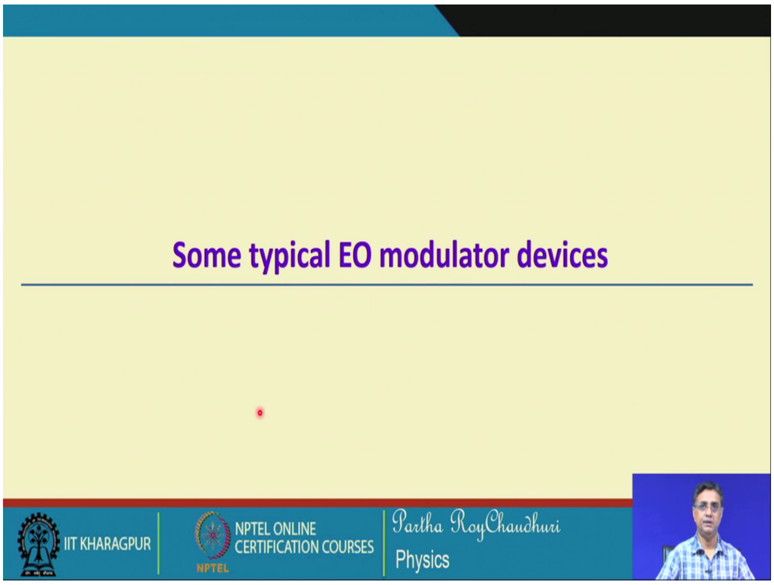

Now, we will discuss some typical modulator devices which are very important and we will also try to understand how they operate.

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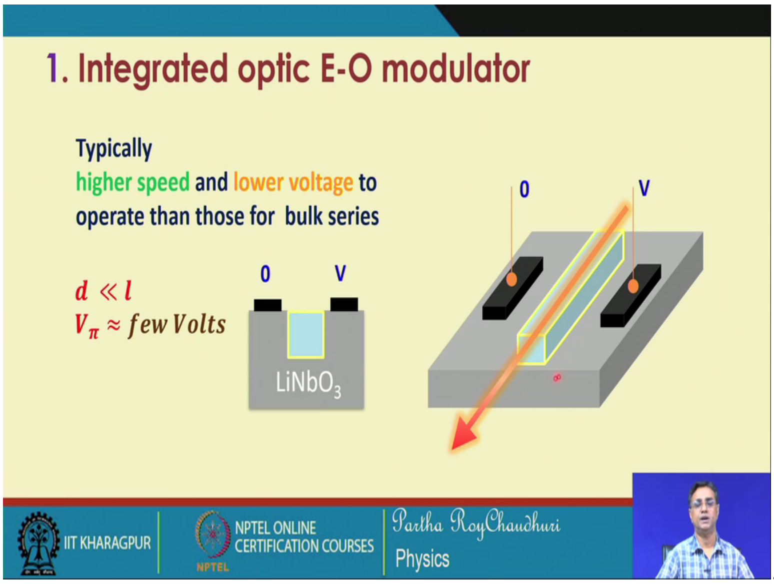

Integrated optic electro optic modulator, the basics configuration is this. Y ou have a light signal which is passing through the wave guide integrated optic waveguide. This is the high index region that is the core of the waveguide. And these are the electrodes which are connected to the applied voltage.

This is the ground, this is the potential V and this is a cross section of a typical lithium niobate electro optic modulator V pi we have seen we have studied with examples and numbers also that it requires only a few volts.

But basically this is based on the principle of phase delay between the 2 Eigen polarization polarized light.

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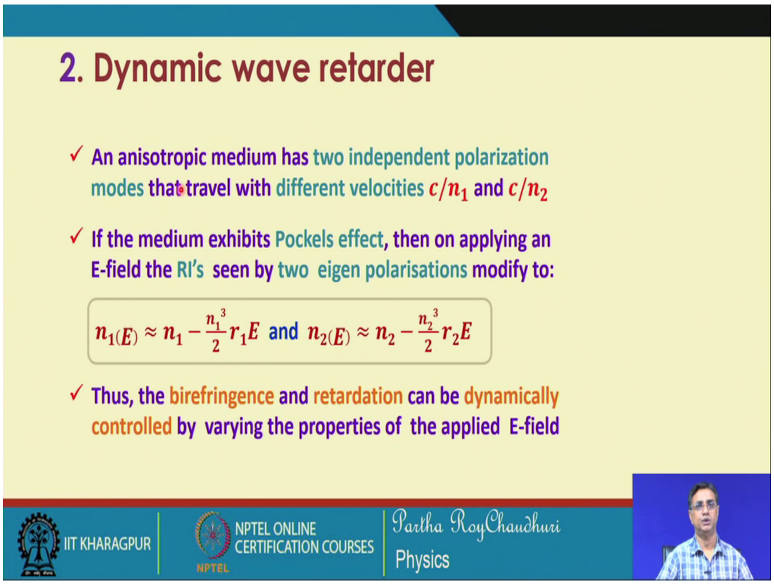

That is propagating to the crystal and making use of that fact this dynamic wave retarder is very versatile and a tunable retarder device which is very useful for many applications the but the basic philosophy is that this anisotropic medium has 2 independent polarizations, polarization modes and they have 2 different phase velocities in the inside the crystal, but because of the different phase velocities they will develop a phase difference, which will lead to a phase delay. And this phase delay that is the retardation that can be controlled by externally applied electric field.

In the medium, if the medium is a Pockel type of medium Pockel crystal Pockels crystal then on applying an electric field this refractive index seen by the 2 Eigen polarizations will be modified, as long as the electric field is present. We will have n 1 polarization refractive index is this the other one n 2 is this. And therefore, there is a birefringence the induced between these 2 as long as the electric field is present, apart from the fixed birefringence which will come from n 1 and n 2 that is the static birefringence which is independent of the external voltage.

So, this voltage dependent birefringence can be controlled to get a tunable and dynamic to match the requirement of a specific application.

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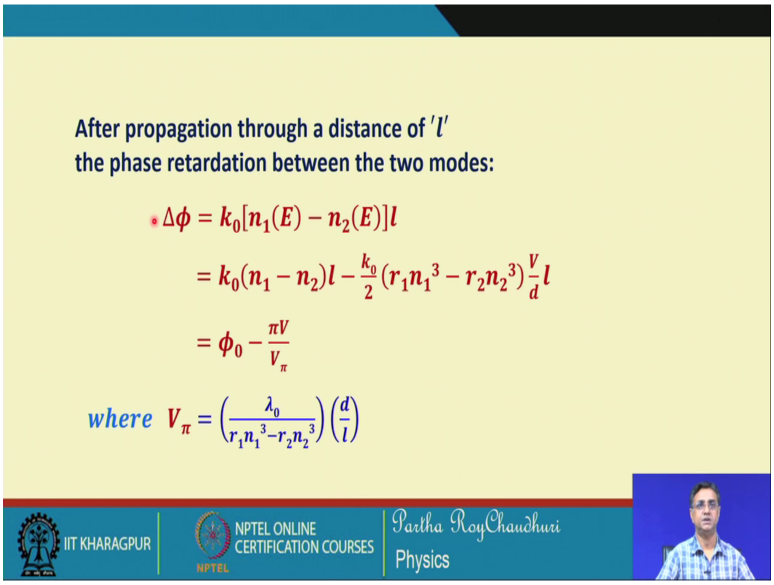

So, this delta phi which is equal to k 0 that is twice pi upon lambda then n 1 and n 2, but n 1 and n 2 this is the fixed static birefringence in absence of the electric field, but this is the field induced birefringence.

So, with more compact notation this phi 0, the static birefringence is the one which is always sitting there and this is the voltage dependent birefringence and you can express this we have seen that this is pi V by V pi; V pi is the half voltage to switch the modulator to get a phase difference of pi. So, this V is this that also we have seen in the case of transverse modulator because d by l it appears, d is the width of the crystal, l is the length of the crystal and these are the electro optic coefficients ok.

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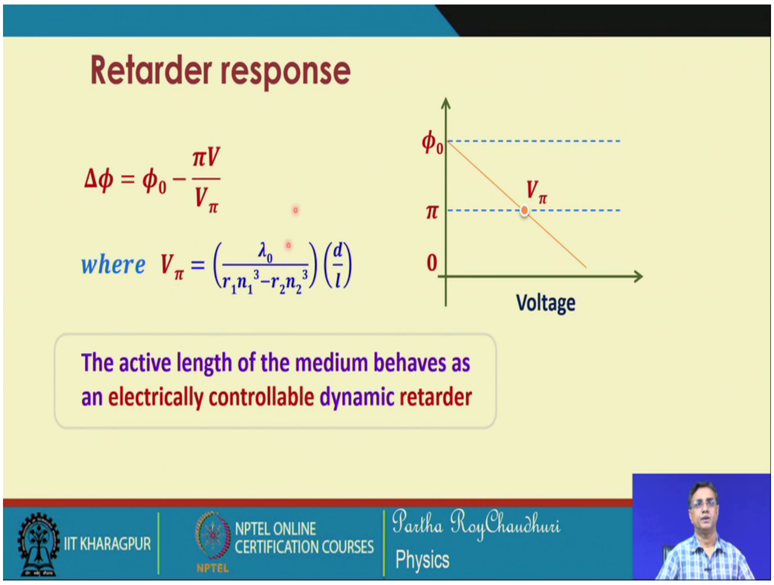

So, the response of this because you have a static birefringence sitting here, so, when the applied voltage is 0, applied voltage is 0 you get the phase delay phi 0 which is equal to this, but as the voltage increases this will take away from the total phase take away from phi 0 to get the net phase effective phase delay. So, it decreases as the voltage increases.

And it becomes pi which we will call the switching voltage the V pi that is the half voltage and that is in this case this we have seen before also. So, the active length of the medium behaves as an electrically controlled controllable dynamic retarder. So, just by changing the applied voltage one can actually get the obtain any desired amount of phase between 0 to pi by 2. So, that is a very useful device.

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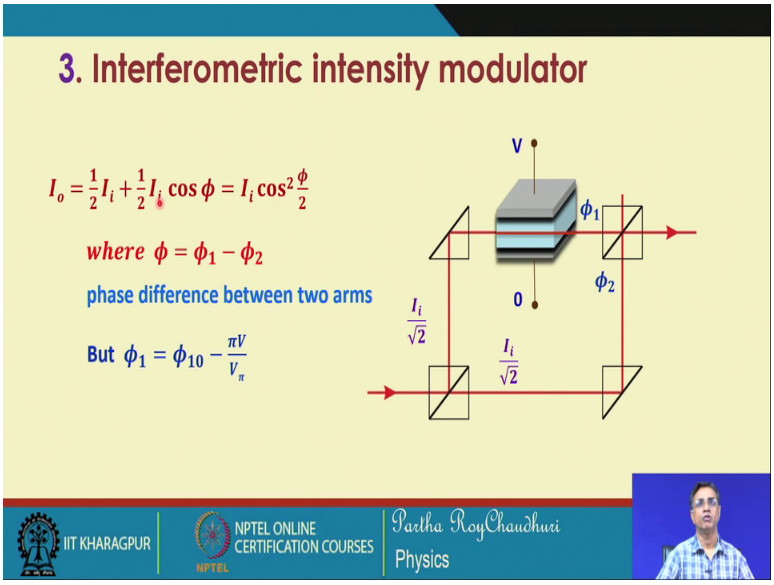

Now, intensity interferometric intensity modulator; this is actually a Mach-Zehnder scheme where you have an input light which is part of the light is 50 percent in the ideal situation. The part of the light is reflected and again it is reflected then there is another beam splitter from which part of the light is reflected and part of the light 50 percent of the light is transmitted. And in the same way the remaining half of the light which is transmitted through this first beam splitter again gets reflected then again it is a part of the light is reflected and 50 percent of the light is transmitted.

So, if you observe that the path that is travelled by both these waves are the same because you have 1 reflection here, 2 reflection here and if we consider this wave then it is 3 reflection here. In this case, it is transmitted, reflected and again transmitted. So and the other way if you look at the transmitter then you have 2 reflection and you have 2 reflection; one here, one here and one transmission here.

So, it is only the phase that is accumulated due to the propagation. In addition, there is another phase which is added as an induced phase by applying the external voltage, where the light beam has to travel through an electro optic medium. So, this is the basic working principle of this interferometric intensity modulator.

Now, that this when these 2 waves are mixed at one of the outputs this is one output and this is another output, when they are mixed at one of the outputs this depending on the phase if the phase difference between these 2 is pi then there is no light here and if the phase difference is 0 or twice pi we will get the maximum intensity. Or depending on the phase it can have any intensity distribution between these 2. So, any one of these outputs can be used as an intensity modulator.

So, this is the basic understanding that you have I input by under root 2 is the no so, this is this will be square root of square root of I. So, this is and then if you take the is this should be E I by root 2 E I by root 2 and this travels through a length of this. So, if I add these 2 vectorially or the phaser addition including this cosine phi 1 and cosine phi 2, then we can get this I intensity is equal to this which is the intensity available.

And then phi is the phase difference between these 2 light beams is phi 1 and phi 2; phi 1 is the phase difference which is due to this path and phi 2 is the phase difference along this path.

Now, phi 1 because you have an additional phase which is incorporated by this impressed external electric field. So, this is apart from the best phase you have an additional variable phase.

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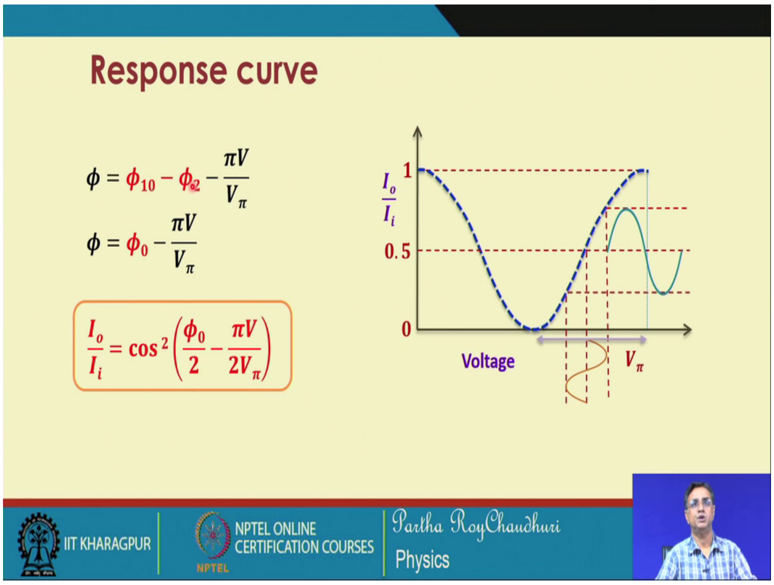

So, this phi 1 0 minus because if I plug in this phi 1 value here in this expression then we it will get that phi equal to phi 0 minus pi V by pi. And then this look at this expression, this is this intensity output intensity as a cosine square function of the input intensity and you have this response this cosine square function which looks like this. If this is the input intensity you get the output intensity which is modulated in this form.

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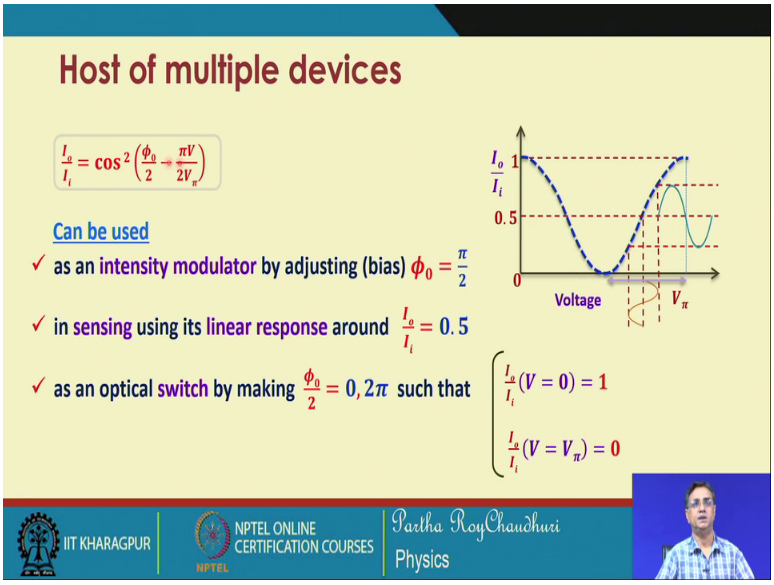

So, this is a very interesting application and one can see that if you put this phi 0 by 2 this phi 0 equal to pi by 2. Then this will be equal to pi by 4 and it can be used as an intensity modulator. In that case you can use this Mach-Zehnder, this setup as a as to control the intensity of the light in sensing using the linear response where I 0 by I equal to 0.5, this value is 0.5 at this region you can get a linear.

You look at this part of the curve is almost linear and it can be used by making phi 0 by 2 equal to 0 or twice pi. So, if it is 0 then cosine square of this will be just you can look at this V equal to 0 I 0 by I 0 this is already 0. So, cosine 0 will give you 1 and V equal to V pi will give you 0.

So, you can switch the light in any of the output port just by controlling the voltage. When volt there is no applied voltage then the state is 1, when the applied voltage is V pi the state is 0. And the reverse will happen in the other port that is a complimentary port; we have 2 ports, here 2 out exit ports. So, it can be used as a switch which is very powerful and very much useful.

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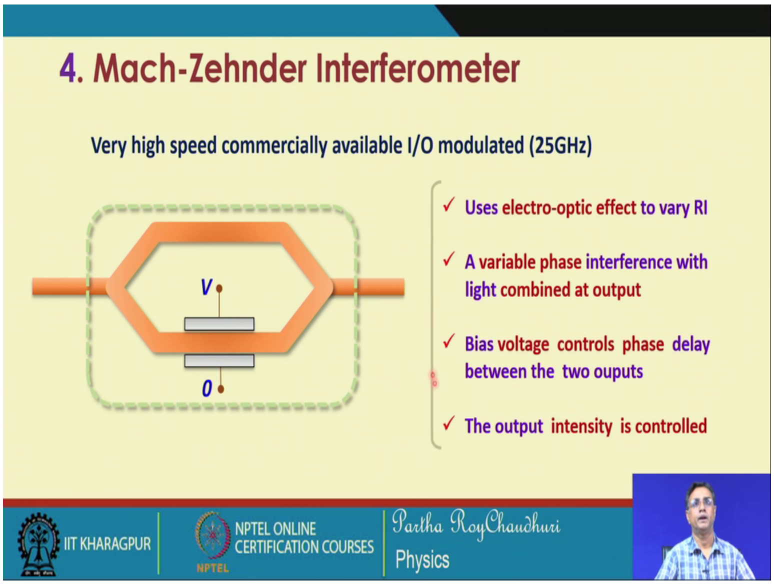

Then this is also a Mach-Zehnder setup where you have beam where optical path which is split into 2 parts. And then again they are combined into one signal and in the paths in between one of the arm is mounted with this electro optic modulator. And when you apply the external field it works in the same way as discussed in the free space this intensity modulation scheme. It works in exactly in the same way.

And so, by applying this bias you applying this bias one can modulate the refractive index and as a result a variable phase interference pattern; so, interference pattern that is in terms of the intensity of the light only. There is no special pattern in this case and that that is controllable by the externally applied electric field. So, this bias voltage can control the phase delay between these 2 and the output intensity can be controlled.

So, this basic understanding is the same as we discussed in the previous case.

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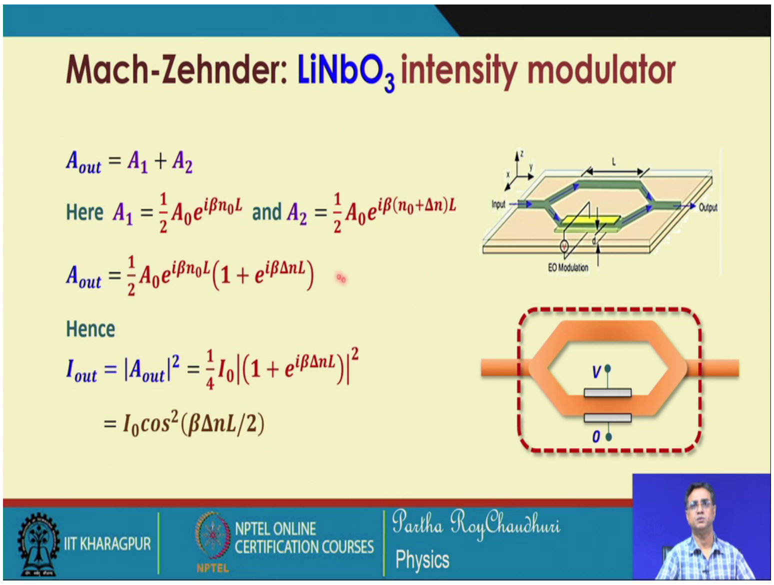

So, again moving with this bit of understanding that this amplitude for this field can be written as n 0 which and the length of propagation L, length of propagation L. And in the case of the second part that is the other beam you have an additional phase delta n which is sitting which is active over a length of L and therefore, A out is the sum of these 2, the sum of these 2 amplitudes and then you take the mod of this, to get the intensity which gives you I 0 cosine square.

This beta is k 0 by twice pi k; this is k 0 that is twice pi by lambda and then delta n into L by 2. So, this gives you the output intensity. And this is a very useful device and commercially available for many applications in communications in photonics in basic optics also.

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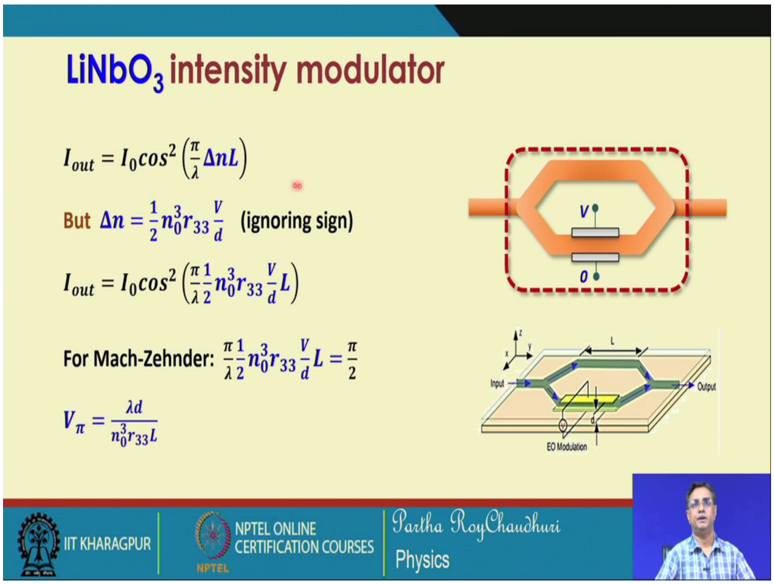

Lithium niobate in the case of this delta n is known we have seen this if you ignore the sign. And under this Mach-Zehnder configuration, then if I have to switch this we put this equal to pi by 2. It gives you that v pi equal to this and this value no having known this value we can use this modulator as a as a switching device.

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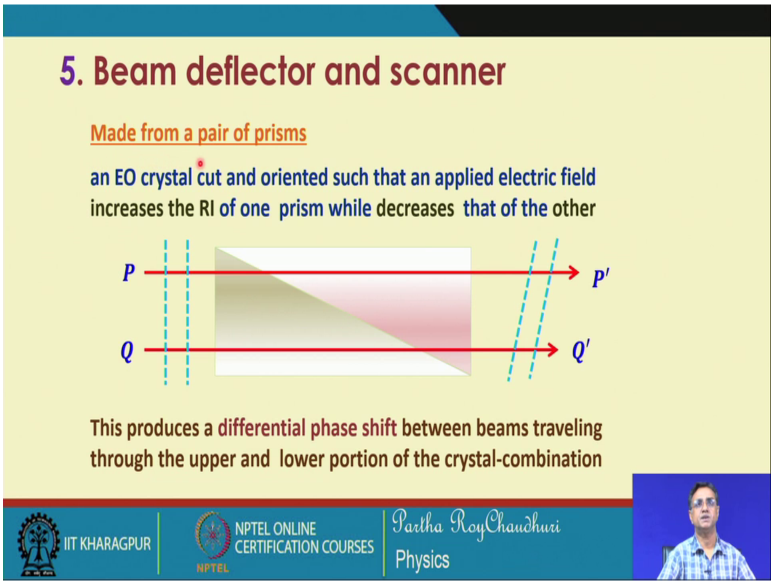

Now a beam scanner this is another very interesting application an electro optic crystal cut and oriented in such a way that the refractive index under the application of external field the refractive index of the one prism increases, while the other prism decreases. The configuration is such that which is we will see which is very simple and doable.

This produces the differential phase delay because the light which is travelling at the lower part and that one which is travelling at the per part they will see different optical path and there will be a phase delay. And the beam while coming out will be tilted and in order to maintain this the plane wave front of the input then this entire beam will be deflected with a certain divergence angle.

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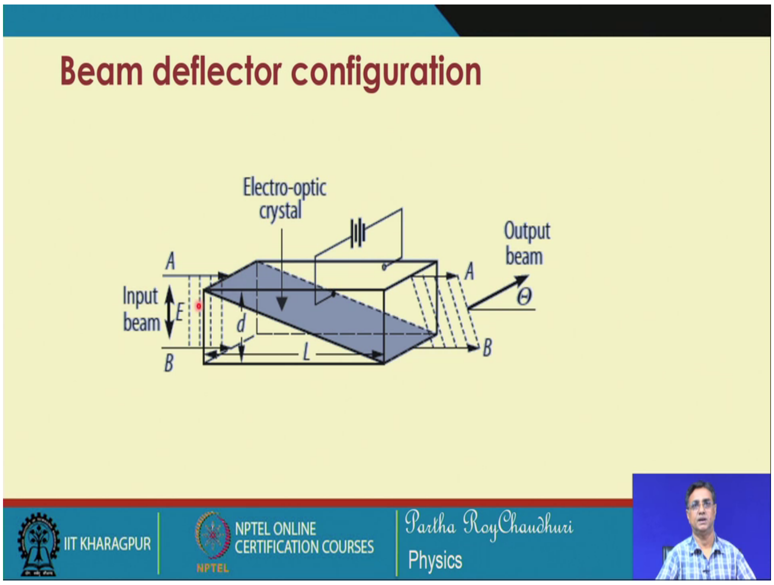

And let us see this is the configuration you have the electro optic crystal you apply the transverse configure in the transverse mode. So, you have an a applied voltage the beam is this is the input side, where the a beam is launched and this is the deflected beam and it makes an angle theta. Is the same this is how it is configured is very useful to understand.

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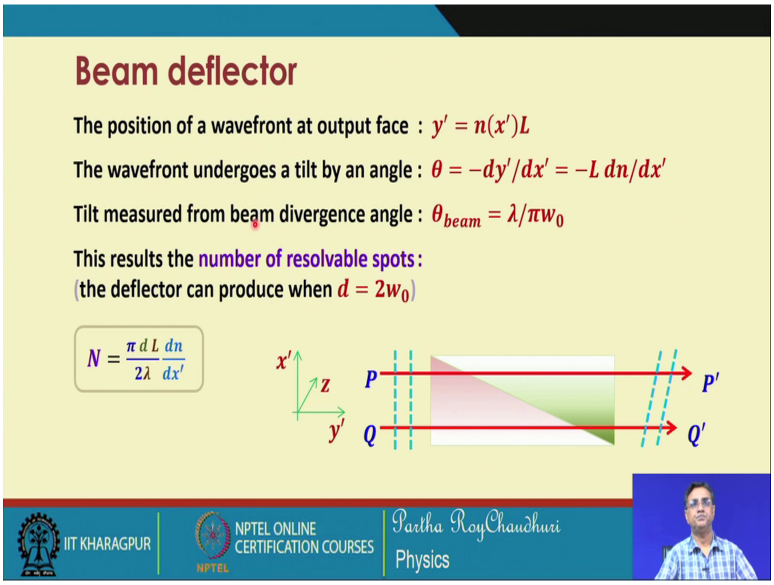

Then the let us try to understand how it works the position of a wavefront at the output is here equal to you see this refractive index as a function of x prime. Because it varies from here to here for the wavefront undergoes a tilt by an angle theta you see there is a there is an tilt by an angle theta which this is from the basic prism optics that this tilt angle is L dn dx.

This is the differential change in the refractive index over the length this dx. And that gives you the beam divergence angle beam and for this beam divergence can be can be calculated as this lambda by pi omega 0 where omega 0 is the spot size of the beam the width of the beam.

So, this results in the number of resolvable spots under this confogal configuration this deflection can produce d when it is d equal to twice the spot size that is the W 0. And with this one can have the number resolvable spots given by this expression. We will see how it comes this number of resolvable parts which is very useful in designing a device for beam deflection operation.

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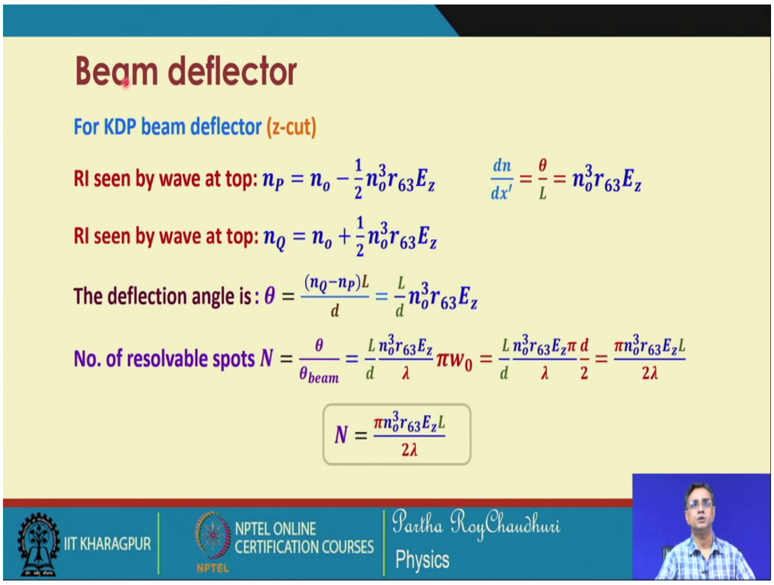

So, for a KDP crystal let us suppose then we take the values the numbers here. So, for the upper part of the beam upper part of the beam which travels in a refractive index effective refractive index n p equal to this and for the lower part of the beam which travels through an effective refractive index this is induced birefringence between them is just the difference of this and L into dn dx is the divergence theta equal to L times dn dx prime. So, that gives you this relation because the difference between these 2 is n 0 r 6 3 Ez.

Now, the deflection angle theta this theta equal to L times dn dx, which can be written as nQ minus nP by d. And that straight forward it comes out from here difference of this n P minus nQ L by d that is what is here. So, number of resolvable spots is the divergence and divided by the beam divergence the deflection of the spot total by the beam divergence. So, if you take this if I plug in the values for theta, I use this number and for theta beam I will use this number pi by lambda by pi W 0, but W 0 under this optimum condition will be equal to d by 2.

So, it turns out 2 lambda by pi d 2 lambda by pi d. So, 2 lambda by pi d. So, when put together we get this expression which is the number of resolvable spots number of resolvable spots. So, that is what is shown here this, dn dx if you write in place of that the difference this electro optic coefficient refractive index cube and the external field.

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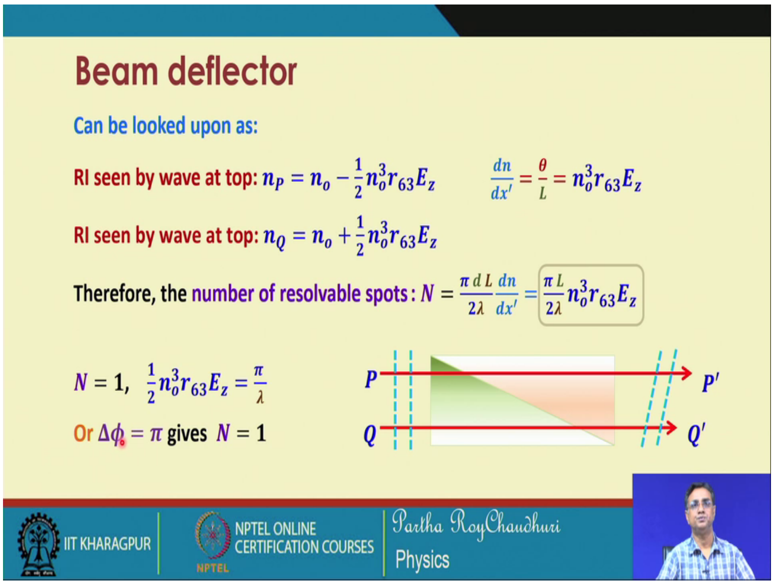

Now, this would be lambda by now if you set n equal to 1 into this expression n equal to 1 then lambda by pi will be equal to lambda by pi will come to this side will be equal to n 0 r 6 3 Ez L divided by 2. So, that is equal to what or the other way round that if we put delta phi or the phase difference equal to pi we will get n equal to 1.

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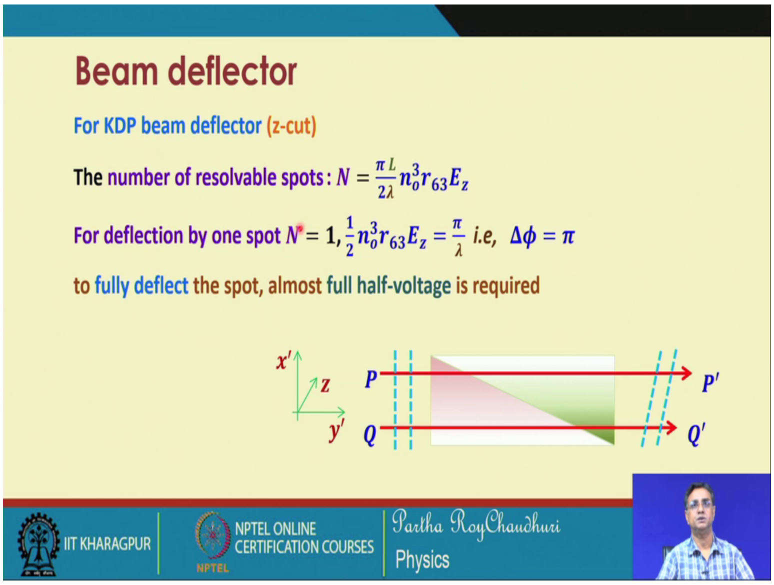

So, for one resolvable points we require this and. So, the deflection for at least by one spot we require this condition that n equal to 1. It is the other way that if you put del phi equal to pi you will get n equal to 1. To fully deflect the spot almost full half voltage is required that is very interesting, but usually for electro optic crystal is the voltage requirement is very high. So, in practice in some applications this is used, but more frequently used is the acousto optic beam deflector which we will be discussing in later occasion.

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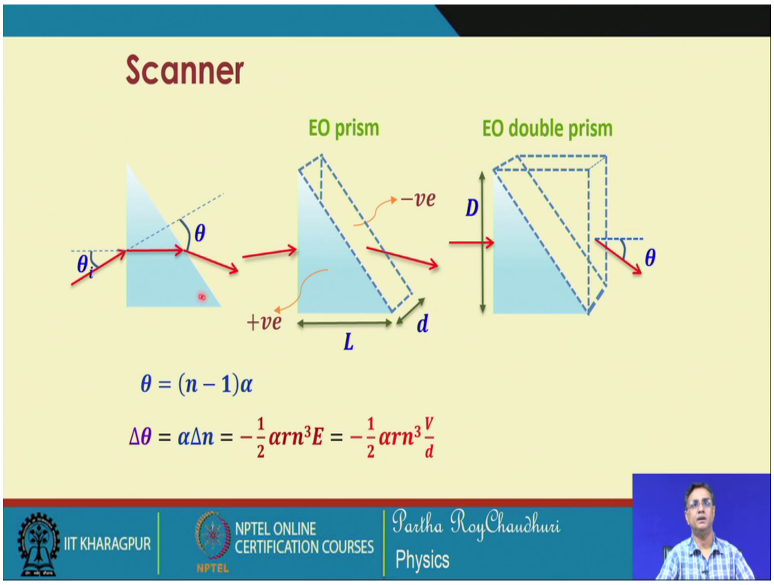

Now, the scanner this is another important device, but basically based on the same principle of the beam deflection for individual prism we know that is for thin prism that this refractive index minus 1 which is an alpha is the angle of the prism. So, you have delta theta which is equal to this. And now by applied voltage V you can actually control the you know the angle of emergence from the prism which can be used to scan different objects on the screen.

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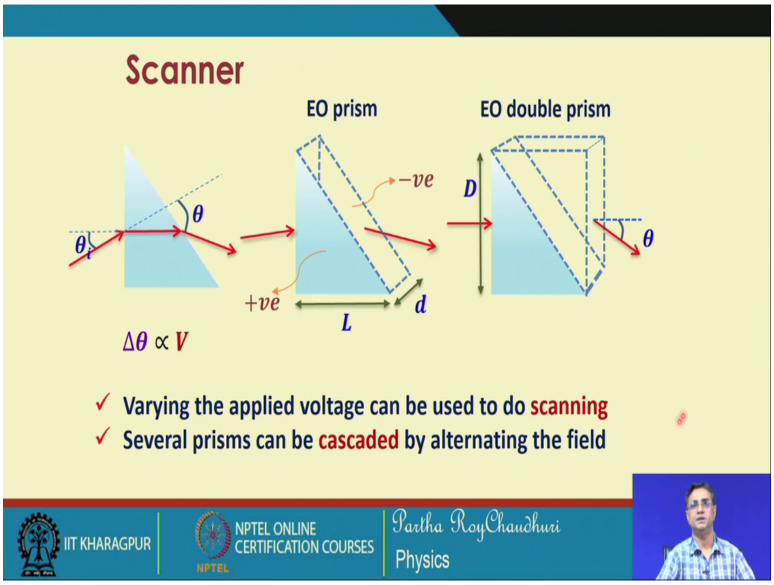

So, by varying this and it can be actually the gain can be multiplied by cascading several prisms in the appropriate you notice a with appropriate design configuration

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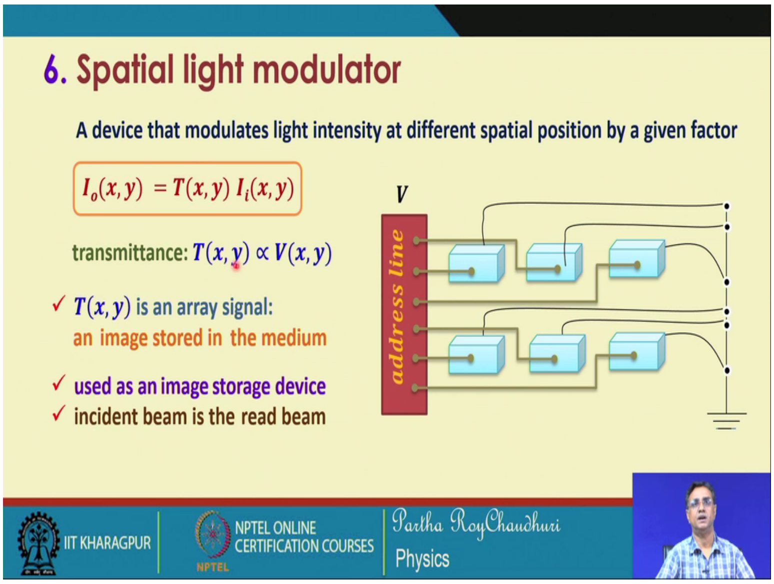

Then there is another interesting application because by making use of this it can be used as a spatial light modulator where I 0 is a function of this transmission. And this applied voltage the spots you know the different points can be a modulated and it can be used as an image storage incident beam is a read beam. And the same beam can be used for right beam also.

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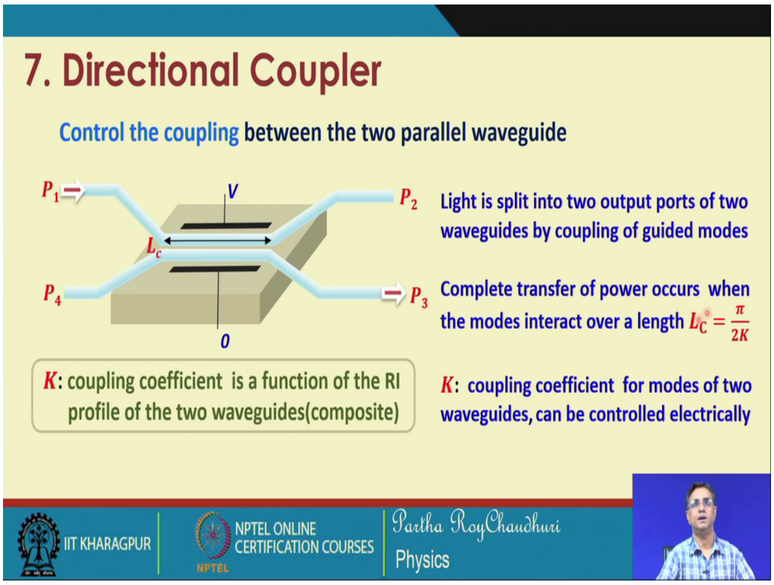

Directional coupler this is another very powerful device which where this electro optic effect is used to control the power output we have seen that if you launch light into one of the ports it can be split into 2 ports. Let us suppose that this is the 50 divider splitter, then by applying this voltage this refractive index of the composite structure can be controlled because this coupling coefficient this is this the length required to switch light from one port to another is the coupling length, which is the function of this kappa, but this kappa the coupling coefficient is a function of the refractive index of the composite structure of the total structure, the way it is done figured if it is just to.

So, but actually it is both the parallel wave guides through which this refractive index is one controlled. So, by controlling the voltage across this the west of the coupler, one can modulate the refractive index which will modulate the phase of the light which is travelling through this. And the splitting ratio can be controlled and this is this is very useful you may like to switch the light from here to here, but for a fixed coupler you cannot do, but using a electro optic modulation scheme, you can switch the light from here to here back and forth depending on the requirement which is which can be used for router applications for modulation applications and many more.

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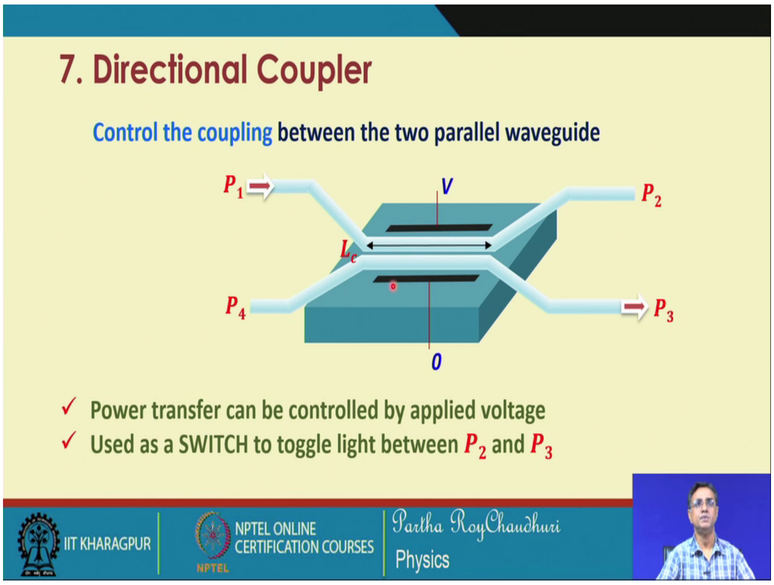

So, this directional coupler basically the basic physics that I have. So, you can switch this light from P 2 and P 3 by just applying the voltage.

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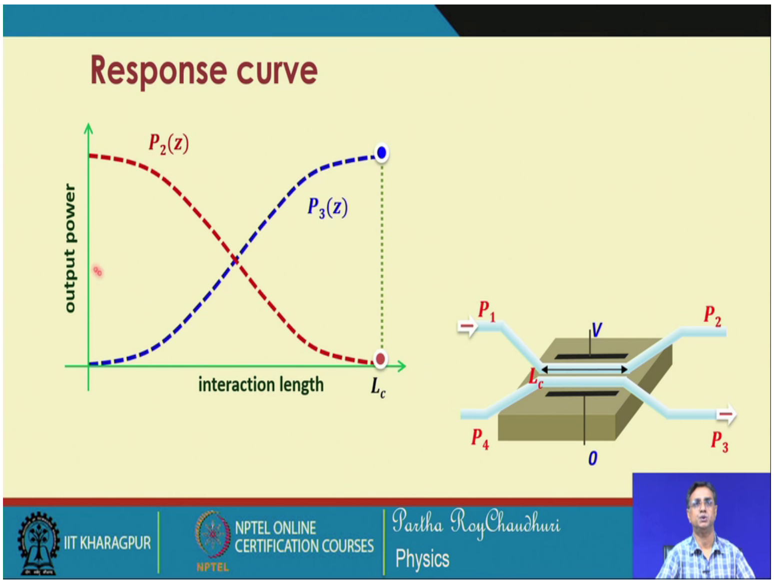

Between these 2, the response curve we have seen that it is a sine square cosine square function. In the case of optical directional coupler, you have seen this and at the switching point where L equal to L c you have this point. So, the power is here and in the case of this L c that is coupling port here the power is this. So, the light can be switched back and forth just by applying this external bias voltage, which is a very useful device.

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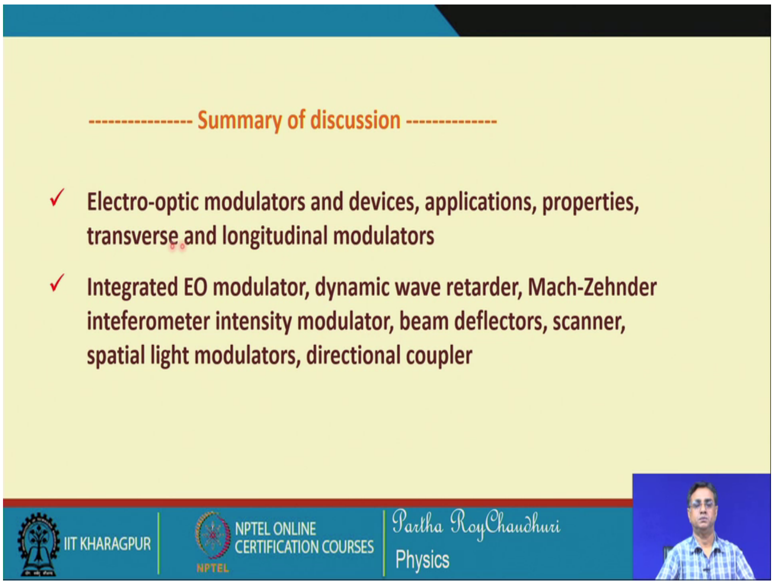

So, through this discussion we have tried to understand we have actually described few very useful electro optic modulators and devices, there the requirements to configure it as a longitudinal or a transverse modulator in terms of the geometry in terms of the properties. Then we discussed few devices in integrated electro optic modulator dynamically retarder Mach-Zehnder intensity modulator beam deflector scanner and directional coupler spatial light modulator.

Thank you very much.