Modern Optics
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Lecture – 32
Electro-optic Effect (Contd.)

So, in the last occasion we discussed the electro optic effect in isotropic medium; particularly we chose the gallium arsenide. We will take a break and we will going to the some basics of the modulation properties light modulation properties as far as this electro-optic crystals are concerned.

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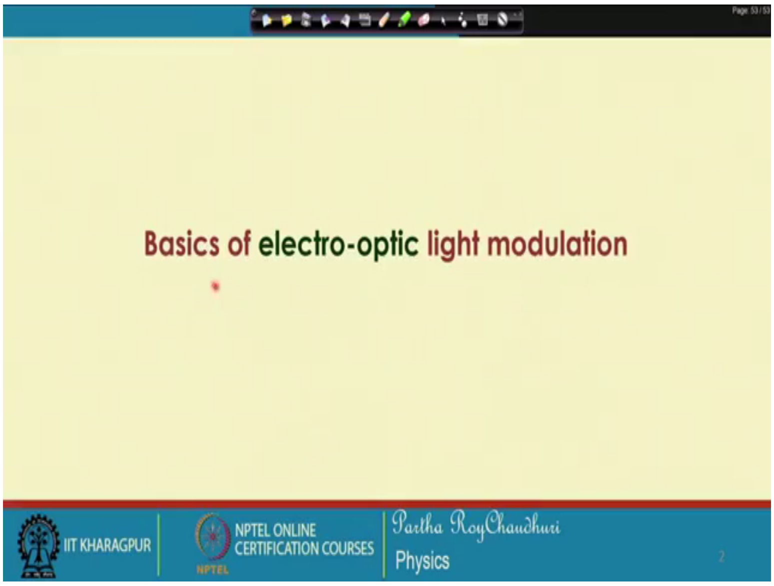

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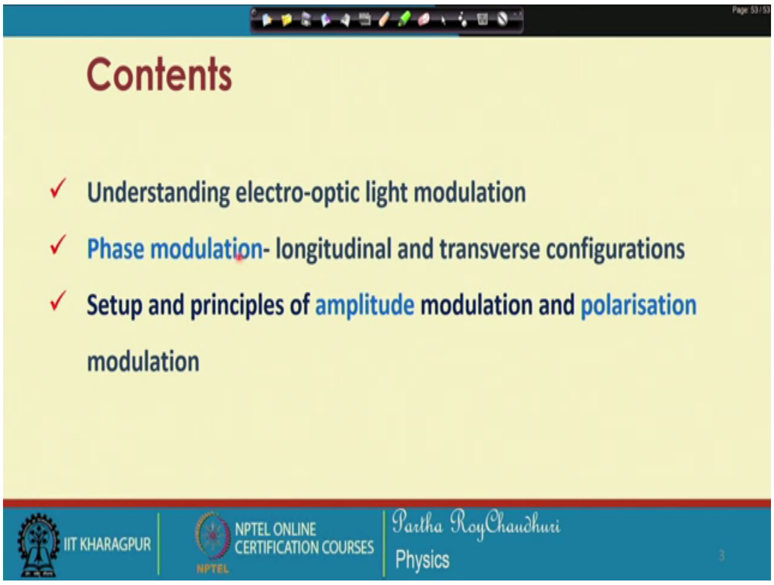

So, we will be discussing these topics understanding the electro optic light modulation faithfully start with the phase modulation for longitudinal and transverse configurations. Then we will be talking about the experimental setup and the principles of the amplitude modulation and polarization modulation.

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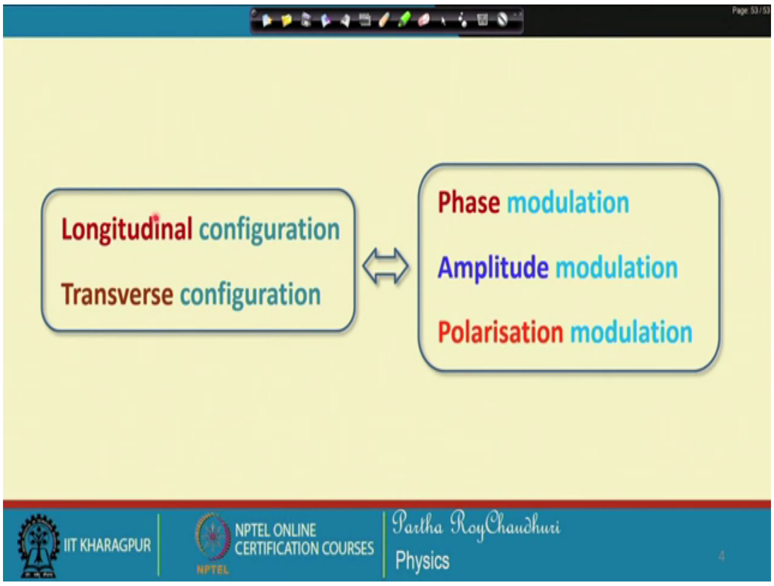

So, we divide this under two categories that is longitudinal configuration and transverse configuration, for this phase modulation amplitude modulation and polarization modulation. There are three very important properties of electromagnetic waves, which can be modulated to develop various kinds of measurement instrument sensors and several other technologies phase modulation.

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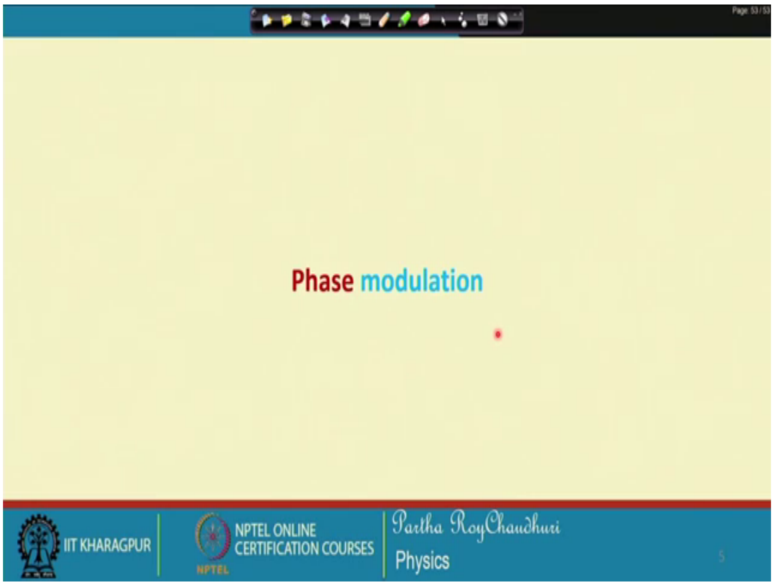

So, let us try to understand what phase modulation is and you know we will first consider a simple case very simple case of a plane wave z propagating plane electromagnetic wave.

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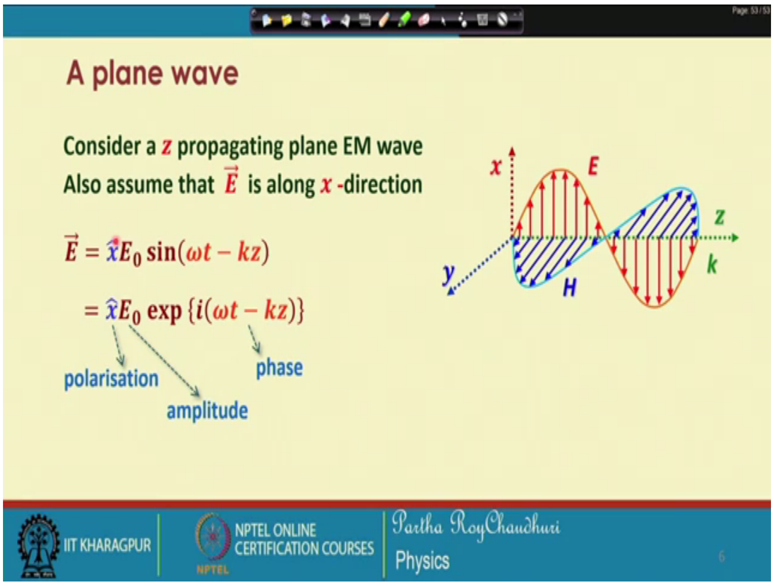

And let us assume that this electric field vector is oriented along the x direction. So, in that case we can write down this plane wave equation in the form of sinusoidal equation, it could be we represented as an exponential phase equation as well. So, look at this x cap indicates the polarization, E naught is the amplitude and this is a phase vector. Now, these are the three things which can be modulated; polarization, the amplitude and the phase.

Amplitude modulation is relatively are simpler to understand it can happen just by blocking the electromagnetic wave, with a frequency with the characteristic frequency of the modulating wave. There are, but in this case we will apply some electro optic method to modulate the amplitude. But phase modulation and polarization modulation they are slightly different to understand in this context. So, we will first talk about the phase modulation then polarization modulation.

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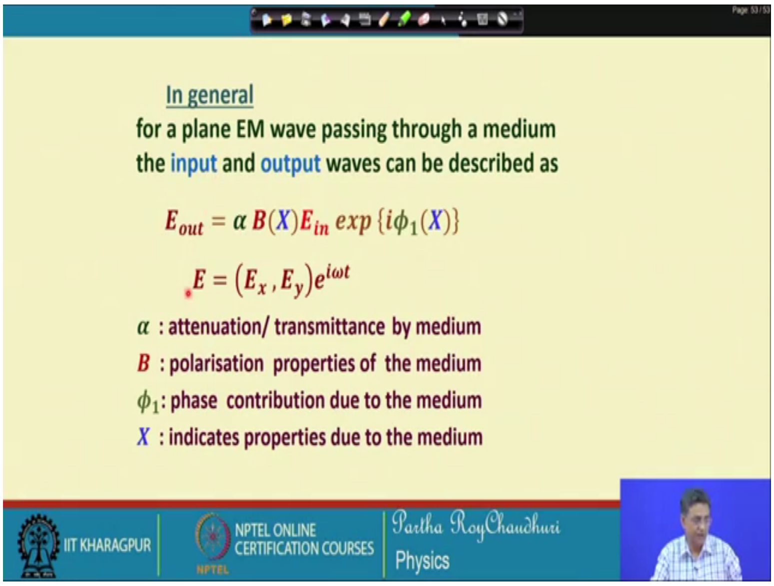

So, in general we started with a simple plane electromagnetic wave which is propagating along the z direction, and the polarization is along x look at the phase amplitude at polarization. But, in general for a plane wave passing through a medium of certain length that is a travel length is a finite, then in that case the input and output waves can be described in this form. E out equal to alpha, B of XE input exponential i this phase factor which is also the property of the medium.

So, alpha is the attenuation or it could be the transmittance by the medium B is the polarization properties of the medium, phase contribution due to the medium is described by phi 1, this is the contribution of the phase due to the medium and x indicates the properties which are related to the medium. So, there would be some sort of influence of the medium, which will be appearing in this plane wave equation in the form of the polarization, the phase and the amplitude.

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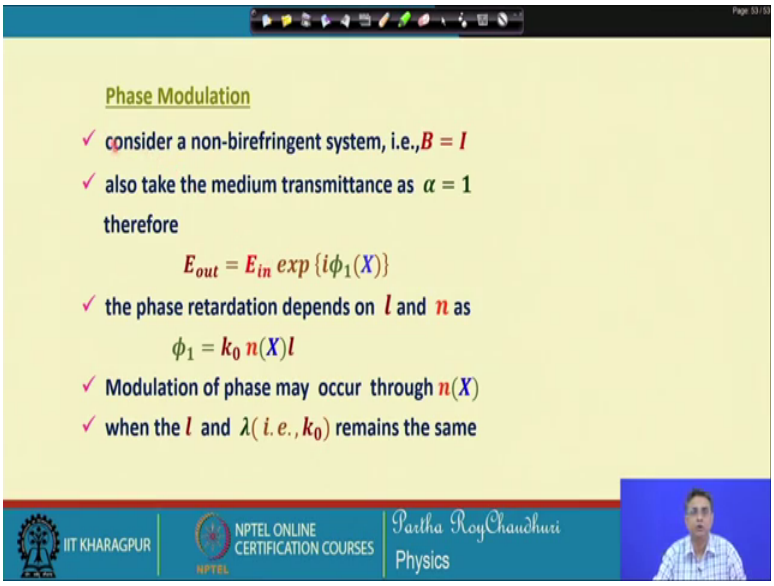

So, for phase modulation let us consider look at this equation lets considered that the medium is non birefringent; that means, B is equal to unitary I. So, this B term does not appear here and also considered that the medium transmittance is alpha equal to 1 that is there is no attenuation and then this previous equation this can be represented as E out equal to E in and this exponential of X factor phi 1. The phase retardation that depends on l and n; so, this is the very basic point to understand the phase modulation.

So, this is the phase, which is which is the function of the medium dependent refractive index that is seen by the propagating electromagnetic wave, and the length of the travel. So, put together this is a phase; now if you can modulate this length is l anyway is fixed and lambda if you choose a certain monochromatic wave of wavelength lambda. So, this n this l and lambda their phase and it is only the refractive index that can be that if we can modulate, which will intern result in the modulation of the phase phi and we will see how we can implement this phase modulation scheme in the case of electro optic modulators.

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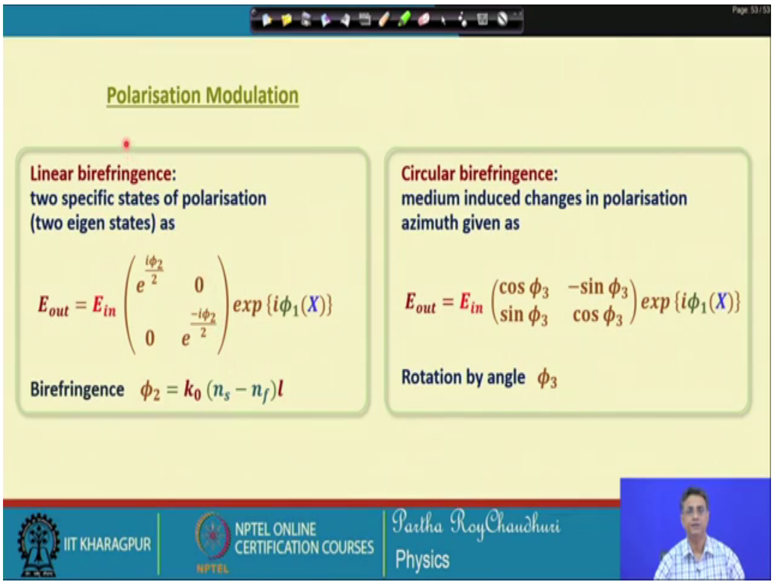

For polarization modulation, for polarization modulation if we considered the linear birefringence then there will be two specific states of polarization the two ideal states and we can describe this polarization eigen matrix by this, where this phi 2 is the birefringence the phase retardation slow access, fast access refractive indices. And this is the length l over which the two polarization states are travelling.

So, we can represent this effect of the medium through this matrix are to relate the input and output electromagnetic wave. For circular birefringence the medium induce changes in the polarization azimuth is given by this equation, where this phi three is the rotation angle which is caused by the by the medium phi 1 remains the phase that is that is the medium dependent phase ok.

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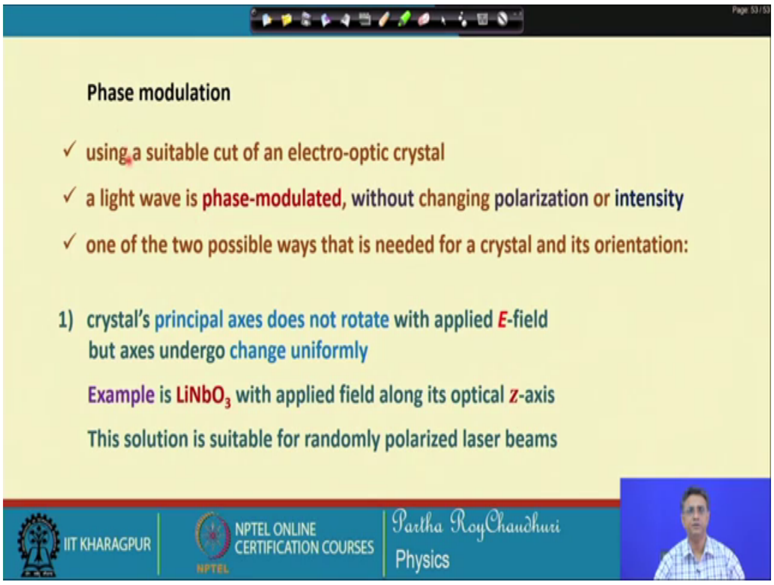

So, for phase modulation, when can use a suitable cut of the electro optic medium electro-optic crystal, a light wave is phase modulated without changing the polarization or intensity; because, otherwise it will be a mixed and will be difficult to decide for the phase modulation information. So, this phase modulation can be achieved one of the two possible ways that, that is needed for a crystal and its orientation one is that the crystals principal axes does not rotate with the applied electric field, but the axes undergo change uniformly.

So, this example we will discuss in the case of lithium niobates electro optic effect that when you apply an electric field along the optical z axis of the of the crystal, then the index ellipsoid does not rotate, , but the length of all the three axes three semi axes they increase uniformly. And these results in results in the whether is know the principal axes principal refractive indices only change its magnitude, but there is no change in the direction. So, you can have phase modulation if you apply a modulating voltage, then the because this delta n of x or delta n of y alone will change with the modulating voltage and as a result the output light will be phase modulated we will see this example

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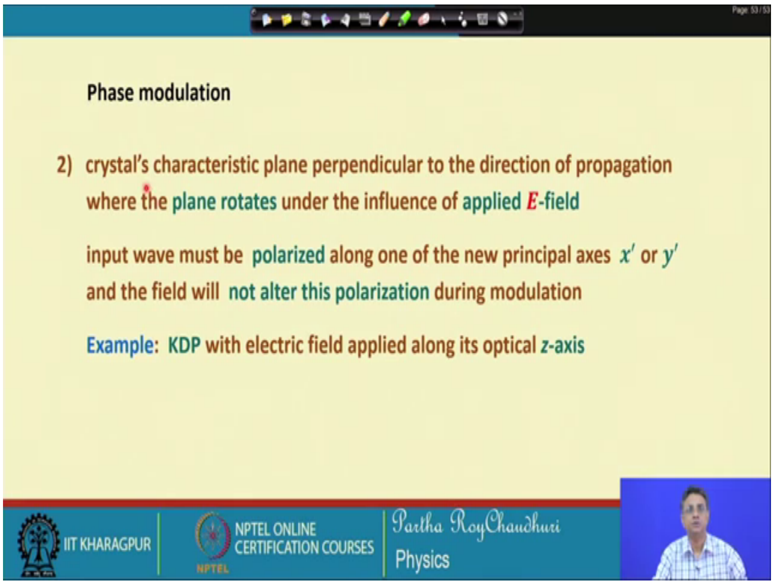

So, the second way is that the crystals characteristic plane perpendicular to the direction of propagation, where the plane rotates under the influence of the applied field. In the case when that the plane rotates, then input wave must be polarized along one of the new principal axes that is after the electric field after the rotation of the index ellipsoid, this x dash or y dash the input polarization has to be along x dash or y dash that is the new principal axes system in that.

And the field will not alter this polarization during the modulation; that means, that electric field application of the electric field will be fixed only there will be a modulating field, the result will be the modulation in the value of the x polarized refractive index or y polarized refractive index the result will be reflected in the phase of the light that is propagating through the crystal. An example of this also we will discuss we will see that KDP that is potassium di hydrogen phosphate the electric field applied along its optical x axis we will give rise to this effect and will see in details about this effect.

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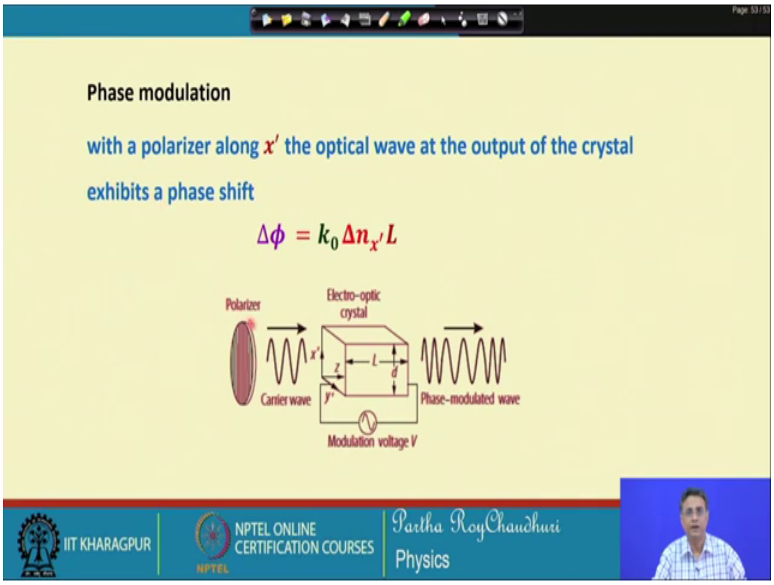

With the polarize that the second case that if you have a polarizers pass axes which is along the new principal axis x axis, and the light is now incident. But this axis will be active as long as the voltage will be applied in the longitudinal direction in this direction. So, when the voltage is there this axis will be active and the value of this the value of the refractive index will be starting from the base value that is n0 to the to the delta n value which is proportional to the applied electric field.

So, the phase will be modulated starting from the base value corresponding to the n 0 value to the new value which is dependent on the applied electric also as a result. But there is no change in the direction of anything it is only this polarized light and this polarized light will be out only there will be a modulation in the phase, just because there will be a modulation in the refractive index new refractive index starting from n 0 to the new value n x dash.

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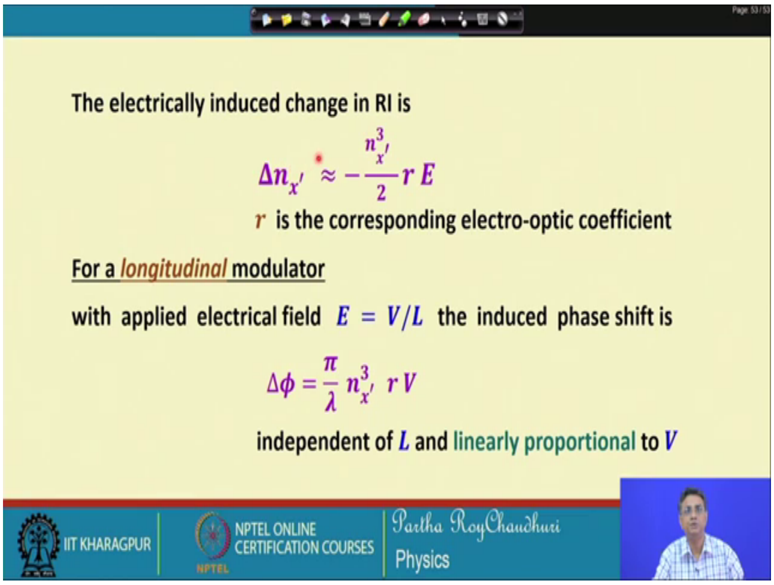

The electrical induced change in the refractive index this is the one which I i mentioned just now that is delta n x will be this much. But originally it was n 0 in absence of electric field plus this will be the new refractive index. So, this is the effect which has come from the external field. For a longitudinal case this delta phi phase in this case this will be just this multiplied by k 0 and the length of the crystal that is E equal to V into L, if I write V into Land V by L into L then this will give you that the phase which is this is the phase which will be modulated over the best phase that is related to the n x not n x dash independent this phase is independent of length Land is linearly proportional to V. So, as you modulate V then the phase will be also modulated I hope this is very interesting.

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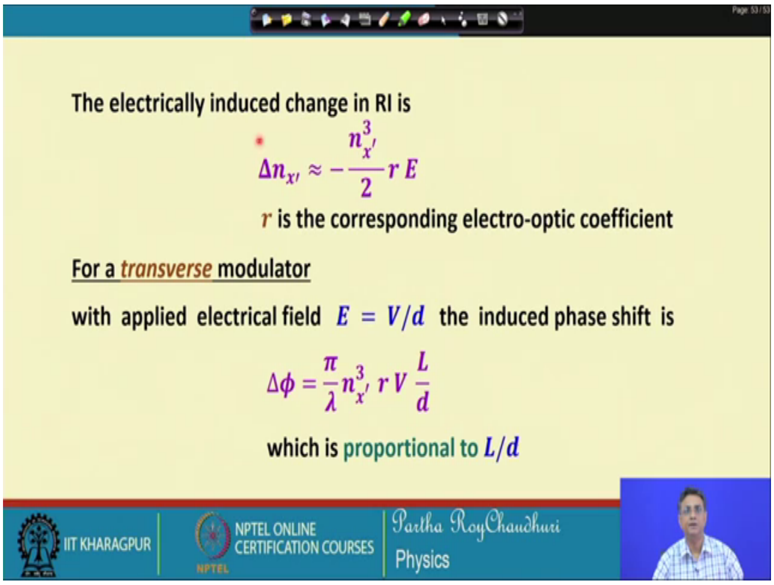

The electrical induced phase change will be this for the case of a transverse modulator with the applied voltage if the modulator is a transverse one, then V by d is the electric field which will be represented by this one and as a result this will be proportional to L by d

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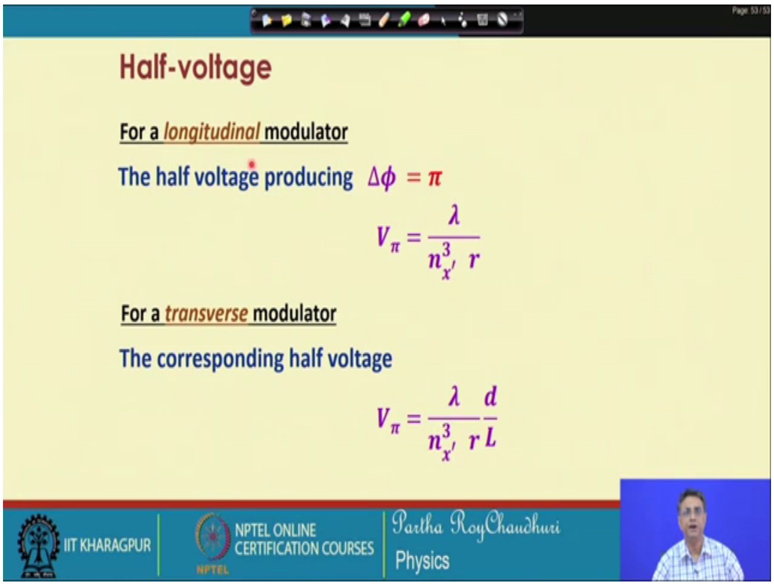

So, corresponding half wave voltage for the case of longitudinal one which is delta phi this has to be equal to pi. So, if we put that delta phi equal to pi this gives you a half voltage half wave voltage, which is equal to this the new refractive index property and for the transverse modulator the corresponding half wave voltage will be this. So, this these are the voltages which are required to switch the modulator from state one to state 0 or vice versa the way we choose the convention of switching modulator.

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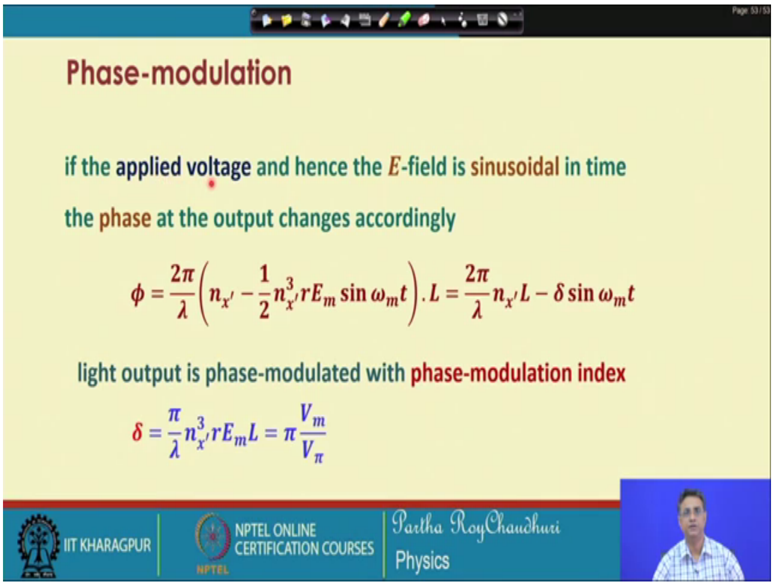

Now, in the in case of phase modulation if the applied voltage and hence the electric field if it is sinusoidal in time the phase of the output can be represented by this. So, twice pi by x the into n x dash plus additional this much of the phase. So, which can be represented as this; so, the light output is for phase modulated with the modulation index which is equal to this value, because this is the total phase new phase

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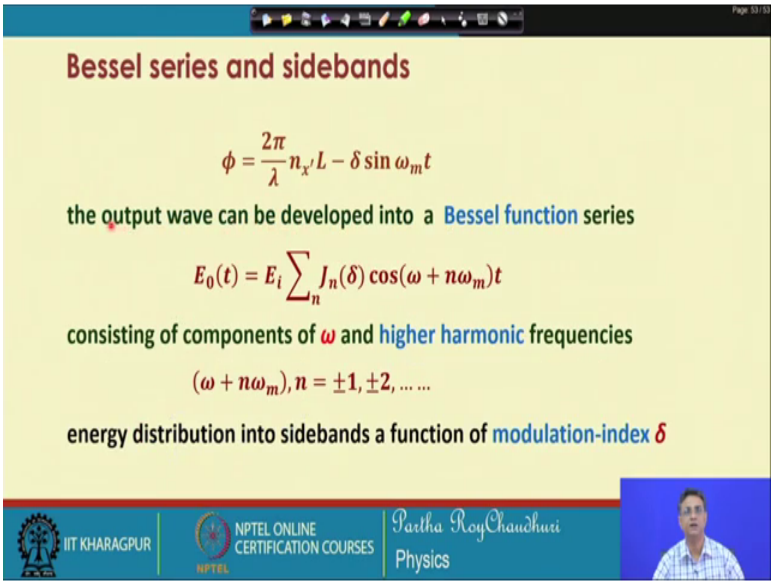

From this equation from this expression it tells you that it can be developed into a Bessel series del phi E 0 oft can be written in the form of this equation consisting of components of omega and higher harmonics. We will see this in the case of phase modulation for a particular crystal, then it can be it can have the component frequency is omega and n omega where n equal to plus minus 1, those are the sideband frequencies and will be the modulation index delta .

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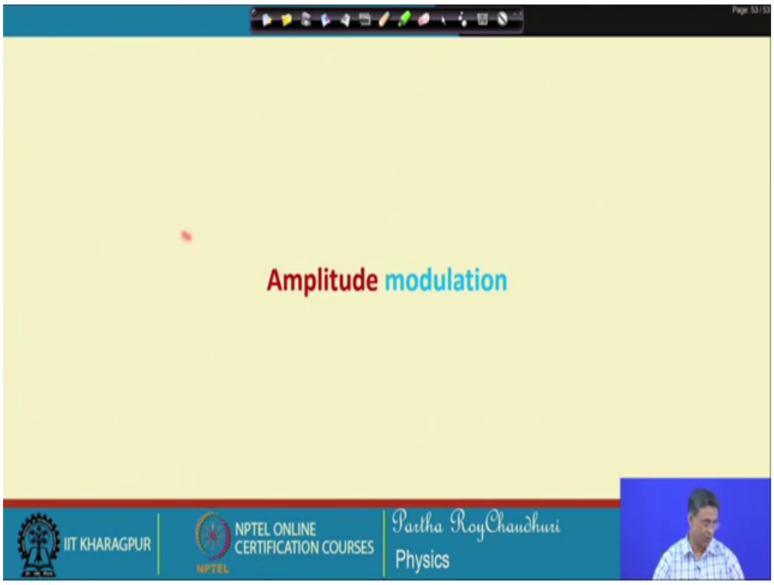

Now, we will discuss the amplitude modulation and how we can make use of this configuration of the polarizer and analyzer and the crystal in the case of longitudinal or transverse to get the intensity of the light modulated by the external electric field.

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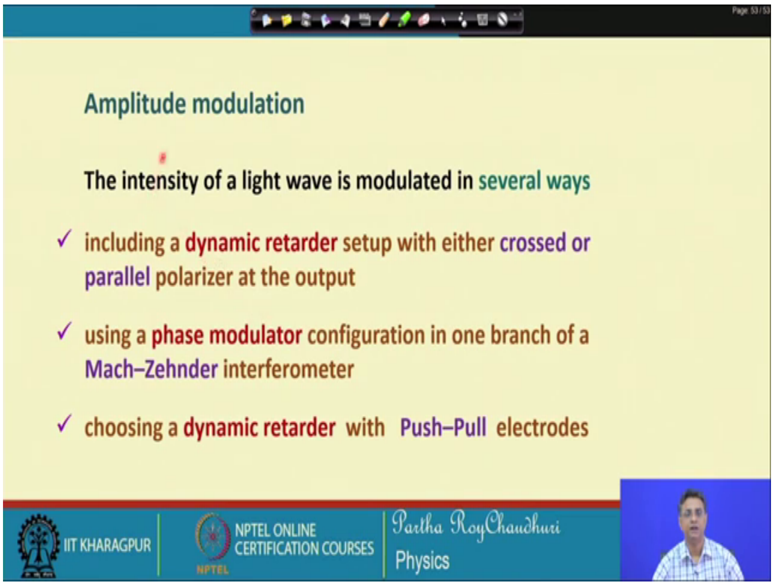

The intensity of a light wave is modulated in several ways using a dynamic retarder setup with a cross polarizer, which is the most popular and most common technique to implement the intensity modulation or amplitude modulation. Phase modulator configuration is also used particularly using a Mach Zehnder setup where you have to electrometric waves first split and then again mixed, and giving rise to the depending on the phase of phase difference between the individual arms which will result in the phase modulation. Then by choosing a dynamic retarder with a push pull electrodes these are the means to implement to realize phase module amplitude modulation by external electric field.

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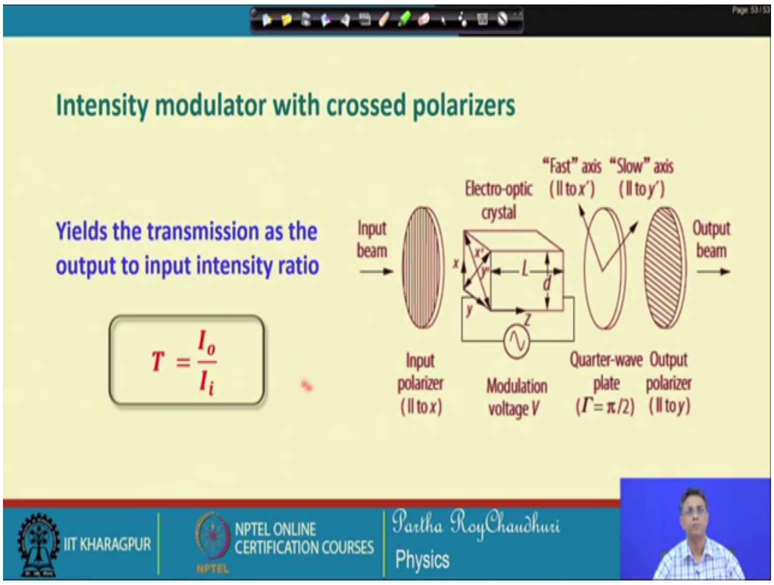

Intensity modulator with cross polarizers this in this case you see that you have the pass axes of the input polarizer, which is along which is along the old principal axes it could be x or y, then the light can be thought of split into two orthogonal polarizations which are x prime and y prime these are the new principal coordinate principal refractive in principal axes and therefore, the little have equal share with x and y prime, which you will travel along this length. But depending on the x prime and y prime refractive indices there will be a phase difference, there will be a retardation, there will be a delay and then because you have a cross polarizer. So, the output will be modulated the output will be modulated depending on the applied voltage.

Because applied voltage will make this the two orthogonal polarizations amplitude dynamic because of the delay and this is there is a quarter wave plate which is to come to bias this modulator this is what will call the optical biasing to shift the operating system to the 0 position to the linear region and this also we will see. And the transmittance this can be represented by this I 0 by I i this is I output intensity output by intensity input ok.

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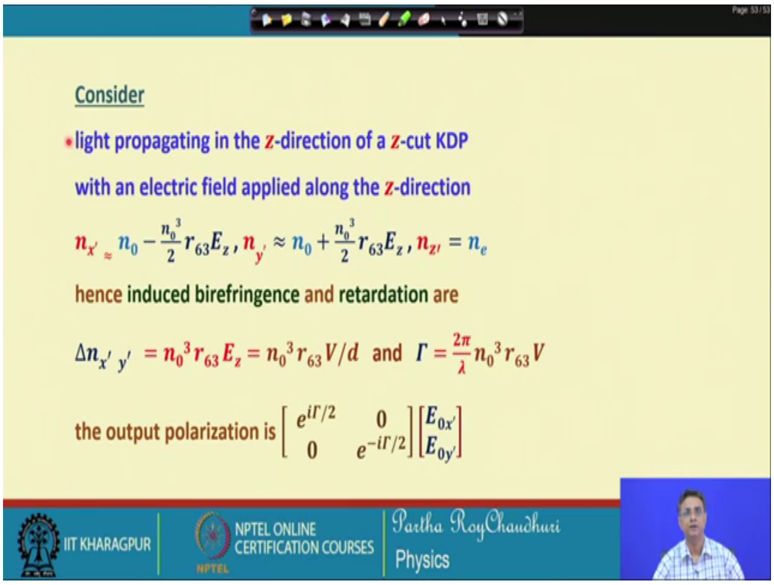

So, let us consider light propagating in the z axis with z cut KDP crystal, we will discuss this just to give us some an idea with an electric field applied along z direction then n x prime is equal to this and n y prime is equal to this n 0 plus this quantity, n z does not change it remains that extraordinary refractive index that is the induced birefringence and the retardation and the retardation are given by this equation that is delta n x which will be the retardation.

So, n x prime difference n y prime will give you twice of this. So, that is what is appearing here n 0 cube r 63 E z z E z if you replace by the voltage that is V by d then the retardation that is the phase delta pi will be which is represented by tau here is for a specific purpose that will use this matrix formulation to understand this polarization. So, these twice pi by lambda n 0 cube r63into v this will be the phase retardation. So, the output polarization can be represented by this matrix equation E to the power of i tau by 2E to the power of minus it au by 2 and then E 0 x dash E 0 y dash.

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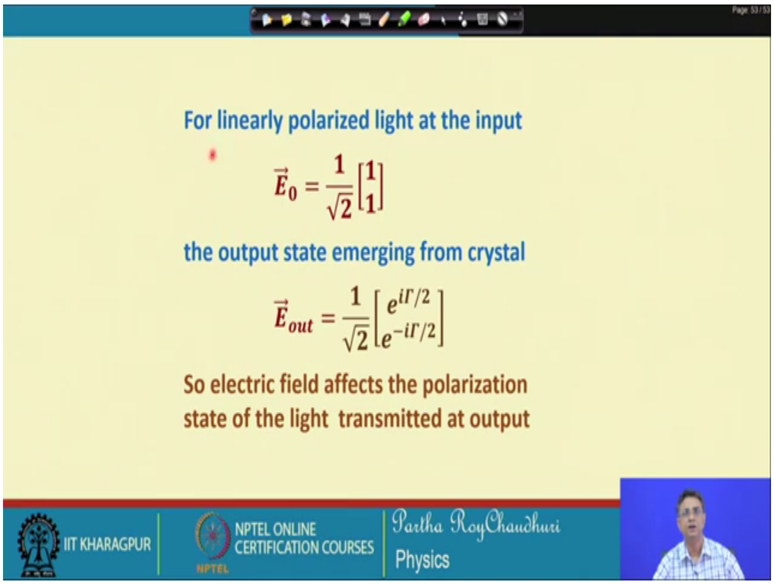

For a linear to have a more clear understanding to for a linear polarized linearly polarized light at the output input, if it is represented by this 1 by under root2 11the output state emerging from the crystal will be this which includes the effect of the medium with the retardation that is tau, tau it appears as tau by 2.

So, the electric field affect the polarization state of the light transmitted at the output in this way. You started with this was the input and now you get the output like this.

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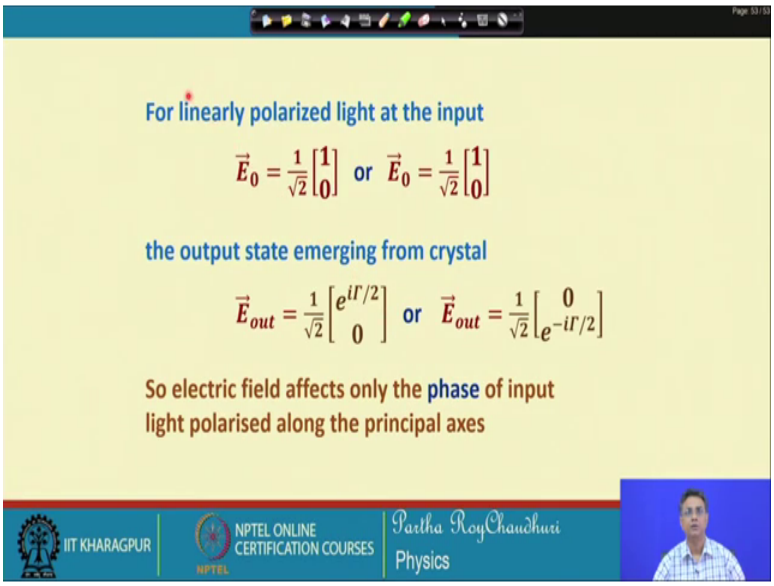

For a linearly polarized light at the input of this state1 0 or 0 1 oh this is this is by mistake this should be 0 and1 1 0 or 0 1 we will give respectively the output state from the crystal, which will be E to the power of i tau by 2 0 or corresponding to the this state this will be E out will be this.

So, the electric field affects only the phase of the input light, polarized along the principal axes. So, this is one of the principal axes one of the principal axes and the corresponding light is only affected in its phase, here also for the other eigen state it is affected in the phase.

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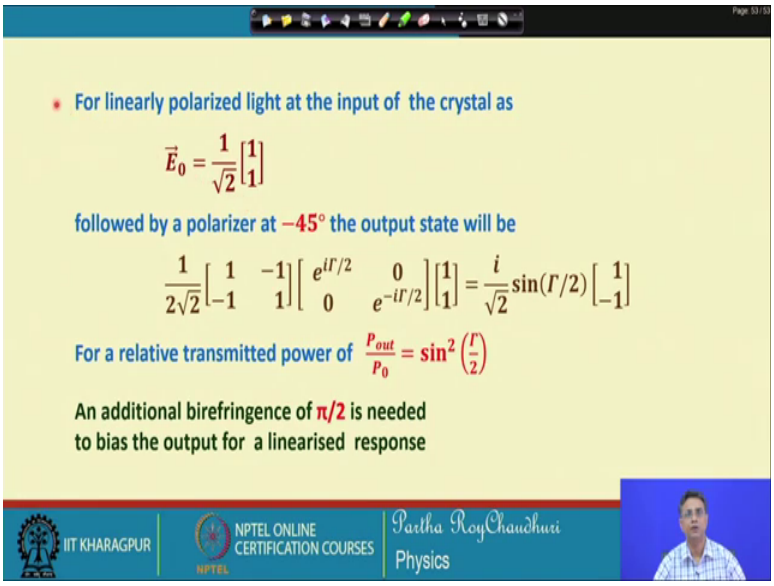

For a linearly polarized light at the input that is you have both11 and which is followed by a polarizer at minus 45 degree, the output state will be like this. So, this is now both of them and then 45 degree. So, you have the effect of 45 degree appearing here which will result in this state. That is why you have sine tau by 2 appearing in the power output to power input. So, P 0 is the input P out is the output power for a relative transmittance transmitted power if you look at this if you take the square of this.

So, this will be equal to tau by 2 by i 2. So, this will give you that P out by P 0 equal to sine square tau by 2 and additional birefringence of pi by 2 is the needed because of this factor to bias the output for a linearised response.

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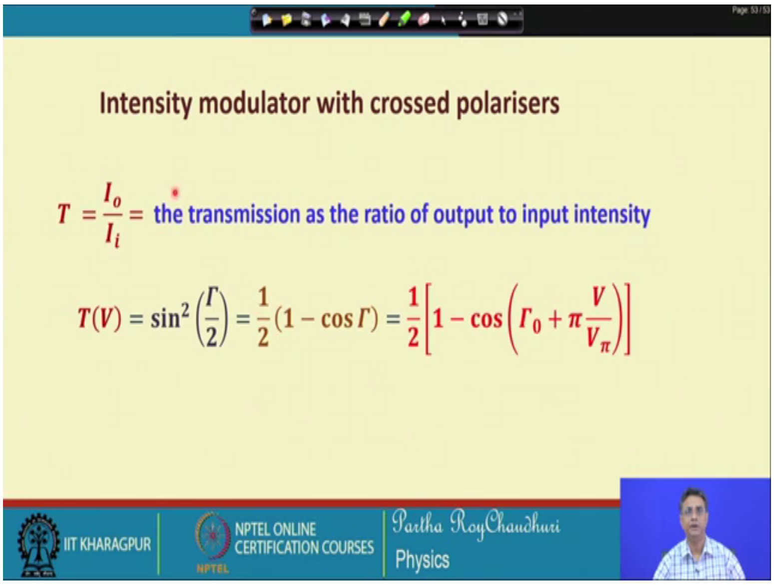

Now, intensity modulator with cross polarizer you have this t equal to I o by I input I output by I input is equal to the transmission as the ratio of the input to the output intensity. So, this you have seen that this is equal to sine square tau by 2 you can rewrite this as1minus cosine tau and you can further rewrite this as because tau phase retardation will be equal to tau 0 the birefringence without the field and this is due to the field which is proportional to the field V pi this is the half voltage half wave voltage and V is the applied voltage. So, this will appear in this form, we will see this expression later also for the specific kind of crystals at a given orientation when we will be discussing about that.

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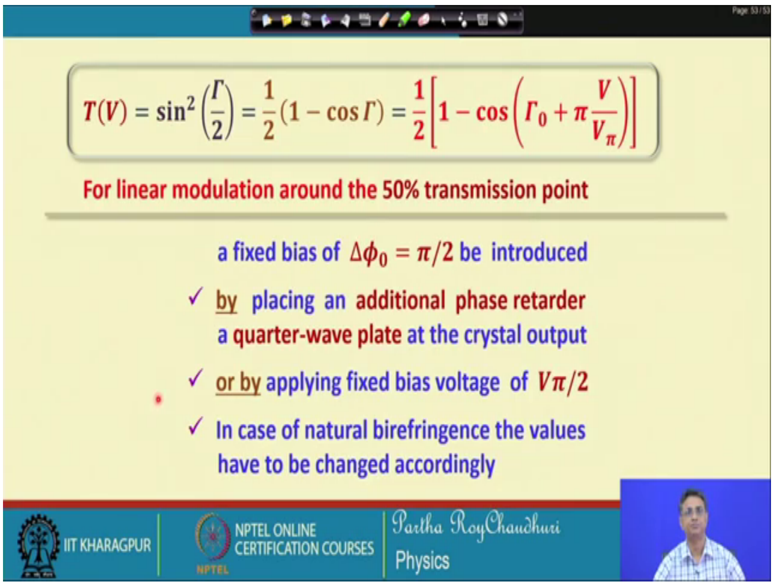

So, you have this expression that this transmittance is equal to half of 1 minus cosine tau 0 plus pi V by pi. For linear modulation around50 percent transmission point a fixed bias of del phi 0 equal to pi by 2 has to be introduced here. By this is done by placing an additional phase retarder, this I think we have shown earlier an additional phase retarder by placing this quarter wave plate it can be done by applying an additional voltage,, but we say that the disadvantage is it requires very high voltage.

So, this can be achieved by putting an additional phase retarder in the form of a quarter wave plate or by applying a fixed bias voltage which is equal to V pi by 2 in the case of natural birefringence the values have to be changed accordingly. These values have to be changed depending on the natural the magnitude of the natural birefringence.

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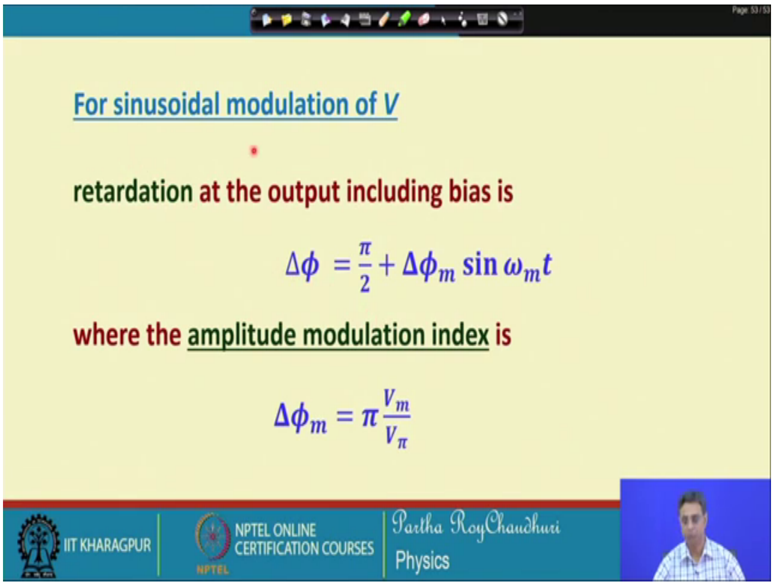

For sinusoidal modulation of the voltage the retardation at the output including the bias is given by this pi by 2 plus del phi sine omega t, then this del phi m is the amplitude modulation index because this is a depth of modulation the strength of modulation amplitude modulation index which is equal to this you will see that this del phi m is equal to pi V m by V pi is the modulating voltage V m or it could be V 0 also.

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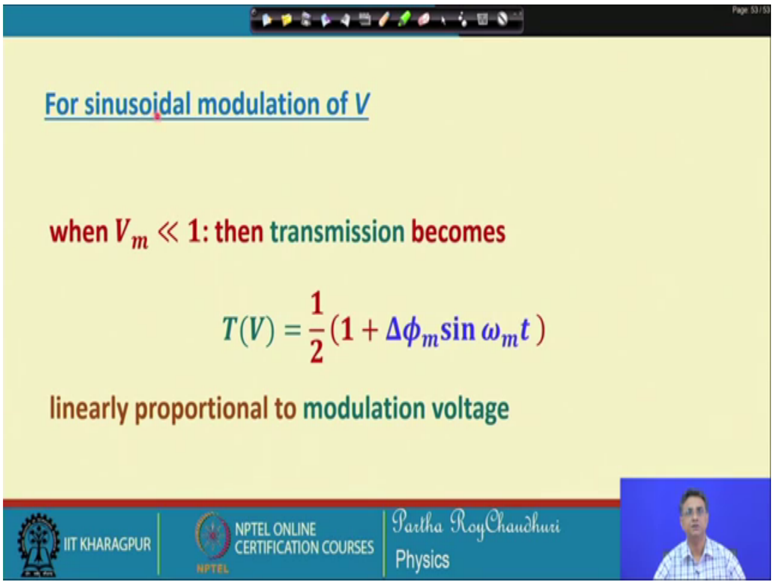

For sinusoidal modulation of V when V m is much much less than 1 that is for a very weak signal very small modulating signal, the transmission becomes this you can write equal to this and you can see that it is proportional to the modulating voltage, because it appears in the form of this modulating voltage linearly proportional to the modulating voltage.

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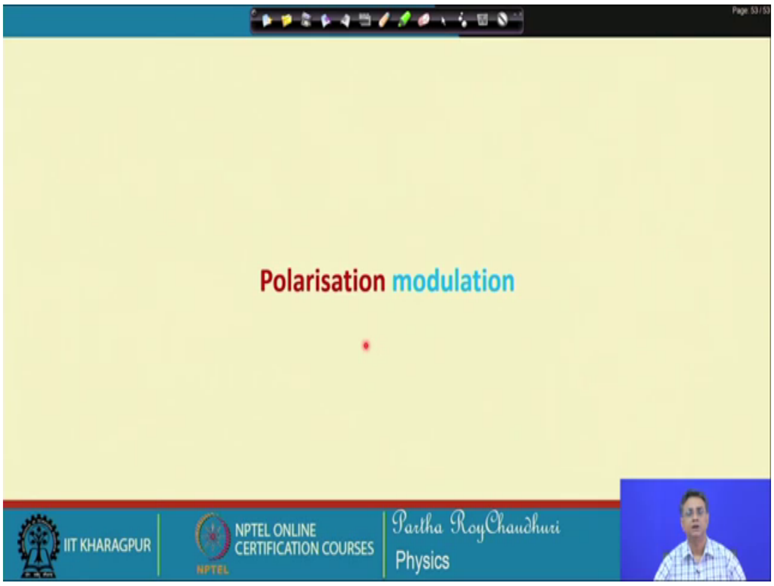

Now, we will quickly, is it through the polarization modulation.

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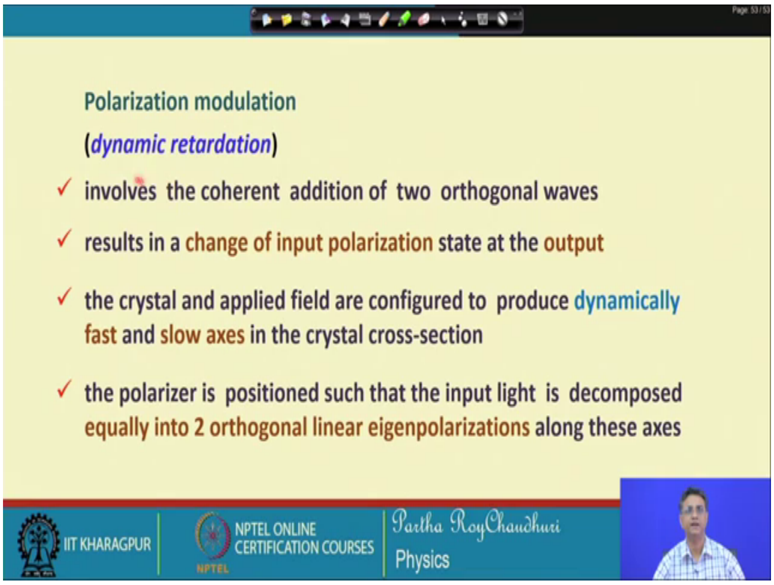

This is again this polarization modulation requires a dynamic retardation and it involves the coherence addition of two orthogonal waves. The thing that is required to understand that; in case of polarization modulation there is no change in the intensity or there is no change in the direction of polarization. The polarization axes will be same, but only the state of polarization will change at the output and to do that and you know that the state of polarization can be varied from linear polarization to elliptical polarization or circular polarization and back to linear polarization, this variation will be the modulated output.

So, the result it results in a change of the input polarization state at the output. So, the state of polarization will change, but the direction of polarization. So, the crystal and the applied field are configured in such a way that there will be a dynamic fast and slow axes, excited in the crystal across the cross section. The polarization polarizer is positioned such that the input light is decomposed into two orthogonal linear polarizations along these axes along these two orthogonal eigen axes.

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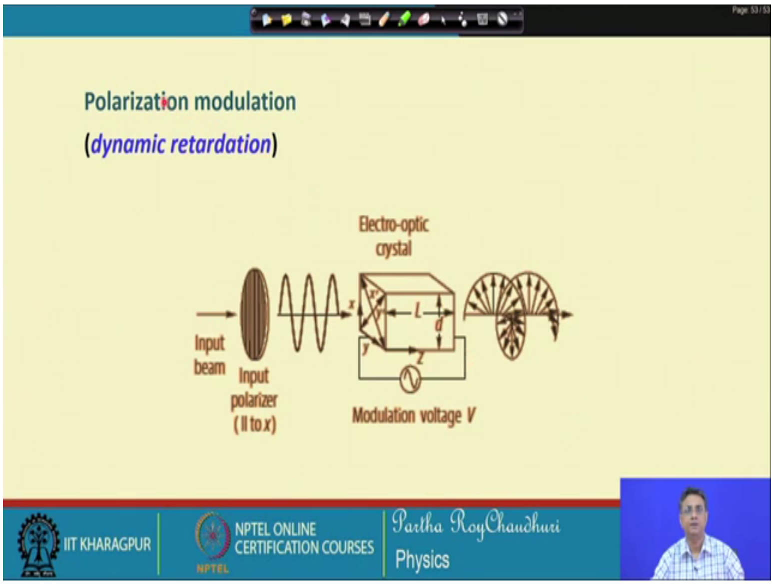

And let us see this setup you have an input polarizer which has this pass axes along the old principal axes of the system, old by saying old I want mean that in absence of any voltage this is the principal axes system principal axis x and principal axis y and any how principal axis z does not change, but once I apply the voltage, the principal axes the new principal axes are x dash and y dash. So, I launch the light input polarization with which is halfway between the x prime and y prime that is along the x polarization axis.

Now, because x prime and y prime refractive indices along these directions, this for these polarization are different. So, they will develop a birefringence, but the polarization axis will remain same. So, as a result depending on the depending on the applied voltage and hence depending on the retardation between these two polarization that is x dash and y dash, the output polarization state will be changing from linear to electrical and back to linear.

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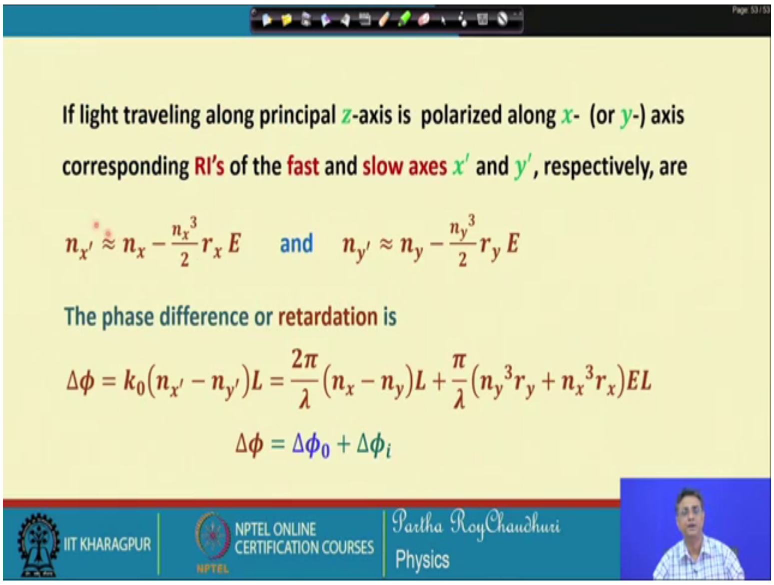

Depending on in this case it will be circular if I give equal 45 degree inclination to x prime and y prime along when the polarization is along x axis. So, if light is travelling along the principal z axis, and is polarized along x or y x or y axis the corresponding refractive indices of the first and slow axis will be represented by this x prime and y prime, and these are the values associated with this refractive indices new refractive indices which are voltage dependent electric field dependent refractive indices.

These are n x and n y are anyway 0 n 0. So, therefore, you have a birefringence which is which is electric field dependent birefringence which can be represented by this. Now, n x n y and r y r x these are the crystals electro-optic properties and this is the general way of looking at it depends on the specific crystal. So, delta phi is now you can see that you have a you have a natural birefringence of the medium and this is the induced birefringence of the medium. So, delta phi 0 is a natural one delta phi I is the induced birefringence due to the applied external electric field.

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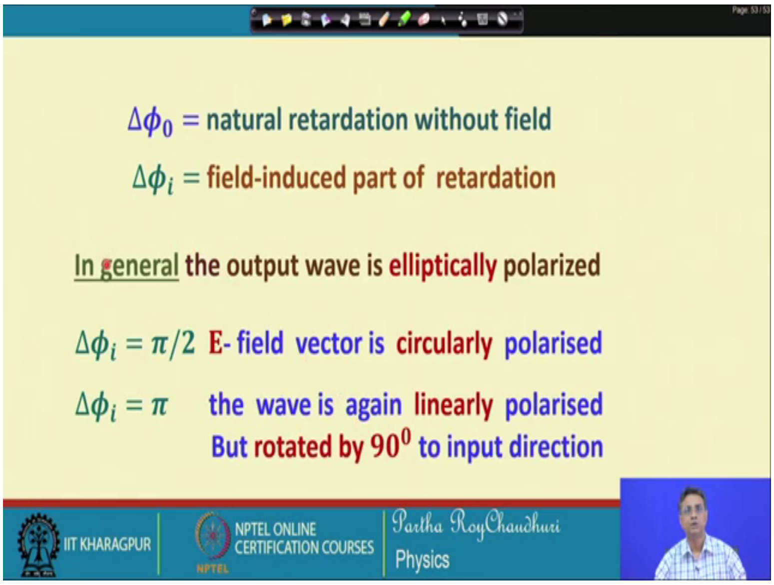

In general the output wave is elliptically polarized. But if you if you are induced birefringence say size that which is an electric field dependent property voltage dependent property is equal to pi by 2,then the electric field vector is circularly polarized that the output, but if it is pi then it will be linearly polarized.

So, by changing the voltage from 0 to pi you can have linear to circular linear to circular to linear and back to circular and so on and so forth by rotated by 90 degree to the input direction. So, this is how you can switch you can change you can continuously modulate the polarization of the output.

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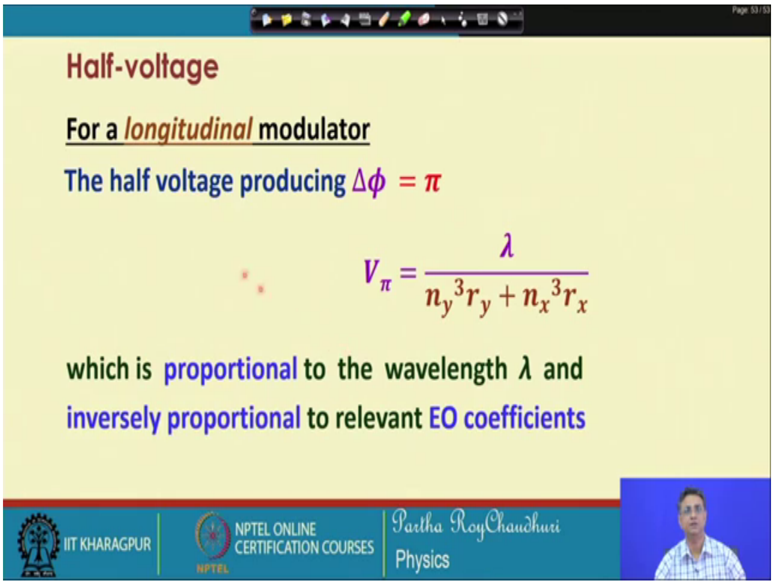

And in this case the corresponding half voltage is given by this equation, which comes from this equation that is your the voltage which is required to switch the modulator this must be put equal to pi.

So, this is a phase that has to be equal to pi. So, that gives to V pi the half voltage that is required for this modulators switching fromstate1 to state 0 or so, and this is proportional to the wave length lambda as you can see. So, this half voltage depends on the wavelength also is linearly proportional higher the voltage higher will be the half voltage required, and it is inversely proportional to the relevant electro optic coefficient that is r y and r x.

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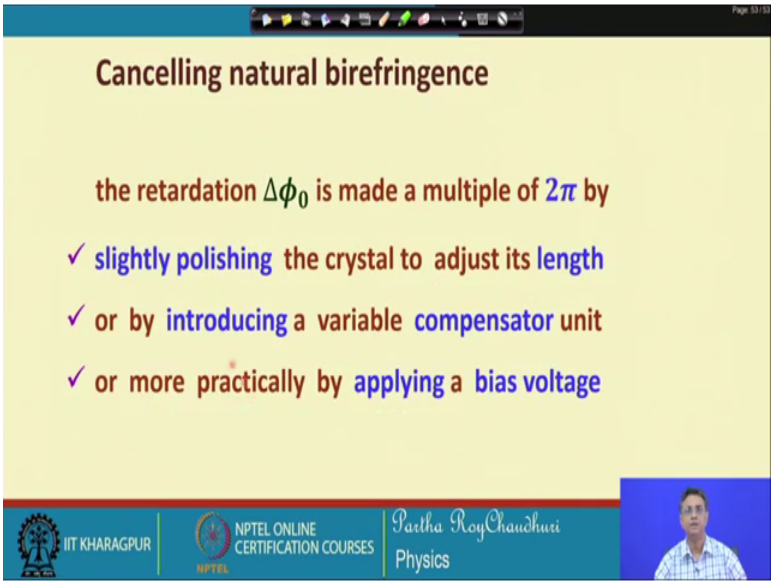

Now, so this canceling this, this is one important requirement that just to make this is the birefringence is just proportional to the applied voltage we need to cancel this natural birefringence which can be done by optical biasing or by applying a bias voltage. So, this retardation delta phi is made a multiple of twice pi, which can be done by slightly polishing the crystal to adjust its length. Because it is length dependent natural birefringence is length dependent k 0 delta n x y into l.

So, this l and all put together if it is made equal twice phi then there is no natural bias birefringence that is this term will not contribute or by introducing a variable compensator unit just to compensate cancel out the effect of this delta phi 0 that can be inserted and a more. Practical approach is to tune the applying voltage by a small bias voltage which will just cancel the effect of delta phi 0

So, by this discussion we have tried to understand how the phase modulation amplitude modulation or the polarization modulation work in the case of light wave, and in the in the relevance of the electro optic modulation by applying and electric field.

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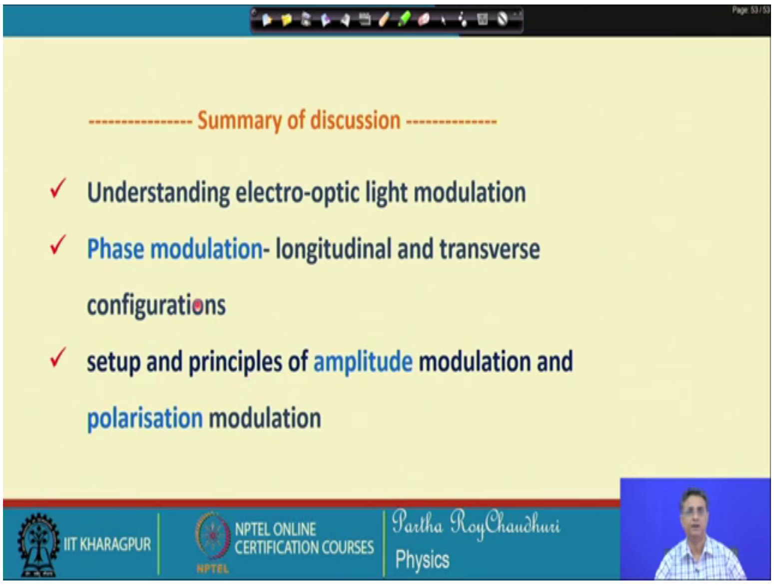

So, you understood tried to discuss this electro optic light modulation, in terms of phase modulation under longitudinal and transverse configurations. We also discussed the setup for the amplitude g m modulation and polarization modulation with the basic principles and how the phase amplitude and polarization can be modulated try to understand.

Thank you.