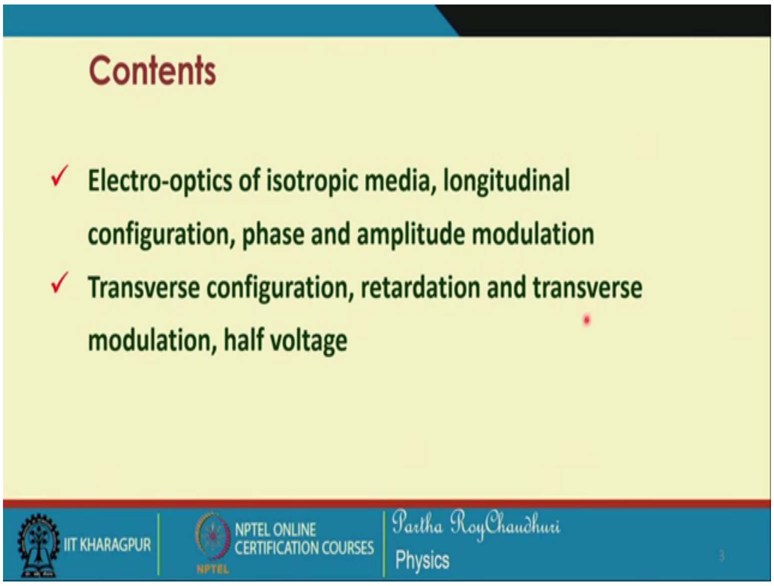
Modern Optics
Prof. Partha Roy Chaudhuri
Department of Physics
Indian Institute of Technology, Kharagpur

Lecture – 33
Electro-optic Effect (Contd.)

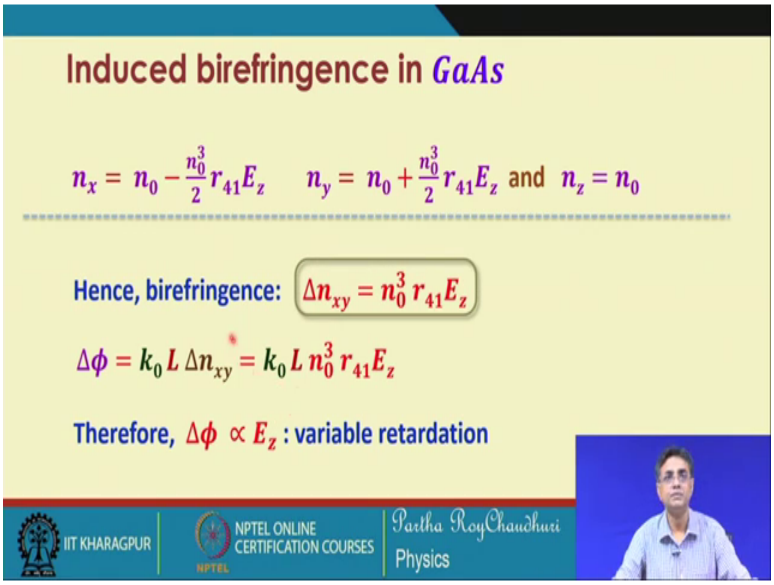
We were discussing the electro-optics for isotropic medium and we started discussing the electro-optic effect in gallium arsenide. In between we took up the a discussion on the basics of how the light can be amplitude modulated, phase modulated and polarized polarization modulation. And, the basic configuration required and how the modulation take places. And we will be again continuing with the electro optics of this isotropic medium that is in particular this gallium arsenide crystal.

(Refer Slide Time: 01:01)



And we will be discussing now, that the longitudinal configuration that is when you apply a voltage along the length of the crystal along which the light is propagating. Then how it has to be configured for phase modulation and for amplitude modulation then what will be the consequence of that in terms of the modulation birefringence, then half voltage. So, in the then after that we will consider this transverse configuration. In the transverse configuration we will see the retardation phase retardation and then the transverse modulation. How what is the half voltage required in that case to switch the modulator.

(Refer Slide Time: 01:52)

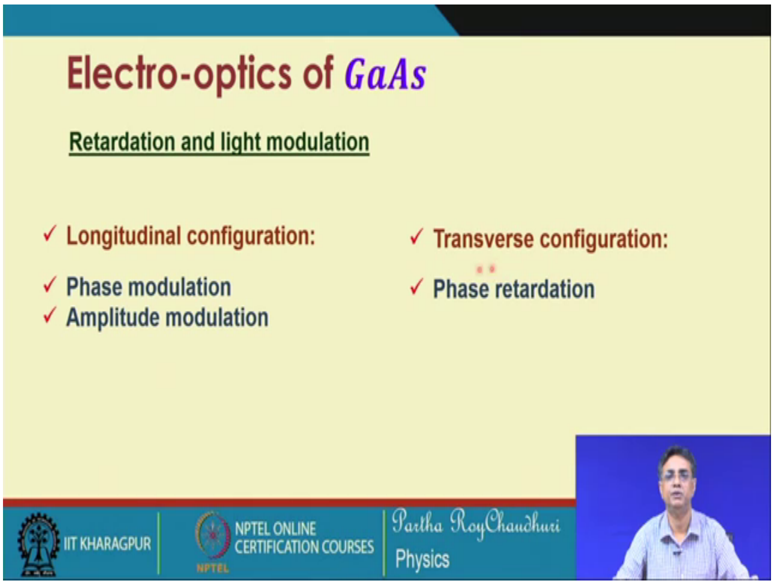


So, let us recall that in the case of an isotropic medium with gallium arsenide, the new principal axes in the principal axes system, the refractive index n x can be written in this form with the original refractive index n 0 minus this quantity is a function of the applied electric field along z direction. And, in the similar way the refractive index seen by the light for y polarized light will be this and for n z there is no change.

And so, these are the set of new principal axes system refractive indices. Therefore, the birefringence that is seen by the x and y polarized light in the new principal axes system will be delta n xy which is equal to the difference of these two quantities; that is equal to n cube r 41 is the electro optic coefficient of gallium arsenide into E z. And, then the phase retardation phase delay that is equal to k 0 L the length of the crystal along which over which the light propagates and interacts with the crystal. That is k 0 L delta n xy which is equal to this and we are familiar with this quantity and we will be again encountering back and forth with this kind of expression.

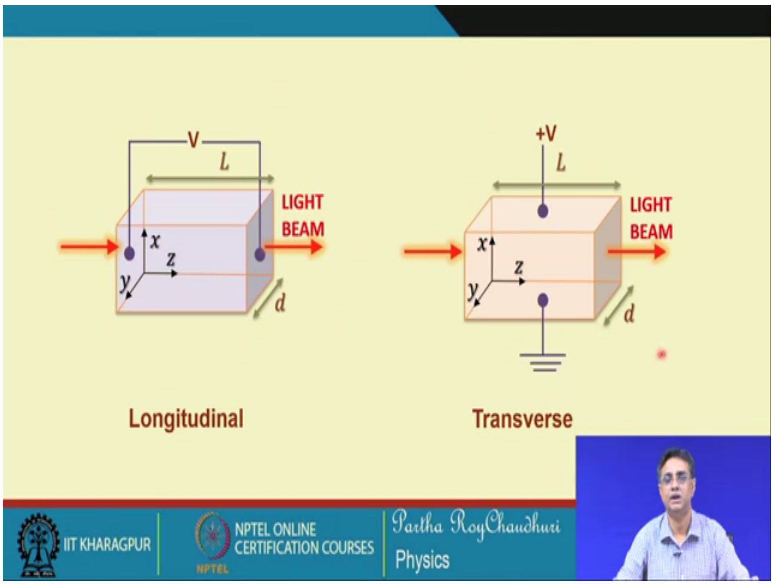
So, we find that this phase retardation delta phi is proportional to the applied electric field. So, in terms of the voltage this will be again this phase retardation is proportional to the applied voltage because, all other quantities remaining constant k 0 involves the wavelength wave space wavelength. Then n 0 the refractive index of the crystal, in absence of any electric field length L is the length of interaction.

(Refer Slide Time: 04:09)



So, now we will consider the longitudinal configuration with emphasis on the phase modulation and amplitude modulation. Then we will consider the transverse configuration which is different from this and we will see that how the performance of the crystal can be improved by choosing the geometrical considerations like the length and the width of the crystal which will be involved in this case. And, this will improve the performance of the modulator.

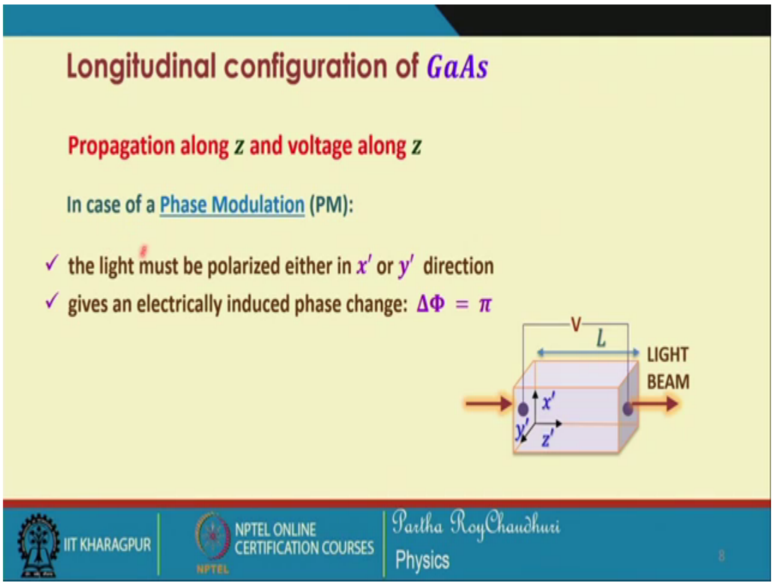
(Refer Slide Time: 04:46)



So, in the longitudinal configuration as we know you have a length L and you apply the voltage along the length of the crystal and the light beam is propagating through the crystal in the z direction. Whereas, in the transverse configuration you apply the electric field the voltage that is across the modulator in the x or in the y direction whereas, the light is propagating along the z direction. The length of the crystal is L, we will assume and the width of the crystal is d.

Therefore, for longitudinal configuration we will first take up the phase modulation. As you will remember that for phase modulation we will have to launch the light to the crystal with its polarization axes, which will be along one of the new eigen axes that is x dash or y dash and light will be propagating along the z direction.

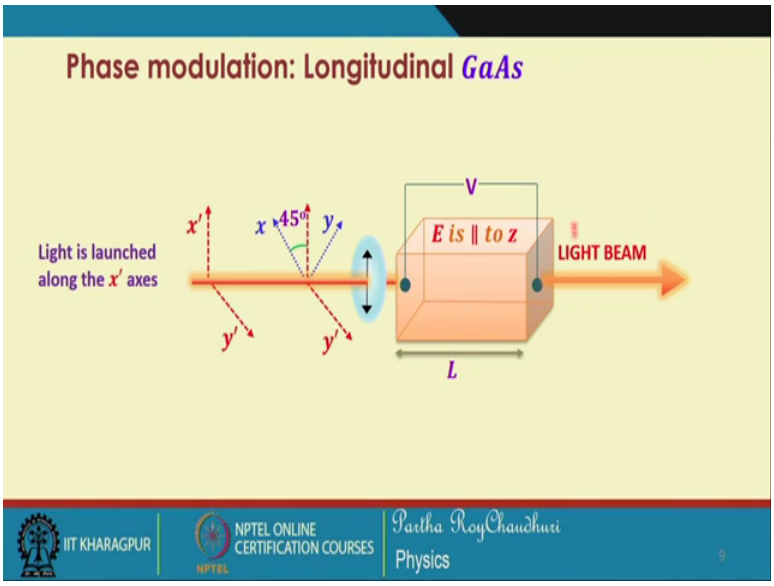
(Refer Slide Time: 05:50)



So, under this configuration so, let us look at this configuration that will be launching light along x prime or y prime these any of these directions. And, light will be propagating along these direction that is along z direction which is z prime because, z and z prime are the same. Crystal undergoes a, the a principal axes system it undergoes a rotation about z. So, z and z prime remains the same.

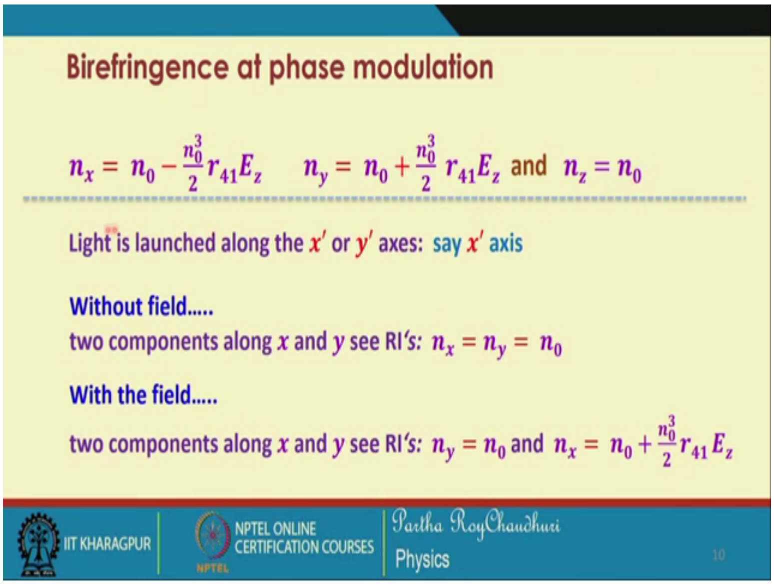
So, in this case the light must be polarized either in the x dash or y dash direction as I have mentioned. Because, once we apply the voltage the polarization axes x dash or y dash I only require the change in the change in the refractive index along any of these directions, which will modulate the change in the refractive index. We modulate the light and there will be no no analyzer at the output, there will be one polarizer which will which will be to launch the light along the z dash polarization axes say x prime or y prime.

(Refer Slide Time: 06:57)



So, this is the configuration light will be launched along x prime axes or y prime axes. Now, this is your this is your x dash yeah x prime axes, this is y prime. It could be launched, this is the input polarization I have shown with this arrow, this is the input pollution which is half wave through x and y axis of the old system without any field. So, this polarization now moves to the crystal and because the electric field changes; so, this refractive index seen by this polarized light will be modulated as a result the phase will be modulated. So, this polarized light which will be available here will be modulated with the applied voltage, the phase of this light will be modulated.

(Refer Slide Time: 07:49)

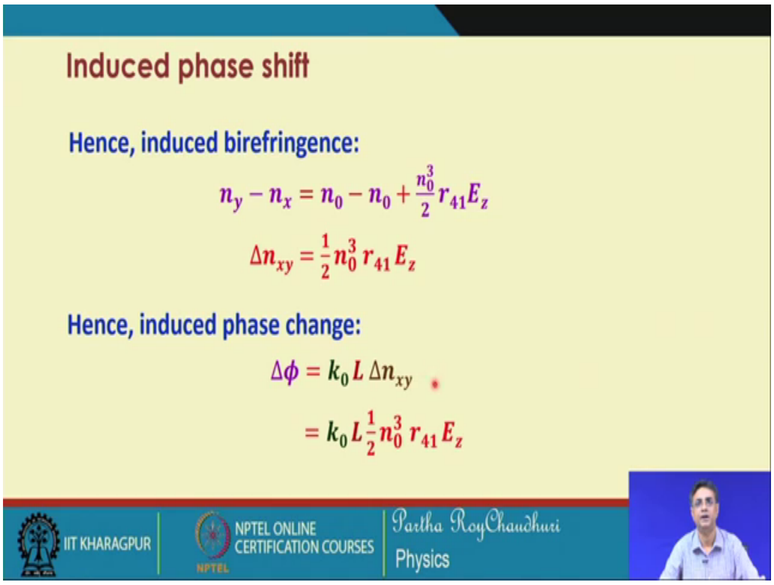


So, let us see that once again this n x is represented by this, n y is represented by this which are the signatures of the applied electric field n z is 0. So, light is launched along x prime or y prime axes, let us suppose that first we considered that light is launched along x dash axes. So, without field the two components along x and y sees the refractive index which is n x equal to n equal to n 0. But, with the field the two components along x and y because when you launch light along these axes there will be two components: one is along this, another will be along this.

They are at 90 degree to each other they are normal to each other, these are two orthogonal components. But, both of them this x and y polarized light will see the same refractive index in absence of any field. So, there is no birefringence there is no phase delay, but there will be a phase which will be carried over because of the length of travel along the crystal. So, without field there is no birefringence both the lights along x and y will be will see this n 0.

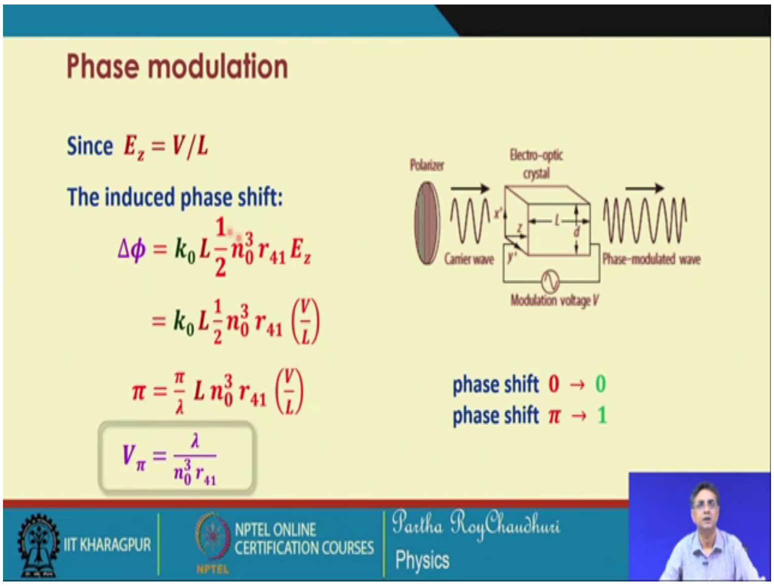
And, with the field the two components applied along x and y will now, become n 0 n y because there is no light along n y. So, the light the component of we have injected light only along this axis. So, along y axis the birefringence, along y axis you have n 0 whereas, along x axis this is the new refractive index in by the light which is which has the component along the old x axis.

(Refer Slide Time: 09:47)



So, this birefringence n y minus n x these are the two refractive indices, the indices to the birefringence and the new along the new coordinates that is x prime and y prime. So, this will be seen by this one hence, the induced phase change will be k 0 L into delta n xy, but delta n xy this has this value. So, we just plug in this value here which will give me the phase retardation that is del phi phase change with respect to as a function of this E z. So, as you change the value of E z the phase will also change. So, it will be phase modulated by this E z that is the applied voltage.

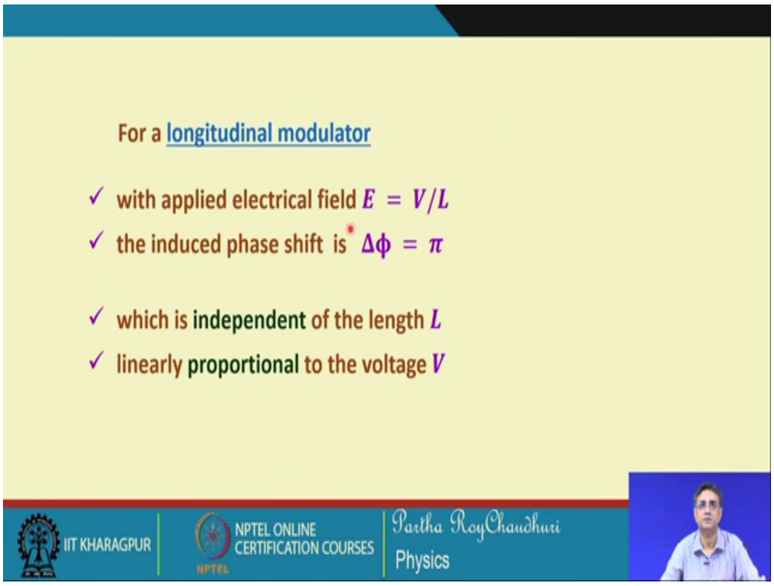
(Refer Slide Time: 10:38)



So, this is the setup you have an input polarization, which is along the new principal axes system let us say x prime x dash. So, this x dash light it undergoes a phase change because the x dash light undergoes a change in the refractive index as a function of the electric field. And, then the output light will be phase modulated because the refractive index changes therefore, the phase also changes. But, this change in the phase is now proportional to E z which is equal to V by L. So, in this case this L L cancels.

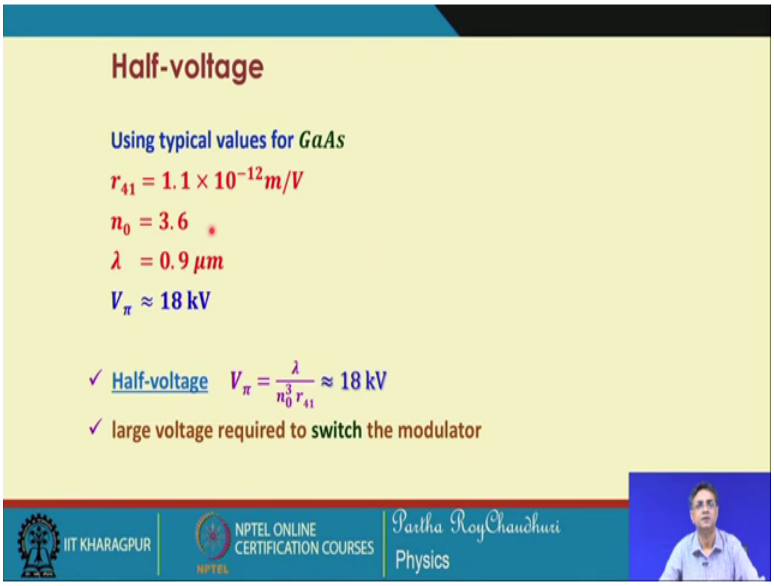
So, therefore the half voltage that is the voltage that is required to get a phase change of del phi equal to pi that is equal to V pi equal to lambda by n cube r 41. So, this means that the phase change equal to it can be convention that phase change equal to 0 which is equal to 0, but phase change equal to pi which is equal to r. So, switching from 0 to 1 requires a phase change of pi or from 1 to 0 depending on the convention, depending on the protocol of the modulated design. Then the phase shift pi correspond to corresponds to switching off the modulator from the state 0 to state 1. So, that requires a voltage V pi.

(Refer Slide Time: 12:07)



So, this we find that with the applied electric field V by L the modulator, the induced phase shift is del phi is equal to pi that is the requirement for switching. And, this is you can see that it does not involve any L or any other quantity. It is only the your the wavelength, the original refractive index and the electro optic coefficients. So, it does not involve any other thing. So, therefore which is independent of the length L and it is linearly proportional to the voltage; that is this switching is linearly proportional to the voltage. The phase changes proportional to the voltage.

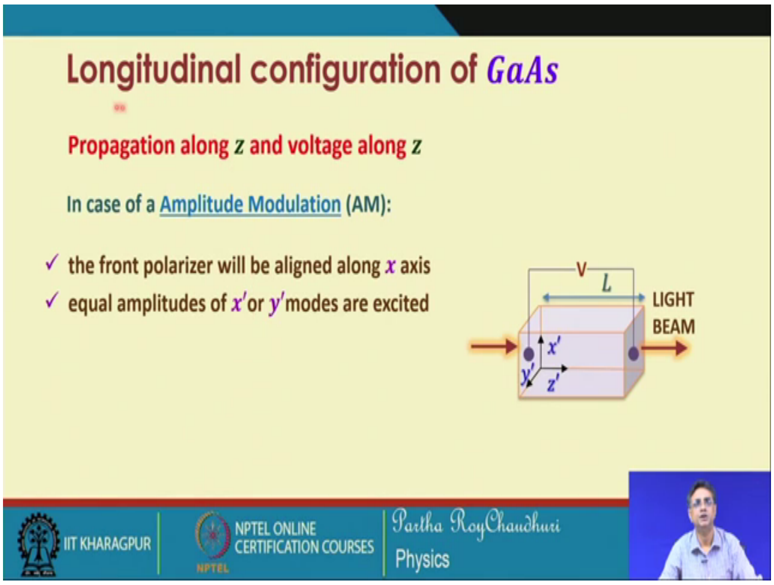
(Refer Slide Time: 12:57)



So, let us use the typical values for gallium arsenide. These are the quoted values; we have shown that r 41 is equal to this and n 0 for gallium arsenide is a 3.5, 3.4, 3.6, 3.5. Let us assume that this is 3.6 and if we use a wavelength of 0.9 micrometer, then the V phi value that approximately it comes out to be 18 kilovolt, which is a very large voltage. And, it requires a very careful setup to handle with 18 kilovolt of its electrical voltage.

Now so, in this case this half voltage is about 18 kilovolt. So, you conclude that the for switching off the modulator we require a voltage which is of the order of some 18 kilovolt and that is pretty high. And, now we will see that if you change the configuration intelligently whether, we can reduce this half voltage for switching this modulator. Indeed for the amplitude modulation scheme, we will see that the half voltage required will be less will be half of the, half voltage that is required for the phase modulation.

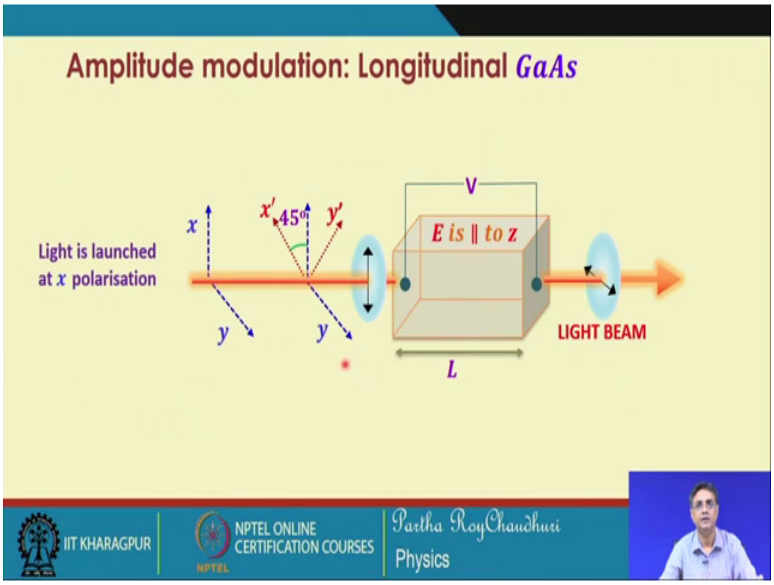
(Refer Slide Time: 14:19)



So, in this case we consider this setup now, as we will remember that for amplitude modulation you have to set the polarization half wave between the new principal axes system that is x dash and y dash half wave through. So, that the moment you apply the voltage both the components along x dash and y dash will have equal excitation. So, the front polarizer will be aligned with x axis and this x axis will give you 50 percent of x prime and 50 percent of y prime when the voltage will be applied.

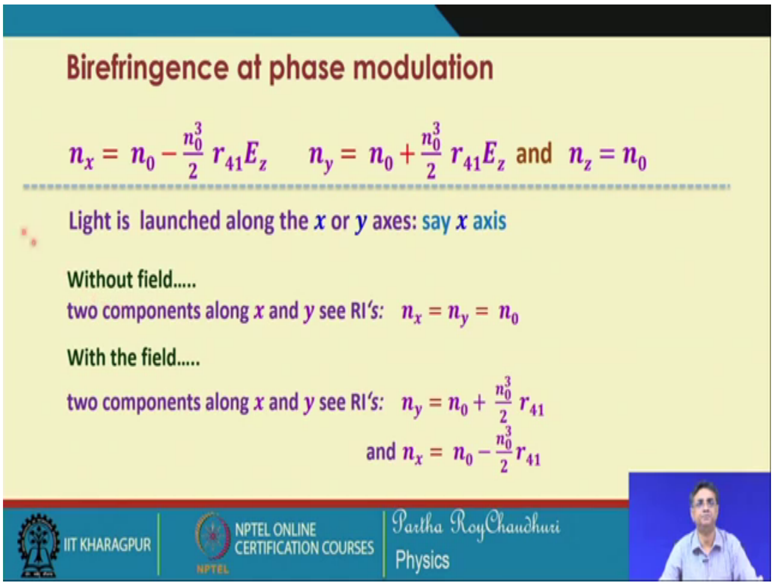
So, that is the philosophy and then there will be an analyzer at the output of the crystal. So, now the light which will be decomposed into x prime and y prime axes they will travel with two different velocities because, these two light lights will see different effective indices because, of the electro optic effect and there will be a birefringence between these two lights.

(Refer Slide Time: 15:21)



And then this birefringence acting over the length will give you the phase retardation and if you placed an analyzer which is crossed with the input then the light will be periodically modulated with the frequency of the input signal. So, light this is the configuration light is launched along the old x axis and it will be shared by the two orthogonal polarizations, which are the new principal axes system of the crystal. And, then it propagates develops a phase delay, there is a cross polarizer you get a modulated output.

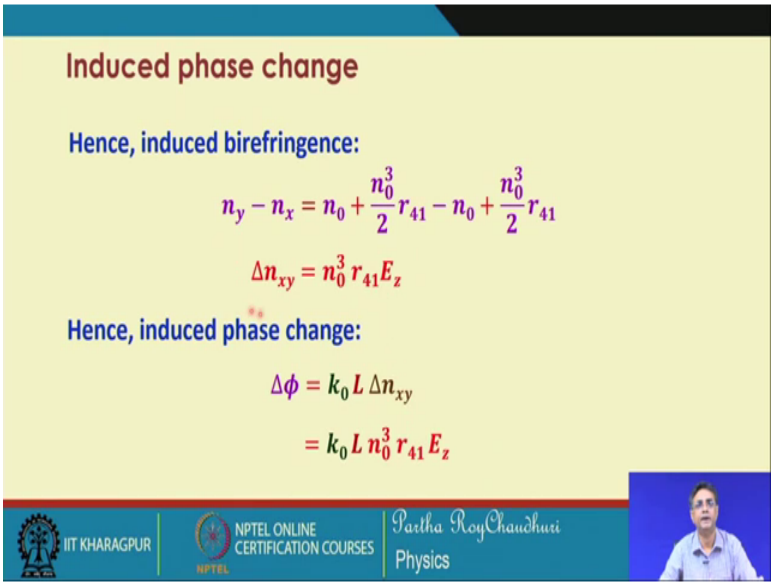
(Refer Slide Time: 15:59)



So, once again so, this is the same relation for the same crystal and under the same configuration of the voltage and light propagation. So, now without field the two components along x and y they will once again the same thing will see the same refractive index n 0 and there is no birefringence. But, when you apply the field with the two components along x and y we will see these new refractive indices.

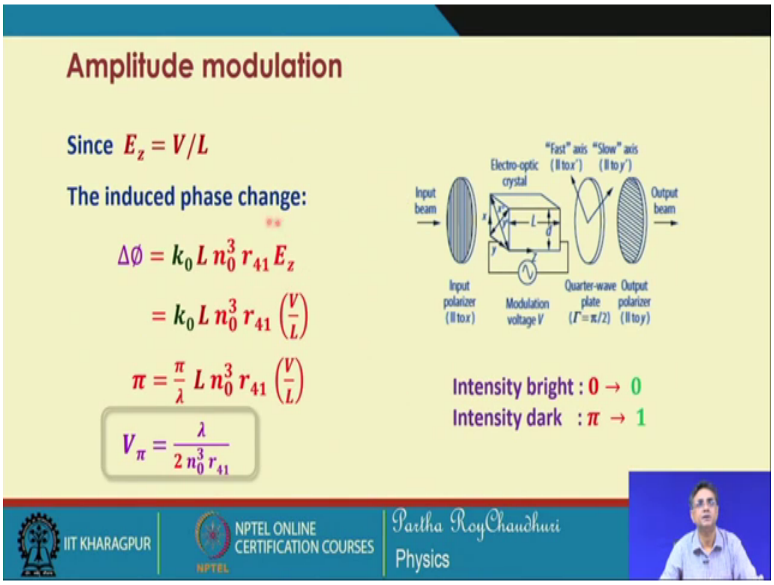
So, you can see that one is more another is less depending on the value of the magnitude of the coefficient one is more another is less. So, that develop say because they will travel with two different phase velocity because, the see two different refractive indices. And, they will in turn develop a delay between this and this delay will develop a phase difference between them.

(Refer Slide Time: 16:55)



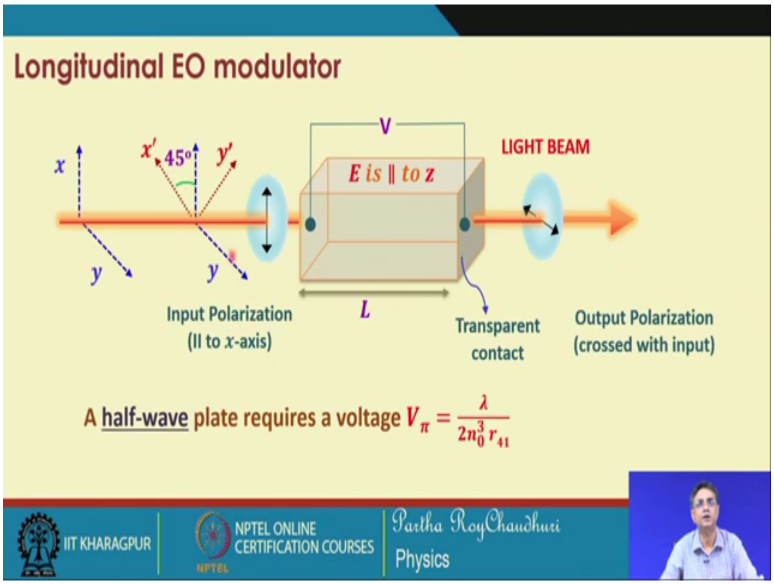
So, the birefringence here is n 0 cube r 41 E z which is double in the case of if you consider the phase modulation, where there was a divided by 2 factor here. So, the induced phase change in this case you will have to multiply with k 0 and the length of the crystal. So, that this will be the induced change in the phase between the two orthogonal polarized light in the new principal axes system. As a result you see that this birefringence is now, proportional to the applied electric fold electric field.

(Refer Slide Time: 17:38)



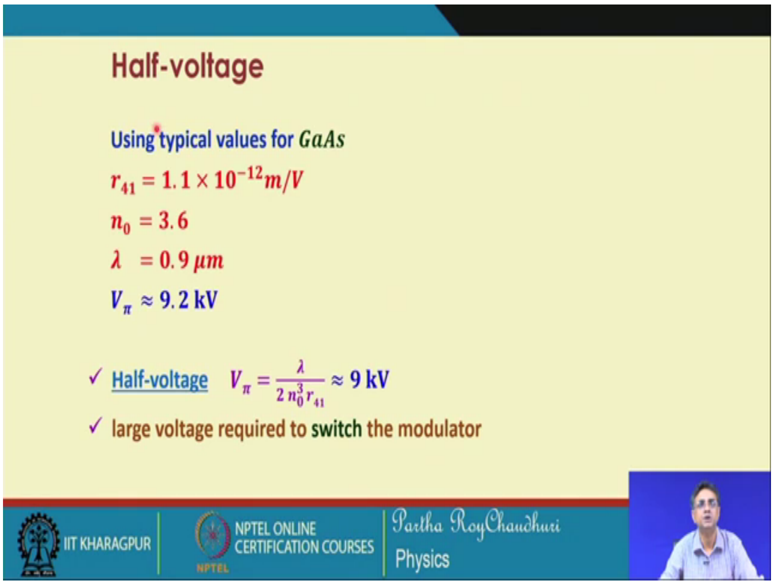
And we see how with it depends on the electric field you can see that L and L, in this time also will cancel because everything remains the same, only we had arrange the input polarization which is half wave between the x prime and y prime axes. And, you have set an analyzer at the output which is crossed with the input is only difference in the configuration. And, as a result you get V pi which is equal to this and you can see that it is reduced by a factor half.

(Refer Slide Time: 18:10)



And consequently, after this is the setup for this. We have this polarization which is launched along this which is half wave through x prime and y prime. Then the develop the delay between the two eigenpolarizations, which are along x prime and y prime. And, the because they will see different refractive indices and at the output of this modulator of this polarizer which is a cross position with respect to the input we will get it. So, the half voltage required is now equal to V pi which is half of the half voltage that is that was required in the case of phase modulation.

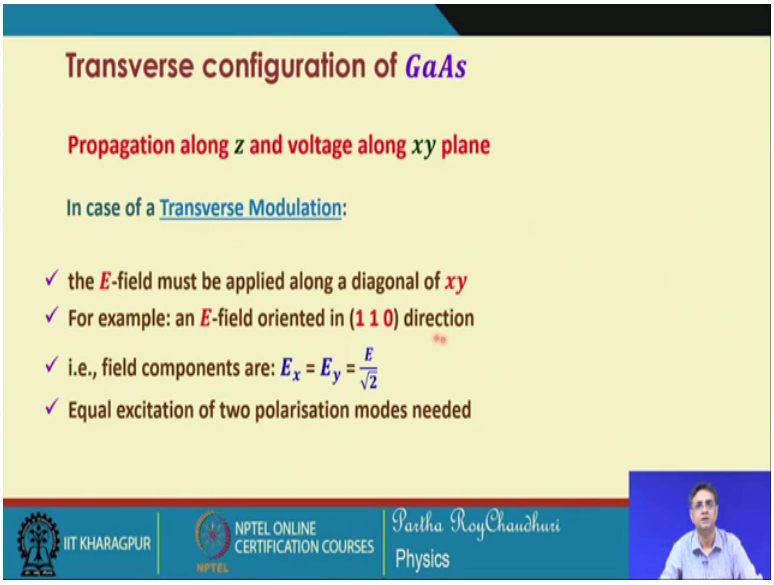
(Refer Slide Time: 18:58)



So, if we use the typical values then we find for this gallium arsenide using the same numbers that we have used earlier that is n 0 equal to 3.6 lambda equal to 0.9. Find that V pi is of the order of 9 kilovolt which is half the voltage that was required for the phase modulation. So, there has been some improvement when switching from this phase modulation to the amplitude modulation. And, still this required voltage is very light, very high of the order of kilovolt 9 kilovolt.

And, then we will see if we can improve this design of the modulator so, that the half voltage required is much less. So, with that background of this phase and amplitude modulation in the longitudinal configuration; let us now see that how this transverse configuration of gallium arsenide isotropic crystal works.

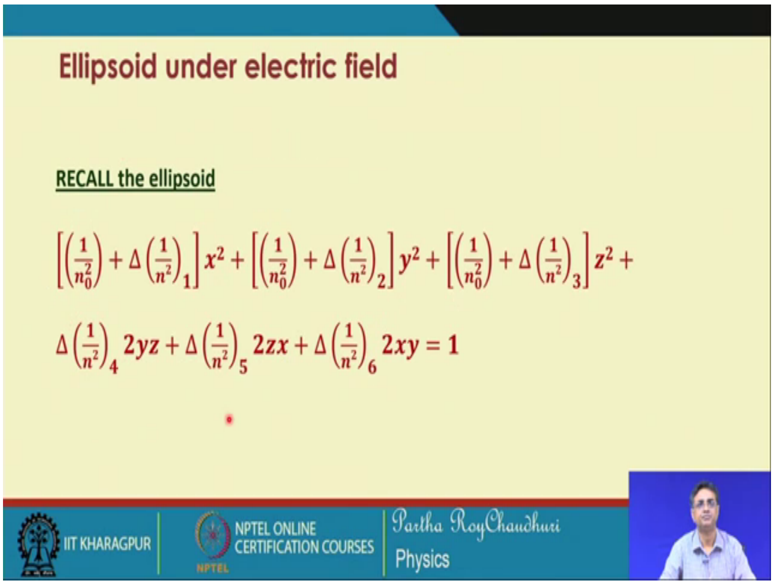
(Refer Slide Time: 20:08)



So, for amplitude modulation the requirement see the propagation along x and the voltage is applied along xy plane that is along the body diagonal of this xy. So, I will show you how this polarization has to be launched. So, in the case of transverse modulation electric field must be applied along a diagonal of xy, that is we have old coordinate system x and y. So, along this line along this line you have to apply a voltage.

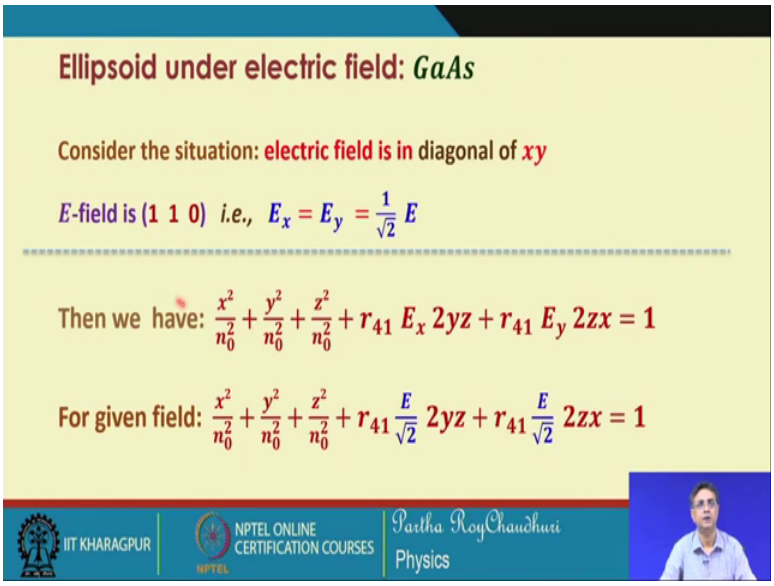
So, we can represent this electric field as 1 1 0 direction. So, the electric field components along x and y will be 45 degree inclination; so, it will be E y under root 2 for both of them which are equal amplitudes. So, that is equal excitation of the two polarization modes are needed to work with this transverse modulation of this electro optic system, using this gallium arsenide an anisotropic material.

(Refer Slide Time: 21:15)



So, let us now once again to this little bit of algebra and recall this ellipsoid, index ellipsoid which is these are the implemental changes in the refractive indices permittivity, impermeability. So, this is this equation is once again very familiar and we know that these are the coefficients which are attached to these cross components that is the x y y z z x. So, this is the after the field has been applied so, this is the new refractive index system. So, will have to use the appropriate electric field configuration, to reduce it to the principal axes system.

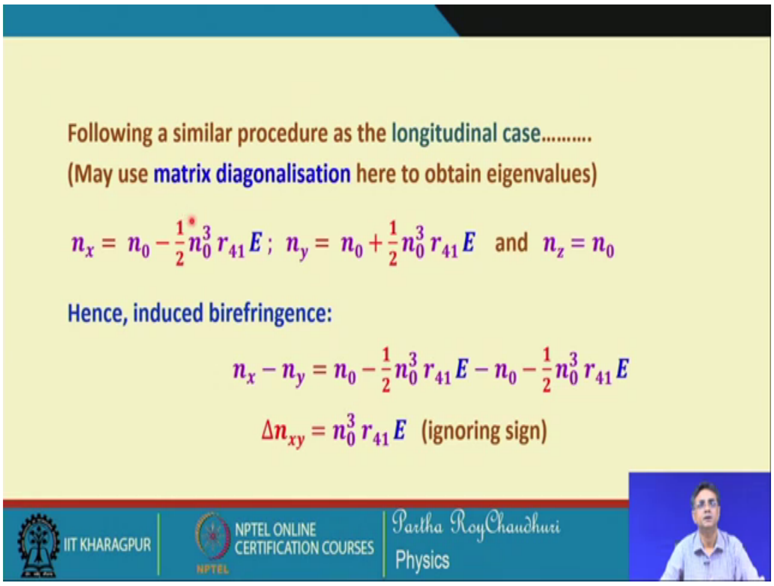
(Refer Slide Time: 22:03)



So, when you apply this electric field 1 1 0 that is this under E x E y and under root 2, this thing then we have this index ellipsoid. Let us look at this system you have there is no trans appearing here, there is no trans appearing here and here. So, this all remains n 0 x square n 0 1 by n 0 square y square etcetera. But, only you have this which is dependent on this coordinate that is this z dependent coordinates that is these two are now excited. So, you have y z and z x therefore, this I replace this E x by E y under root 2.

So, you get this form of the equation. Now, we will use this matrix diagonalization method and to find out the new principal axes system. So, will not do that algebra, but you can because you have done several times. If you do this is you just find the eigenvalues of this matrix equation.

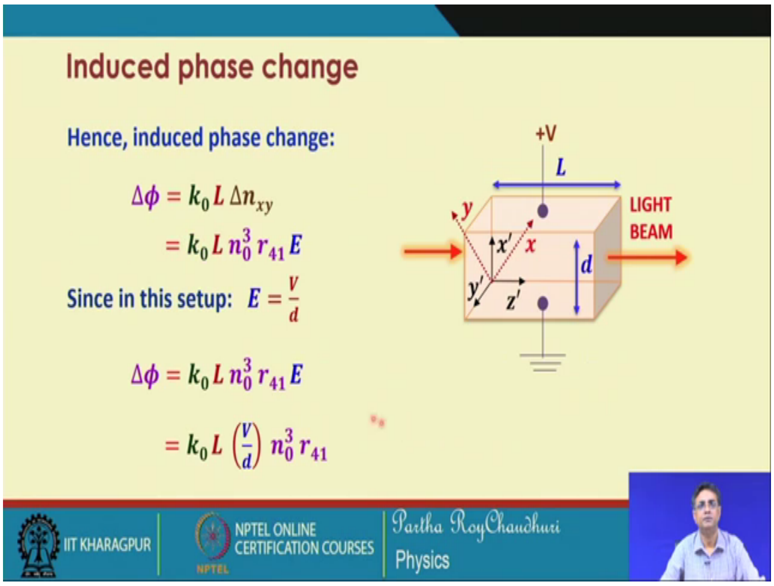
(Refer Slide Time: 23:24)



Then you can see that n x will be equal to this half of n 0 r 41. So, this E is because of E x root 2 under root 2 into E x written as E and here also this n y will be equal to E. So, they are correct and with the appropriate factor. So, because this is E x will have a root 2, if we have to represent this E in terms of E x and E y. So, so n z equal to n 0 hence, the induced birefringence for this.

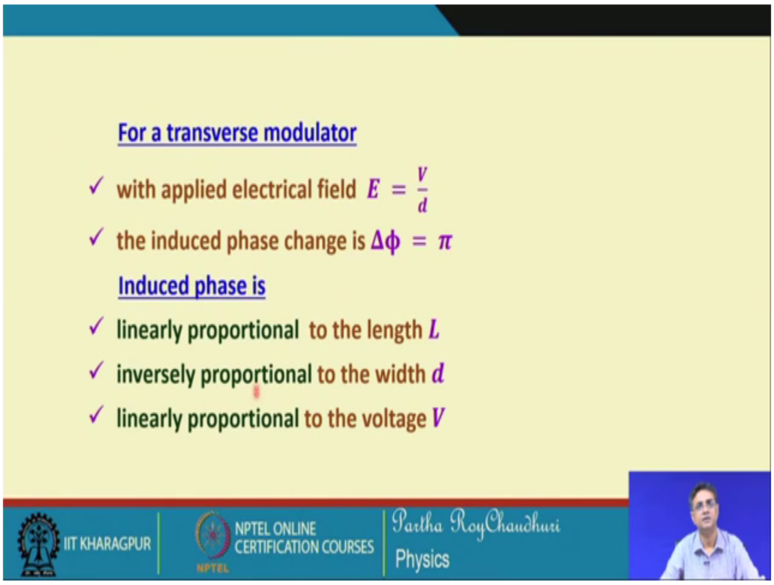
So, after you do this matrix diagonalization of this system of this matrix equation to get the principal axes, the refractive indices for the principal axes system under the electric field. When you get this new refractive indices and the induced birefringence, this sign will be equal to this. Ignoring sign means whether you take n x minus n y or n y minus n x, it is the magnitude which is important which gives you the birefringence.

(Refer Slide Time: 24:40)



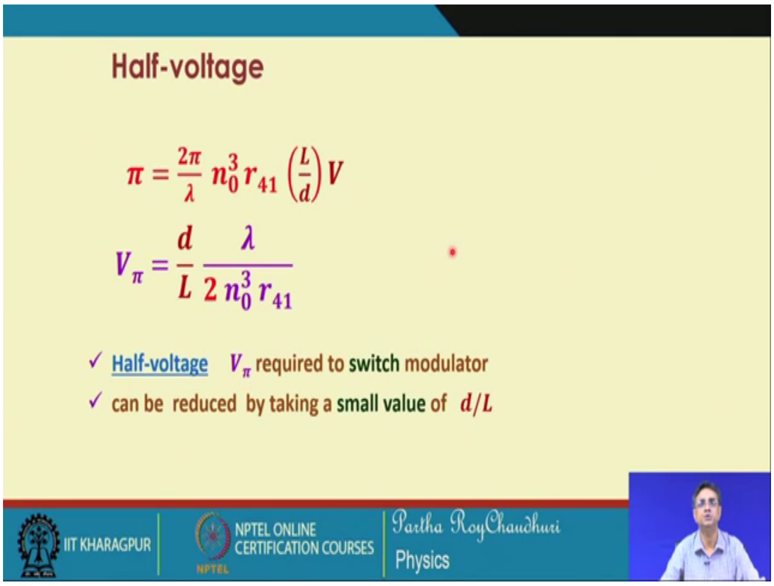
So, now E is again for this setup; so, the other phase induced phase delay between these polarized light orthogonal polarization is now equal to this; you have to again multiply k 0 and L that gives you this equations. So, in this setup we have electric field E is V by d. So, if you plug in that E equal to V by d, you can see that both L and d they exist in the expression for this phase delay. So, del phi is now proportional to L is proportional to the length L.

(Refer Slide Time: 25:15)



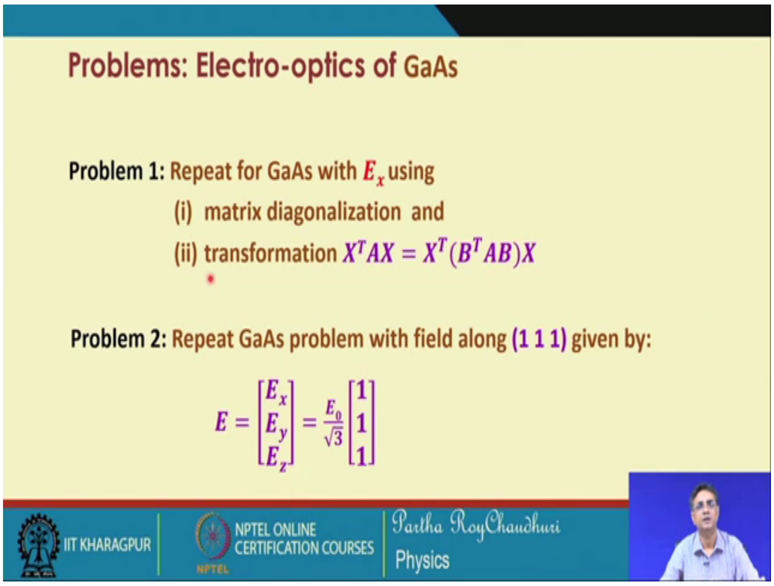
But it is inversely proportional to d; it is inversely proportional to d and it is also proportional to linearly proportional to the voltage. So, you have 3 quantities to control the phase of the modulator. So, for half voltage delta phi this requirement is equal to pi.

(Refer Slide Time: 25:45)



So, let us use so this pi equal to twice pi by lambda n 0 cube r. So, this is once again half voltage is also proportional to this. So, this gives you and a feature that by choosing the ratio L by d you can actually reduce the number, you can actually reduce the number. So, this case this was about 9 kilovolt. Now, let us suppose if this d by L is equal to 1 by 9 then it reduces to 1 kilovolt. So, the half voltage V which is required to switch the modulator can be reduced by taking a small value of d by L.

(Refer Slide Time: 26:33)

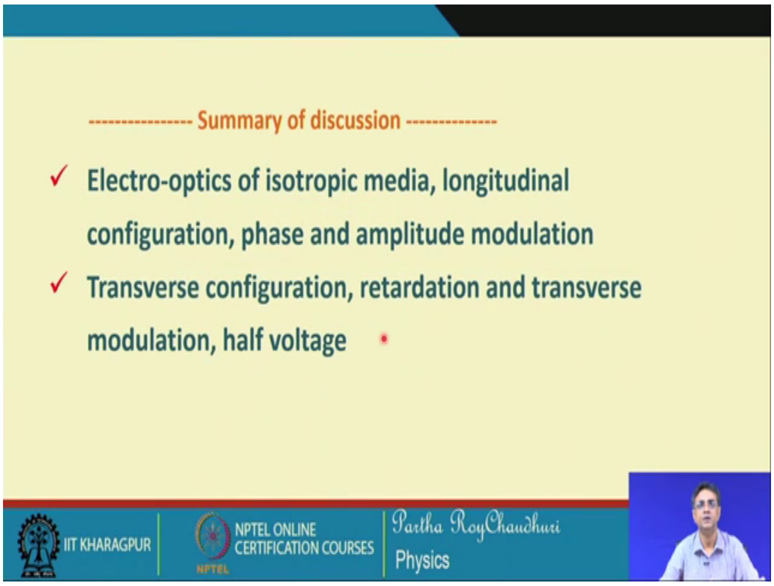


So, this factor is now extra freedom now this time to reduce the half voltage. And, then this is the one which we discussed is about when the voltage is applied across the body diagonal of the x and y in the crystal. But, later suppose you apply field which is, which makes equal angles equal inclination with E x E y and E z then what happens that is the electric field is now applied along 1 1 1 direction. So, let us have a look at this problem and try to find out.

And, we can repeat the same problem using a field which is applied only along x axis. Then you can use this matrix diagonalization to get the principal refractive indices and after having this principal refractive indices, we can calculate the birefringence. And, that is the same protocol, same rule that will have to be followed for all modulators. Then the birefringence from the birefringence we can calculate the phase delay and from the phase delay then we can calculate the half voltage that is, how much voltage is required to get a phase delay of pi. So, that the modulator is can be switched from state 1 to state 0 or state 0 to state 1; so, that we can also calculate for the case of E x.

So, these are the situations that can give a more insight and understanding about the various configurations, that can be used for the crystal for this electro optic crystal. And, to compare which configuration is more useful, which configuration will give you a lesser will require a lesser half voltage that can be (Refer Time: 28:35) find out found out.

(Refer Slide Time: 28:38)



So, the summary of this discussion is that we started with electro-optics of isotropic media and then we were discussing this the basic configurations. How the crystal has to be configured with respect to the propagating light and the applied voltage. So, that it can be used as a longitudinal modulation, phase modulation and in the transverse configuration also how it can be used for amplitude modulation. In the present discussion we worked out that how this what will be the requirement for the configuration in terms of the input polarization, output polarization, the analyzers.

And, then what is the magnitude of the half voltage required for switching modulator. We did the same thing in the case of transverse configuration and we found that this half voltage in the case of transverse configuration, it gives us an additional freedom of choosing the geometrical parameters L and d such that the half voltage can be drastically reduced; that is the length of interaction will be more. Whereas, d will be less, in that case you get a much less half voltage to switch the modulator. We will continue this discussion for other (Refer Time: 30:08)

Thank you very much.