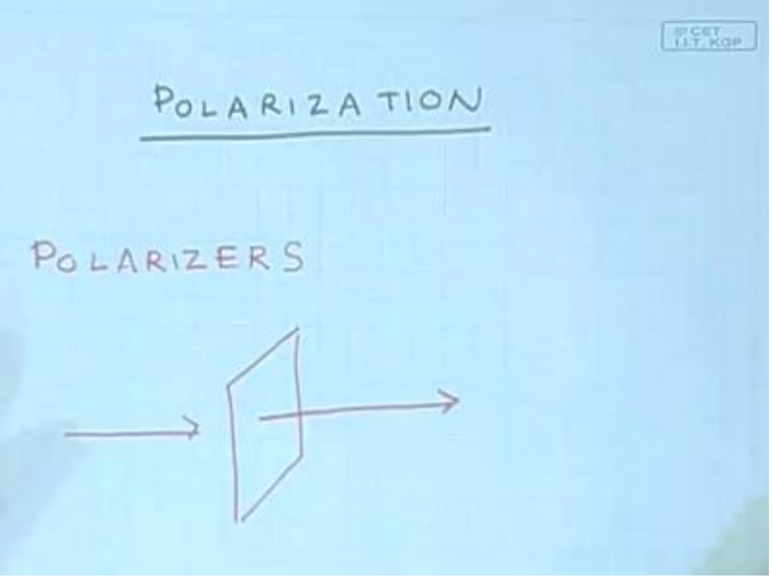
Physics I: Oscillations and Waves
Prof. S. Bharadwaj
Department of Physics and Meteorology
Indian Institute of Technology, Kharagpur

Lecture - 31
Polarization

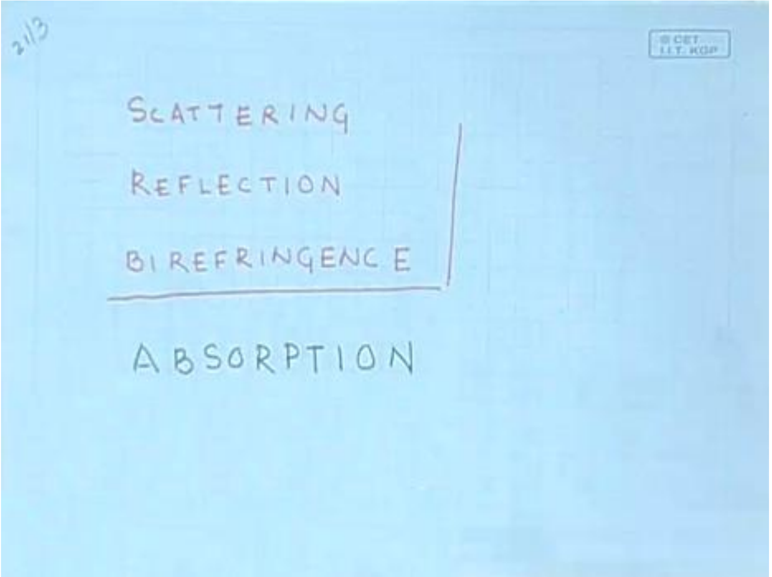
Good morning. We have been discussing polarization and we were looking at the question how we could generate polarized light, how could we manipulate polarized light?

(Refer Slide Time: 01:07)



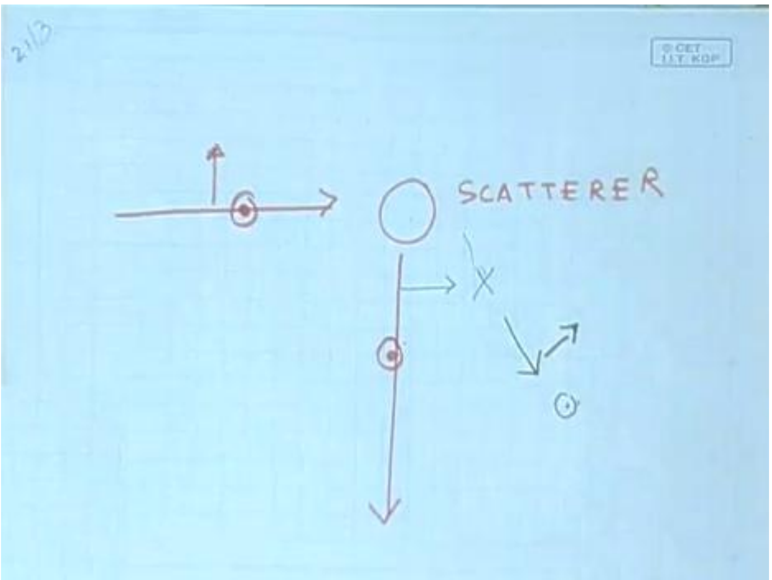
And a polarizer I told you are a device which if you send in natural light it gives out polarized light. So, you could have a linear polarizer which will where the output is going to be linearly polarised or you could have a circular polarizer where the output is going to be circularly polarised etcetera. I also told you that there are essentially 3 different methods to generate polarized light and to manipulate polarized light particularly to generate polarized light.

(Refer Slide Time: 01:44)



And these methods were scattering reflection and birefringence actually there are 4 methods I had forgotten to mention the forth one which is very important. So, let me include the forth method, the forth method is absorption. And I shall be discussing the forth method shortly the absorption. I shall start today's discussion by discussing this method absorption. But before embarking upon this let me just recapitulate that we have already discussed how scattering introduces polarization.

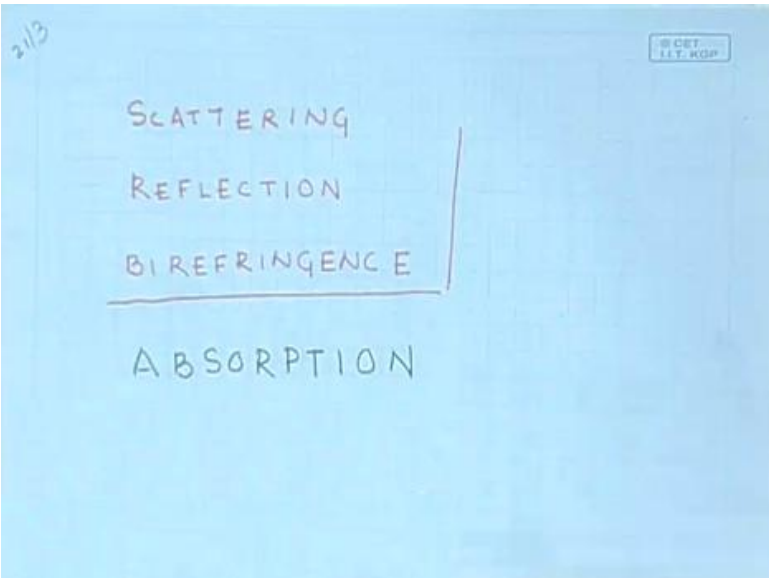
(Refer Slide Time: 02:33)



And here we have a situation where there is a scatterer you have incident light from here. And the scattered we are looking at the scattered radiation at 90 degrees to the direction of incidence. And I told you in the last class that the light that is the incident light can be polarized either like this or like this or in any arbitrary combination of this. If it is natural light the electric field is going to vary randomly between this and this and some arbitrary combination of this. But after the light get scattered the scattered light can in principle be polarized this way that is perpendicular to the plane of scattering or this way in the plane of scattering. But it so, happens that the when you look at the light that is scattered at 90 degrees this particular polarization is going to be absent.

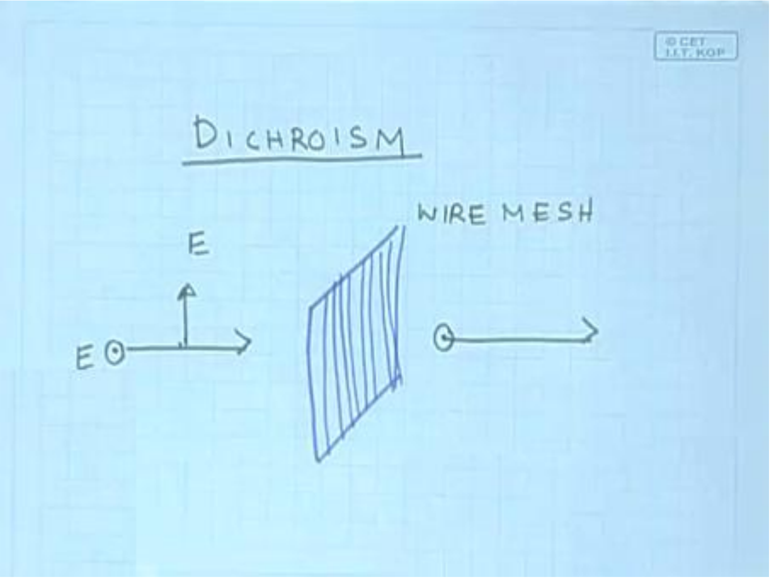
So, when you scattering the when you look at the scattered light at 90 degrees to the direction of incidence the component of polarization in the plane of scattering is going to be absent. There is only going to be a component of polarization in the plane perpendicular to in the direction perpendicular to the plane of scattering. So, this is how scattering introduces polarization. So, the light that comes out in this direction at 90 degrees is going to be totally polarized at any other direction the light is going to be partially polarised. It will be some combination of this polarization and this polarization, but this component is going to be less this component is going to be more. So, it is going to be partially polarized light. Now, so, this I have recapitulated scattering.

(Refer Slide Time: 04:29)



Now, let me go on to absorption and the word here the word that is used here is dichroism.

(Refer Slide Time: 04:37)



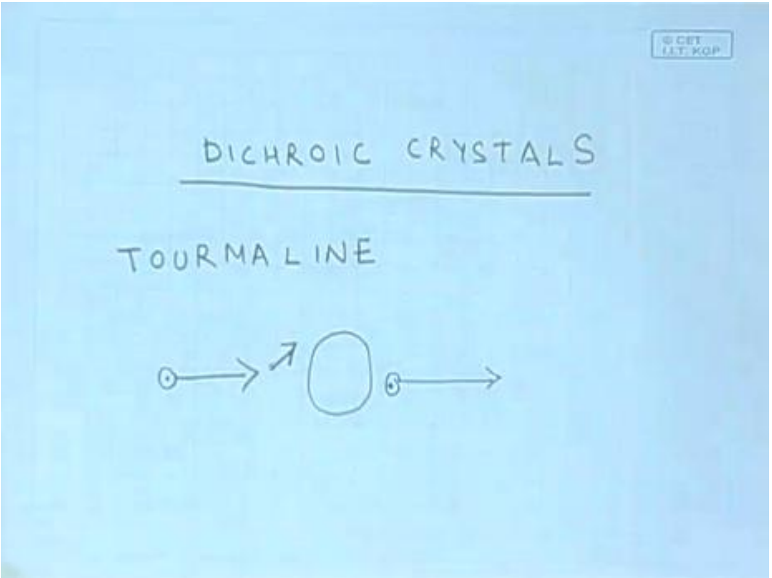
Dichroism and what this dichroism means it dichroism refer to a situation where the absorption properties of a material are different in 2 different for 2 different polarizations. So, dichroism refers to a situation where the absorption properties of the material which you are or of the system that you are dealing with are different in 2 different for 2 different polarizations. So, the simplest possible situation is very have a wire mesh. So, let me draw the wire mesh through this shows you a wire mesh we have a set of wires metallic wires arranged like this in the vertical direction. The wires are equally spaced I mean my drawing does not reflect that, but the wires are actually equally spaced and they are all vertical and there is light which is incident upon this. The incident radiation can be polarized the electric field of the incidence radiation can be broken up into 2 components. One which is parallel to these wires these metallic conducting wires and a component which is perpendicular to these conducting wires.

So, these are the 2 possible components into which the electric field of the incident radiation can be decomposed. And we have natural light incident upon this wire mesh so, this is a wire mesh. Now, let us ask what happens to each of these components of the electric field separately. So, the component of the electric field which is parallel to the wires is going to set up currents inside these wires. It is going to set the electrons inside these wires into motion up and down and these currents inside the wires if the wires have a resistance which it will have. So, then the energy in this component of the electric field is going to get converted into heat, because the current is going to get dissipated by ohm’s ohmic resistance. So, a part of the energy of the of this component of the electric field is going to get dissipated at as heat. The this component of the electric field is also going to set up the this oscillating current here is also going to re radiate and it is going to re radiate in both forward and backward directions.

Now, it turns out that the radiation in the forward direction is going to cancel out with the incident waves. So, the amount of radiation in that is radiated that is that comes out in the forward direction in this particular polarization is going to be quite small significant amount may be reflected. So, the crucial point is that this point this polarization is not allowed to pass thorough by this wire mesh. Let us now, discuss what happens to this polarization. This polarization is normal to the direction of the wire. So, it does not set up much of a current and this polarization which is perpendicular to the direction of the mesh is actually passes through. So, the radiation that comes out is going to have only 1 polarization like this. The other component is going to be heavily decreased. And this is an example the wire mesh is an example of dichroism how selective absorption introduces polarization.

It is possible to construct such wire meshes easily in the say for radio frequencies microwave frequencies where the wave length is large. The spacing between the wires in the wire mesh should be smaller than the wave length considerably smaller than the wave length. So, these wire meshes are useful in say radio communication if you want to receive only a particular polarization. You can put such a wire mesh in front of your antenna and it will allow only a particular polarization to pass through. But it is very difficult to construct such wire meshes in the optical band. People have been successful in constructing such wire meshes in the infrared using very sophisticated techniques. But in the optical this you clearly cannot construct such a wire mesh. Now, let me consider another example of dichroism there are dichroic crystals.

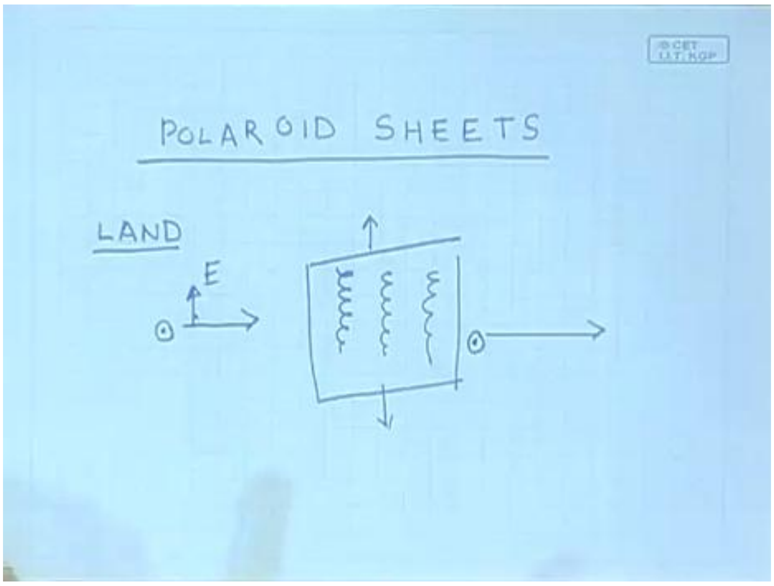
(Refer Slide Time: 09:51)



An example being tourmaline which is a precious stone Tourmaline this is a crystal of tourmaline if you if there are natural light incident on it. Tourmaline has the property that it is it will absorb it will preferentially absorb 1 component of the polarization. So, let us say that it absorbs this component of the polarization preferentially. It depends on the crystal how you have oriented your crystal. And it allows other components of the polarization. So, it i will allow other components of the polarization to pass through. So, the light which comes out is going to be polarized like this and this particular component is going to be heavily absorbed inside. Now, the how this functions I shall explain later in today's lecture not right now. But such dichroic crystals have a limitation they function the, this dichroism is very wave length dependent.

And it this preferential absorption of 1 polarization is very wave length dependent. So, it preferentially absorbs 1 wave length only in a certain range of wave lengths not over the large band. For example, at the tourmaline crystal appears green, because it preferentially absorbs the other wave lengths. And so, it has a very narrow range of wave lengths over which it works. So, the spectrum of the incident light gets modified when it by the time it comes out. So, this is a limitation of the, it also reduces the intensity of the other polarization quite significantly. So, this has got limited applications. Let me now, discuss a third a third example of a dichroic polarizer these are called Polaroid sheets. And this is the common most commonly used polarizer a linear polarizer at present. So, let me discuss this. So, we have what are called Polaroid sheets.

(Refer Slide Time: 12:13)

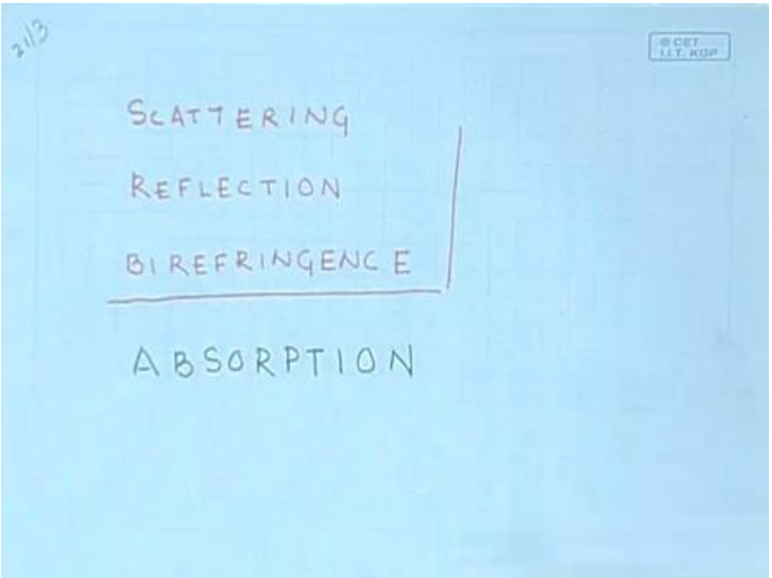


And these were invented by a person called Land in who in the 19 mid 1920 who had that time was an undergraduate student at MIT he was only 19 years old when he invented the first Polaroid sheet. And later on he developed it further and he developed the he developed the a kind of sheets which are which are quite commonly used now. So, the basic idea let me explain to you what the basic idea over here is. So, you take a sheet of some kind of organic substance for example, polyvinyl alcohol. So, this is a transparent sheet like somewhat like plastic take such a sheet. And heat it and extend the sheet apply stress on the sheet in 1 direction. So, you take a sheet of polyvinyl alcohol heat the sheet and pull it in 1 direction. Now, in these polyvinyl alcohol molecules these are organic compounds hydrocarbons these are long chain molecules.

So, when you take a sheet of polyvinyl alcohol the molecules will be randomly oriented inside this. Now, when you heat it and pull it in 1 direction the molecules will preferentially get aligned in that direction. So, by heating and stretching the polyvinyl alcohol sheet you align the hydrocarbon molecules then you dip this sheet in ink which is rich in iodine. And what this does is it causes the iodine to be deposited along the length of the polyvinyl alcohol molecule. So, you have iodine now, deposited preferentially in 1 in linear chains. Now, if you have radiation incident on this let us let me draw a picture for example, this is just a schematic diagram you have these molecules long molecules all aligned like this. Now if you have radiation. So, this is your sheet it has been stretched in this direction and then you have dipped it in iodine. So, the molecules are all aligned like this.

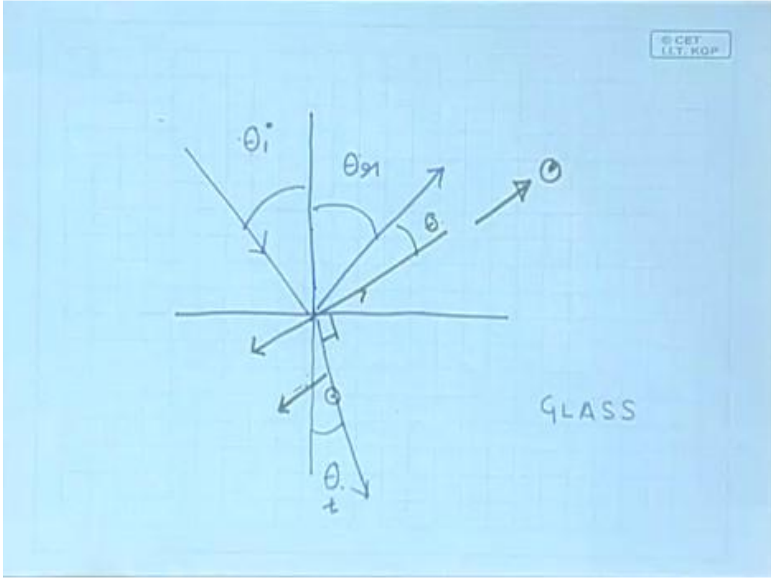
Now, if you send in radiation which is polarized in this fashion the electric field in this radiation. So, is going to generate currents in the electrons in the iodine. The iodine is all aligned in this fashion. It is going to generate electrical currents in these electrons in the iodine. And this component of the electric field is going to be heavily absorbed inside its going to set up currents and it is going to be absorbed. Whereas, this component of the electric field is not going is perpendicular to the direction of the molecule. So, it will not be setting of much of currents inside and it will be allowed to pass through. So, the radiation that comes out is going to be polarized like this. And these are the so, this is how Polaroid sheets are made they are dichroic sheets they produce linearly polarized light.

(Refer Slide Time: 16:01)



So, we have discussed 2 of the methods by which we can generate a polarized light. We have discussed how scattering generates polarized light. And we have also discussed how absorption preferential absorption or dichroism is used to generate polarized light. Let me now, discuss a third method reflection how reflection can generate polarized light. So, a situation that we are going to consider is as follows.

(Refer Slide Time: 16:46)



We have a dielectric medium let us say glass or some other kind of dielectric medium. So, inside this is the dielectric medium and there is light incidence on this at an angle of incidence theta i. So, there is light incident on a glass slab let us say this is glass or some other dielectric for that matter at an angle of incidence theta i. Now, it is well known that a part of this light is going to be transmitted. So, we have a part of the light which is going to be transmitted and this angle of this angle over here I am calling theta t the angle of the transmitted light. And a part of it is going to be reflected and this we are going to call theta r. Now, theta r and theta i are exactly the same. They are exactly identical be incident and reflected light are at make the same angle to the normal the transmitted angle is going to be different.

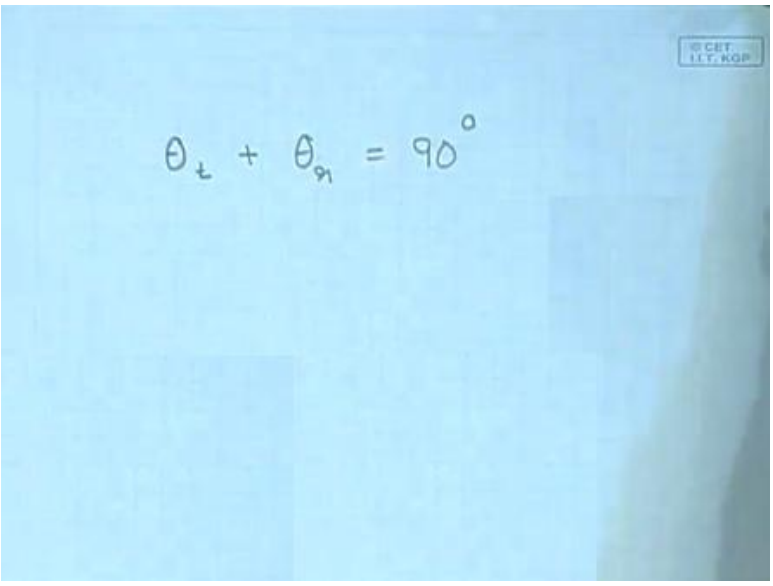
Now, let us go back to the basic question why does why what is the origin of this phenomena of refraction? How does the electromagnetic wave interact with the dielectric medium with this medium into which it is entering? What is it that produces the reflected wave? And from our discussion it should be clear that the basic microscopic the microscopic underline principle like microscopic principle is as follows. The electromagnetic wave is an oscillating electric field which is propagating forward. Now, inside the glass the glass is a dipole so, when you have an electric field inside the glass the electric field is going to generate is going to act on the electrons mainly. So, the inside the glass you have electrons which are bound to positive nuclei. So, these could be atoms or molecules so, inside the molecular atom you have these electrons they are bound to the positive nuclei. The oscillating electric field is going to cause the electrons to accelerate.

So, it is oscillating electric field acting on a bound electron and v electron when it oscillates it emits radiation again. So, an oscillating electron we know emits radiation there is going to the electron is going to oscillate like a dipole and it is going to emit radiation and it is this radiation that we call the transmitted and the reflected wave. So, we will focus on the reflected wave. The reflected wave is essentially the radiation emitted from these electrons inside the material which are oscillating. Now, the transmitted wave inside the material is in this direction we have already discussed this. So, inside the material the electric field is going to oscillate in 2 possible directions which are both of which are perpendicular to this transmitted direction. One is in the plane of incidence which is this component and the other is in the plane perpendicular which is like this. So, inside the medium glass the electric field is going to be perpendicular to the direction in which the transmitted wave is going and the electric field is going to oscillate like this.

So, the electron inside will be oscillating like this, because of this particular oscillating electric field. It could be also oscillating up and down perpendicular to the plane of incidence the plane of the paper. So, there are 2 possibilities and it is these oscillating electrons that produce the reflected wave that comes out. So, this is the direction in which the electrons are oscillating. And this is the direction in which we are interested in the radiation which is the reflected radiation they 2 make an angle theta. Now, let us ask the question what will happen when this angle theta between the directions of between this reflected direction of the reflected wave. And the direction of the electron motion oscillations inside the material when this angle theta becomes 0 what is going to happen? We know that a dipole an oscillating dipole does not emit any radiation in the direction of oscillation. So, what we can say is that when this angle becomes theta this particular oscillating electron is not going to emit any radiation which is to be reflected.

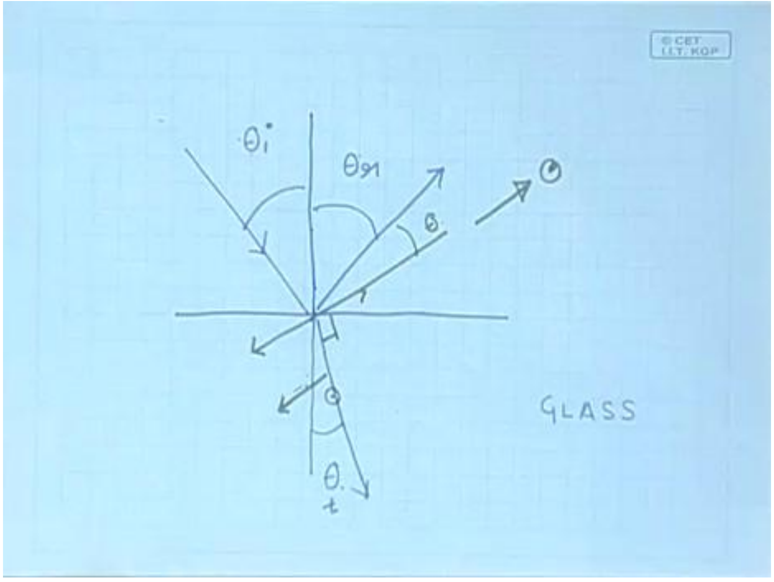
So, when reflected wave is along this direction when theta is 0 there is going to be no contribution from this oscillating electron. Let us know look at this oscillating electron which is oscillating perpendicular to the plane of incidence. This oscillating electron is perpendicular to the direction of the reflected wave then it is going to emit as usual. So, what we can say is that when this angle theta becomes 0 the light that comes out. So, the reflected light which comes out in this direction is going to be polarized only in this direction perpendicular to the plane of incidence. There is no going to be no polarization component in the plane of incidence there is going to be no polarization component in this direction. It is going to be completely polarized perpendicular to the plane of this paper um. So, the question now is what is the condition that has to be satisfied at what angle for what reflection angle is this condition going to be satisfied? So, what we see is that if theta is 0 this angle we know is 90. So, if theta is 0 this total is 180. So, when theta is 0 the transmitted theta t plus the reflected angle theta r should be equal to 90 degrees that is the condition.

(Refer Slide Time: 24:07)



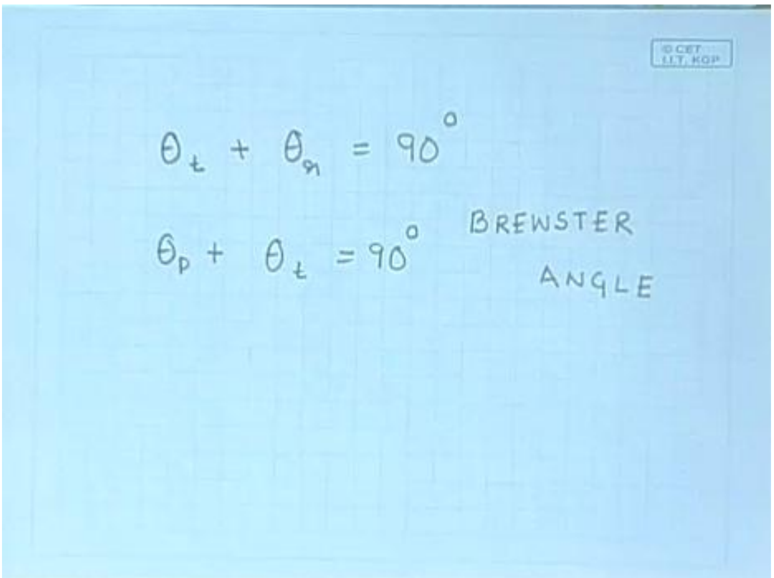
So, the condition is that theta transmitted plus theta reflected should be equal to 90 degrees.

(Refer Slide Time: 24:20)



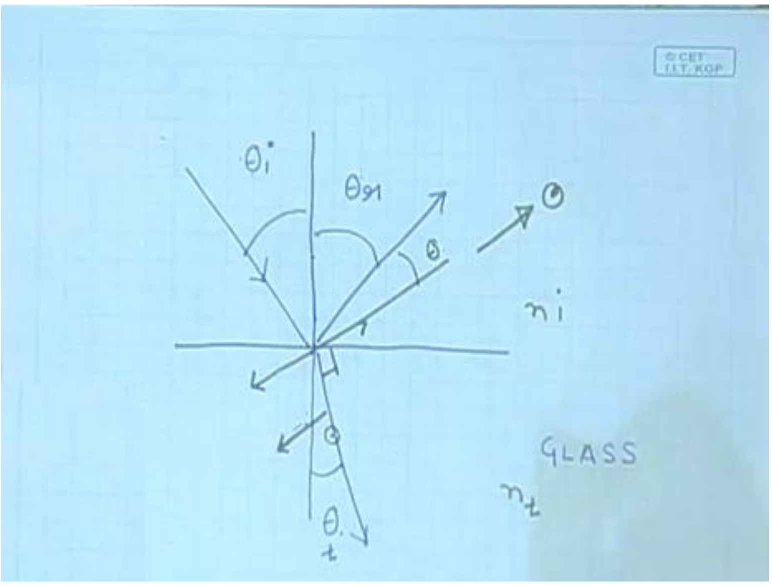
When this condition is satisfied the light that comes out is going to be linearly polarized perpendicular to this plane there is going to be no polarization component parallel to the plane. And the reflection angle and the incident angle are the same. And the particular value of the incident angle where this condition is satisfied where the reflected light is linearly polarized is called the polarization angle.

(Refer Slide Time: 24:47)



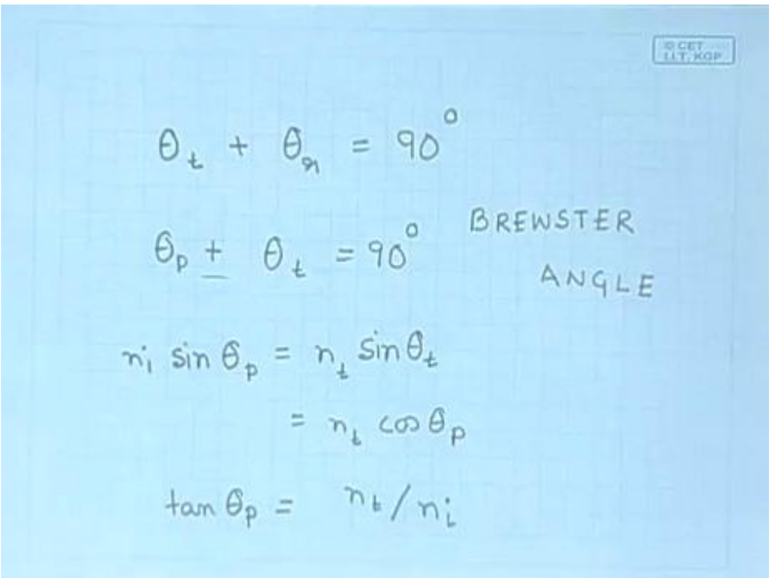
And that is indicated by theta p. So, the condition for the polarization angle satisfies this condition this angle theta p is also called the Brewster angle. So, this is also called the Brewster angle.

(Refer Slide Time: 25:26)



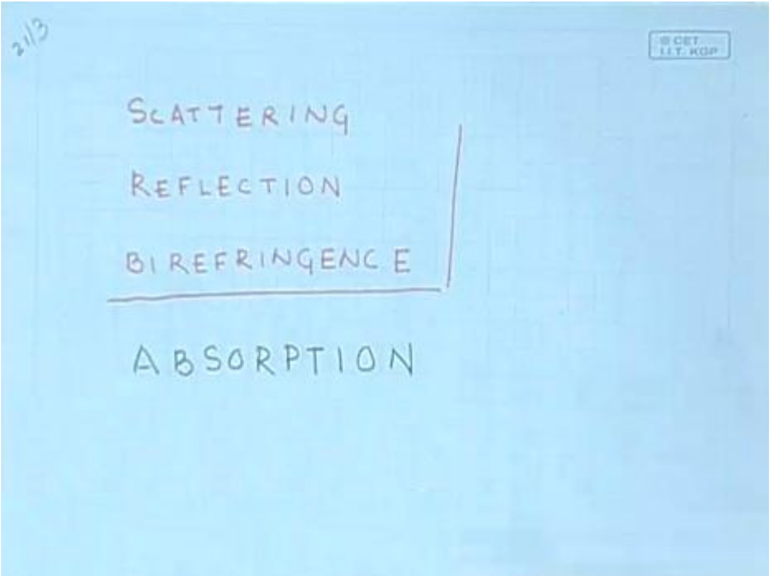
And we know that the Snell’s law can also be applied here. So, if I say that this has a refractive index ni and this has a refractive index nt the transmitted medium and the incident medium.

(Refer Slide Time: 25:39)



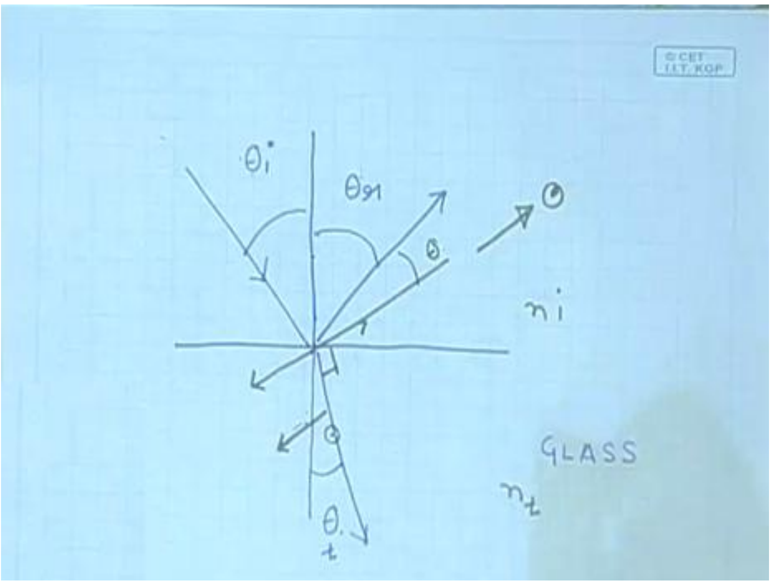
Then ni sin theta i which is the same as the polarization angle when this condition is satisfied is equal to nt sin theta t. And theta t the transmitted angle is equal to 90 minus theta p. So, we can write this as nt cos theta p using this and then, if I divide this by cos theta p. And divide the whole thing by the refractive index of the incident medium what we get is that the Brewster angle or the polarization angle should satisfy this relation. It should be equal to the refractive the ratio of the refractive index of the transmitted medium divided by the refractive index of the incident medium. So, let me now, summarise what we have just learnt.

(Refer Slide Time: 26:57)



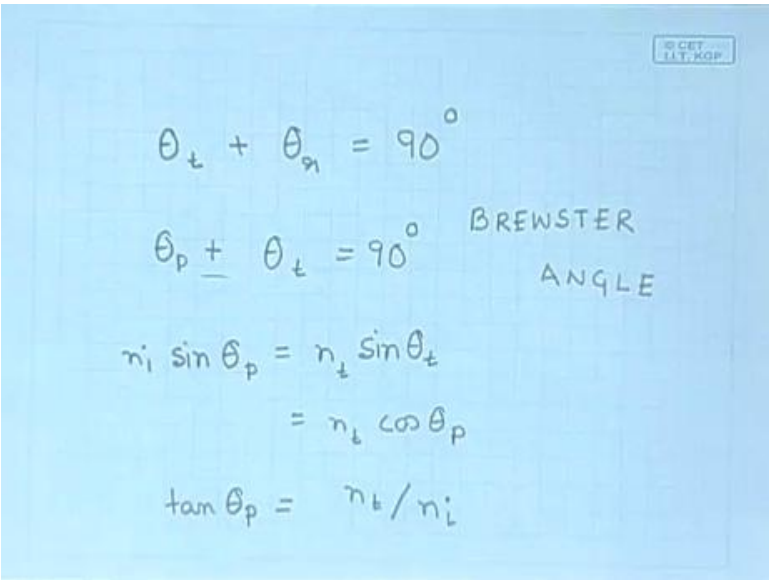
We have been studying how reflection introduces polarization.

(Refer Slide Time: 27:03)



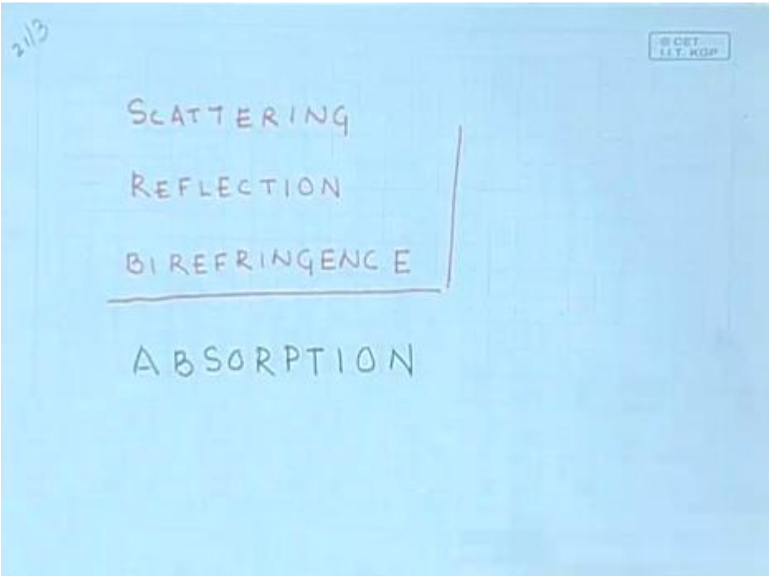
And what I told you is that there is a certain angle called the polarization angle or the Brewster angle certain angle of incidence called the polarization angle or Brewster angle when the light is incident on some medium on say the glass slab at the Brewster angle. The reflected light is going to linearly polarized and the component of polarization in the plane in which the refraction occurs which here is the plane of the paper is going to be absent. It is going to be polarised in the plane in it is going to linearly polarized in the direction perpendicular to the plane. So, only this polarization is going to be present and this angle is going to occur when the reflected wave the reflected ray and the transmitted rays are at 90 degrees to one another. So, when the reflected and transmitted waves are at 90 degrees direction to one another.

(Refer Slide Time: 028:04)



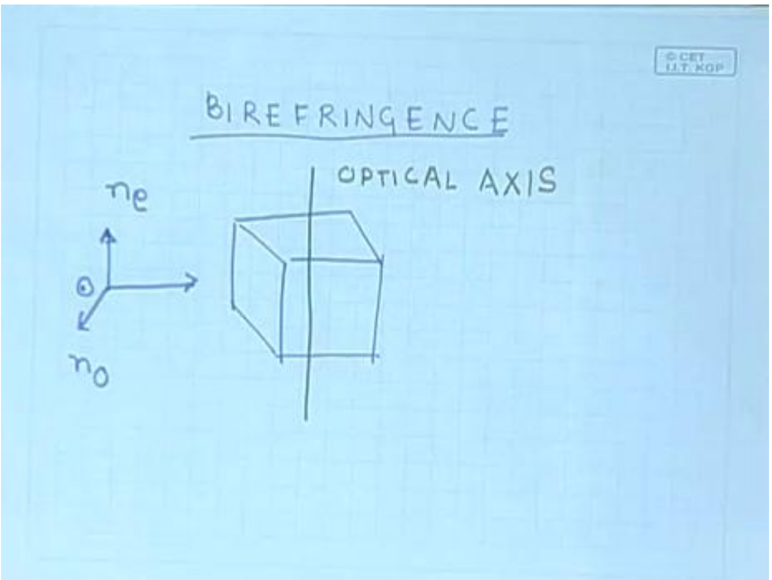
The reflected wave is going to be linearly polarized in the direction perpendicular to the plane of incidence.

(Refer Slide Time: 28:18)



So, we have finished discussing how polarization is introduced by scattering. We have discussed how polarization is introduced by produced by reflection. We have discussed how polarization is produced by absorption. Let us finally, discuss birefringence.

(Refer Slide Time: 28:46)



The word birefringence means double refraction birefringence literally means double refraction. And there are birefringence crystals which have the property that if you look at an object through the crystal you will see 2 refracted images that is why they are called birefringence crystals. So, it means to double refraction you see 2 refracted images at slightly different angles of the same object. And it is a birefringence is a very it is a very big topic and it is a complicated phenomena. And we shall not go into a very detailed a very elaborate discussion of birefringence in this set of lectures in this course. So, I am going to only take up a particular situation of birefringence which will give us some idea of what it is all about. It will also give us some idea of how you can manipulate and how you can produce polarize light using the phenomena of birefringence. So, the discussion here is going to be limited to only a particular situation not birefringence in general. So, the situation of interest over here is as follows.

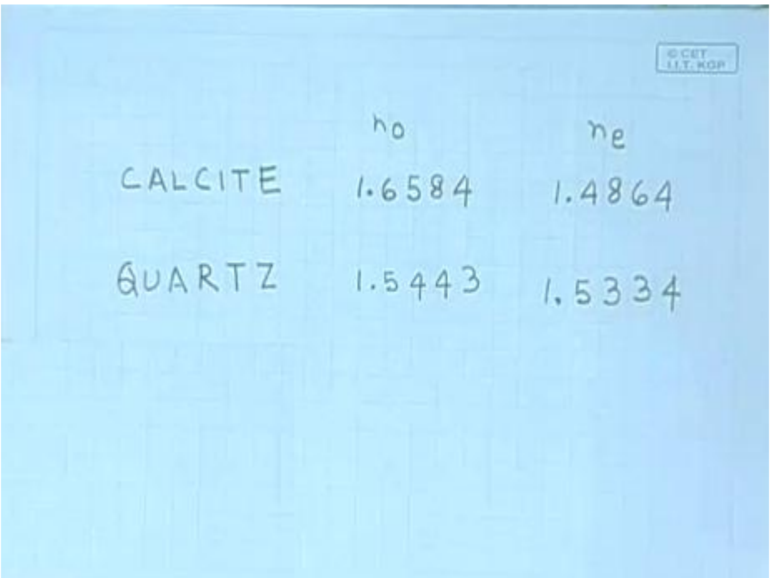
So, let us let me draw a birefringence crystal and a let me so, this let me draw birefringence crystal. So, I am schematically representing a birefringence crystal. Let me also want you that birefringence crystals in general will not be cubic, but I have just drawn 1 schematically for simplicity to get the basic idea across to you. So, think of this as some birefringence material I have just drawn it in this particular fashion just for convenience. It is not think of it essentially necessarily the cube and the basic property of birefringence of the particular situation that we are discussing is as follows. There is a particular direction in this material called the optic optical axis. So, there is a particular direction it is not a particular axis I should bare this in mind. So, in this material in this birefringence material that we are discussing, there is a particular direction called the optical axis. By direction we mean it could be at all points there is a particular direction called the optical axis. It is not to be thought of as a line, but as a direction inside this.

And if I send so, the situation which we are considering the surface this material has been drawn is such that it is parallel to this optical axis or you may say that the normal to this surface is also normal to the optical axis. So, this is a simple situation that we are analysing you could have more general situations we shall not go into those here. So, we will consider light which is incident on this surface and the light that is incident on this surface. The electric field can oscillate in any direction in this plane perpendicular to the direction of the incident light. And we will break up the electric field into 2 components 1 which is parallel to the optic axis optic axis and one which is perpendicular to the optic axis which we can also denote by this way. So, this is the component of the electric field which is perpendicular to the optical axis this is the component parallel to the optical axis.

Now, it is the property of birefringence materials that the refractive index depends on the direction of the electric field. So, when the electric for the when the component of the electric field is aligned with the optical axis. This particular wave ray of light or wave whatever you call it is going to experience a refractive index n e. The extraordinary refractive index when the light is polarized when the electric field is perpendicular to the optical axis is going to experience a refractive index on the ordinary refractive index. So, let me repeat we are discussing birefringence and we are going to take only a particular situation which is simple to analyse we are considering a material a crystal as shown over here it has a prefer direction called the optical axis. The surface there is light incident on the surface over here.

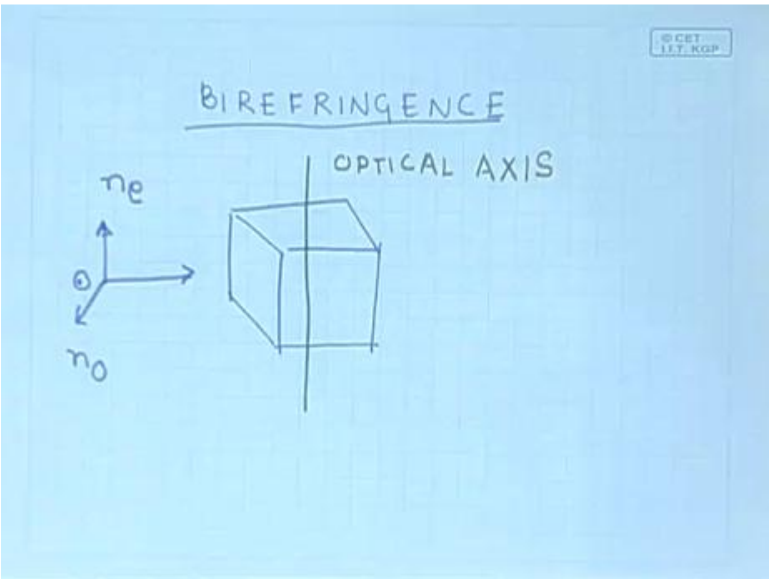
Now, what we mean by birefringence in this particular context is that when the light that is incident is has the electric field aligned with the optical axis. It experiences a refractive index ne the extraordinary refractive index for this material the same wave if it is incident n o this with the electric field perpendicular to the optical axis the light is going to experience a refractive index n o the ordinary refractive index. And the direction perpendicular to the optical axis could be anywhere in this plane. So, in this particular this is only a particular situation if the electric field had been aligned in some other direction of perpendicular to the optical axis. It would have the wave would have still experienced the same refractive index no. So, there are some materials there are some materials which have this kind of behaviour.

(Refer Slide Time: 36:09)



Let me give you 2 examples first for example we have calcite calcium carbonate it is calcite is calcium carbonate crystal. So, for example, the marble is made up of calcium of calcium carbonate and calcium carbonate crystals are referred to as calcite. Calcite has 2 different refractive indices depending on which way the incident light is polarized. If it is polarized perpendicular to the optical axis the light will see this refractive index. If the light is polarized parallel to the optical axis if the electric field is aligned with the optical axis the light will experience this refractive index. Similarly, we have quartz sio2 again for quartz we have birefringence the ordinary refractive index has this value the extraordinary refractive index has this value.

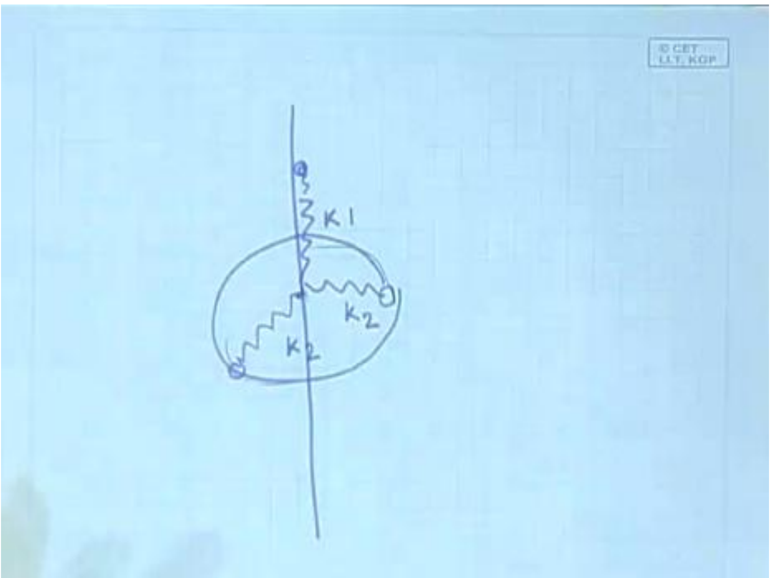
(Refer Slide Time: 37:10)



So, I have given you 2 examples of birefringent materials I have also told you the extraordinary the ordinary refractive indices. Now, let me give you an idea of why you have such kind of behaviour. So, such behaviour where the refractive index depends on which way the electric field is aligned. This has to do with the structure of the material itself if the arrangement of atoms inside the material is anisotropic. For example, calcium carbonate the arrangement of atoms of the calcium carbon and oxygen atoms inside calcium carbonate is anisotropic. Then the electron distribution the electrical distribution of electrons inside this material is also going to be anisotropic. And the phenomena of refractive index I have already told you have to do with the response of electrons to the external electric field. We all possibly know this already in a dielectric medium when you have an external electric field it induces dipole moments inside the material and it is the dielectric. So, it is the amount of dipole that is produced inside the material that goes into the dielectric constant. And we also know that the dielectric constant related to be refractive index.

So, what we see is that the amount of dipole that is induced inside the material has directly direct relation with the refractive index. Now, in an anisotropic the bound in any material the electrons are bound to the atoms and the molecules. So, the electron in this material are bound and we can think of these bound electrons as being attached by springs. We have again this is something that we have already discussed, because any system which is in stable equilibrium if you want to study its behaviour under a small disturbances you can think of it has being a spring mass system. So, similarly you can think of this electron bound electrons has been attached to the centre of the molecules are atom by springs and when you give an external electric field you see how much it gets displaced. And it is this displacement that produces a dipole moment which causes the dipole moment and when you have an oscillating field you have an oscillating dipole. Now, inside these anisotropic materials the spring constant is basically different in different directions. So, you can think of the electrons inside this birefringent material they are bound.

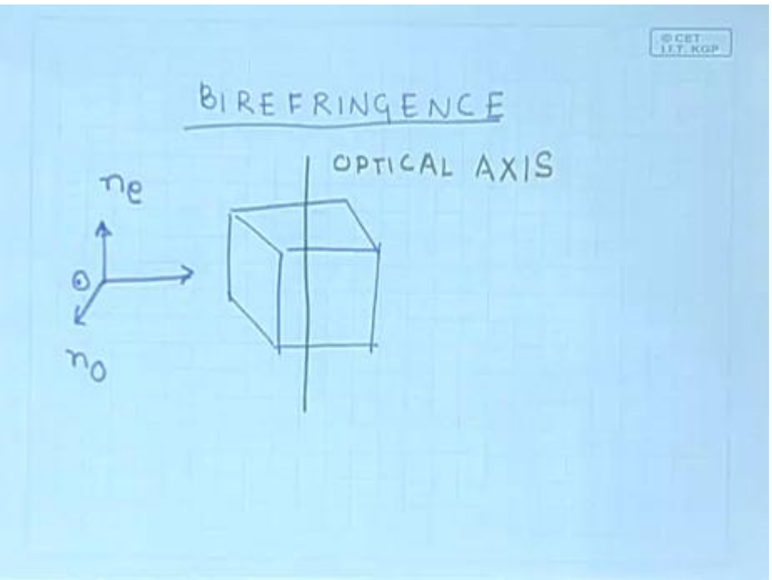
(Refer Slide Time: 40:19)



And you can think of them as being bound by springs which have different spring constant in different directions. Now, the situation which we are considering the spring constant as a value k 1 in this direction and it has a same value k 2 in the 2 in the perpendicular direction. So, it is isotropic it is the same the response is going to be the same. If it is in the plane perpendicular to this direction this is the direction of the optical axis here. And the response of this electron is going to be the same whichever way you disturb it in these planes. But if you try to disturb it somewhere perpendicular to the plane the response is going to be different. And if you try to disturb it in somewhere in between the response is going to be a superposition of this response and this response. So, you can model the electrons the response to the external electric field in terms of springs and in an anisotropic material like calcium carbonate where the arrangement of atoms is anisotropic.

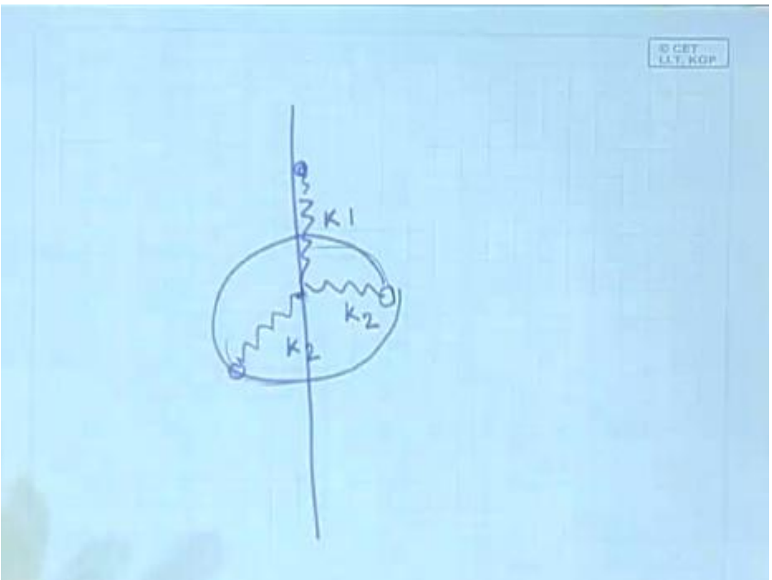
It is not the same in all directions you can model the response of the electron in terms of anisotropic oscillators where the spring constants are different in different directions. Now, if you have an external electric field let us consider 2 situations. If you have an external electric field it is going to induce a different dipole moment the same electric field is going to introduce a different type of moment in this direction, because it is going to produce a different displacement. The same electric field if it is in this direction is going to produce a different dipole moment. And so, the dielectric constants are different in these 2 directions and this for electric fields in this direction and this direction. So, as a consequence the reflective index is also different when the electric field is like this or when the electric field is anywhere in this plane.

(Refer Slide Time: 42:23)



So, this explains why how the refractive index this gives your picture basically of how the how it turns out. Then the refractive index depends on the direction of the electric field of the incident wave.

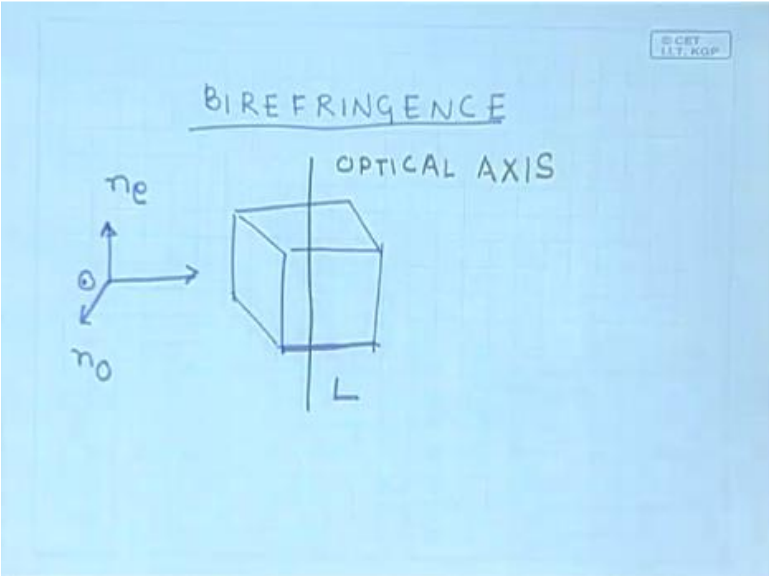
(Refer Slide Time: 42:37)



Now, let us also consider a situation where the light which we are sending in the frequency of the light which we are sending in matches with the resonance frequency of one of these directions. Let us consider a situation where the light that we are sending in matches with the resonance the frequency of that light matches with the resonance frequency of this particular direction, but it does not match with this. Question is what is going to happen now when you excite when you have an electric field which is oscillating in this direction which corresponds to the resonance. The electric field is going to set up enormous vibrations over here we know that if you have an external force with the same with the resonance frequency. It is going to setup enormous vibrations and the radiation is going to be absorbed it is not going to be emitted. So, if you send in radiation at the resonance frequency it is going to absorbed.

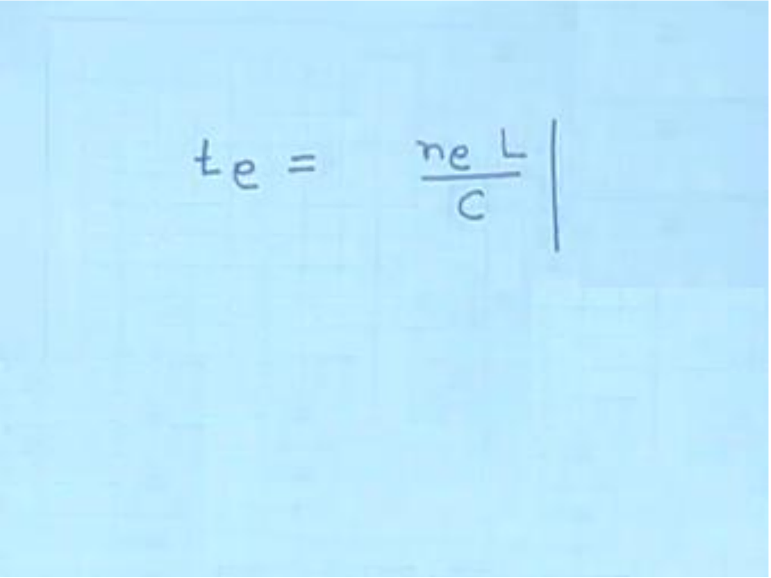
Then it is going to be very little coming out. If the electric field is in this direction it is not at the resonance. So, it is going to go through. So, you see that if one of the, if in an anisotropic medium you if the anisotropic medium is such that you are working at a wave length where for 1 polarization you are at the resonance for the other you are not at the resonance. You have the dichroic behaviour for example, Tomalin where one of the polarization components gets absorbed the other 1 passes through. But remember that resonance is very frequency dependent. So, this will work only for a small range of frequencies. So, we have some idea know of how this dichroic material Tomalin also works. It all has to do with the response of the electron inside the material to electric fields in different directions which you can model as a spring mass system with an external force. So, let us now, come back with this idea of how this how this birefringence occurs?

(Refer Slide Time: 45:56)



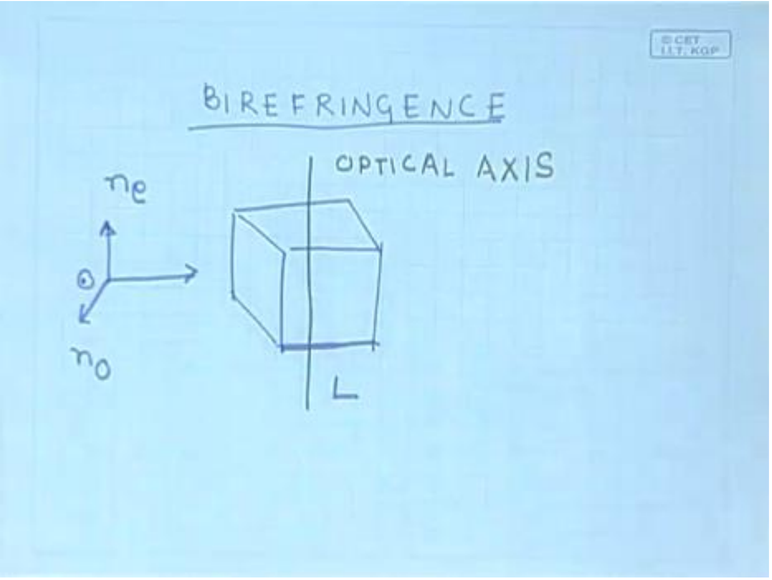
Let us come back to our discussion of how you can manipulate polarised light using birefringent materials? So, the situation that we are going to consider now is as follows. Let us assume that this system has a length L and let us ask the question, what is the time that the light will take to propagate the length of this crystal L? If the electric field is parallel to the optic axis optical axis we will call that t e. So, let us calculate t e the time that this particular the light will take to cross this crystal if the electrical field is parallel to the optical axis. And we know the refractive index is so, the speed of light the speed of light in this material for light with electric field in this direction. The speed of light is going to be C divided by ne and the time it will take is L divided by the speed which is ne into L by C.

(Refer Slide Time: 46:16)



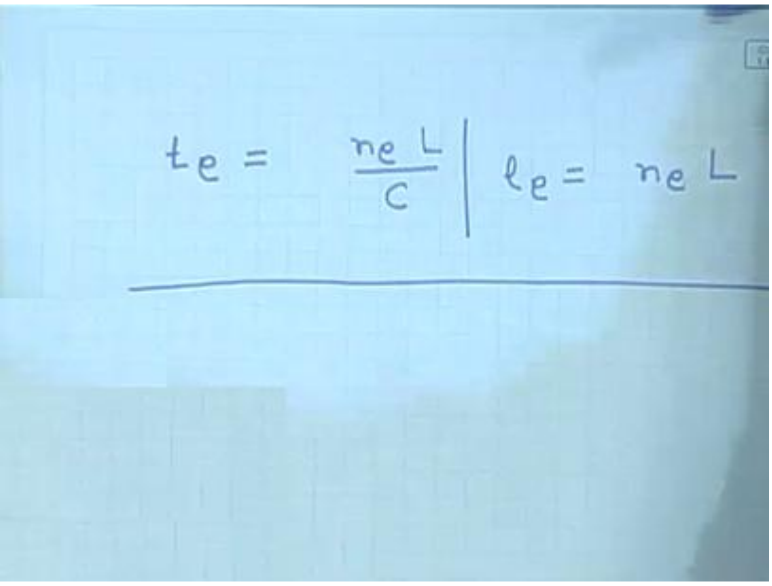
So, for the extraordinary polarization when electric field is along the optical axis the time the light will take is going to be ne L by C or if you ask the question what is the optical path?

(Refer Slide Time: 46:38)



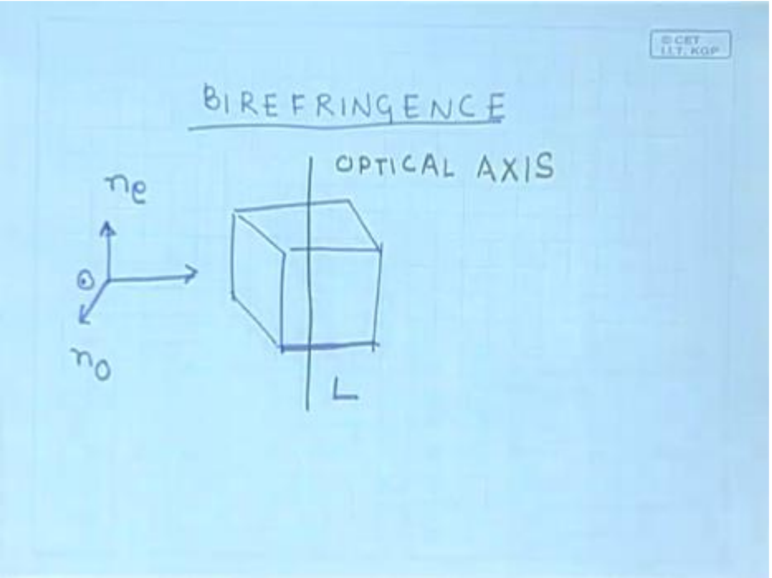
Corresponding to this, for the wave with electric field along the optical axis, the optical path.

(Refer Slide Time: 46:46)



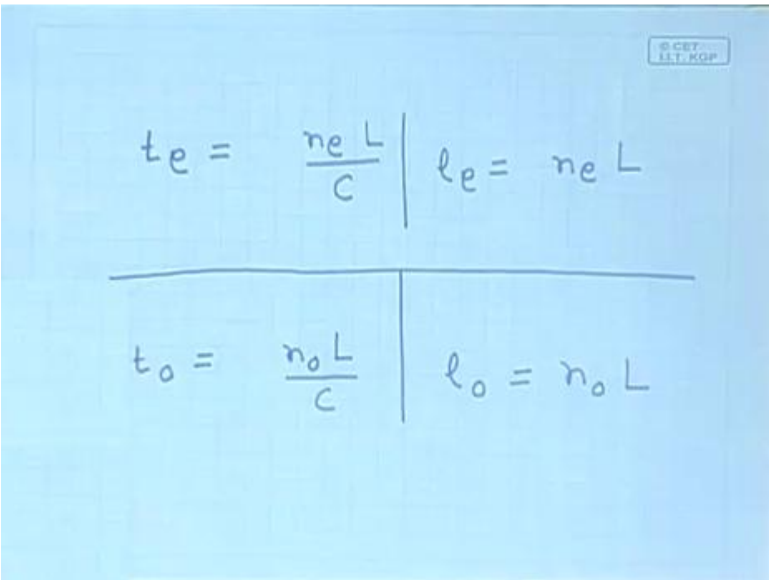
Let me call it le the optical path is the going to be ne times the actual length.

(Refer Slide Time: 47:01)



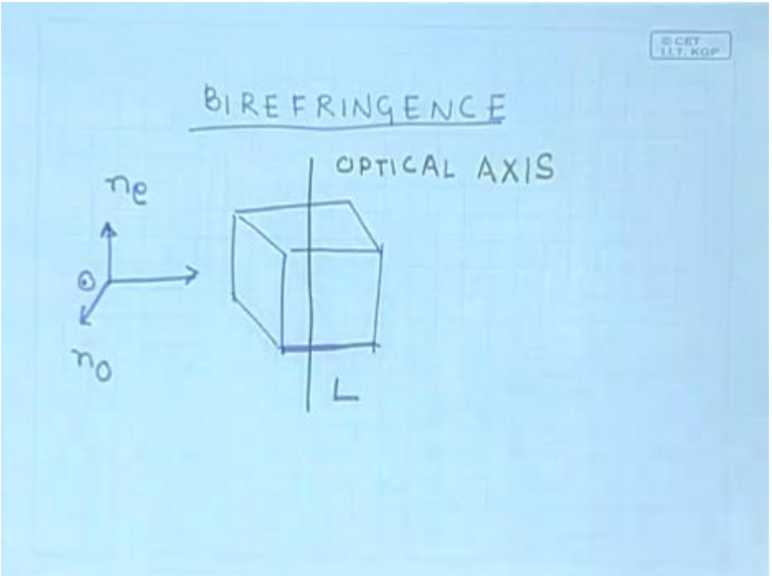
Let us ask the same question for the situation where the electric field is perpendicular to the optical axis. So, when the electric field is perpendicular to the optical axis the refractive index is no.

(Refer Slide Time: 47:16)



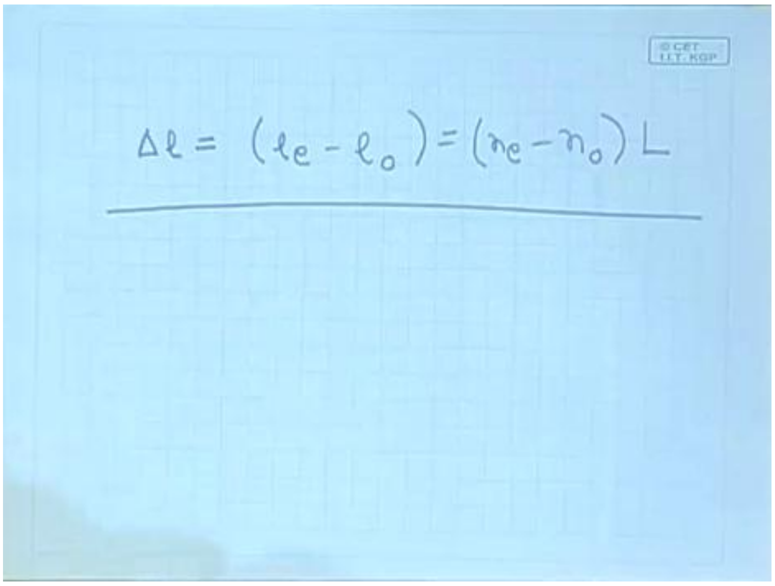
And the time which the wave will take across the crystal is to it is no into L by C or the optical length of the optical path of the crystal for this particular wave is going to be l ordinary which is the ordinary refractive index into the length of the crystal. So, what we see here is something very interesting.

(Refer Slide Time: 47:43)



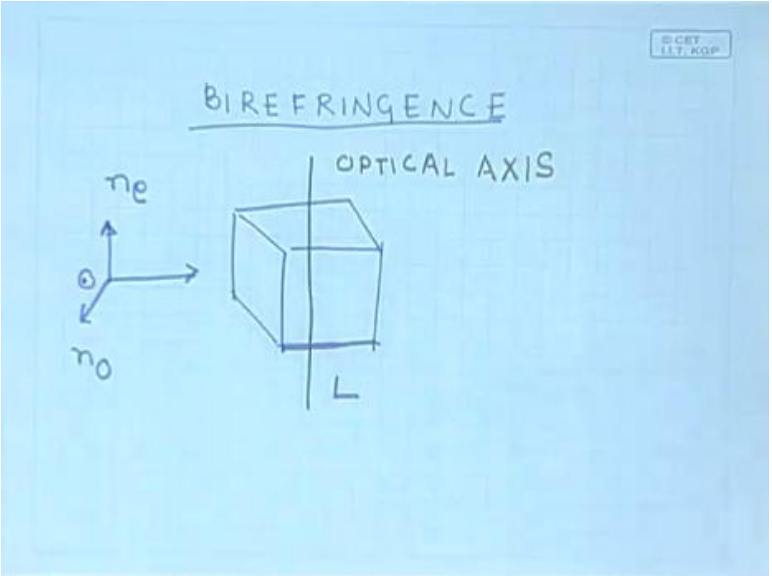
What we see here is that the light wave the electromagnetic wave or the light will take the time; the time the light takes to cross this crystal is going to be different depending on which way the electric field is aligned. And if I send in light which is a combination of these 2 polarizations then by the time the light comes out the 2 different polarizations are going to have a phase difference. So, let us ask the question what is the phase difference or what is the let us first ask the question what is the difference in optical path for these 2 different polarizations?

(Refer Slide Time: 48:34)



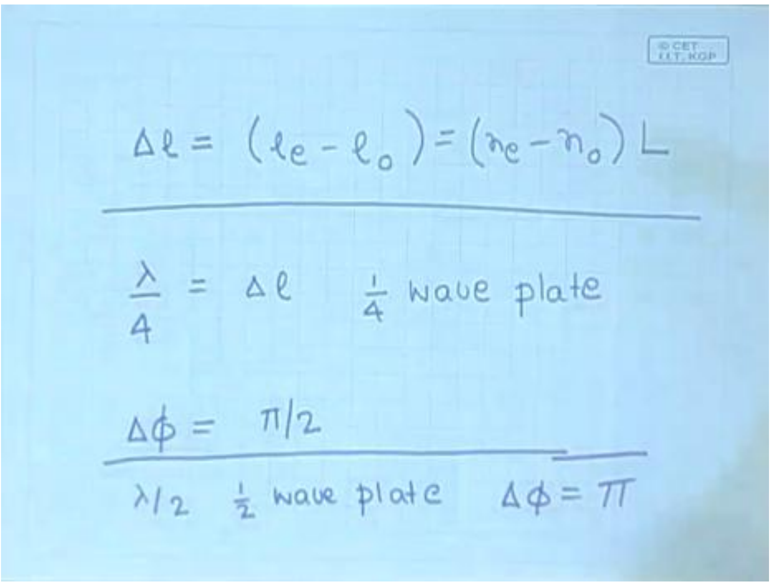
So, the difference in the optical path for 2 different polarizations is le minus l o. Well, this could be positive or negative we are not really interested in sign we are interested in just the magnitude. So, this is going to be the difference in the refractive indices divided by into the length of the crystal. This has got several applications let me for example, you could make water called quarter wave plates.

(Refer Slide Time: 49:19)



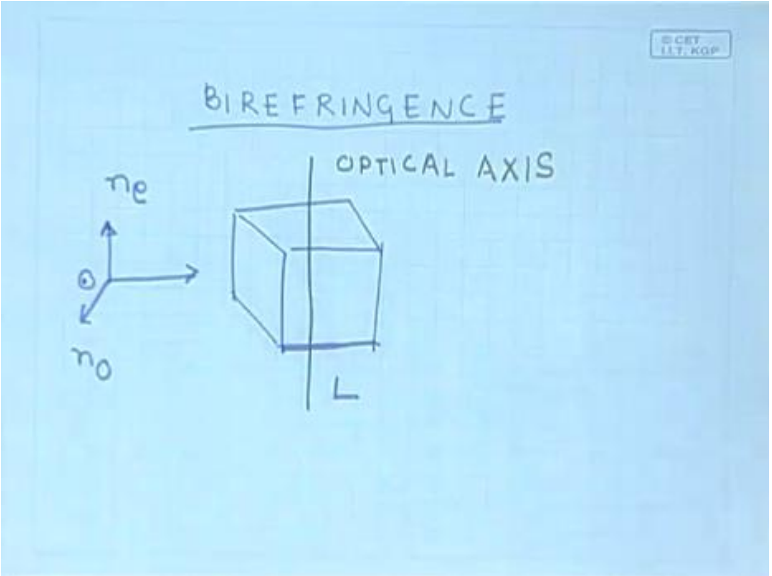
So, quarter wave plates are crystals like this where the length has been adjusted. So that the optical path difference between this polarization and polarization between these 2 is lambda by 4.

(Refer Slide Time: 49:32)



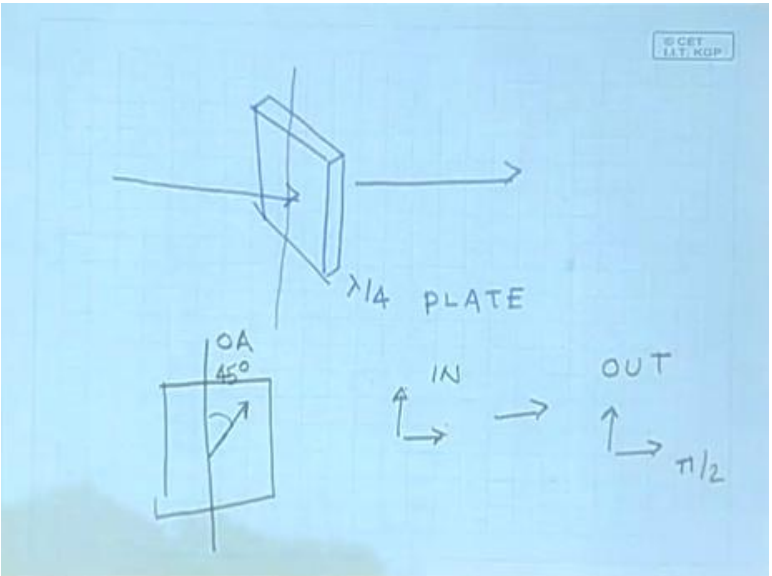
So, if this optical path difference is lambda by 4 then the crystal is called a quarter wave plates. And a quarter wave plate if the optical path difference is lambda by 4. Let us ask the question, how phase difference does a quarter? Wave plate introduces an optical path length difference of lambda is a phase difference of 2 pi. So, lambda by 4 is a phase difference of 2 pi by 4 which is pi by 2. So, this introduces a delta phase of pi by 2. Similarly, you could you have lambda by 2 plate which is called a half wave plate which will introduce a phase difference of pi and so forth.

(Refer Slide Time: 50:41)



So, these are very useful applications of birefringence of the phenomena birefringence. Let me demonstrate how it is utility. So, we have a quarter wave plate over here let me draw the quarter wave plate.

(Refer Slide Time: 50:57)

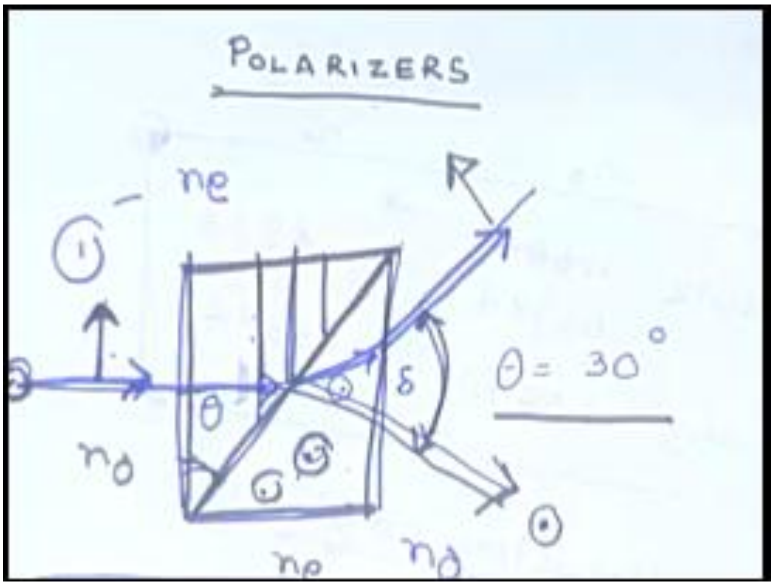


So, this is the quarter wave plate and there is light incident on it like this and the light comes out. So, this is a quarter waves lambda by 4 plates what does a lambda by 4 plate do a quarter wave plate do. It introduces a phase difference if this is the optical axis it introduces a phase difference so, of pi by 2 between light which is polarized like this and light which is polarized perpendicular to the optical axis. Now, let us consider a situation let me draw a picture phase on. So, this is the quarter wave plates seen phase on this is the optical axis and let us considered a situation where the incidental light is polarized at 45 degrees to the optical axis. So, the incident light is polarized at 45 degree to the optical axis. Now, the incidental light is. So, the incident light can be broken up into 2 components linearly polarized components 1 parallel to the optical axis and 1 perpendicular to the optical axis.

And when the light is lineally polarized we know that both these components have equally magnitude. And they will be oscillating with exacting the same phase. So, if combine both of these I will get light it which is polarized at 45 degrees. Now, when the light comes out so, this is the incident light when the light comes out you have introduced a phase difference of pi by 2 between these. So, know when the comes out this is in when the light comes out you have the same thing, but there is a phase difference of pi by 2 between these 2. So, now you have mutually perpendicular oscillations with a phase difference of pi by 2. And we remember that if I have mutually perpendicular oscillations of the same magnitude with the phase difference of pi by 2 we have circularly polarized light.

So, what we see is that quarter wave plate converts lineally polarized light at 45 degrees polarized at 45 degrees to the optical axis it converts it to circularly polarize light. Similarly, you could use half wave plates and so forth and you can quarter away plates combinations of half wave plates, quarter wave plates to convert lineally polarized light to circularly polarized light. Circularly polarized light to lineally polarized light or a lineally polarised to elliptically polarised light that all such transformations between different polarizations states are possible using quarter wave plates etcetera and half wave plates. And so far let me now give you a problem and end today’s lecture the problem is shown over here. Let me to as we are running short of time let me show you the problem over here.

(Refer Slide Time: 54:32)



We have a prisms; we have 2 prisms. So, let me again we have 2 prisms 1 like this and another like this these 2 prisms are made of birefringent materials. And the optical axis of this prism is shown over here. The optical axis of this prism is perpendicular to the paper it is like this. Now, consider a situation where we have unpolarized light incident on this. The unpolarized light can be broken up into 2 polarization components 1 like this and 1 will which is perpendicular to the plane of paper let us considered them 1 by 1. So, for this particular component 1 for the component 1 the polarization is the electric field is parallel to the optical axis. So, for 1 in this prism the refractive index is going to be ne the extraordinary refractive index and in this prism you see the electric field is in this direction. So, once it enters this prism it is going to experience the electric field is going to be perpendicular to the optical axis. So, it is going to experience n o. So, it is there is an interface over here on which. So, it is going to go straight through this and then when it comes to this interface there are 2 different refractive indices.

So, it will bend in some direction and then it will come out. For the other polarization it will see the ordinary refractive index in this medium, because the polarization is perpendicular to the optical axis it will see the extraordinary refractive index in this medium. So, this will go from a refractive index no to a refractive index ne. So, it is going to take a different path and it will come out like this. So, what you get is 2 rays coming out you sent in 1 ray you have 2 rays coming out. This is why this is called birefringent in the first place you have double refraction right. So, you see 2 images of the same sources and this ray that comes out is going to be polarized in this fashion. And this ray that comes out is going to be polarized in this fashion. So, the problem here is to determine this angle between these 2 rays that emerge you are given the fact that the angle of the prism over here is 30 degrees. And you can assume that this these are made up of calcite I have already given you the ordinary and extraordinary refractive index for calcite. So, you should do the problem assuming those values I shall discuss the solution in the next class.