Experimental Physics - II
Prof. Amal Kumar Das
Department of Physics
Indian Institute of Technology, Kharagpur

Lecture - 48
Theory of polarization (Contd.)

I will continue discussion on the Polarization of double refraction. we have seen these two types of uniaxial crystal, calcite crystal and quartz crystal. double refraction is occurs because when light enter into this crystal, say, it split into two rays. one is called the e-ray, and another is called the o-ray. e-ray is bipolarized, and o-ray is sigma polarized.

one thing is clear that when unpolarized light is falling on entering into this crystal, unpolarized light is nothing but the we can consider mutually perpendicular two electric component. these two electric components they become separated. o-ray and e-ray all the time it is polarized light. It has only one direction linear direction polarization, ok, electric field vectors in a particular direction.

depending on the direction of the electric component this stuff becomes sigma polarized or it become bipolarized. sigma polarized one is called the o-ray or inner (Refer Time: 02:11) and bipolarized one is called the e-ray. in uniaxial crystal velocity of e-ray and o-ray or refractive index of e-ray and o-ray are same along a particular direction that is called the optics axis. uniaxial crystals it has a one direction it is called optics axis.

in that direction the o-ray and e-ray their velocity or refractive index of the material with respect to this o-ray and e-ray are same. In other two direction, if that direction we take as a one of the principle axis, so that is z axis. other two direction x axis and y axis, these two directions are isotropic, in that sense you can tell isotropic means same. Refractive index and velocity are same along the x axis and y axis. But it is same for a particular ray for a o-ray and separately it is same for e-ray, but for o-ray and e-ray along x axis or along y axis, so velocity is different,

along the optics axis velocity or refractive index for o-ray and e-ray are same, but along the x axis or y axis velocity or refractive index are different for o-ray and e-ray, ok, but for a only o-ray along the x and y axis velocity and refractive index are same. For e-ray

that is different from the o-ray, the property is different from the e-ray because the velocity refractive index; for e-ray are same in x axis and y axis, but that refractive index or velocity that is different from that of the o-ray, all.

in uniaxial crystal that is calcite crystal or quartz crystal. optics axis is very important that is the reference axis. And what are the property of o-ray and e-ray in these crystals, so that we have learned. Now, we will discuss further. there are some devices based on this double refraction and how it is fabricated, so that we learn and how it will be used for our experiments or some for some application that we will see now,

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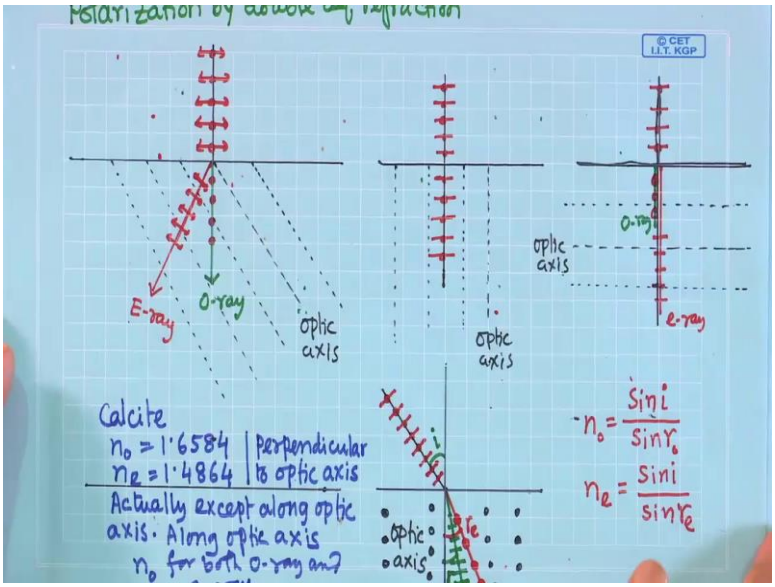

this is a crystal. now, we will just take one crystal. we are taking the calcite crystal because calcite crystal and your quartz crystal say just laser is opposite. next whatever we will discuss. this we will discuss for taking the calcite crystal, because both we will not discuss than things will be confused. But one can take example of the other crystal other one al, but we will prefer to discuss using calcite crystal.

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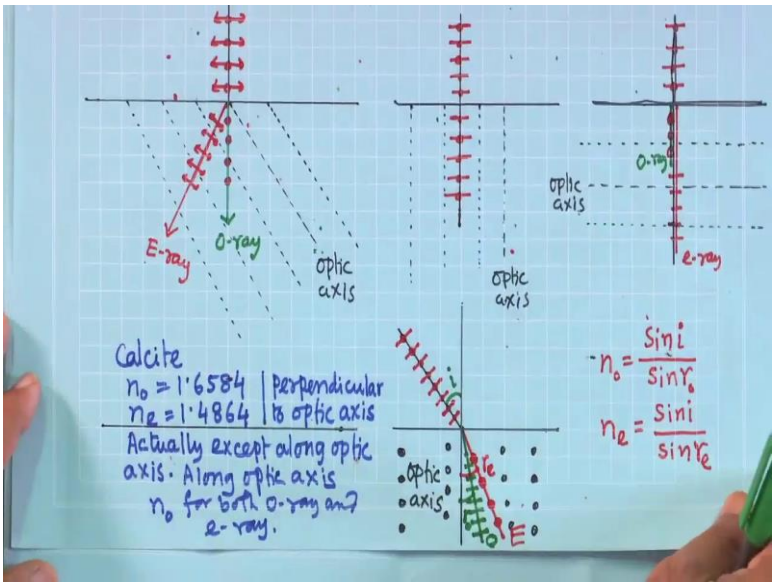

for calcite crystal what is the; what is the property? for calcite crystal this refractive index for o-ray is greater than the refractive index of e-ray, and so, this value since along the optics axis O-ray and E-ray are same their refractive index velocity is same. refractive whatever we are talking here, so definitely that is this value is perpendicular to the optics axis, all.

velocity of the o-ray is less than the velocity of the e-ray along the perpendicular to the optics axis, (Refer Time: 08:03) along the optics axis; obviously, both will be same, but that value will be this that is the for o-ray whatever the value for o-ray, so that will be E-ray also will have the same value along the optics axis but perpendicular direction, so they are different,

depending on the; depending on the optics axis. we can see; we can see the behavior of o-ray and e-ray. here, here you see we have taken one example. this is the calcite crystal; this is the calcite crystal. this is the optics axis. optics axis is not a line, it is a direction, it is not a just single line, optics axis is along this direction, that is why I have drawn this many parallel lines dotted lines. that is the direction of optics axis. It is not a single line, it is the it is direction, this is the calcite crystal, this is the surface of this calcite crystal. this optics axis is like this, ok like this.

Now, if unpolarized light, so it has two mutually perpendicular electric component unpolarized light falls on the surface perpendicularly, if this is just normal glass, so what

do you expect? What we would expect? We would expect that there will be refraction just this way, because incident angle here is 0. refracted angle also will be 0.

Yes, it happens for, so we will get refraction along this direction, so that is we tell that is the O-ray sigma polarized light and this electric component will be perpendicular to the optics axis, It will be perpendicular to the optics axis because this optics axis is on the plane of incidence, ok, optics axis is on the plane of incidence, so O-ray is sigma polarized light, so plane of polarization,

it will be perpendicular to this plane of incidence, so this direction of this electric component will be this dotted one, fine for ordinary glass. it is following the Snell's law, it is following the Snell's law, all. as such here in this case in this example its looks like that. we are getting another ray, it is the refracted another ray, after refraction we are getting two ray, one is just following the Snell's law this is called ordinary ray and another is along this direction, and this way is called the E-ray, extraordinary ray,

Now, why it is called extraordinary? It is a clear that it is not following the Snell's law, it seems it is not following the Snell's law, but it follows. that we people came to know later on. why it is happening? Know, this is happening because the refractive index is different for O-ray and E-ray and it depends on the crystal. In case of normal crystal, normal glass we can do see this one.

Al whether you will see this two rays separate rays that also depends on the incidence of light whether it is falling along the optics axis or perpendicular to the optics axis or it is falling like this, it depends on the optics axis of the crystal, those things are now known to earlier. it is a magic crystal, if this is the situation somehow it is achieved, so people from for one object people used to see the two image,

Now, you rotate the crystal if you rotate this crystal just keeping this on the axis rotation axis if you rotate. what happens? one object is constant, and another object is moving on a circle about the; about the; about the axis of rotation, that is object which is rotating that is that is formed by the E-ray.

now, if you consider this situation, here I am trying to show you that this refraction double refraction in depends on the direction of the optics axis of course and how crystal is cut and how the incident light is falling on it. it matters. if crystal is cut like this,

calcite crystal. this is the optics axis. it is perpendicular to the surface of the crystal and now this unpolarized light is falling perpendicularly on the surface of the crystal, so now, incident angle in 0.

What will happen? In this case, we will see only one refracted rays at 0 angle, refraction angle of refraction 0. both cases light is falling on the surface of the crystal. these depends we are seeing that is because of how the optics axis is, how the crystal is cut and there how this optics axis are present; what is the direction of the optics axis with respect to the surface of the crystal, in this case velocity or refractive index are same for O-ray and E-ray, it is a there, they are moving along the optics axis, so it they will not be separated like this,

I told that as if this E-ray does not follow the Snell's law, but that is not true. this happens because refractive index are different for refractive index is different for the E-ray, that is I think is no I should not tell that way refractive index are different that is fine, but in this case as if here we are seeing as if it is a violating the Snell's law is violated, , incident angle for both case is the for both case is the 0, but here we are seeing that E-ray there is the angle of refraction. for it is the definition we follow for the ordinary isotopic medium. in this case definition will be different,

here definition is for Snell's law if you define taking the reference of these optics axis, then one can explain, one can could probably could explain the; could explain the that both E-ray and O-ray follows the Snell's law because we write the refractive index for o-ray that is sin i by sign r. Similarly, for refractive index for e-ray also we write sin i by sin r.

extraordinary rays also follow the also follows the Snell's law club because this only we write from the Snell's law, both follows. sometimes, so from the angle of our conventional definition of the refractive index, for isotopic mediums. from that point of view, so as if it is violate,

here there will not be separation of o-ray and e-ray, there will not be any double refraction. same crystal, so whether we will see the double refraction or not. See, it is there, it is there, but whether it is separated or not that depends on the direction of light and the crystal cut; crystal cut following the optics axis, how crystal was cut, keeping the

optics axis in which way, in which direction. that is the method for seeing the double refraction,

in this case we will not see the double refraction. they will just move as usual following the ordinary glass whatever the, what happens, so that will be followed. as if here you can see that optics axis, as if the optics axis as if the whatever normal in case of angle we consider with respect to the normal. as if here it is considered this with respect to the; with respect to the optics axis, not with respect to the normal to the surface,

In this case, if this is the; this is the optics axis, so following this optics axis. with optics axis whatever the angle for angle incident angle, so for E-ray so that angle is defined not with respect to the normal is defined with respect to the probably this optics axis, probably this optics axis. It may happen, because in case of E-ray you know in case of E-ray, in this crystal this refractive index is refractive index is smaller; that means, if this is the direction in case.

whatever the normal to the surface if you replace that one with the direction of the optics axis. this is the direction of the optics axis. this will be the angles; this will be the angle incident angle. Now, refractive index is smaller in this crystal, refractive index is smaller, then the ordinary ray, so whatever with this, whatever with this, in this crystal whatever this ordinary ray will make angle externally extraordinary ray will make the higher angle because refractive index for O-ray is higher than the e-ray.

here you will get the higher angle for E-ray, higher angle for e-ray if it is angle is higher, I think from here you can see if angle is higher it is the denominator, so refracted index is lower, Snell's law is following. in case of e-ray, so that angle it is not with respect to the normal to the surface that angle incident angle and the refracted angle is defined with respect to the optics axis, direction of the optics axis.

then as if this is following the Snell's law, that is the reason we tell this in our common whatever we are habituated with the refraction in class in that sense it is not following the Snell's law, but it follows the normal to the surface is not considered for E-ray. optics axis is the deciding factor of the incident angle and angle of refraction,

here is the, it is fine I discuss along the optics axis. This situation will arise, it will not be separated. And this other situation, if optics axis are these parallel to the surface of the

crystal, ok, so rays are incident rays are falling perpendicular to this surface then in this direction perpendicular to the optics axis, ok, so here also we will not see, here also we will not see the separation of the o-ray and e-ray. We will not see the separation of the o-ray and e-ray.

We will not see the probably two image. or we can see that will depend on the situation, but this case here they are well separated, these two ray are separated, in this case, both ray will follow the same path, incident angle whatever 0 here for both rays refracted angle also 0 with respect to the normal,

but perpendicular to the optics axis we know along the optics axis velocity of refractive angle is same perpendicular to the optics axis velocity for e-ray and o-ray are not same, so they are different their refractive index is different. in this situation what we will see? velocity of o-ray is less than the velocity of e-ray in calcite crystal, in quartz crystal it will be opposite.

this the o-ray, this is the o-ray, when it will reach here, e-ray will reach here, as if this same incident ray inside they are moving in the same direction, but there will be retardation between these o-ray and e-ray whereas, in this case it will not happen, they will move in with the same velocity, here they are moving with different velocity. there will be retardation,

this is if this type of a, it has very important application I will discuss. here why I am discussing this? This concept is very useful for application and that is why I emphasized on the direction of the optics axis with respect to the surface of the crystal and also the direction of the incident light falling on the surface of crystal; other case if crystal is cut in such a way this optics axis is like this, dotted lines this is the optics axis. this is the perpendicular to this optics axis is perpendicular to the surface to the plane of this paper.

now, in this case incident. if incident light is falling with an angle, falling with an angle, so in this case you can see this. they are moving in this plane they will move plane of you see plane of incidence is this, plane of paper. they are moving or refracted in the plane which is perpendicular to the optics axis, so their velocity or refractive index will be different. o-ray and e-ray will be separated,

here as if here with this normal, ok, here we are getting o-ray and e-ray separated and from this angle one can find out the refractive index for this crystal, ok, for this crystal calcite crystal measuring the; measuring the incident angle and the refracted angle for o-ray and e-ray and calculate the following the Snell's law calculate that. Snell's law is following or not that depends on the cut of the crystal,

And in this situation, it is clearly following this Snell's law and utilizing this one, one can measure the refracted index of the quartz crystal or the calcite crystal in the direction to the perpendicular to the optics axis. this we will use, in our laboratory use this type of cut to demonstrate how to measure the refractive index for o-ray and e-ray for calcite crystal.

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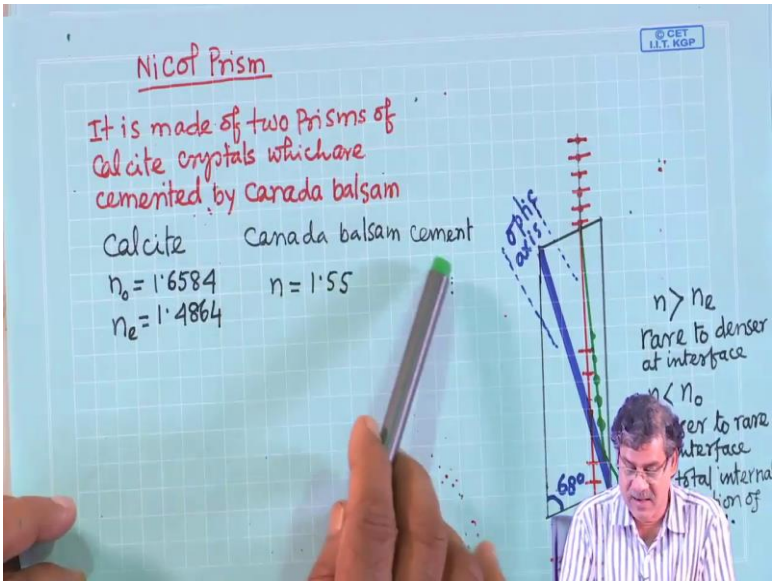

if I continue as I told this concept we use for device. prism is a device, optical device type, so Nicol prism. Nicol prism it is made of two prisms of calcite crystals, these are device; prism is called Nicol prism. it is made of two prisms of calcite crystals which are cemented by Canada balsam cement, ok, Canada balsam cement. Means cement means you can attach two object.

bricks, wall for house wall we use bricks and cement for attaching with each other the bricks with one bricks to the other bricks we use to attach them we use that is called cementing, cemented. that is Canada balsam. Canada balsam the refractive index of this Canada balsam is in middle in intermediate, it is an intermediate value of refractive index

for o-ray and e-ray, calcite crystal refractive index as I mentioned this the 1.6584 and for e-ray that is 1.4864, and this is 1.55,

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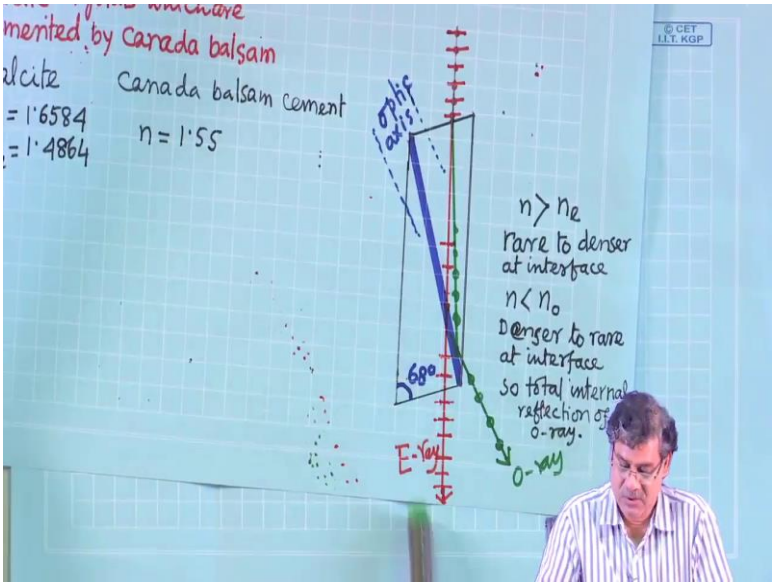

now this is one prism, this is one prism, and this is another prism. they are cemented they are cemented. these the Canada balsam cement. they are cemented like this and their optics axis are for both crystals prism, this optics axis in same direction. this is the single piece. If you cut a rectangular something single piece optics axis is like this. Now, cut along this direction detach them and then cement it with the using the Canada balsam, this we tell that is the nickel prism,

this nickel prism is used for separating the O-ray and E-ray. this is used as a polarizer, you know polarizer is used to polarize the light means unpolarized light is incident light is unpolarized light when it is passing through this sheet, then we tell is a polarized, we are getting polarized light, how it is polarized? Now, it is clear, now it is clear.

the sheet we use that this type of it is there are other kind of course Nicol prism is one type, this Nicol prism this is used as a polarizer. here what happens? Refractive index for one case it is a for ordinary ray, the effective index is higher and Canada balsam refractive index is lower, for ordinary ray what happens? from denser medium it is entering to the rarer medium.

there will be, so this prism this angle is such that when this falling these angles will be, when it is falling this angle will be there will be internal there will be internal total reflection, internal total reflection. it will be reflected. Whereas, the other one, it is going from its the refractive index lower it is going from higher lower refractive index of the higher refractive index. both are higher.

for extraordinary ray, so this these both are lower refractive index 1.48 and this one is 1.5. from rarer medium to denser medium it is entering. as usual refraction we will get. it will be refracted, and it will pass like this, from this surface you are getting the O-ray and directly you are getting the E-ray. thus, so you design such way, so catch only these light from the surface so that means, incident light was unpolarized light and you are getting outside the polarized light,

it can be either O-ray or it can be either E-ray. that is nickel prism in used to separate this to polarize the light and the polarizer just we tell the polarize analyzer. that works based on this principle.

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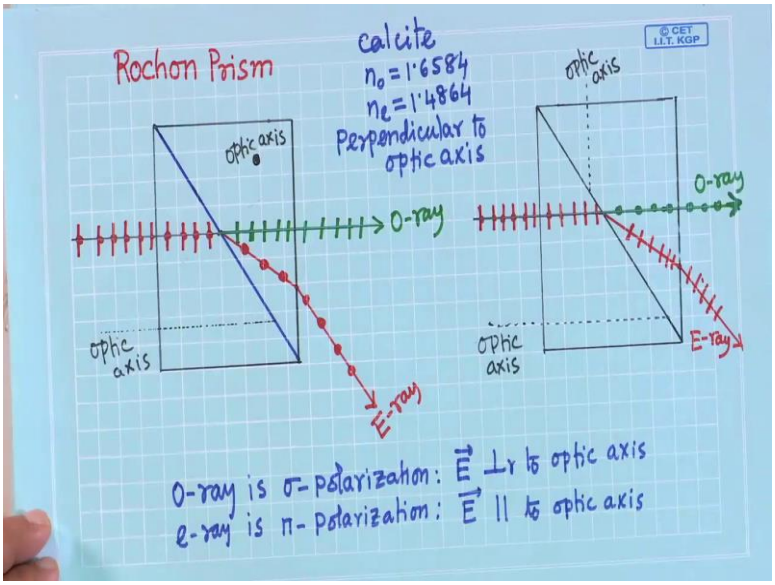

next there are another prism very useful it is called Rochon prism, Rochon prism, it is the again calcite prism, it is the made of calcite. it has again two part, it has two part, in this case, in this case this part this part here, this part, it has optics axis along this direction. we are taking this two part and another part is this one. here these two part has the different direction of optics axis.

this is the direction of the optics axis for this part and for other part direction of optics axis is perpendicular to the plane of the paper. now, in this case what happens? If this is the construction of the prism, so unpolarized light is coming. it is from this part it is passing along the optics axis, it is passing the passing along the optics axis, optics axis they will not be separate that is what we have seen.

When it is entering to the next part, so it is moving perpendicular to the optics axis, here E-ray, so this two this E-ray and O-ray here we will get the E-ray and O-ray, for O-ray see its property its refractive index is same in all direction, velocity is same in all direction, , but O-ray that differs. when the same crystal same refractive index for O-ray seeks the light is falling perpendicularly just go out,

But E-ray it will be refracted, it will it will be refracted here because for E-ray; it is the along the optics axis what will be the refractive index? Perpendicular to the refractive in, perpendicular to the optics axis refractive index are different. it will be refracted along this direction. we said you know, Rochon prism is used to separate the O-ray and E-ray. Actually, this separation is huge, ok, so we can polarize the light, we can catch only one light, so especially it is the huge separation, huge separation,

here one thing you can see, this one generally this dotted one we use for the sigma sigma polarized light and that is ordinary ray, but here it is opposite because in this crystal here optics axis along this direction. as I told these for sigma polarized, bipolarized light or for E-ray. it is it is not for E-ray, so this electric component it will be parallel to the optics axis and for O-ray it is perpendicular to the optics axis, that is why here its looks different.

similar case also happens if optics axis is optics axis are mutually perpendicular to these two half; if situation is like this optics axis one is this and another is this then also you can it happens that, it happens that in this case in this part it is same way here whatever we saw because it is along the optics axis. Now, here optics axis along this direction, now here you can see the O-ray the polarization,

this it is sigma polarized, this electric component is seen now perpendicular to the plane of the paper because optics axis is on the paper on the plane of the paper and this for E-ray now this on that plane of incident, this now on the plane of incidence, O-ray and E-ray here just it is opposite way, so that it is because of the direction of optics axis,

o-ray is sigma polarized polarization, and, in that case, electric component is perpendicular to the optics axis. E-ray is bi polarization, electric component is parallel to the optics axis. this way also we define the sigma polarization and bipolarization,

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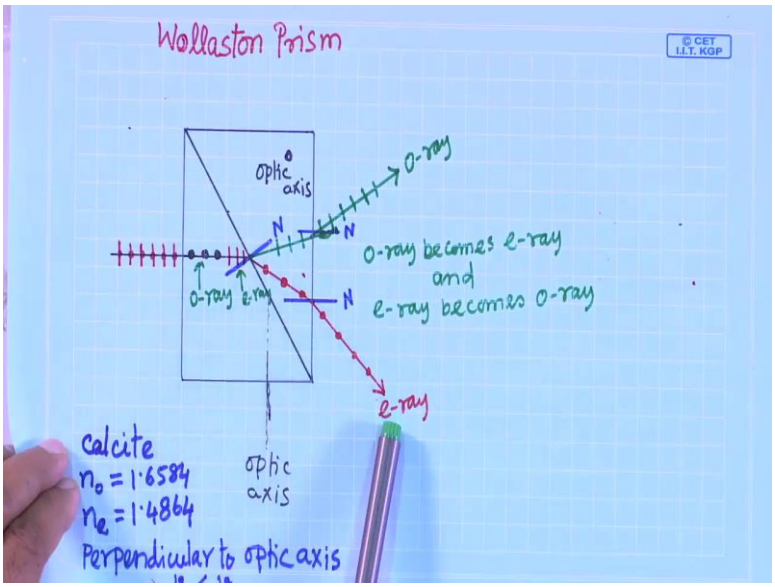

next another prism, see it is called Wollaston prism, In this case, this two half this half has optics axis perpendicular to the planar paper and other half, other half sorry this half optics axis is this direction is this and this half optics axis is perpendicular to the paper, here when it is entering. it is unpolarized light now it is going perpendicular to the optics axis, not parallel to the optics axis,

not parallel to the optics axis. what will happen? Perpendicular to the optics axis is velocity of O-ray if they are different, so there will be retardation as I mentioned, is the parallel to the; parallel to the this its surface incident surface, they will move in same direction, but they are separated. E-ray will move faster than the O-ray.

Now, when it is going to the other part optics axis now perpendicular to the plane of this paper, now also in this case they are moving perpendicular to the perpendicular direction to the optics axis, here what will happen you know; this O-ray that is the electric component, now here when it will enter here, so this electric component now it is it will be in this case it is perpendicular to the optics axis, but other case here it is parallel to the optics axis. when this is parallel to the optics axis then it becomes the e-ray and other one perpendicular to the optics axis. that is o-ray,

what will happen? o-ray in another half o-ray will be e-ray, o-ray will be e-ray and e-ray will be o-ray. because of that what will happen? The refractive index for in this part whatever the refractive index for o-ray, e-ray, they are different in perpendicular direction. in other half it will be just exchange, Refractive index will be just exchange, ok and you will get this type of refraction,

they are more well separated, they are more well separated then the Rochon prism, Rochon prism. It was going directly, so it is the. this is called Wollaston prism. these are very useful device for the experiment for the application. that we discuss is the generally calcite crystal pistol is used. Quartz crystal can be also used,

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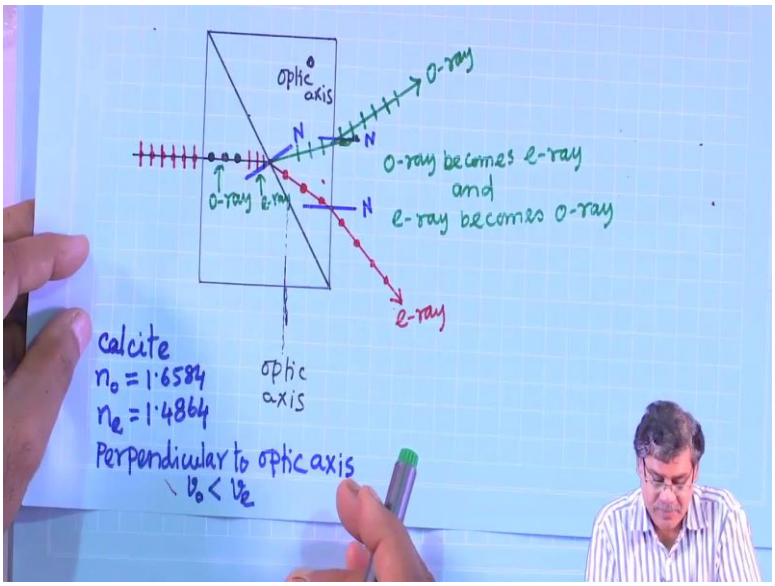

another important aspect just I will tell you that it is a called retarder say, retarders, retarders,

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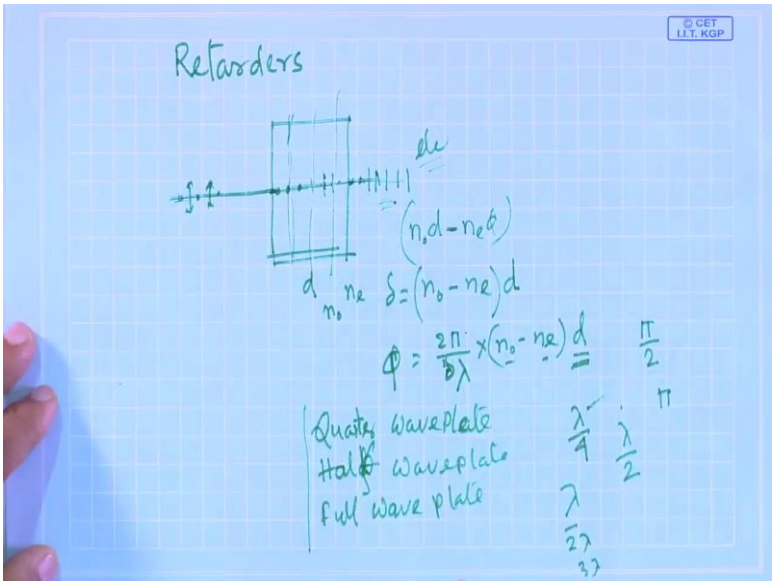

what we have seen? This when. What we have seen? When this is the crystal light is falling this way, unpolarized light, unpolarized light and. if this if optics axis is parallel to the surface, optics axis is parallel to the surface this is the direction when light is moving, so e-ray is moving faster e-ray is moving faster than the o-ray that is what we have seen, this is used.

when they will come out when they will come out, ok, so e-ray is faster, it will come out first and o-ray is retarded ray, o-ray is retarded ray. both we are moving in same direction, but o-ray, e-ray is moving faster than the o-ray. their refractive index is different, there will be; this retardation means there will be phase introduced, when they will come out, ~~they~~ are falling in this incident along the same time, when same phase, when come coming out from this crystal,

this there will be path difference means phase difference between o-ray and e-ray, all though they are moving the same direction. these that is these plates, these this is called retarder, what will be the path difference? if thickness is say d and refractive index for o-ray and e-ray is n 0, n e, optical path for this case one case n 0 d and for other case n e d, path difference between these two rays will be this.

this equal to n 0 minus n e or n e minus n 0 depending on the which one is greater. this is the path difference, is the path difference between o-ray and e-ray, and corresponding

phase difference, phase difference phi will be 2 pi by lambda; 2 pi by lambda into this path different delta. that is nothing, but n 0 minus n e into d,

it depends on the; for calcite crystal it is a n 0 and ne is defined you cannot change only this path difference or phase difference you can introduce just changing the thickness, if thickness is such that, if thickness is such that this phase is introduced it is pi by 2, ok; that means, path difference in it is lambda by 4 or lambda by 4 then that plate is called quarter wave plate. This is called quarter wave plate, quarter wave plate

If thickness is such that it is the introduce this phase difference pi; that means, the path difference is lambda by 2, that plate is called half wave plate, half wave plate, half wave plate half sorry half wave plate, If it is lambda thickness is such that if it is lambda then it is called full wave plate and you know it is the lambda or 2 lambda or 3 lambda these are same, this is the lambda multiple of lambda, this lambda by 2 or all multiple of this lambda by 2. that way for quarter wave plate also.

So this plates are in laboratory for application is very important to change the polarization state, these two ray when it will come out, so you will get you can, you get the gel this plate one can use for linearly polarized light, If you want to get elliptically polarized light or circularly polarized light, so between two components you have to introduce the phase difference or path difference; depending on the phase difference and path difference and the amplitude of the e-ray and o-ray, ok, so it will be decided that whether you will get elliptical polarized light or optical polarized light.

if you want to introduce phase difference then you are, we are using the wave plate, quarter wave plate, retarded wave plate, so and also it can be variable wave plate. that piece called Babinet Compensator, continuously you can vary the phase or path difference that also another device that is called Babinet compensator,

I will stop here. Thank you for your attention.