Experimental Stress Analysis
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Lecture - 10
Light Ellipse Passage of Light through a Crystal Plate

Let us continue our discussion on transmission photo-elasticity and for you to understand photo-elasticity you need to develop concepts related to crystal optics.

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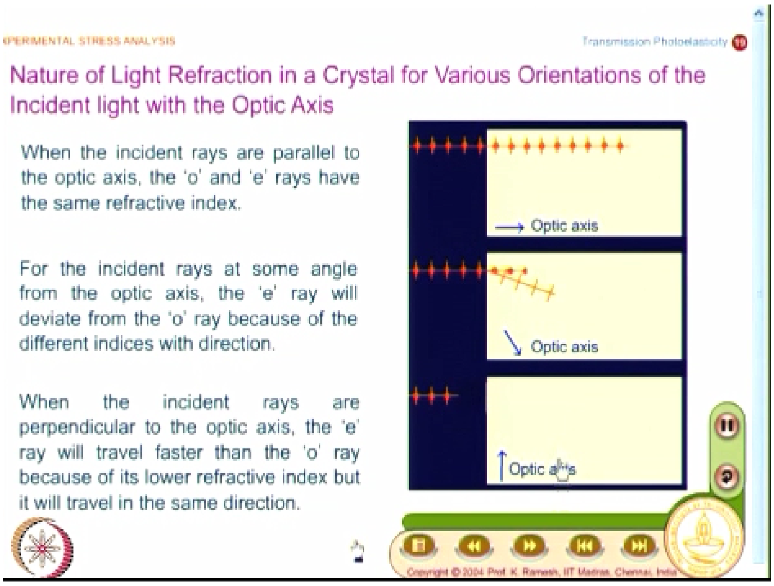

And in this one of the very important concepts that we saw in the last class was when I have a crystal and when I have a light incident on it I can look at the incident light with respect to the optic axis. In the first case, the incident light is along the optic axis. In the second case, the incident light is at an angle to the optic axis. In the third case, the incident light is perpendicular to the optic axis.

And what I mentioned in the last class was the third case is particularly attractive to photo-elasticity. The second case really brings out how does one looks at 2 images in a crystal. So the second case helps in understanding what is birefringence. On the other hand, the third case what is useful from photo-elasticity point of view. In the first case is very similar to what happens in an isotropic medium.

And in the third case both the ordinary and extraordinary rays travel in the same direction, but because of different in refractive indices they travel with different velocities. So now what I find is for one incident beam I have 2 refracted beams they are planes of polarization or mutually perpendicular. They also acquire a retardation within the crystal.

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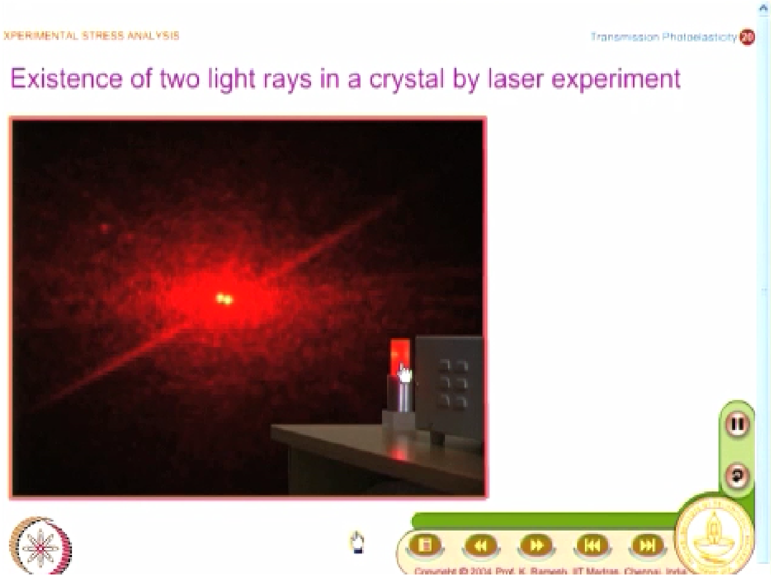

And in order to give you an idea it indeed so we have also rotated a crystal and we saw that 1 dot becomes 2 dots which indicates that the incident light in relation to the optic axis has a role to play. So now the stage is set for how to analyze this mathematically.

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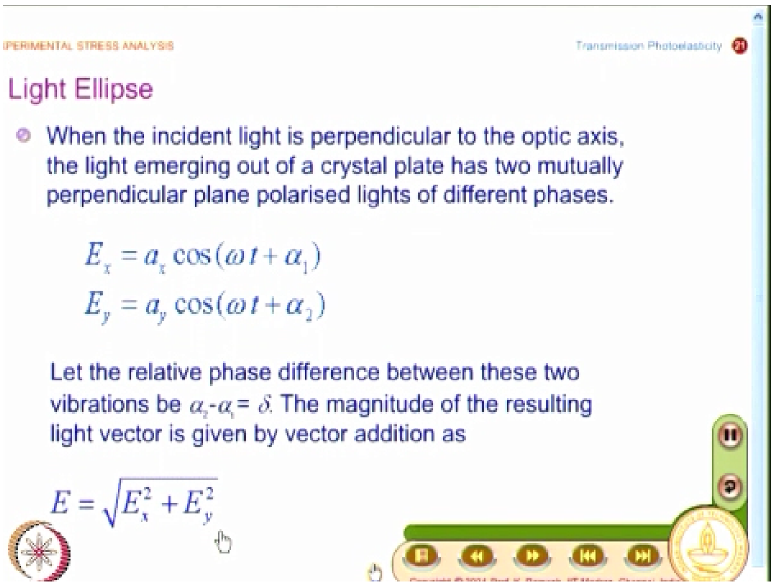

And even before developing the concept we have labeled this as Light Ellipse. So you can say that whatever we are going to do finally we end up with an equation for an ellipse and what you have is for 1 incident light I have two refracted beams and they travel with different velocities and they could be easily represented by ax cos omega t +alpha 1 and ay cos omega t +alpha 2.

So what I have is I essentially have 2 simple harmonic motions one in the x direction, one in the y direction. They have different amplitudes ax and ay.

And in general you could also think of a phase alpha 1 and alpha 2. See what you will find is in photo-elasticity literature more than the absolute phase it is a relative retardation that is very important. So keeping this idea in mind we would also go back and **re-class** the equation that is what we will do later. So what we will look at is we will look at relative phase difference between these 2 vibrations labeled that as delta.

And delta is nothing, but alpha 2- alpha 1. So it is a relative phase difference that is very important. So what I have is for 1 incident light I have 2 refracted beams and they are simple harmonic planes of vibration are mutually perpendicular and when I want to find out what is the resultant the magnitude of the resultant light vector is given by simple vector addition. Suppose I want to find out what is E at a particular incident of time.

I have to simply take the amplitude of this, I have to simply take this square root of it. So I have this as Ex square + Ey square. I can find out the amplitude and this I do because they are mutually perpendicular. It is not like when I go to the pond drop the 2 pebbles both the waves in the same plane. Here the waves are mutually perpendicular they travel with difference phase.

They acquire a phase retardation when it comes out of the crystal. When it comes out of the crystal you see the interaction of this and what would be the nature of this interaction? The polarization behavior changes. So that is what we are going to look at. Now my interest is what would be the trace of this light that comes out of the crystal plate. So for me to do that I have to eliminate time.

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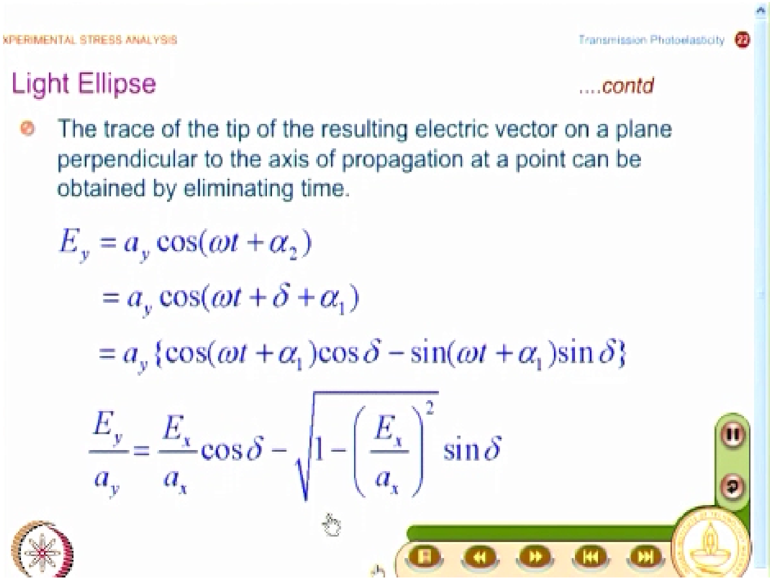

So what I want is I want to get that trace of that tip of the resulting electric vector on a plane perpendicular to the axis of propagation this is my interest and this can be obtained by eliminating time. And I have already mentioned that for you to carry on with photo-elasticity you need to brush up your trigonometric identities. We will use several of them even for this development we will use a trigonometric identity and simplify the set of expressions.

I will give you the clue you have the expression for Ey and that has a phase alpha 2 and I said in photo-elasticity we are interested only in relative phase difference. So write that in terms of delta and alpha 1 and you can simplify I, take 2 minutes of your time and do it. I have Ey as this and I would like you to simplify this expression as simple as that. So what is the trigonometric identity I can use cos A+B.

So I can have this as cos omega t+ alpha 1 omega t+ alpha 1 I can take it as A as delta as B. So cos A+B you will get it as cos A cos B- sin A sin B. So when I do that I get this expression. So what I have is I have ay cos omega t+ alpha 1* cos delta- sin omega t+ alpha 1* sin delta and this I could replace in terms of Ex as well as this also I could replace it in terms of capital EX.

So now I will have an expression only consisting of Ey, Ay, Ex, Ax and expression involving delta. You could simplify it can you write it in this fashion. It is straight forward you could do it easily and when I do that I get the expression like this. So I have this as Ex/Ax cos delta- square root of 1-Ex/Ax whole square*sin delta and what I could do is I could segregate the terms.

And finally write what is the expression that would give you the trace of the tip of the resulting electric vector. So what I have done is I have just taken this expression replace alpha 2 in terms of delta+ alpha 1 use trigonometric identity and got this expression then replace this terms involving time by Ex/Ax and now I have the final expression and this could be further simplified.

Can you do that simplification because if you do the simplification right in the class when you revise the notes whatever you have learned becomes very simple.

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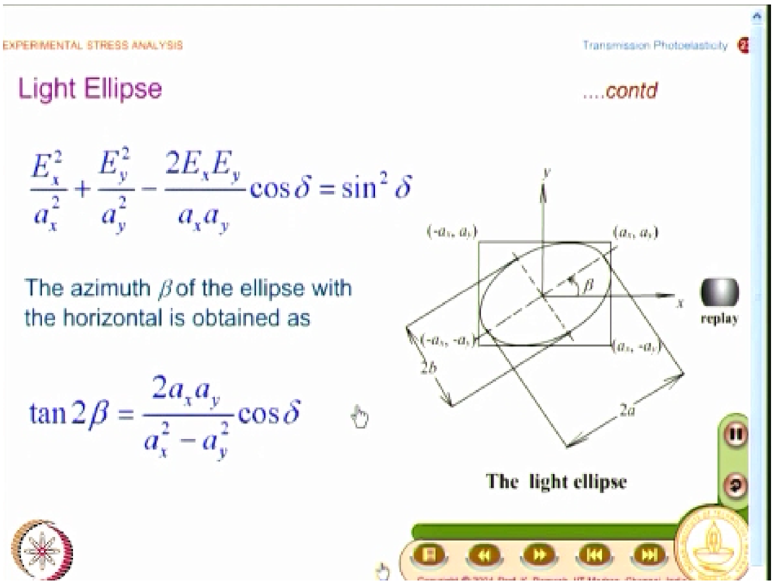

It is a very simple exercise and let see what we get. So I am going to get an expression like this. So what I have is Ex square/ax square+ Ey square/ay square- 2 Ex Ey/ ax ay cos delta = sin square delta and this is the generic expression of an ellipse. Suppose delta becomes (()) (10:35) what happens to this expression. You have this becomes 1 and this term goes to 0 and this is your same as equation of ellipse.

You have x square/ a square+ y square/b square=1. That you all know that is the equation of ellipse and what you have here is this is an equation of an ellipse at some arbitrary angle and that is what you have here. I have this as the light ellipse and this light ellipse the major and minor axis are shown here and this is oriented at an angle beta and this is governed by a generic expression like this and I have the amplitude marked.

And you can also find out the expression for a as well as b in terms of these quantities that is not our focus so we will not really determine that, but we would definitely find out what is the expression for beta and we will directly take that result from what is available in the literature. We will not derive it and what I have here is the azimuth beta of the ellipse with the horizontal is obtained as given as tan 2 beta and that is given in terms of the amplitudes 2 ax ay/ ax square- ay square* cos delta.

And this is a very important learning what you have is when I have 2 simple harmonic motions which travel perpendicularly and they have a phase difference when it comes out and they interact and you essentially get an ellipse and what you have is you have 2 expressions. One expression gives the equation of the ellipse the other expression gives you the orientation of the ellipse and this is called the azimuth.

And if I calculate A and B if I have B/A I also get the ellipticity. In fact, if you go to optics literature there is a quite a good measurement approach is available where they call it as Ellipsometry. They find out the ellipticity, they find out the azimuth, they also find out the handedness of the ellipse. So what you find here is if I add 2 simple harmonic motion which are mutually perpendicular with a phase difference if I add them in general I get the interaction as trace of an ellipse.

This is very important photo-elasticity.

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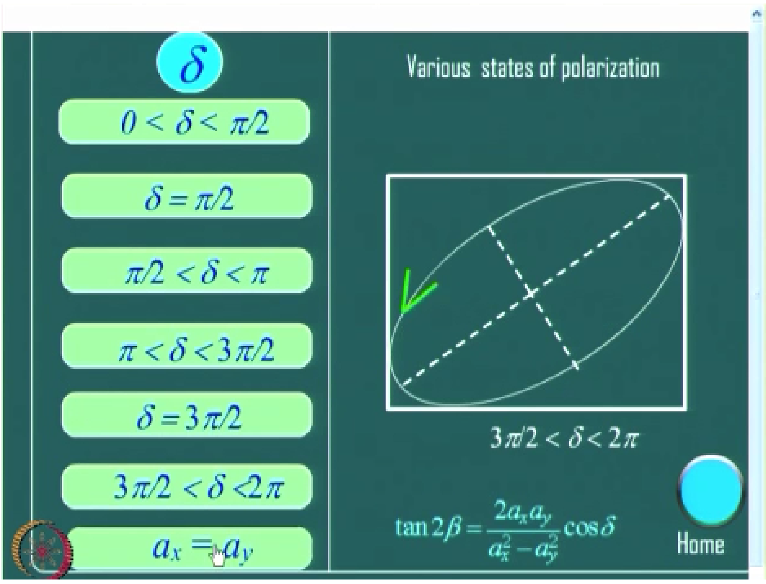

We would also see this little further and what is my interest is when I change delta what happens for various values of delta what way you will get the state of polarization. We have already seen when delta=0 what happens. When I have delta=0 I have 2 vibrations and they will give you a plane polarized light where is the ellipse comes. Ellipse does not come there. When delta= pi/2 then you had equation of a simple ellipse whose axis coincide with the X and Y direction.

And what we are looking here is we want to find out in the range 0 to p/2 when delta lies. It is not 0 or nor pi/2. It is within this range how do you have is you have an ellipse like this. I want you to make a sketch. You will have sketch for all of these cases and also note down that this is rotating in a clockwise direction. So if delta is between 0 to pi/2 the resulting trace of the light would be an ellipse oriented with this orientation.

And it will have handedness indicated in this fashion. And suppose I got a delta=pi/2 which we have already looked at it we will see pictorially. So when delta=pi/2 the major and minor axis of the ellipse coincide with the reference direction X and Y. It is a very important result. It is a very useful result in photo-elasticity. The vibration along the major and minor axis having a phase difference of pi/2 that is a very important information you have.

So if the vibration is having a phase difference of pi/2 then those axis form the axis of the ellipse and what happens when I have the range goes to pi/2 to pi. The orientation changes and you have the handedness still remains. The handedness is still clockwise and when you complete this picture you will have a nice set of picture that you will have. If I go to the range pi to 3 pi/2 you will find the handedness is also changes.

So that is what I have the handedness changes, the orientation remains same but the handedness changes. So what you find here is for different values of delta you see different forms of elliptically polarized light. So you can look at it the other way when I look at the light ellipse it is possible for me to find out what would be the value of delta that would have cause this.

Our interest is the reverse, but in order to understand the cos of delta we will look at for various values of delta how does the light characteristic changes that is what we are looking at. And when I have delta=3 pi/2 pi/2 and 3 pi/2 share a commonality. You will have the axis coincidence with the reference axis, but the handedness changes when it was pi/2 the handedness was clockwise and when it is 3 pi/2 the handedness is anti-clockwise.

And what you need to appreciate here is in conventional photo-elasticity people never bothered about the handedness. It was not really affecting the results. The moment digital photo-elasticity came where they use CCT camera as an electric aid and they wanted to automate the procedure in order to minimize the error sources change of handedness helped in minimizing the error due to quarter wave plate.

So though in conventional photo-elasticity handedness does not play a significant role. It does play an important role when you come to the domain of digital photo-elasticity. So it is better to know the handedness has its importance and when I go to the range 3 pi/2 to 2 pi I have the ellipse oriented in this fashion and this is anti-clockwise. So you have 3 cases where you have anti-clockwise.

You have three cases where you have clockwise and when delta=0 or delta= pi or delta= 2 pi you will have plane polarized light coming out as plane polarized light except the case which is slightly different is when you have delta=pi. When delta= pi it will be rotated by some angles, but the state of polarization will remain still plane but it will get rotated by some angle.

And now we come to another important aspect what happens with this expression when ax=ay. So it becomes undefined when tan 2 beta becomes infinity 1/0 you have. So it becomes undefined.

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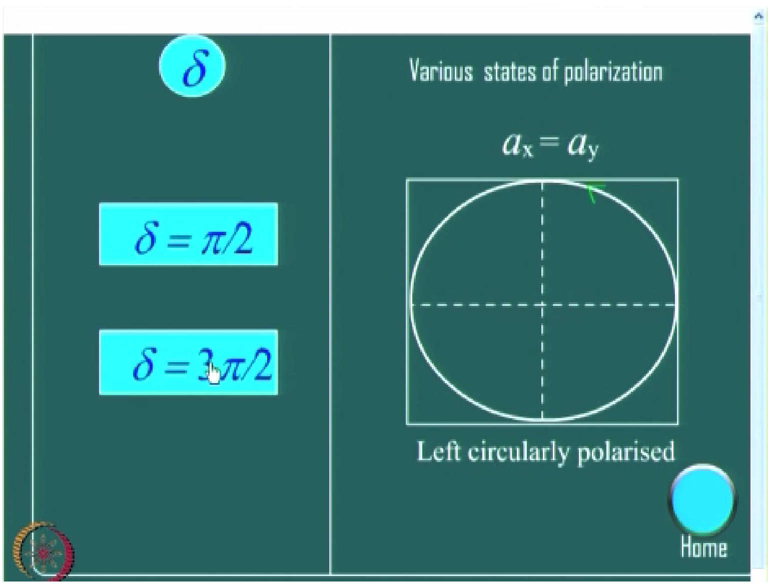

And when the amplitudes are equal you have essentially a circularly polarized light because there is no specific axis. You have only circularly polarized light that comes out of a model and this is a very important state of polarization we want because I said that you have a plane polariscope, you have a circular polariscope. In a plane polariscope you impinge a plane polarized light.

In a circular polariscope you impinge a circularly polarized light. So I need to generate a circularly polarized light and make it hit on the model And this gives you a (()) (21:19). So if I have a crystal plate in between a plane polarized light can be converted into a circularly polarized light and what you have here when delta= pi/2 the handedness is clockwise. When delta=3 pi/2 the handedness is anticlockwise.

So handedness tells you what is the value of delta. So in ellipsometry they measure the ellipticity, they measure the azimuth, they also measure the handedness. So by knowing this you can fix delta. Our idea is to find out delta by optical measurement. I said light is a sensor and light gets modified within the model because of the sources applied and you get exit light which is in general elliptically polarized.

If I analyze what is the light coming out I can fix what is the delta that is what we have learnt it now. We will also look at it in a slightly elaborate way when we look at what is retardation plate. As far as this discussion goes what you find is when I have 2 simple harmonic motions which are mutually perpendicular which have a phase difference for different values of phase difference I get different states of polarization as the exit light.

So this gives you a hope to use light as a sensor because essentially I will find out what happens to the exit light with the exit light I will go back and find out what was the delta that has caused. Now we will relate delta to sigma 1- sigma 2 later that is how we will merge physics and stress analysis. But before we get into that we need to know little more about what happens suppose I take a crystal plate that we will see now.

I will just take a crystal plate and you know you have to observe it very carefully. We will do this 2, 3 times.

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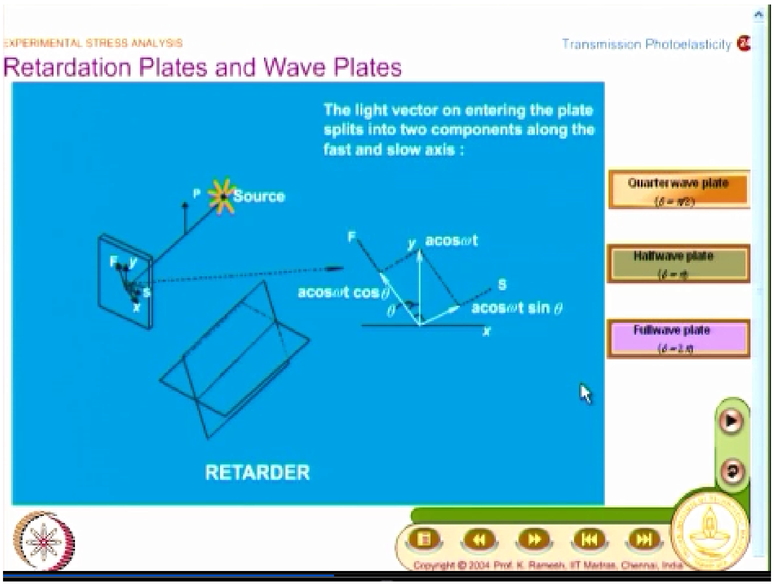

So what I have here is you keep your notebook horizontal and draw this sketch and we will see part by part and then explain and what we are going to discuss is retardation plates and wave plates. So what I have here is I have a crystal plate it is not load at it is a natural crystal and I have this in a form of a plate and what I have is I have a light source and I have put a polarizer.

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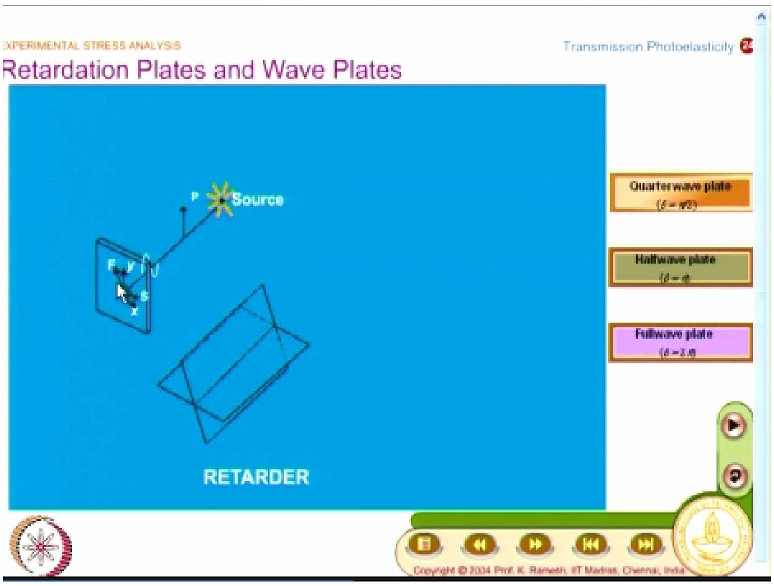

Now you must be familiar and we will just see what happens. So what you have here is I have a natural source of light. After the polarizer, I have a polarized light impinges on the model. So what you have is I have a plane polarized light because I want to use light as a sensor so I know the input light characteristics. Input light is simply a plane polarized light and when it hits the model, when it hits the crystal plate it is not the model.

Model also behaves like a crystal when it is loaded and here we are looking at in general what happens in a crystal plate and what do you anticipate? You anticipate for 1 incident light there will be 2 refracted beams that is what the whole of crystal optics we will see it. For one incident beam I will have 2 refracted beams and these 2 refracted beams are plane polarized under plane of polarization mutually perpendicular.

Let us see this that is what is shown in animation. You carefully watch so what happens is the light vector on entering the plate splits into 2 components along the fast and slow axis. So you have to understand I am bringing in 2 new terminologies fast and slow axis. The reason for this labeling would become clear when we look at what happens. So what we saw is I have natural source of light which becomes plane polarized hits the model and on then on the front surface it splits into 2 components.

Let us see the two components is the idea clear? I send vibration acos omega t. This will become 2 rays within the model within the crystal plate and you have depending on the orientation you have one of these amplitude is longer another amplitude is smaller. So amplitude is split and this is nothing but they are the planes of vibration is in this direction, plane of vibration is in this direction and they are perpendicular.

So for 1 beam within the model I will have 2 rays and what you have here is if you watch it very carefully whatever is the thickness is expanded as 2 planes. I have 1 plane coinciding with the fast axis another plane coinciding with the slow axis and let us see what happens. So what happens is, you know, that when light enter the crystal it splits into 2 rays and because it is perpendicular to the optic axis they travel the same direction.

But the plane of vibration is mutually perpendicular. You have one plane like this you have another plane like this and you have a wave travels like this and what has happened this wave has travelled past the other wave that is what is shown in the sketch. So this has transverse the thickness of the plate faster than the other wave. So I call this axis as fast axis and this wave has taken little more time and it has acquired a retardation delta within the plate.

I will repeat the animation then you will understand. So what you find here is I have a natural source I put a polarizer I know definitely what kind of light that impinges on the crystal plate and this splits into 2 rays when it enters the model depending on the angle theta you will have the amplitude as acos omega t cos theta acos theta * cos omega t that is the expression for the light vector.

And you will have this as a sin theta cos omega t and within the model which is shown in an expanded fashion I have this like this. Make a neat sketch of this and what do you anticipate. I have 2 simple harmonic motions which are mutually perpendicular which has acquired a phase difference when they come out of the crystal plate how will it appear. We have just now seen mathematical expression.

It will appear like a ellipse that is we developed the mathematics if I have 2 simple harmonic motion which are mutually perpendicular if they have a phase difference depending on the difference in phase you will see lights of different states of polarization and let us see that. So I will have a light ellipse coming out of the model. I use model and crystal plate interchangeably please pardon me.

And model behaves like a crystal plate when stressed. In a crystal plate it is naturally having birefringence that is the only difference. So what I have here is when I have a normal light source I have a polarizer I put a crystal plate in general I will have a light ellipse and how this light ellipse has come about. I know that within the crystal plate I have 2 rays travelling one plane of vibration is in this plane and another in the plane perpendicular to it.

They acquire a phase difference delta and we have just now has seen if I have 2 simple harmonic motions with a phase difference which are mutually perpendicular I get essentially the ellipse. If you understand this the whole of photo-elasticity is mastered and what we will do is we will see the animation again and I will stop at intermediate stages and you can verify your drawing as well as improve our understanding.

So what this shows is I have a source of light, I have a plane polarizer. After the plane polarizer, I have a plane polarized light hits the crystal plate as well as it touches the front surface it splits into 2 components because within the crystal you will have 2 refracted beams you are not going to have only 1 refracted ray and these 2 refracted rays will have different amplitudes which are shown which is dictated by the angle theta.

So when you look at a crystal, crystal will always have a fast axis and slow axis which are mutually perpendicular and you may have to perform on an experiment to find out these axis. They are labeled (()) (33:20) again arbitrary. Clearly we do not know whether it is a fast axis or a slow axis. You can label it as fast axis and carry on, but once you do this you must match your optical arrangement to the actual physical polariscope.

And again in conventional photo-elasticity whether it is a fast or slow axis did not play a significant role. The moment you come to digital photo-elasticity whether at the point of interest the axis could be labeled as fast or slow had an effect in digital photo-elasticity that is very important you had ambiguity and this ambiguous zones need to be corrected. So it is better to know it is arbitrary labeled and how to do it you have to do an extra step.

You have to do some kind of calibration to establish this without calibration you cannot do it and with this you can really go back and see which way you can relate these 2 stress analysis even without looking at what others have done it with the information you have gathered you can really find out we have also looked at photo-elasticity gives a sigma of 1 –sigma 2 and then it gives you orientation of theta you have answer for that in the slide.

One answer is when I look at fast and slow axis they could be thinking of coinciding with the sigma 1 and sigma 2 direction and this is what your theta. So you find out the theta you get the (()) (35:02) direction and we have been talking about delta that is acquired within the crystal plate and this delta whatever the delta you have acquired is nothing but sigma 1-signma 2. In a crystal plate the fast and slow axis are same at every point in the whole crystal plate.

In an actual model the fast and slow axis changed from point to point depending on the state of stress as simple as that and you have a very nice animation here. This animation you know gives you what happens pictorially within the model and what you see when the light comes out and when light comes out you have this as a elliptically polarized beam of light.

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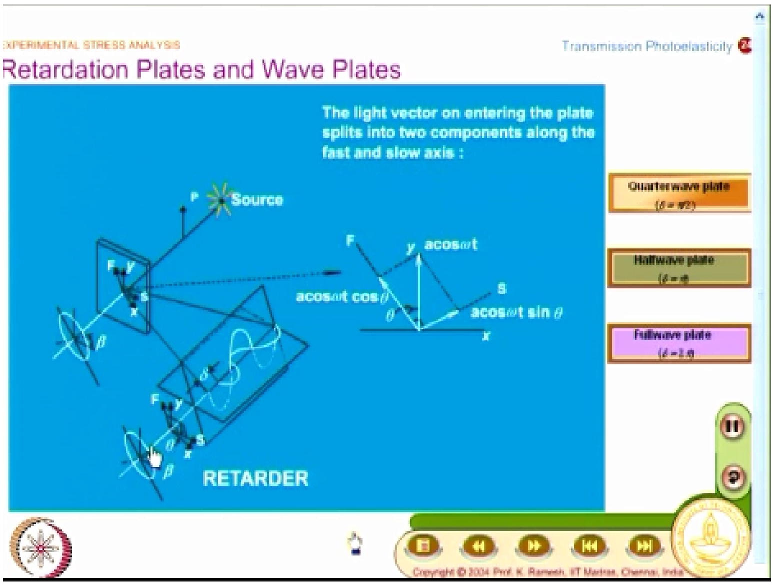

And now what I want to do is I am not going to stop in between I am going to redo this animation you just watch whatever the concept that I have developed you will understand. So is the idea clear. I have a natural light source you have a plane polarized beam of light when it hits the front surface it splits into 2 components within the thickness of the crystal plates it acquires the retardation.

Why it acquires the retardation? Because it has different refractive indices and we have looked at refractive index as ratios of velocity that is why I said we always want to look at as ratios of velocities because want to feel that one way we will travel faster than the other. I have ordinary and extraordinary ray that travel with different velocities and when they come out you have this as elliptically polarized beam of light.

Suppose I go and adjust the thickness of the plate and then ensure that I have delta=pi/2. It is one quarter of a wave.

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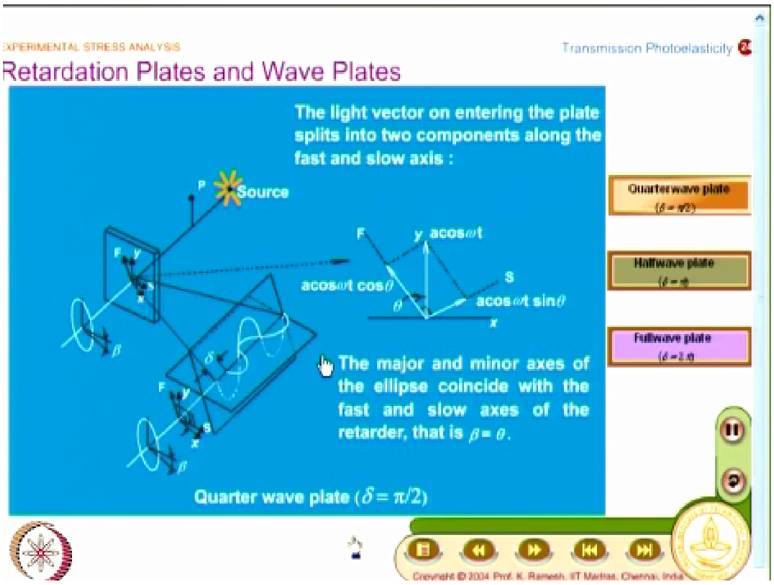

So I call that as a quarter wave plate. So what happens here this beta will coincide with theta whatever I have shown this as beta it will coincide with theta. The major and minor axis of the ellipse coincide with the fast and slow axis of the retarder. So what do you get is you get beta=theta. You write only this statement you do not have to redraw this complete figure what you learn here is the major and minor axis of the ellipse coincide with the fast and slow axis of the retarder.

So if I have a quarter wave plate when I send the beam of light because the fast and slow axis themselves become the axis of the light ellipse that comes out of it. In general, it is an ellipse in particular cases it can be a plane polarized or it could be circularly polarized depending on how do I manipulate the amplitudes. How do I manipulate the amplitude? I can orient this theta in such a way that I make it 0 I make theta 0 the fast axis coincides with the plane of incidence light.

What happens only a plane polarized light will pass through. On the other hand, when I have this angle as 45 degrees I will have this as amplitude same. When the amplitude is same I will have a circularly polarized light and in fact if I have a polarizer and a quarter wave plate I can get light ellipse of any azimuth, any ellipticity you have complete control. How do I control the azimuth I simply rotate the quarter wave plate and axis and that determines?

Because I know the quarter wave plate slow and fast axis acts like major and minor axis of the light ellipse so that I can control and if I control the relative orientation between the quarter wave plate axis and the polarizer axis. I can control the ellipticity. So I can have light of all characteristics generated with combination of polarizer and a quarter wave plate and what is fundamental here.

Fundamental to our photo-elasticity is I should get a plane polarized beam of light and it is worthwhile to go back to the literature and find out how we can look at it.

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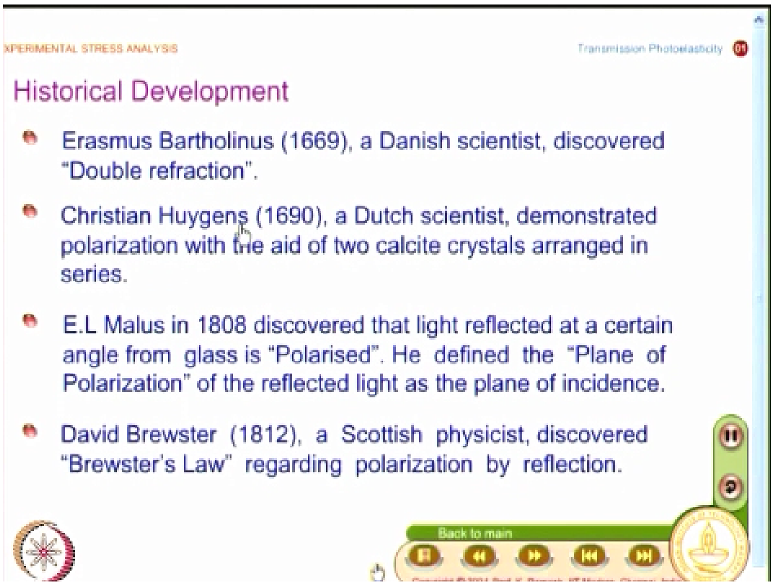

There is a large body literature available and has a very nice development starting from 1669. See we do all this quickly and you know you have this double refraction was found out in 1669. Double refraction is a first concept then you have in 1690 a Huygens a Dutch scientist demonstrated polarization with the aid of two calcite crystals arranged in series then what you have.

Then you have Malus in 1808 observed that light reflected at a certain angle from glass is polarized and he defined the plane of polarization of the reflected light as the plane of incidence that is a definition he has used and it was Brewster who developed this Brewster law. So what he found is double refraction is crucial that is how crystals behaves and even for this understanding he took almost 150 years.

It is not so simple. We see that very quickly now so you have to have a concept of double refraction then they understood what is polarization then Malus found out that light reflected at a certain angle gets polarized and it was Brewster who formulated this as a law it is his honor the law is given and we also know the Brewster found out temporary birefringence then photo-elasticity got developed.

So we want a plane polarized beam of light and if we look at these names they are the celebrated people in the field of physics and you have for each one of them you have laws associated with them and Huygens principle is very famous in wave optics.

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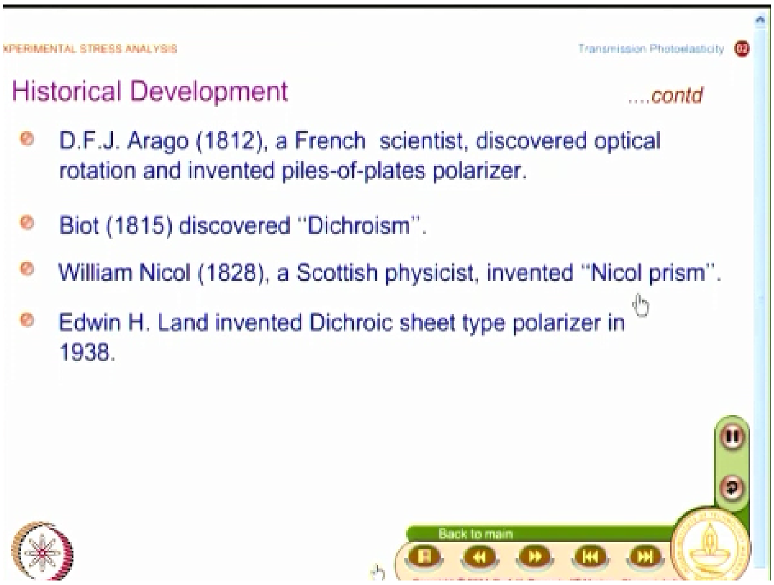

And then what happened? Then what all development that took place. You also had Arago in 1812 he invented optical rotation that you will understand when you look at a half wave plate it behaves like a rotator and he invented piles of plates polarizer. He invented a new form of getting a polarized beam of light and Biot in 1815 discovered Dichroism. This is important from the point of view of the polarized sheet that we have.

We have a polarized sheet and I have simply said in polarize sheet if you put a polarize sheet then natural light becomes polarized. How it functions as a polarizer we have to understand that understanding is better because we are going to use polarized sheet in and out in photo-elasticity. So it operates on the principle of Dichroism. So you have to understand what is Dichroism.

And once you talk of polarization optics you cannot forget Nicol you have the Nicol prism that is also another form of getting the polarized beam of light I have already mentioned that you get very high quality polarized beam of light when you use the prism, but the field of view is limited and it was Land who invented Dichroic sheet type polarizer in 1938. See Dichroism was observed in 1815 and it became available as a commercial product for us to use in photo-elasticity only in 1938.

So any physics it takes a long time for it to become as a technology that must be a need for it. People should know where to use it. They observed the physics, but that has to be translated into technology and we have also seen it is only around 1930s photo-elasticity became popular. So when photo-elasticity became popular they also felt you need larger and larger field of view. So that prompted people to look for alternatives.

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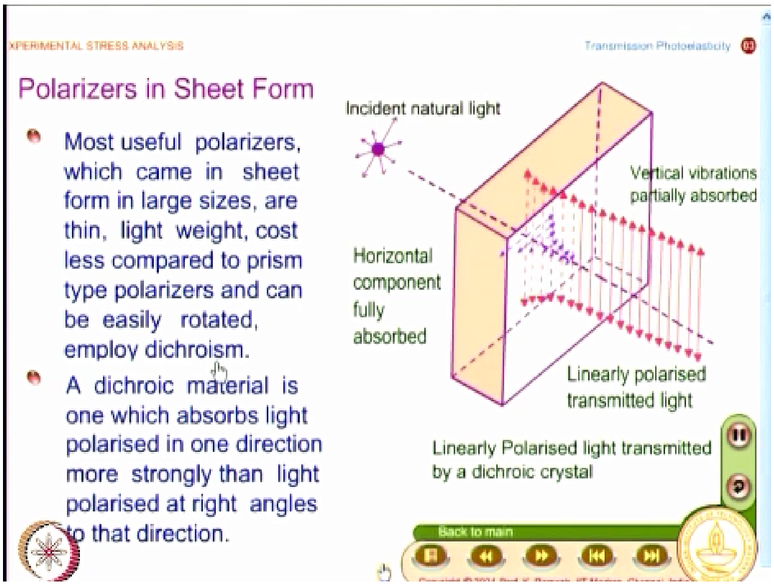

And this is what you have to understand. Most useful polarizer which came in sheet form in large sizes are thin, light weight they cost less compared to prism type polarizers and can be easily rotated is the advantage because when I want to analyze light I want to rotate the polarizer. If I have a crystal, I need to have some kind of folding arrangement and do it becomes difficult.

And they all have the characteristic to call dichroism and what is dichroism. The dichroic material is one which absorbs light polarized in one direction more strongly than light polarized at right angles to that direction. We have to look at crystal optics. In crystal optics we found for one incident ray you have two refracted beam.

And these 2 refracted beams travel with different velocities in a crystal at appropriate orientation we have seen, but in a dichroic material one of these rays is absorbed so that helps you and we have seen that these are light with different planes of polarization they are mutually perpendicular they are plane polarized and that is what is depicted in the figure. It is a complex figure.

You see the horizontal component as it travels within the crystal it gets absorbed. The vertical component go undiminished whether I incident a natural light or a polarized beam of light within the crystal you will have only polarized beam of light and what do you find in a dichroic material is one of the vibrations is completely absorbed within the thickness. So it allows only one light to pass through.

So I have this plane polarized horizontal component is fully absorbed, vertical vibration partially observed so I get a linearly polarized transmitted light. It is a useful information I have a dichroic material that is a useful information we make a neat sketch of this and for your benefit I can show the animation again. So what I have here the horizontal component gets absorbed.

The animation is not shown simultaneously for vertical and horizontal it is only emphasized for the horizontal. The horizontal components get observed over the thickness of the sheet. So what you have here is the most useful polarizers employ dichroism and what is the meaning of dichroism. A dichroic material is one which absorbs light polarized in one direction more strongly than light polarized at right angles to the direction.

So that is what you see here this horizontal component is absorbed vertical component is allowed to pass through and we will continue our discussion further in the next class and what we have seen today was we have looked at for a crystal you have for a single incident beam of light you have 2 refracted beam they travel in the same direction when the incident light perpendicular to the optic axis of the crystal.

And these 2 waves travel in the same direction, but with different velocities, 2 simple harmonic motions with different phases when they interact they give the trace of light as an ellipse and by changing the retardation delta you get different forms of light ellipse. So by looking at light ellipse you can go back and find out what delta that has caused that is the main focus of this lecture.

And we also looked at in a crystal plate what really happens when I impinge a plane polarized beam of light. We have seen one light travels faster in one plane. We label that plane as fast axis. We also label another axis which is perpendicular to this as slow axis and I mention that these 2 are arbitrary classifications and you have to do some kind of a calibration to fix this is the fast and slow axis.

And we also indirectly saw this fast and slow axis could be related to sigma 1 and sigma 2 directions and we have already seen your famous expression tan 2 theta= (()) (51:27) sigma x-sigma y is ambiguous. So if you want to resolve that ambiguity you need auxiliary information like more circle or go for a eigenvalue, eigenvector type of recasting the mathematics to fix the direction.

Similar exercise you may also have to do when you do an experiment and finally what we saw was in order to use light as a sensor it is not good sending a natural light I might have the complete control on incident light and one of the simplest light in photo-elasticity is plane polarized light and we saw how you get a plane polarized beam of light. These sheets polarizers are essentially diachroic in nature.

We will continue this discussion further. We will spend few more minutes on this dichroic sheet polarizer then we move on to other aspects of photo-elasticity we will also develop stress optic law in the next class. Thank you.