Experimental Stress Analysis
Prof K Ramesh
Department of Applied Mechanics
Indian Institute of Technology Madras

Module No # 02
Lecture No # 11

Introduction to Transmission Photoelasticity

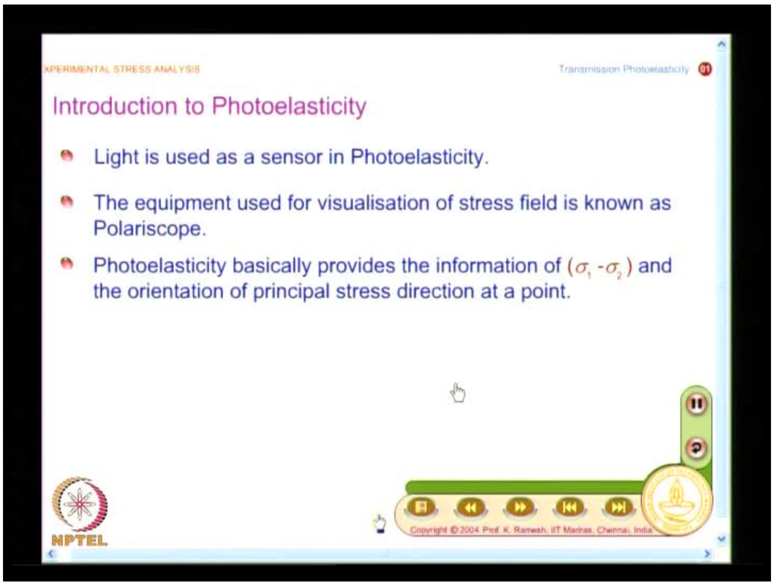
In the last class we had a long discussion on overview of experimental stress analysis and towards the end I had reviewed certain concepts from solid mechanics. Some of these concepts you need to brush up and some of the concept though you have learned you have to view it from a different perspective to apply in experimental stress analysis. One of the first concepts we looked at was same as the expression that we have for finding principles stress direction which gives you multiple answers as you had some multi valued function. You need to know how to associate the direction of principle stress one to the magnitude of principle stress one and if you go to Mohr circle you will be able to make the relationship comfortable. But you have a different mathematical approach, if you coin the same problem of finding out the principle stress and it is orientation to an eigen value and eigen vector problem you can associate the magnitude as well as the direction.

And as I said we have to look at this mathematically by an appropriate approach. In photo elasticity when we find out the principle stress direction and associate with maximum principle stress, we need to do an extra step which is unavoidable. When you go to strain gauge you have to understand the loss of tensorial transcription.

When we come to specifying the boundary condition as we learnt stress vector and stress tensor we need to understand what happens on a free surface. We found that when you define a surface by an out ward normal and if the surface n is free then t n should be equal to zero and should be a null vector. We also got a very important answer that on free outward corners stress tensor has to be zero.

One more concept that I would like to show here is let us take two circular disks one disk is of aluminum and another disk is of polyurethane. What I do is I try to apply a load on them and find what happens to both of this. When I apply the same load on both of them the polyurethane will deform more. We will also find out what would be the nature of stresses develop in these two materials which are of same size.

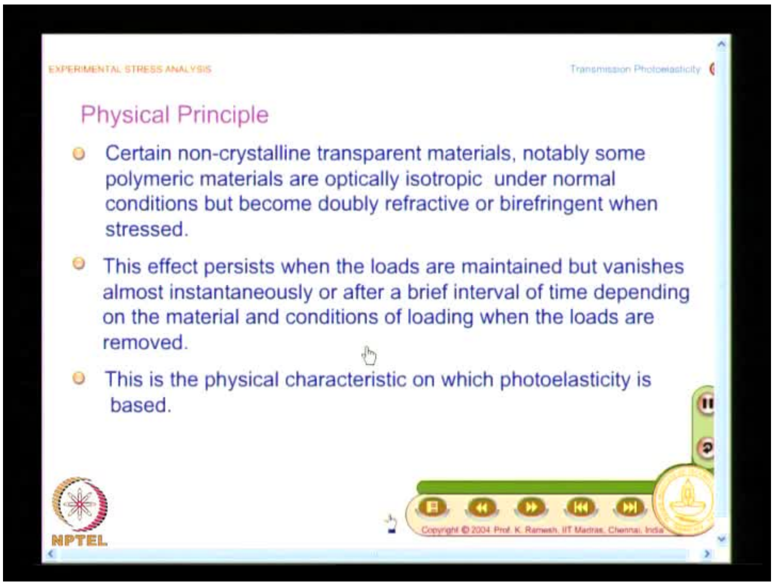
(Refer Slide Time: 04:01)



We have seen that in photo elasticity light is used as a sensor. So when it is used as a sensor we should know the property of light which is impinging on the model completely and the equipment that will be used for visualization is called a polariscope. You essentially use polarization optics to reveal the stress information.

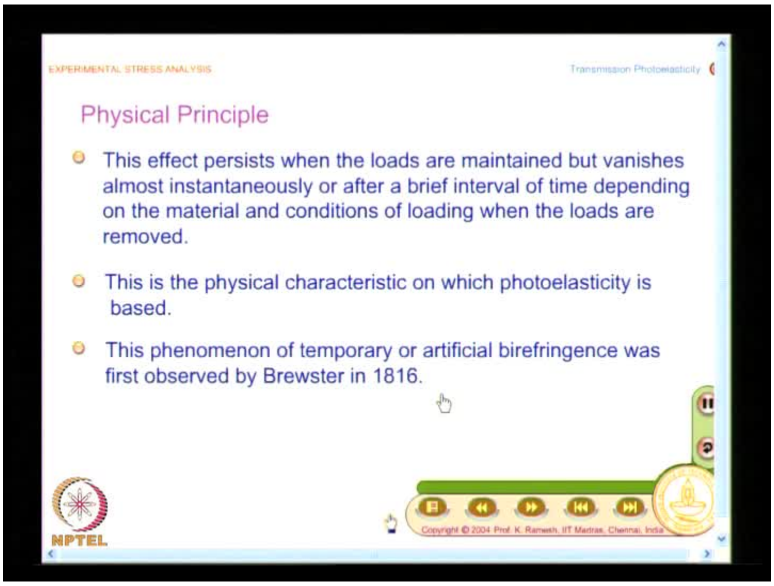
We have also seen very clearly from a solid mechanics point of view that photo elasticity basically provides the information of sigma 1 and sigma 2 contours which are also called iso chromatics and the orientation of principle stress direction at a point. So at a point you will get sigma 1 minus sigma 2 as well as principle stress direction for the entire model.

(Refer Slide Time: 05:39)



The physics behind this is that certain non-crystalline transparent materials notably some polymeric materials are optically iso tropic under normal conditions but become doubly refractive or birefringent when stressed. This is the key concept and you need to understand birefringent to appreciate photo elasticity. The birefringent is caused because of a stresses induced on the model. Hence we find out the stresses that has cause this behavior of birefringent which in turn alters the polarization behavior of the light that passes through because the model behaves like a crystal.

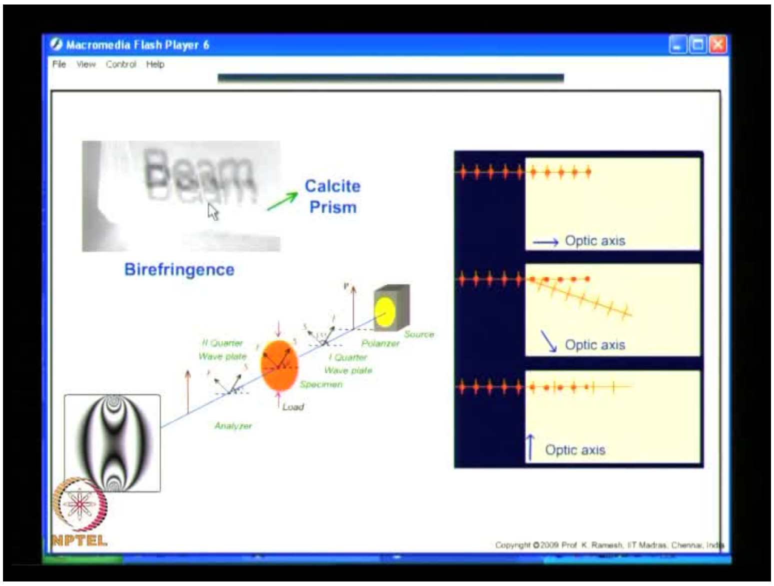
(Refer Slide Time: 08:15)



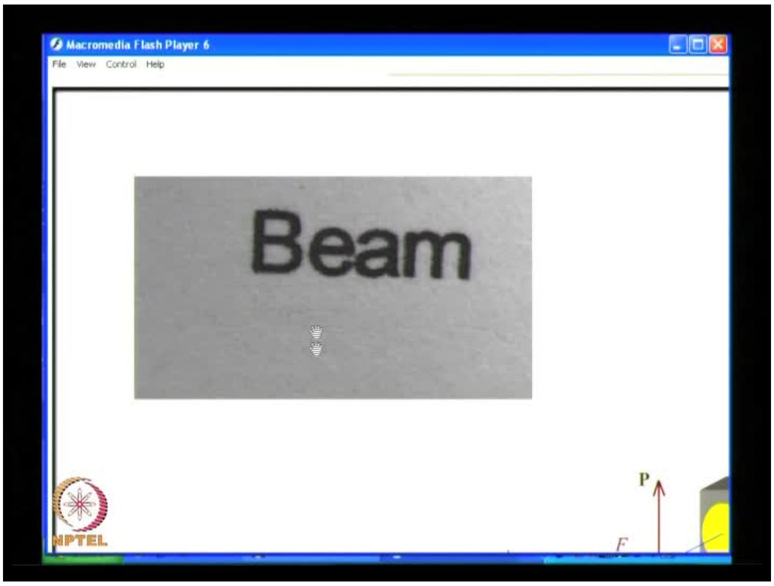
So this effect persists when the loads are maintained but vanishes almost instantaneously or after a brief interval of time depending on the material and conditions of loading when the loads are removed. Hence you see that the birefringent under normal conditions are isotropic and they become doubly refractive when stressed. This effect persists as long as the loads are maintained. Later on we will see a very special process where you freeze this stress information by a thermal cycling process. But when you want do it under a live role condition the effect persist as long as the loads are maintained and of a brief interval of time depending on the material and conditions of loading. When the loads are removed we do not see this effect.

So as a physical phenomena this was identify by Brewster in 1816. Now we will quickly look at what is birefringent, what does the term birefringent means and then come back and see how photo elasticity uses this concept.

(Refer Slide Time: 09:05)

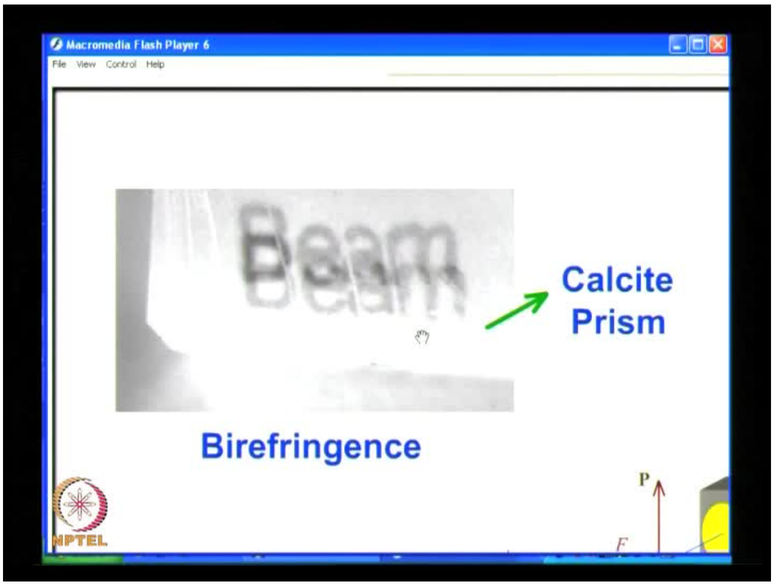


(Refer Slide Time: 09:09)

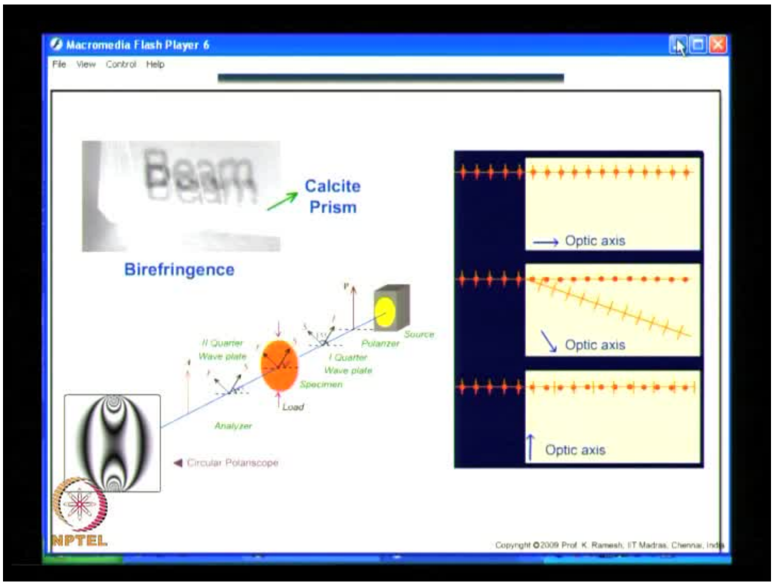


So what I have here is I have a letter beam written. and the moment I put a calcite prism I see two images, I see the word beam on the bottom also.

(Refer Slide Time: 09:54)

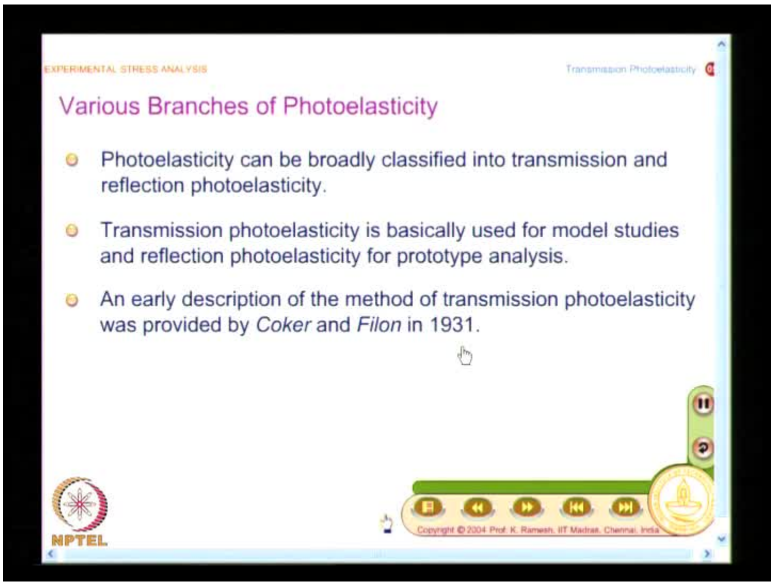


(Refer Slide Time: 10:35)



So when I place a calcite crystal the word beam is seen twice because the crystal has the property of birefringents even without the application of load. The difference in photo elasticity model is when it is stressed it behaves like a crystal. So if I have to find out from optics point of view how the changes are related to stresses I need to know what happens in a crystal. Here in Refer Slide Time: 10:35, I have a light impinging on a crystal for different orientation on optic axis. So how does this light behave is very important and if you understand this slide the whole of photo elasticity is understood. A polariscope is used for measuring the stresses. In this case it shows a circular polariscope where I have a dark field as well as bright field and these details you will understand as we develop the mathematics behind it. The purpose here is not just appreciating the qualitative information but also get in to quantitative analysis.

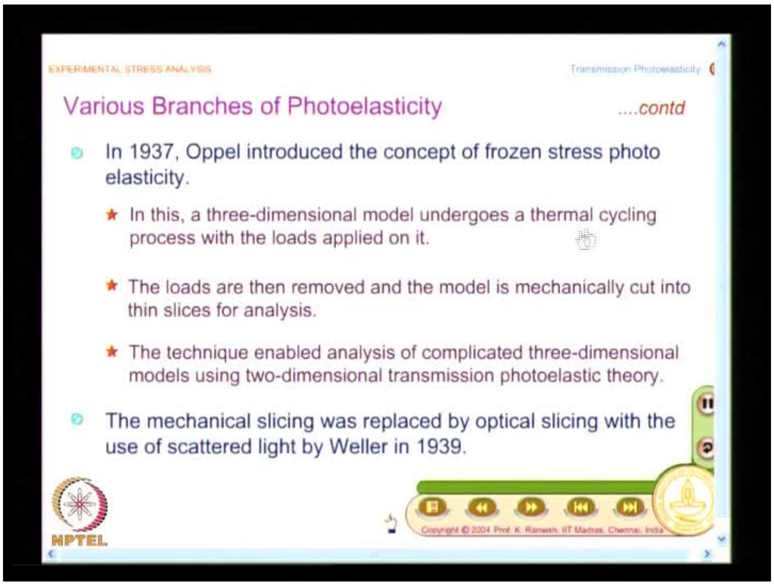
(Refer Slide Time: 11:21)



Before we get in to the details let us have a brief look at what are the various branches of photo elasticity. It can be broadly classified into transmission and reflection photo elasticity. We will also see some of the other classifications with in it and in any technique you need to know briefly the history of development, who has contributed what and also some time line.

So what you find is one of the early description on the method of photoelasticity was provided by Coker and Filon in 1931who had a celebrated book. In1816 the physics was identified and as a practice it came up in 1931. Next we have that the transmission photo elasticity is basically used for model studies and reflection photo elasticity for prototype analysis and both of these techniques. It took almost more than 100 years for the technique to develop as you need technology also to help you in doing this.

(Refer Slide Time: 12:53)

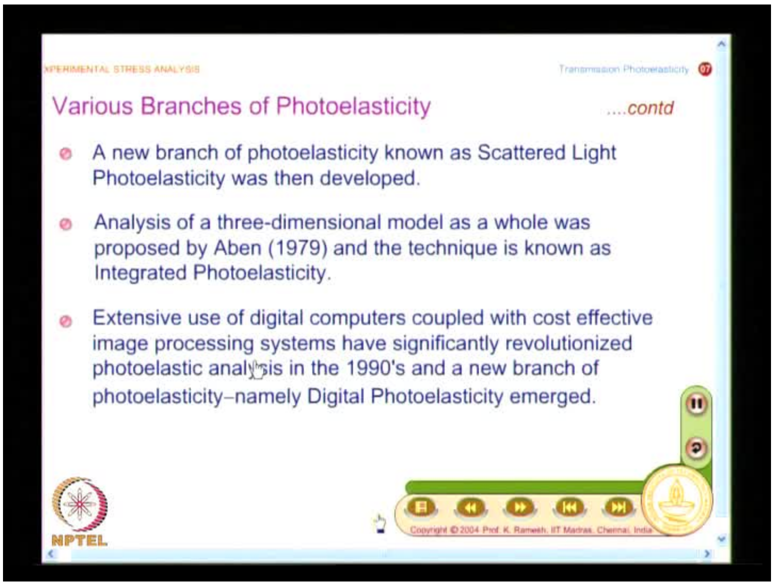


You have another development which is very significant and was introduced in 1937 by Oppel in Germany. He introduced the concept of frozen stress photoelasticity and this was definitely a (( )). What you will find is many of the three dimensional problems is in nineteen thirty's when they wanted to establish the design practices they need to find out the stresses developed on three dimensional components and the concept of frozen stress photoelasticity have helped in analyzing models. Here the model undergoes a thermal cycling with the load applied on it and this thermal cycling helps to freeze the stresses within the model. It is only a thermal cycling and not a freezing operation. Later we will see why we call it as stress freezing. The advantage you have in analysis is the loads are then removed and the model is mechanically cut into thin slices for analysis. You have to be very carefully while cutting into slices so that you do not introduce thermal stresses and whatever the two dimensional photo elasticity you develop. You can use two dimensional photoelastic theory for analyzing complicated three dimensional models.

So what you have here is that the model is stressed and mechanically sliced and analyzed by employing two dimensional concepts. What you need to look at is that whenever there is a development there is a parallel criticism about it. When you are doing a mechanical slicing in those region where you slice you lose some material. So people thought that why not improve the process and so they came out with what you have is the mechanical slicing which replaced the optical slicing with the use of scattered light by Weller in 1939.

So you have another branch of photoelasticity called scattered light photo elasticity (( )) existence. In this photo elasticity you basically use laser elimination instead of normal monochromatic light source where as normal photo elasticity is done by mercury wrapper lab or sodium wrapper lab which are all essentially monochromatic light source.

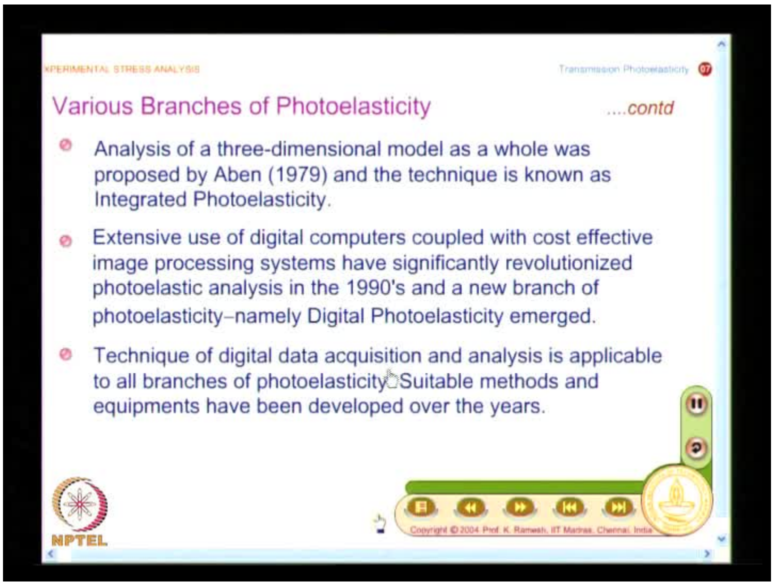
(Refer Slide Time: 16:23)



Then what you have is the three dimensional model which was proposed by Aben in 1979 (( )). Whatever you do you have to pay a price and the technique is known as integrated photo elasticity. When I do stress freezing and slicing I have to pay a price in terms of more of experimentation where I have to go for mechanical slicing but analysis become two dimensional. When you want to remove that restriction, analysis become mathematically challenging. So in three dimensional photo elasticity scattered light photo elasticity, integrated photo elasticity are the conventional stress freezing and slicing. So what happened parallelly was that when all this developments where taking place , extensive use of digital computers coupled with cost effective image processing systems was developed and revolutionized photo elastic analysis in nineteen nineties and a new branch of photo elasticity namely digital photo elasticity emerged.

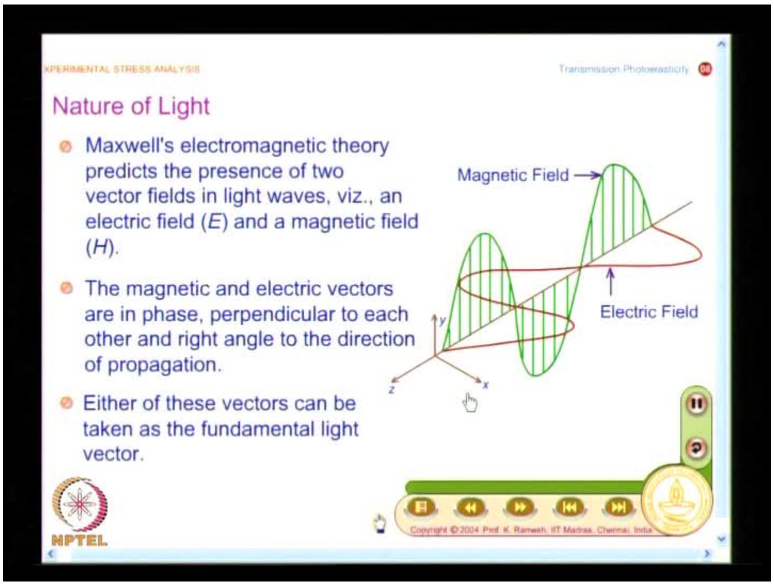
So what you have here is people have replaced human eye with an electronic eye and newer methods of processing data came into existence. In fact these concepts could be applied to all branches of photo elasticity we have transmission photo elasticity, reflection photo elasticity, scatter light photo elasticity and we also have other branches like photo plasticity, photo orthotropic elasticity, dynamic photo elasticity. There are too many variants but if you understand transmission photo elasticity the same concepts could be extended and that is why we focus on transmission photo elasticity and reflection photo elasticity. Transmission is meant for module studies and reflection is meant for prototype in general. When I apply transmission photo elasticity on glass it becomes prototype analysis itself because glass is photo elastically sensitive.

(Refer Slide Time: 19:14)



The technique of digital data acquisition and analysis is applicable to all branches of photo elasticity. Suitable methods and equipments have been developed over the years. So digital photo elasticity is a generic term which implies that it will use digital computers for data acquisition and processing as such it is applicable to all branches of photo elasticity.

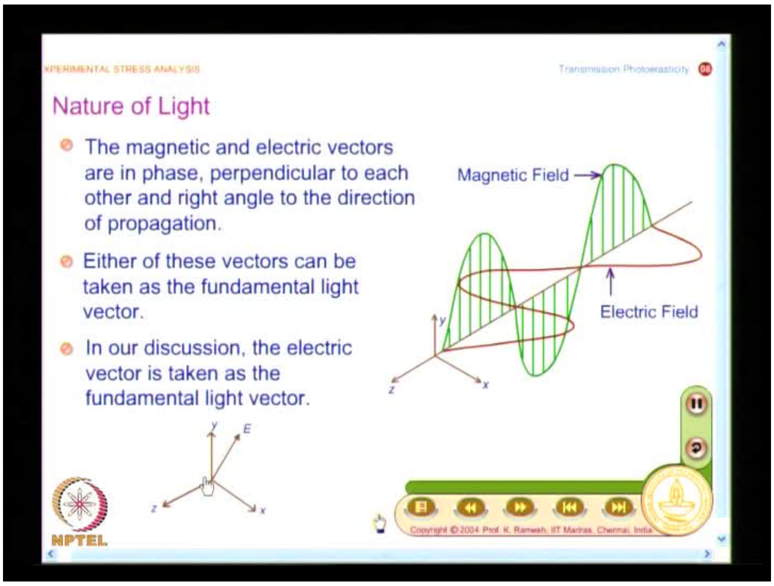
(Refer Slide Time: 19:49)



In photo elasticity light is used as a sensor which is an electromagnetic disturbance and it predicts two vector fields; an electric field and a magnetic field. Now our focus is to mathematically define this.

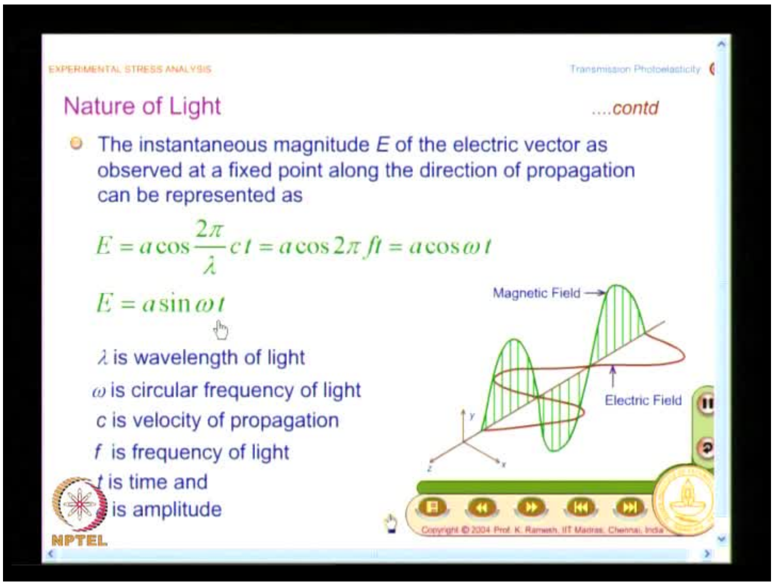
So as shown in Refer Slide Time: 19:45, you have a light wave, an electric field and a magnetic field and the direction of propagation. Here the magnetic and electric vectors are in phase, perpendicular to each other and right angle to the direction of propagation. What is my interest is I need to go and have a mathematical description of this slide and when I want to do this I can use either the electric field vector or the magnetic field vector. For simplicity what I am going to do is I define the electric vector.

(Refer Slide Time: 21:38)



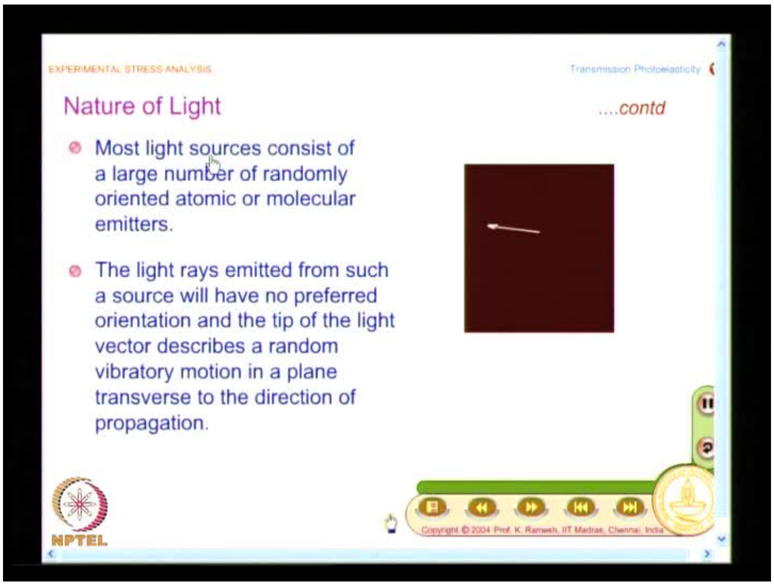
We will have the electric vector as light vector and what we need to understand is if you have an electric vector you have a magnetic vector perpendicular to it. If this is shown as an orbitery direction then in this case the electric vector is horizontal. For the generic case we have an electric vector, a magnetic vector and as these are vector you have a direction. So you need to find out how this happens in a natural light which will give you an idea about the need to go for polarization optics.

(Refer Slide Time: 23:07)

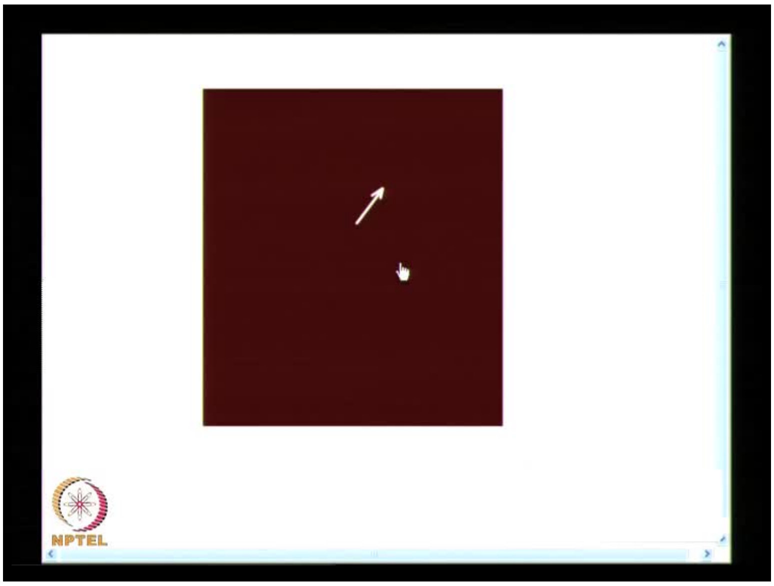


So we will have a mathematical description. I have a sinusoidal wave which is defined in terms of cos omega t and a sin omega t. So I have definition as a cos two pi by lambda c into t and where lambda is the wavelength of light, c the velocity of propagation and t is the time. This 2 pi by lambda into c can be bundled to 2 pi f and I can have this 2 pi f as omega either. So I can represent it as a cos omega t where a is the amplitude and I can also equally represent it as a sin omega t.

(Refer Slide Time: 25:03)



(Refer Slide Time: 25:14)

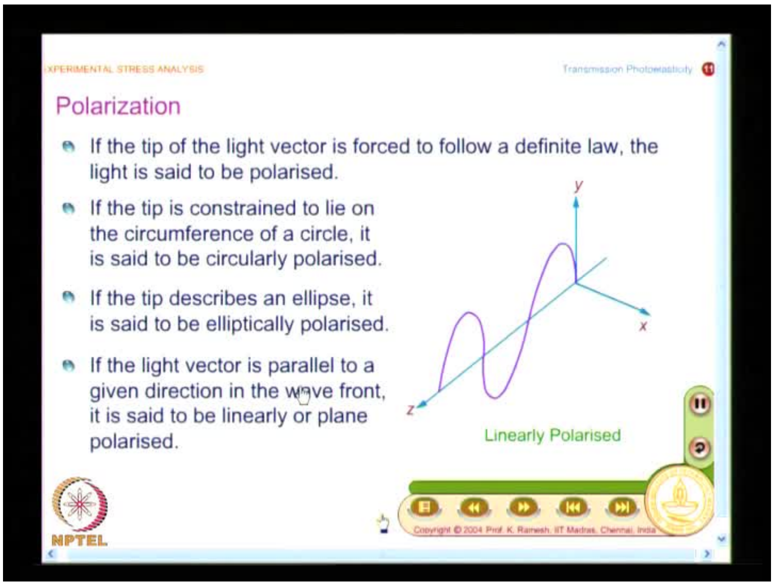


So now I have a mathematical description. Now I will go and look at how does a natural light source emits light. You can see in Refer Slide Time: 25:14 that I have an emitted light which can be represented by a vector. What you find here is that does the length of the vector and the orientation remain constant or both are changing. If both the length and direction are changing then I need to interpret the changes because I should have a constant light impinging on the model and I should know the input light characteristics. I should also detect the modification that takes place within the model which modifies the property of the light that is passing through.

So for me to do that, I need to find out ways to send a constant source of light. I should have a monochromatic wave length for convenience in mathematical development. As I said you can also go for color white light for which people have developed methodologies. One thing you need to keep in mind is that the common light sources give you light vector as random (( )). So this is not convenient for you to relate the output light to input light characteristics. I should have a constant input light characteristics and that is what you have here. So most light sources consist of large number of randomly oriented atomic or molecular emitters.

The light rays emitted from such a source will have no preferred orientation and the tip of the light vector describes a random vibratory motion which is inconvenient. So I need to look at is what should I do for the input light and for that we have to understand what is polarization.

(Refer Slide Time: 27:56)



Suppose I constraint the tip of the light vector in a preferred manner, then I call that the light polarized. So that is why you need polarization because I need to have a constant property of incident light and I should have complete understanding of the characteristics of the incident light.

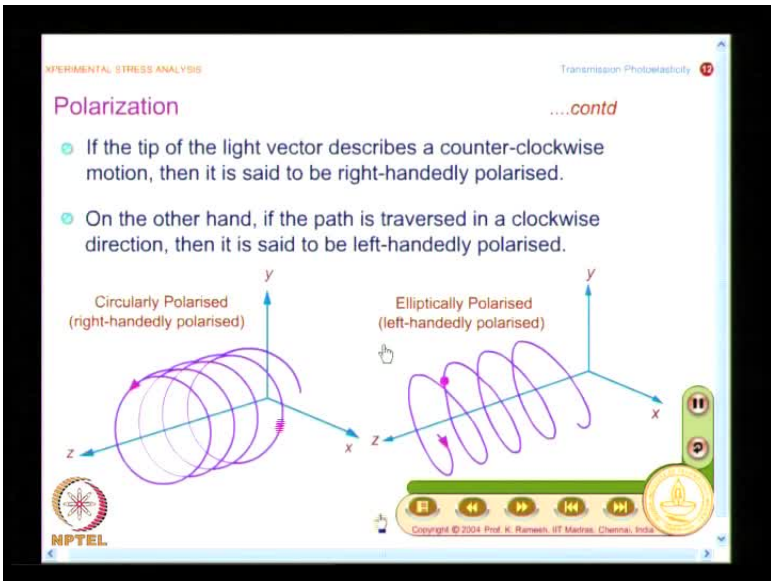
So to do that I send a polarized beam of light and as the model is going to behave like a crystal this polarization behavior change by the model because of the stresses introduced. I have another set of optics to find out what is exit light. So this is how we do photo elasticity. In order to understand the physics behind it I need to understand polarization, I need to bind birefringents and I need to understand bit about that crystal optics. Then I will go and merge stresses and the change in optics.

So we will take a little tour on solid mechanics and get in to polarization and crystal optics in a systematic fashion. So suppose if we have that the tip is constrained to lie on the circumference on a circle then I call this as circularly polarized. Here we have to see how the magnitude varies the direction. In circularly polarized light, vector magnitude does not vary only the orientation varies. If it is an ellipse then I call this as elliptically polarized. So our interest is to see what the polarization at tip of the light vector is if it is force to follow a definite law.

Here why I am taking elliptical polarization is that in the limiting case it can become a circle or it can become a plane wave. If the light vector lies in a single plane parallel to a given direction in the wave front it is said to be linearly or plane polarized. Later you will see that from a natural light you first get a linearly polarized light then this light is converted into either a circularly polarized or elliptically polarized for the performance of your experiments. So from polarization point of you I can have linear polarization, elliptical polarization and circular polarization.

We will choose some of this and find out how we use them in the experiment. That is why you have a plane polariscope, a circular polariscope which implies that in a plane polariscope you incident a plane polarized light on the model and in a circular polariscope the incident light is circularly polarized.

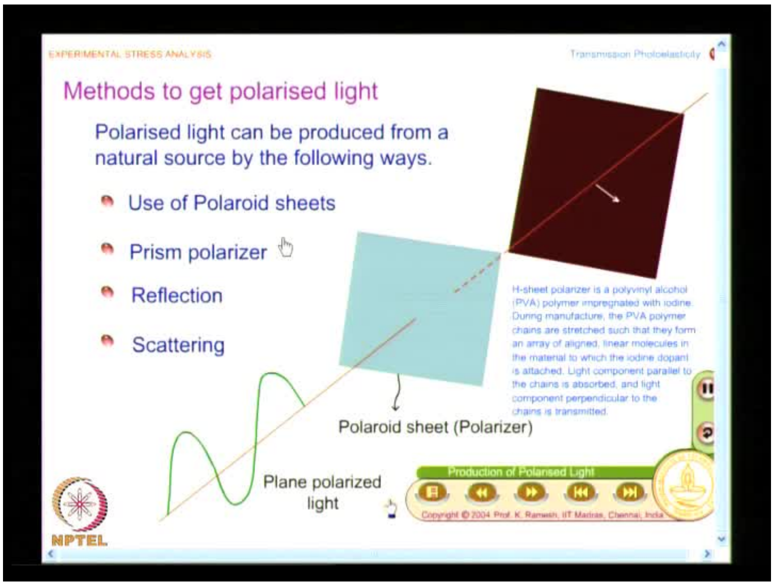
(Refer Slide Time: 32:27)



And if you go to optics literature people also talk about polarization in terms of what is known as handed (( )). We have also looked that in the previous slide we have labled it as right handed and left handed and that is defined here. If the tip of the light vector describes the counter clockwise motion then it is said to be right handedly polarized.

On the other hand if it is moves in a clockwise direction we call that as left handedly polarized. In the elliptical polarization it is in a clock wise direction. Depending on the properties the motion can be clockwise or anti clockwise. Now we will see how these light ellipses are formed. So from polarization optics we essentially measure the handedness and the major and minor access of the light ellipse. So in the next few classes we will be discussing only on optics.

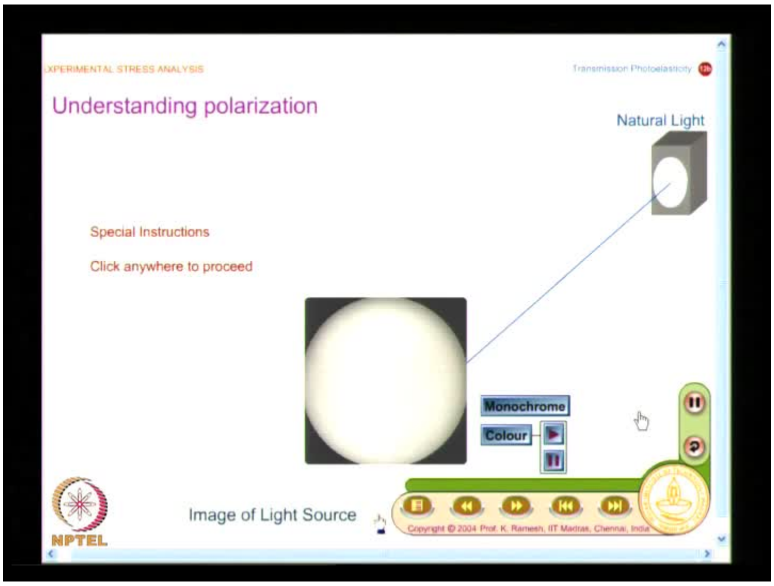
(Refer Slide Time: 34:38)



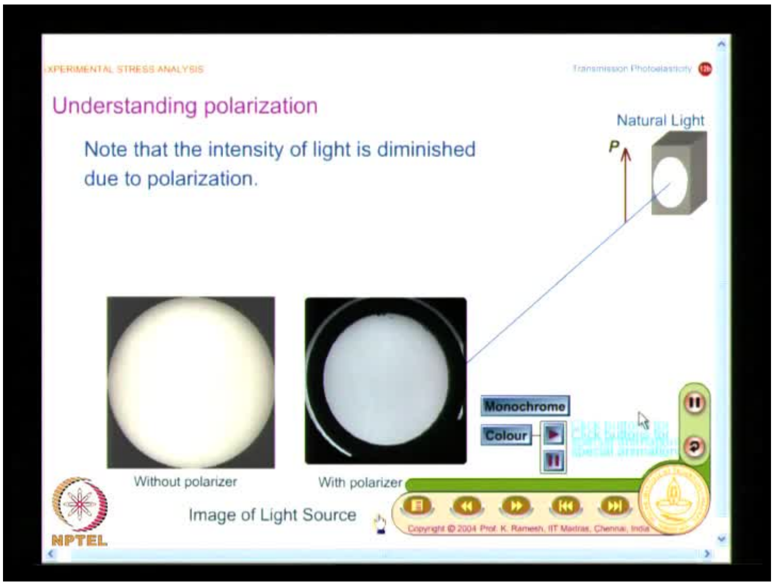
So now we will see various methods to get polarised light. I can use Polaroid sheets, prism polarizer and I can get polarization by reflection and scattering phenomena. In fact it is a huge body of literature and you have people who have contributed on how to get polarization. You have several laws and physics developed on this issue and you also find light waves at different regions all particularly suited for polarization by different methods. So here I have natural light, a polarized sheet and this allows only light in a particular fashion. This acts like a filter and filters all other components and sends only a component in this direction. Here I have two identical individual pieces and what I do is if I keep them in one direction you see a light being transmitted but when I rotate it perpendicular to other you find that light gets cut off. I call the first sheet as polarizer and the second sheet as analyze as it analyses the light that is coming out. The greatest advantage of this polaroid sheet is we have a larger field whereas in prism polarizer the field is small.

Here the sheet polarizer is the polyvinyl alcohol impregnated with iodine that is why you have that ting of color. The PVA polymer chains are stretched such that they form an array of align linear molecules in the material to which the iodine dopant is attached which show that the sheet is made.

(Refer Slide Time: 40:25)



(Refer Slide Time: 40:47)

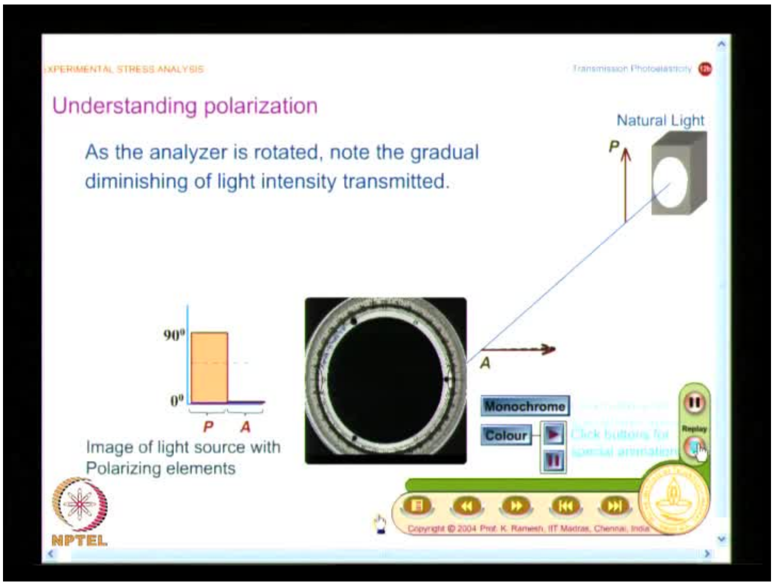


Now we will take a light box and as we do not have any optical element in between the screen and light box we see a light with certain level of intensity. The intensity of light gets diminished the moment we introduce a polarizer as shown in Refer Slide Time: 40:47. Here the polarizer is indicated as a line and this shows the direction of polarization.

Key point here is we have seen earlier from the way it is manufactured that it observes light in the horizontal component so it allows only a vertical component. So what you find is that some amount of light and its intensity is lost from a natural light source which comes to the polarizer. After the polarizer some amount is observed there but later on within the model whatever we do there is no absorption of any kind of light and it travels with the same intensity, only the polarization characteristic changes.

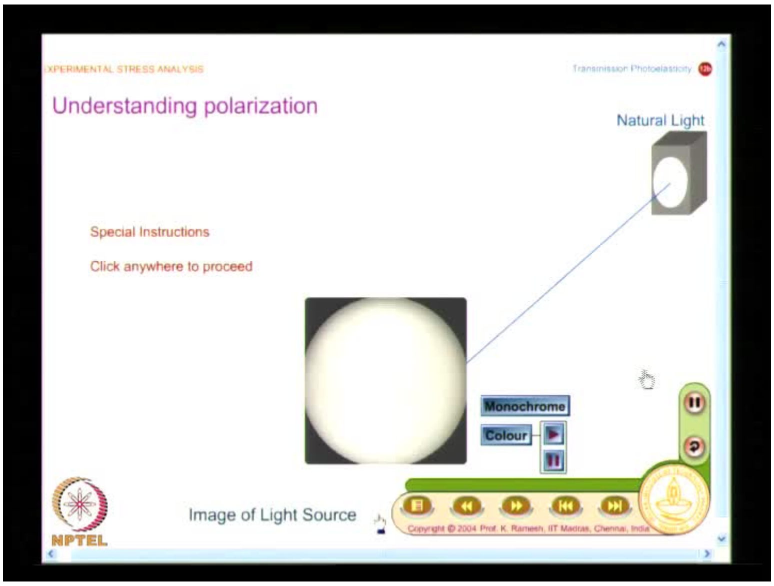
And what we have done as a experiment is that we have put another element perpendicular to it and we will see how does the intensity changes when the two elements are rotated and when one element is fixed another element is rotated.

(Refer Slide Time: 42:35)

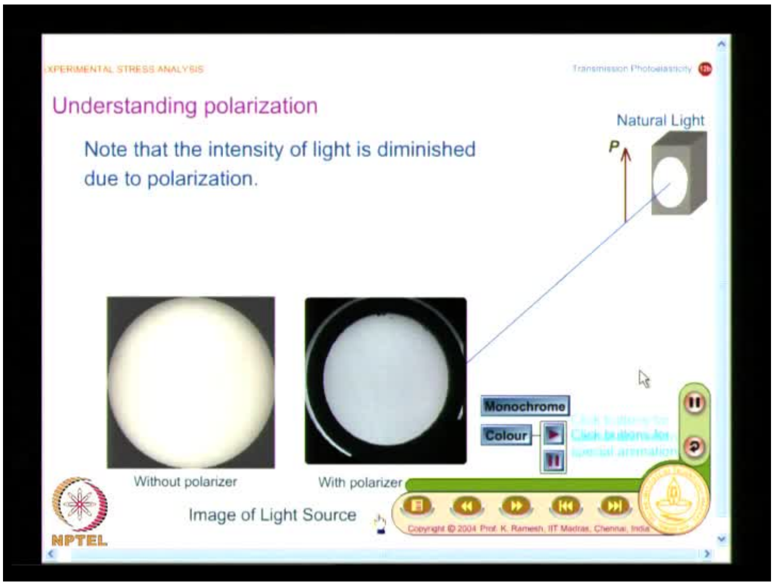


So what I do is that I will introduce another element, rotate it progressively and then bring it to horizontal. So what happens is that the complete light is cut off as the element will allow light only in the horizontal component where as the polarizer will send light in the vertical component. Here you can see the angular variations.

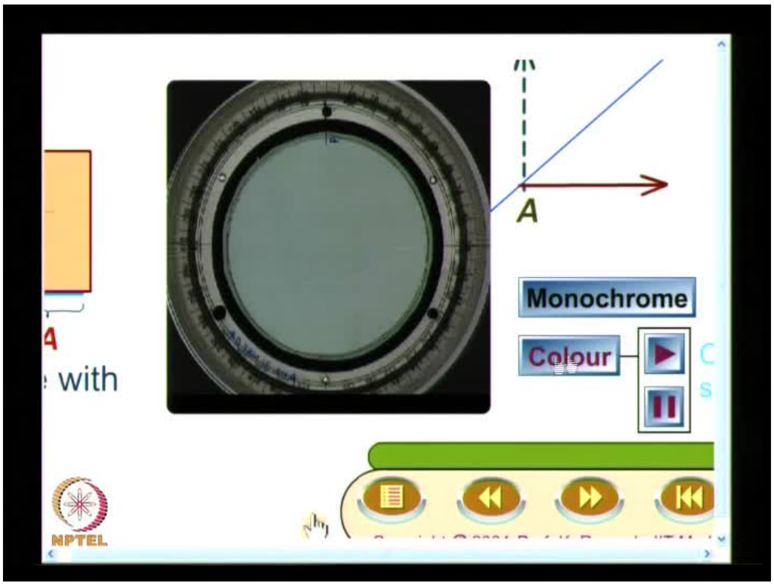
(Refer Slide Time: 40:25)



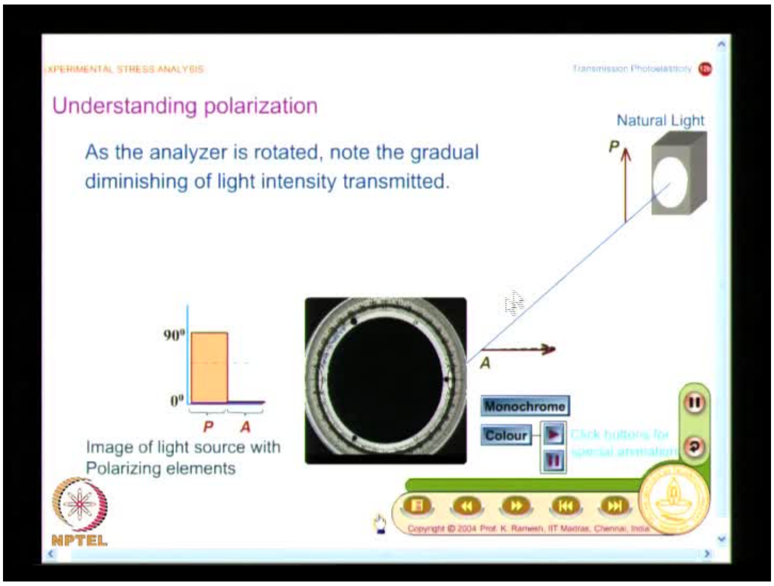
(Refer Slide Time: 40:47)



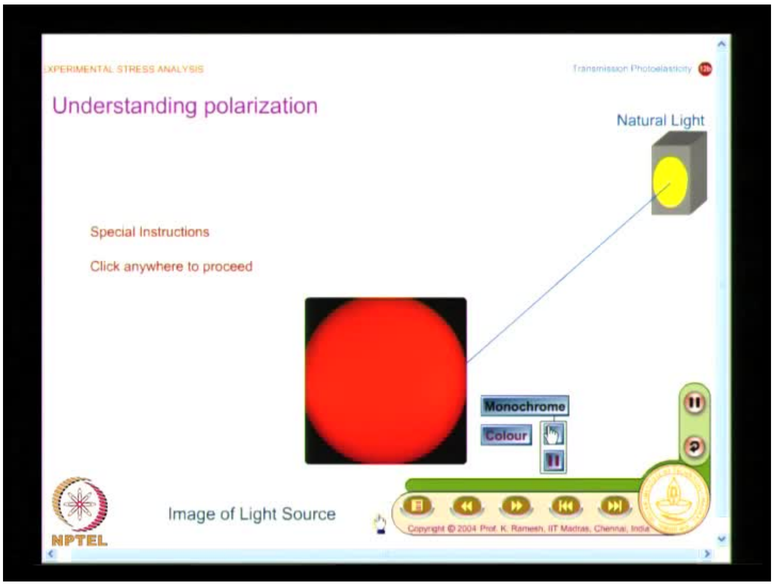
(Refer Slide Time: 43:41)



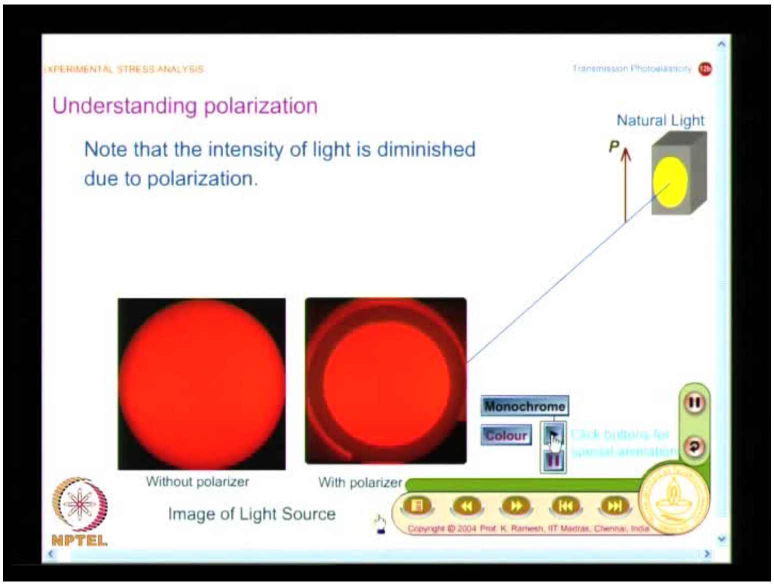
(Refer Slide Time: 42:35)



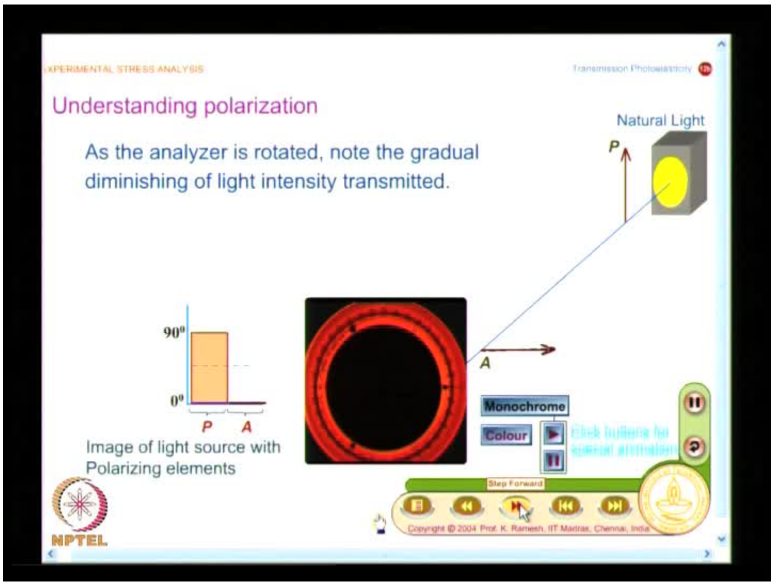
(Refer Slide Time: 44:38)



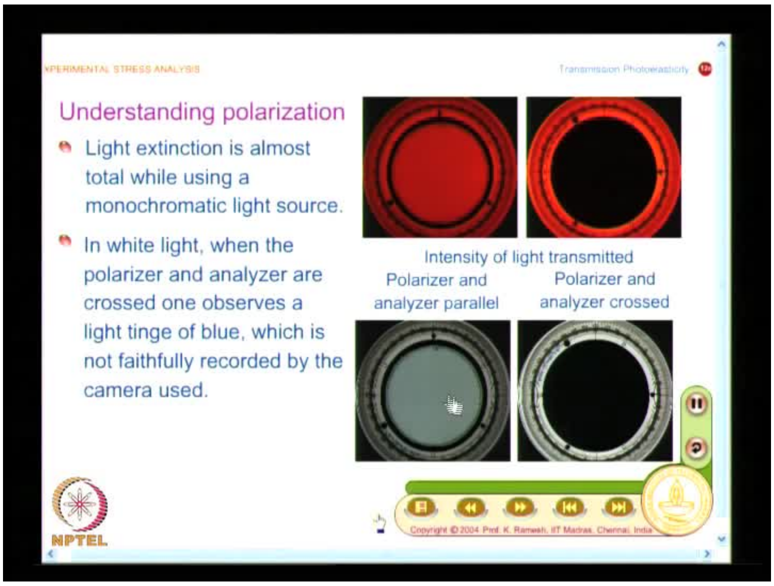
(Refer Slide Time: 44:48)



(Refer Slide Time: 44:58)



(Refer Slide Time: 45:47)



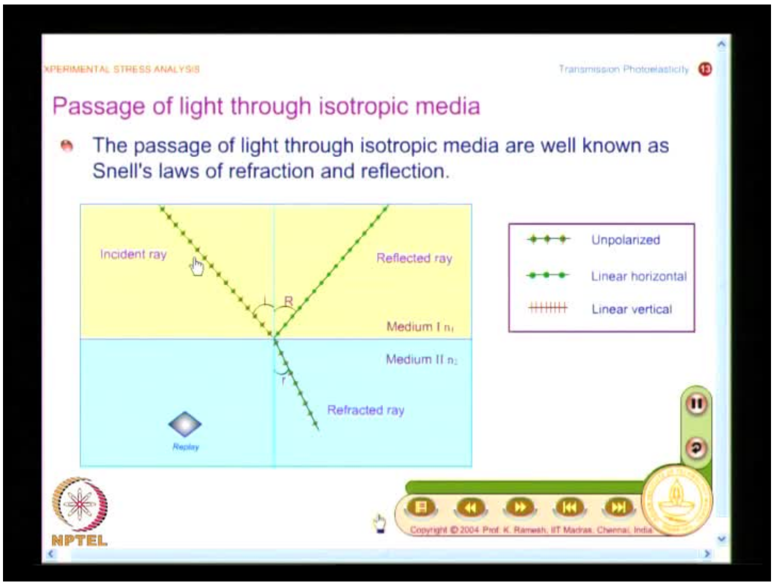
So what you understand about polarization is that as the analyzer is rotated note the gradual diminishing of light intensity transmitted. In three dimensional movies they give you a special filter for you to see it and another way of doing it is with polarization optics.

Then we have that when polarizer and analyzer are parallel light is transmitted whether it is monochromatic or white light source and when they are crossed you have the background is bright and dark as shown in Refer Slide Time: 45: 47. But in the actual experiment when you go and see you will have a light tinge of blue which is not seen here because of your color re protection. This is recorded in a camera. So what you find here is light extension is almost total while using a monochromatic light source.

So what you have learn today is you have found out what is natural light source, recognized light as an electromagnetic disturbance having electric and magnetic vector and for the purpose of convenience we represented always an electric vector as the light vector. We have seen that both electric and light vectors are mutually perpendicular and similarly we have seen the situation with ordinary and extraordinary ray.

We have also seen the electric and magnetic vectors of a light wave are in phase but the two waves which we have seen in photo elasticity will not be in phase.

(Refer Slide Time: 52:10)



Now we will brush up what happens to light when it passes through isotropic medium. So we will simply look at Snell's law and what is meant by refractive index and look at it as ratio of velocities. When an unpolarized beam of light is sent it gets reflected as well as refractive. Generally all the beams are unpolarized. When we go to a crystal, it will only support polarized light within it. When an unpolarized light is sent it will be splited into components and you will have only polarized beam of light. So that is the reason why we try to understand what polarization is. To understand polarization we need to understand (( )) of crystal optics and then only we can understand photo elasticity. We also have developed the mathematics on an elliptical polarization. We have seen richness of (( )) information so we can develop quite of you indirect knowledge on how the stress field varies .You need quantitative evaluation and that is what we need to develop.

In this class we have seen how do define natural light and why we need polarized beam of light and what is polarization. We have looked at linearly polarized light and a polaroid sheet that is being used. You have also seen that when you keep them cross how they get extinguish and when you keep them parallel light is sent but some amount of light is absorbed and the intensity get diminished. But after the polarizer tilled analyzer there is no change in the intensity. This is reasonable approximation to develop mathematical development because any scientific development there are approximation involved and those approximations are reasonably valid as you do not have any optically absorbing element in between. We are only working with polarization optics and so we have developed.

Thank you