Optical Sensors

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Lecture - 04
Basic Optics for Optical Sensing-II: Polarization & Scattering

Welcome to the 4th lecture of Optical Sensors course. In the last lecture we discussed the Basic Optics for Optical Sensing, where we saw that how changing electric field converting to magnetic field and magnetic field giving rise to electric field, becomes a wave and that we saw using Maxwell's equations, we arrived at the wave equation. And, from the wave equation, we deduced that it is a transverse wave and its energy, which is given by the pointing vector, flows in the direction of propagation of wave.

There, I pointed out that it is not always true. Sometimes it is not exactly aligned with the direction of the propagation of the wave like the wave vector, but most of the times, yes! it is true. And, there I raised one issue that can we guess anything about the polarization.

So, what is meant by the polarization of an electromagnetic wave? To understand this, suppose I tie a string to the wall, and I am making this kind of vibrations or in this plane or this plane, or whatever plane. So, the plane of the vibration like the one in the plane where the electric field is vibrating is called the polarization. So, if the electric field vector is changing, when it propagates that will define what kind of polarization does the wave has. Why it is important?

It is important because one must understand that when this kind of electromagnetic wave traverses through a medium, it interacts with it. The way electric field component oscillates will tell you, what will the outcome of it be. And a material when it passes through it, if it has different properties in different directions, then the different polarizations will tend out to give you different results.

So, that is why it is very important to understand what kind of thing it is. And, then when an electromagnetic wave traverses through a medium, tt actually interacts with it. What happens actually, you can understand it very simply like this: you have a molecule and you switch on an electric field.

So, the molecule will become polarized, right. It will become like a dipole. This dipole will start oscillating at the same frequency as the frequency of the light, which is incident on it, because it is also electric field oscillation, say, at a frequency of about 10 to the power 14 per second. And, then you have this molecule oscillating at almost similar frequency. So, it will become like an oscillating dipole and this dipole will re-radiate radiation.

It is called scattering. So, whole of the optics or whole field of electromagnetic research can be divided in two parts; one is a mode problem, where you study a structure and if you solve for the boundary conditions at this structure you will find that these kind of modes will exist - These are the various ways that light can be propagate through it; or you have a scattering problem. A scattering problem means: suppose you have glass, you shine light on it - what will it make?.

Microscopically, you will see that it is interaction of the molecule in an oscillating electric field. So, there will be in an oscillating dipole and it will oscillate and it will re-radiate light in all the directions. And, this radiation from all the dipole, which are getting illuminated, will interfere: there will be a superposition of this electric fields and it will give you the direction of propagation of light in that medium. That is how you do it. You will now see how scattering effects it and at later stages we will try to use it for sensing applications. So, for a given k there are two possible directions of E.

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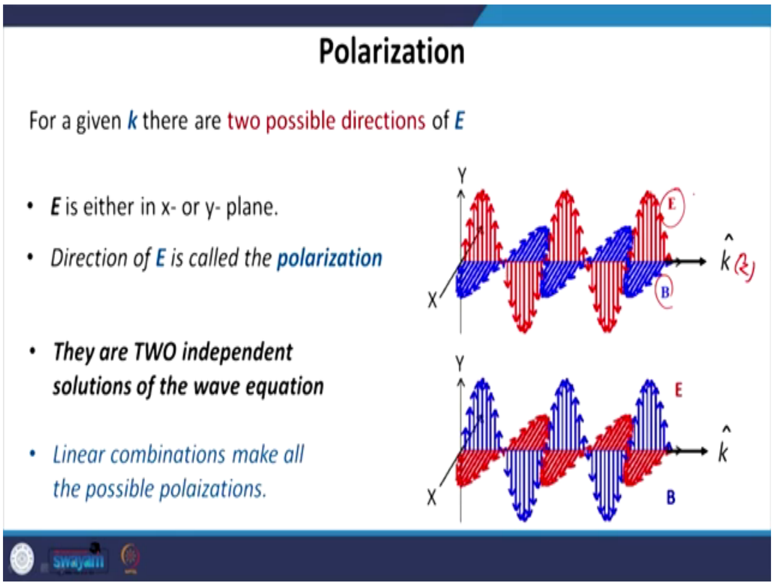

So, suppose this k is propagating in this Z direction so, the way this propagating in Z direction. So, E can be either in x plane or y plane. You can see here the blue ones are magnetic field E is red ones are electric field. So, it is in y plane or in x plane.

Direction of E is called the polarization - direction of E. So, if wave is propagating in Z direction, you can have electric field either in x or in y. These two are called independent solutions of the wave equations. And, if you make a linear combination of it you can have a wave say here in this direction. So, you can make another direction. So, it is like this.

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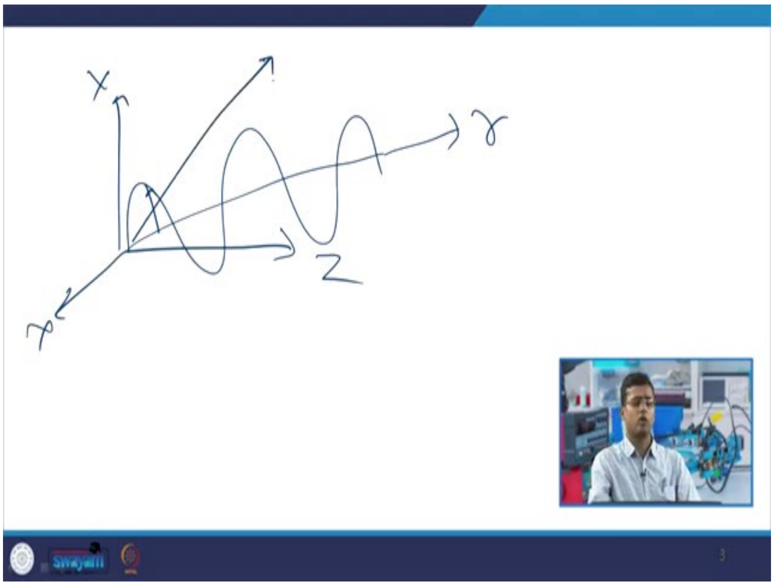

So, suppose you have x y z and you can have a wave which is travelling in this direction r, then it will have electric field components in all the x y z coordinates. You can resolve it in two orthogonal polarizations; we will come to that. And, any other configuration will be a combination of these two independent solutions.

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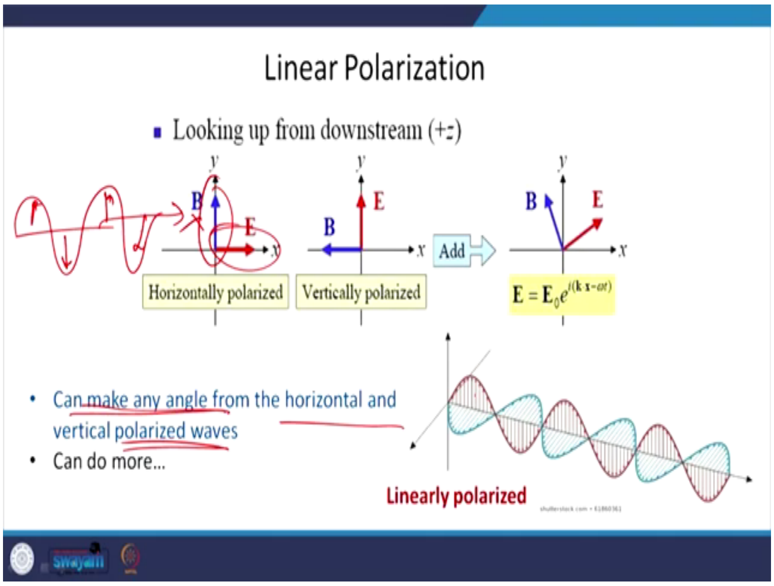

So, if you see for linear polarization, let us say that the wave is going in plus z direction and we see from bottom what will we see? We will see an electric and magnetic field vectors. Basically, it is wave - it is a variation of electric field like this in x direction & magnetic field in y, but what you are actually see is like vectors. You do not see this oscillation, because it is happening in the same plane.

Similarly, the vertical polarization. You do not see any wave. What you see is this vector. The maximum of the vector you see, you do not see the minimum ones. you see the maximum of the vector and that is the electric and magnetic field. And, if you add them together you find any polarization, you can make any angle from the horizontal and vertical polarized wave like this. So, if a wave is travelling in this direction, it will have orthogonal electric and magnetic fields, but the polarization can be any angle from x and y.

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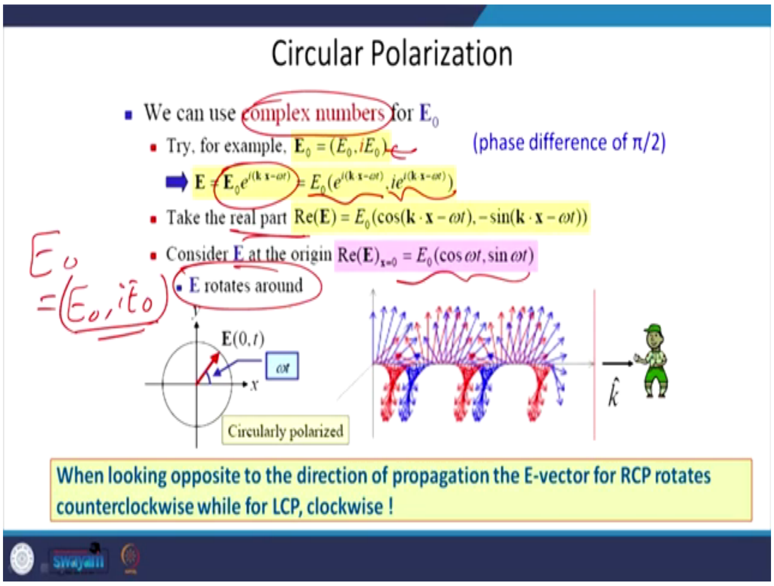

And not only that we can do more also, how? Take a complex number. So, rather writing E 0 as a real function, you can write it E 0, i E 0. What it means here? It means that, now it has 2 components and they have a phase difference of pi by 2 - 90 degrees phase difference. You write the wave equation for a plane wave and you resolve it in 2 components, the real part and the imaginary part.

Now, take the real part and consider E at the origin, you get to this relation and E rotates around. So, if I shine laser from here to you what do you see? You see that the electric field vectors in the direction of propagation of light is in this direction the electric field vector is oscillating in this plane, but this is not fixed it keeps on rotating, while it propagates, and it forms a circle.

So, the tip of the electric field vector forms a circle, while it is propagating towards you. It can be clockwise, or it can be anticlockwise. So, that is how you define, if it is a right circular polarized light or left circular polarized light, but how do you define it?

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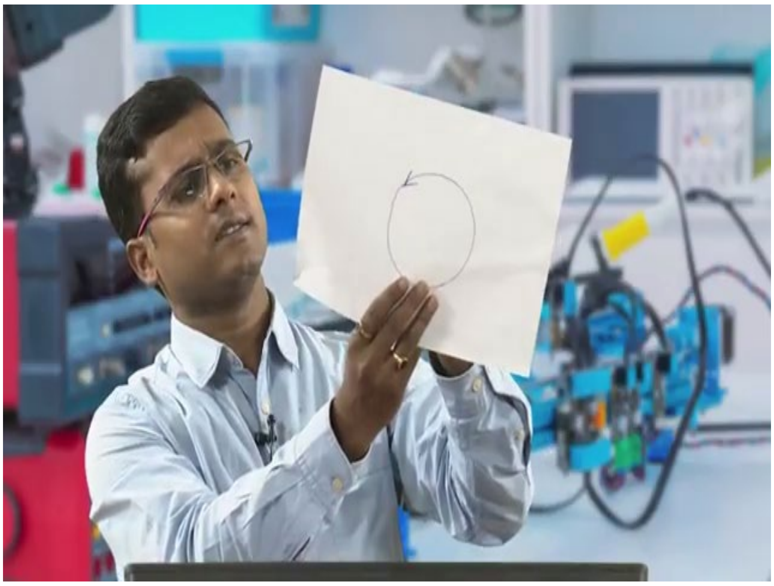

Suppose, I shine light from me to you, what you see? And, for me it is like this, the circle can you see the circle yes? So, what do you see? This is an anticlockwise circle, but for me it is clockwise. So, this is a problem. So, if I shine light, I will say this light is right circularly polarized, but you will say no it is left circularly polarized. So, this is a problem.

This is a problem of convention. I mean, it is a matter of bookkeeping. If you use Born and Wolf and Optics by Ghatak and many other books, then you will find that they have considered the observer to be the one who decides if it is a right circularly polarized light or left circularly polarized light. It is not the laser source of light. It is the observer, but if you use as a Jenkinson White, then they are using it other way.

So, I mean it is a matter of bookkeeping. But for now, let us consider the standard text which we are studying most of the time- Born and Wolf, Ghatak. So, when looking opposite to the direction of propagation: if the light is coming to me, if it is rotating counterclockwise, it is a right circularly polarized, and for LCP it is clockwise ok, that is the convention we will consider. Elliptical polarization - it is a general solution for a combination of linear and circular polarizations. Elliptical polarization is the most general case.

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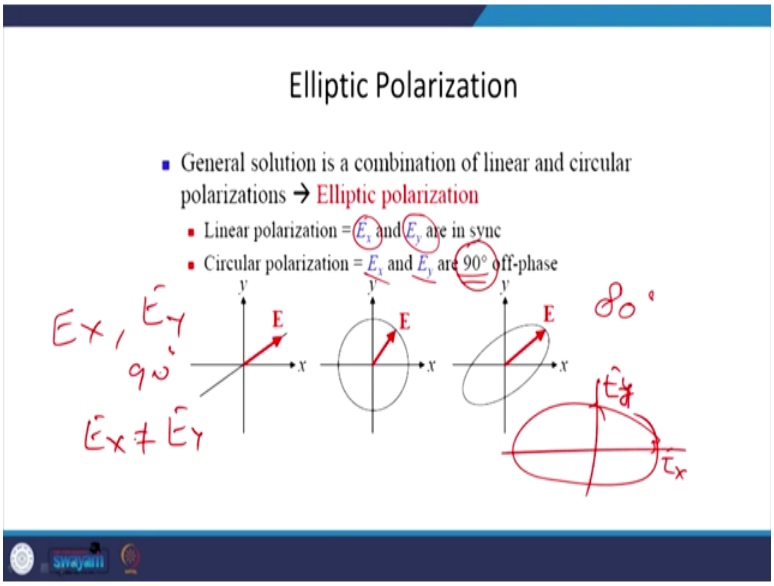

Circular polarization is a special case of elliptical polarization and similarly linear polarization is also a particular case of elliptical polarization. So, you see, that in linear polarization E x and E y are in synchronization. In circular polarization they are 90 degree off phase, but if they are not 90 degree, say they are 80 degree only, what will happen?

What will happen if you have E x and E y are off phase by 90 degree, but E x not equal to E y? So, you will end up with an ellipse, this will be E x and E y. Even though they are at 90 degree off phase, they are not equal. So, they will form an ellipse. So, most general is elliptical polarization and how you solve for it, you solve for it using polarization ellipse.

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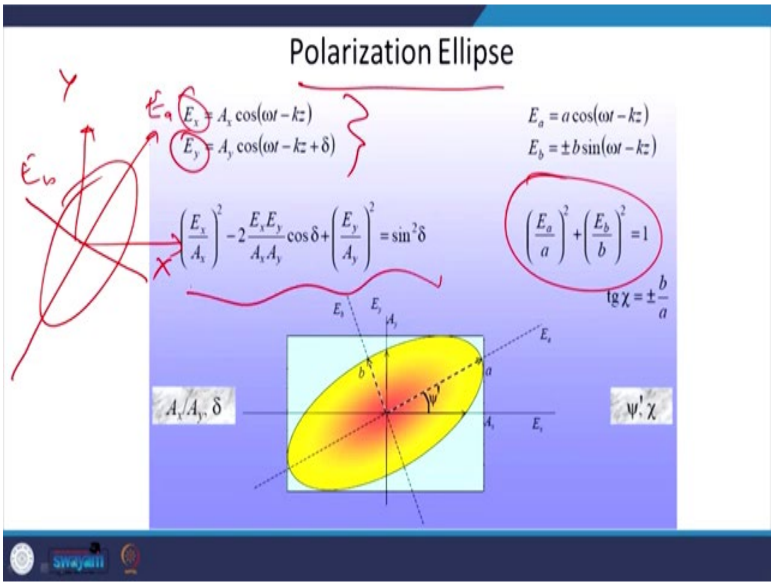

Suppose I have a random elliptical polarization like this. And, if I have a component where I want to measure how much ellipticity it has? what is the direction of polarization? if it is a right circular left right elliptical or left elliptical?, then what we need to do is that we have x and y axis. And, for E x and E y we can write these equations.

If you consider the axis on the major and minor axis of the ellipse, then it will be like E a and E b and then it will be very simple equation, right? This is the equation of an ellipse. If you wish to have in terms of x and y you will have this one. So, it is a matter of choice - what you choose.

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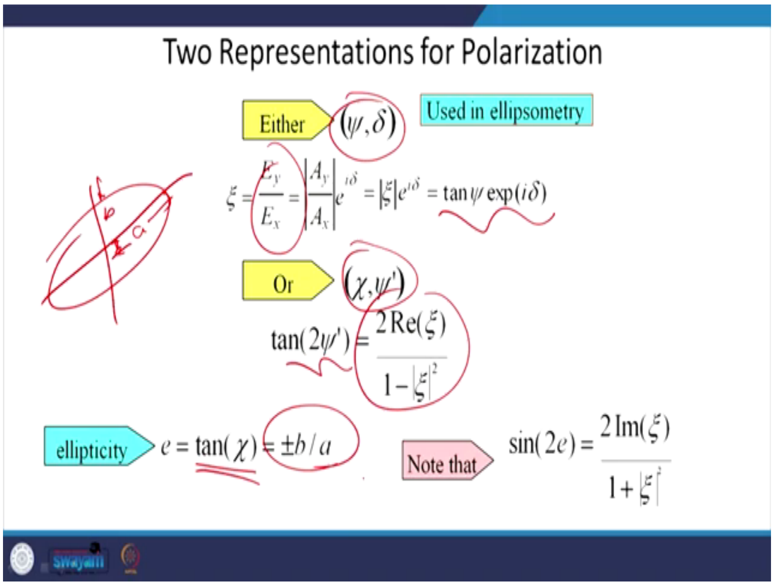

There are two representations for polarization: this one is used in ellipsometry, where you define psi like this zeta and solve for this; or you have this representation, where you take tan 2 psi 0 is equal to this. You define the ellipticity equal to tan of psi - this angle, that comes from b by a. You remember this? When it was ellipse? The minor one is b, major one is a, and you have this ellipse as b by a.

I will not go into detail of this. If you are studying an optics course, there you can study it, you know, thoroughly; but here I wanted to give you a glimpse of what these kinds of polarizations are. We are more considered about linear polarizations here, because in optical sensing, when we come to plasmonics and all the structures we will be using linear polarizations only.

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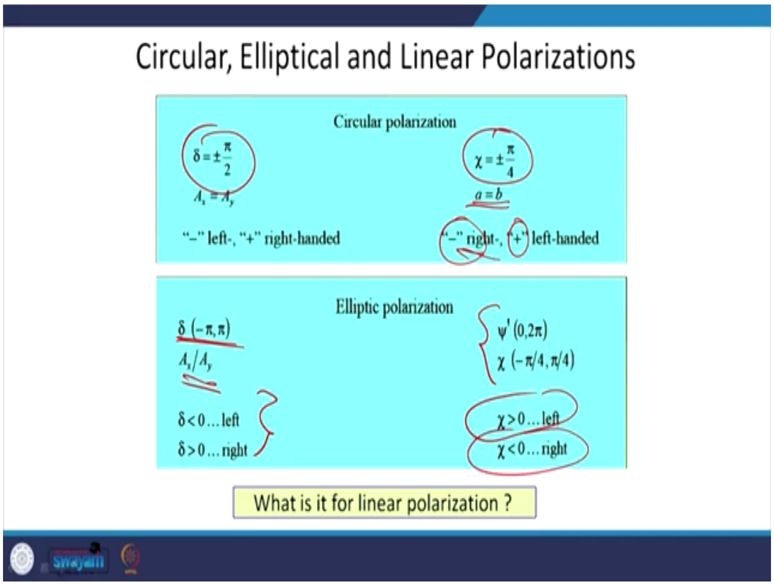

So, if you have elliptical polarizations or say circular polarization delta is equal to plus pi by 2 or minus pi by 2 and you can have psi like this and a must be equal to b. So, if this is negative right circularly polarized you have positive then left circularly polarized and vice versa, same here.

If you have elliptical polarization, you have delta in this range. you calculate A x by A y and this give you right or left elliptical polarization. In the other notation, you have psi 0, psi prime and zi and you see that if this is left circular polar elliptical polarization and this is right elliptical polarization. For linear polarization, I leave it to you. You need to solve it.

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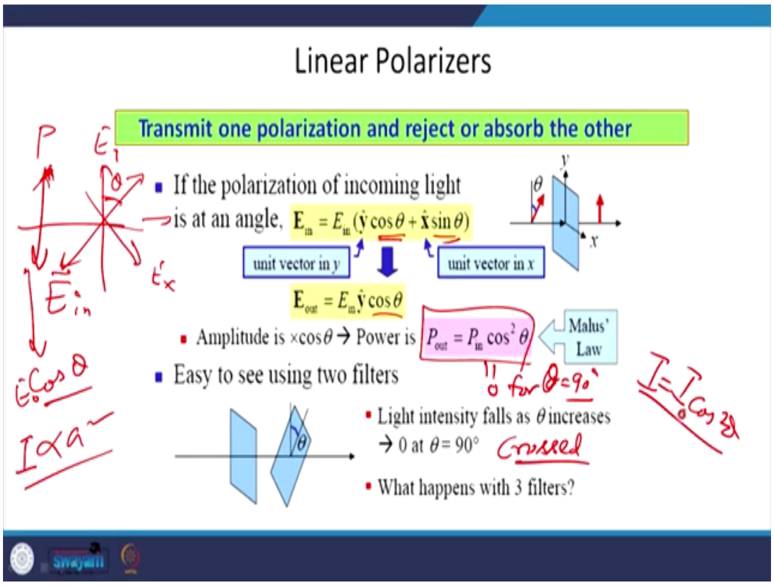

What is the linear polarization? It transmits one polarization - rejects or absorbs the other. Let us come back to that virtual experiment which I told you -that you tie a rope and I am swinging it like this. What I do is that, now I put a chair, which has openings like this. And, I am swinging like this -what will happen? It will not stop the oscillations like this in this plane. So, it is letting it pass through.

Now, I rotate the chair. So, now the opening is this way and I want to do the oscillations this way, what will happen? Will it transmit? The answer is no. Why? Because, this one is blocking the transmission. Similarly a polarizer; what is its role? It has lines, one polarization passes through, other one gets blocked or gets absorbed.

So, if the polarization of the incoming light is at an angle, suppose this is my polarizer, polarizer p and the light which is coming with polarization at an angle theta, then I can resolve it into 2 components. Say, E x and E y that will be cos theta and sine theta components. And, what is coming out is actually E y cos theta, because it is making an angle theta with this. So, if I have my polarizer this way what is coming out is the cos theta component.

So, amplitude is cos theta - E 0 cos theta. Intensity is proportional to amplitude square. So, you will get P out is equal to P in cos square theta or I is equal to I 0 cos square theta, that is called Malus law or law of Malus.

So, if theta is equal to 90 degree, what will happen this term will become equal to 0 for theta equal to 90 degree - there would not be any light. So, if you have a polarizer the light this, you have a polarizer like this, whose pass axes are at 90 degree to each other; they are called crossed polarizers and you do not see any light coming through it.

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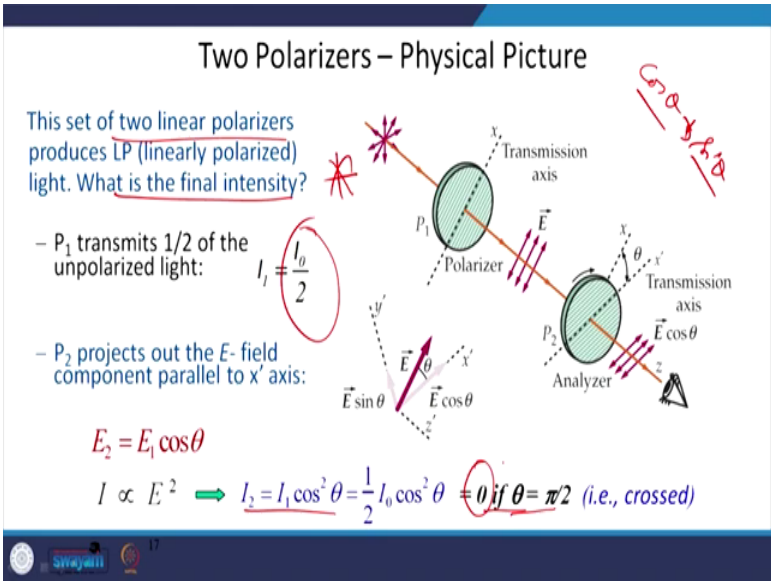

Now, it is like this. If you have a set of 2 polarizers, what is the final intensity? So, if it passes through first one, I becomes I 0 by 2. You had all the directions, what will happen that, you can resolve all the components into cos theta and sine theta terms and you can add them all.

Whatever is coming along the transmission axis - you can add all the components of all the electric field vectors and what you find out is that it is I 0 by 2; half of them are cut down, half of the intensity passes through. Now, I put this one at theta to this. So, I told you that we get I 2 will be I 1 cos square theta and if theta equal to pi by 2 will get 0.

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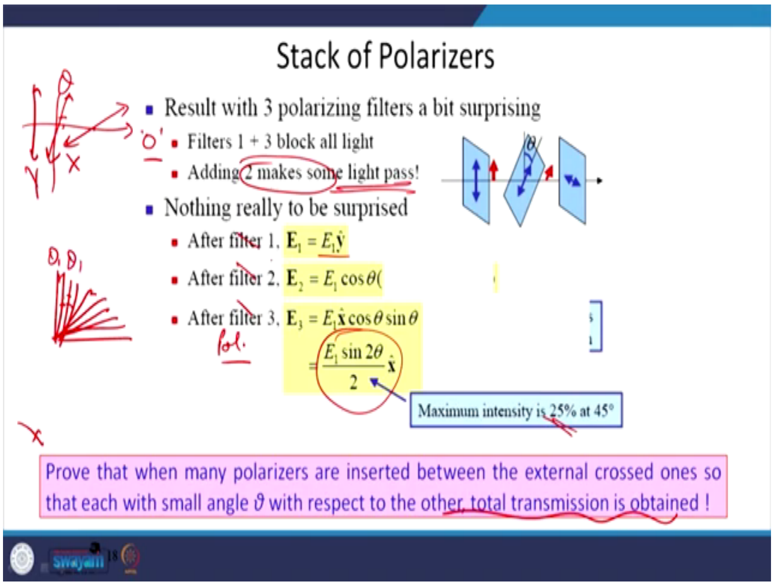

So, that is what we discussed earlier. What will happen if I put 3. So, now, I know that I have one polarizer like this, other polarizer like this and this was y suppose this is x. So, whatever I was getting was 0 - no intensity at all. Now, I put some other polarizer at some angle theta to the first one.

What will happen? Adding 2 makes some light pass. So, you can solve for it. You know, that after filter 1, it will be E1 y. Filter, here, means polarizer. After polarizer 2 it will be E1 cos theta and after polarizer 3, E1 cos theta sine theta, that will be E1 sine 2 theta by 2. So, we get about 25 percent intensity at 45 degree.

Now, if you put, say, many polarizers at small angel theta, theta, theta, theta, theta gradual gradually changing like this from here to here, what will happen? Total transmission is obtained. I leave it to you to prove. Prove that when many polarizers are inserted between the external crossed ones so that each with small theta with respect to the other, total transmission is obtained.

What you do is that this one is at small angle theta 1 and then this 1 again is making theta 1 with the first one the theta 1 with the second one, then the third one, fourth one. And, now you keep on putting like this and what you have that there would not be any light loss. If you put only one there will be about 25 percent, if you put 2 or 3 or more - you keep on increasing - you will get all the light between these 2 polarizers.

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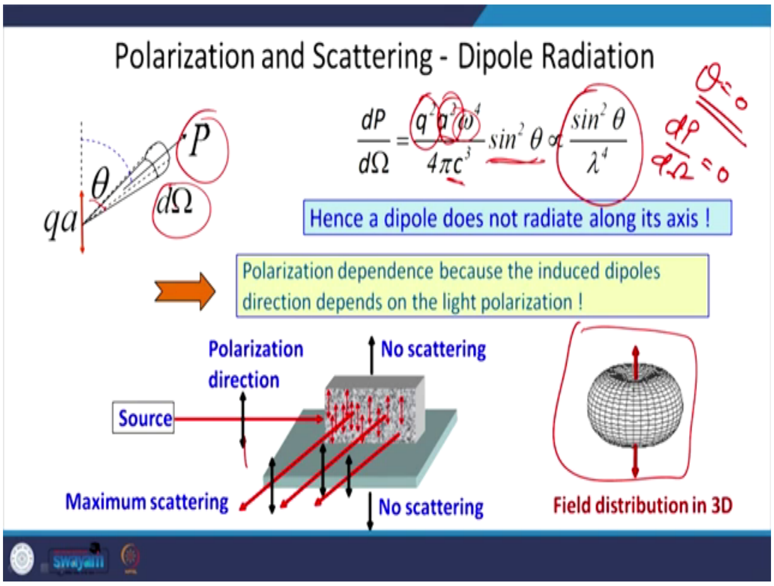

Polarization and scattering: So, in the beginning I was talking about this dipole thing.

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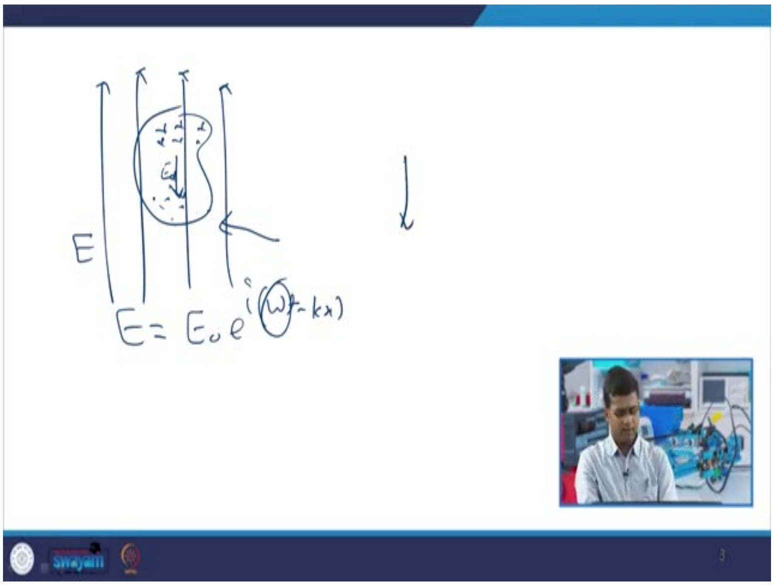

And, I told you that when you have a molecule like this and you have an electric field switched on like this, what will happen that negative ones will come here positive ones will go here and you will form a dipole whose electric field will be in this direction. Dipole will be pointing in that direction; electric field due to dipole will be in this direction.

Now, this dipole, since E is equal to E 0 e to the power i omega t minus k x, you know, that there is this omega term. That is the frequency of the electromagnetic wave. So, if this electric field is switching with a frequency omega, this dipole will also be switching around a frequency omega at resonance, it will be omega.

So, what will happen? It will scatter light. So, suppose I have a dipole here, which has q charges here q 1 and q 2 - plus q and minus q and that the distance between them is a and I want to see that in this solid angle d omega, at an angle theta from the dipole at this solid angle d omega, how much power do I get?.

So, solid angle means like it is a cone. So, my dipole is vibrating in this direction and at an angle theta from here, I want to see how much light is coming in this cone? Suppose, I have this cone making an angle theta from here and I want to see how much power is coming in this cone? So, this is given by this relation d p by d omega equal to q square- q is the charge, a square- how much is the displacement. If you have strong electric field then displacement will be larger. If you have small electric field the displacement will be small. So, that is a square.

Omega – frequency of the radiation which is falling on it - the electromagnetic wave and c is the speed of light and theta - this angle. So, basically it is proportional to sine square theta upon lambda to power 4. What does it mean? It means that, if theta is equal to 0, then d p by d omega is equal to 0; that means, that the dipole does not radiate along its axis. Maximum (Refer Time: 25:08) radiation is coming along the perpendicular direction - that is 90 degree.

So, polarization dependence, because the induced dipole direction dependence on the light polarization. Now it comes here. I was telling you in the beginning- what is the importance of polarization. Here it is coming. So, suppose you have a source here and the direction of polarization is like this. What it will make it like all the polarization will be in this direction. So, if all the molecules are polarized in vertical direction. So, there would not be any scattering in the vertical direction and maximum scattering will be in horizontal direction. So, from the horizontal 1 you will have maximum scattering, but the vertical ones would not have any scattering.

Now, if I change the direction of polarization to horizontal, you will get scattered lights from vertical- both the sides, but not from the horizontal. So, the field distribution in 3 dimension is given by this. So, you can see that in the direction of the oscillation of the dipole you do not have any radiation coming out. The maximum comes in the horizontal direction - 90 degree to it.

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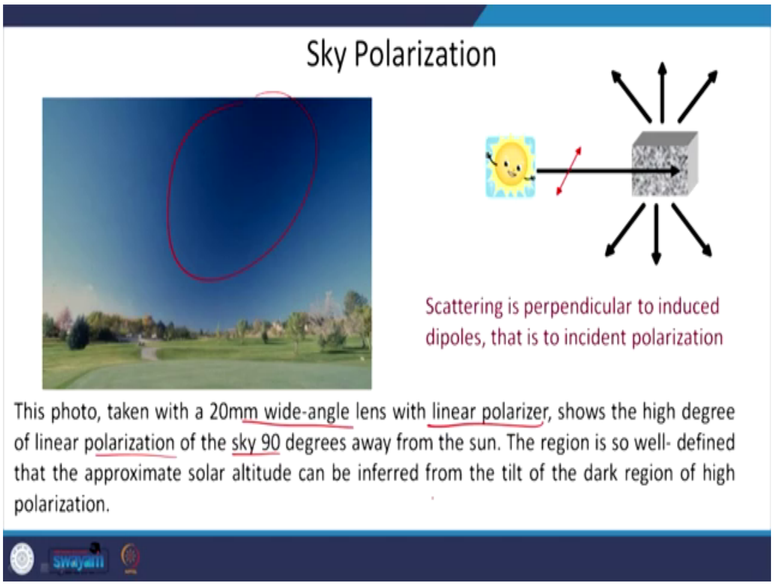

Sky polarization: So, scattering is perpendicular to induced dipoles and that is to incident polarization. So, if you change the polarization, basically you see different orientation of it and different scattered light. So, this photo was taken with a 20 mili- meter wide angle lens with a linear polarizer. And, see high degree of linear polarization of the sky 90 degrees away from the sun. You can see here darker patch.

This region is so well defined that the approximate solar altitude can be inferred from the tilt of the dark region of high polarization. So, from the tilt you can see. But you can see that, when you have polarized light the way you see objects is different. Why? Because now they are radiating in the certain direction. They are not radiating in all directions. So, you can control how molecules behave when light is incident on it. Now, we come to transverse electric and transverse magnetic polarization. That is something very important, when you study optical configurations.

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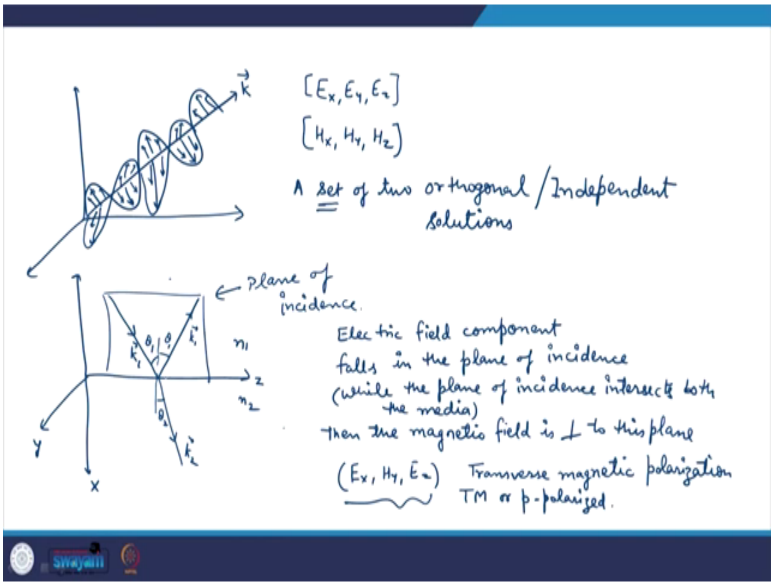

So, suppose we have an electromagnetic wave which is going in an arbitrary direction and the k vector defines the direction of propagation of the wave. The electric field oscillations are like this, and the magnetic field oscillations will be in the perpendicular directions. So, it will be like this, something like this. So, what you see is that if you want to know the electric field and magnetic field in an electromagnetic wave you have to solve for 6 components E x, E y, E z and H x, H y, H z.

So, it becomes very cumbersome to solve the problems of electromagnetics, but what we can do is that we can divide these 6 vectors in a set of two orthogonal or you can say independent solutions. So, it by it will be a set of 2 orthogonal solutions. So, you can make two sets, ok. Let us see how we can do that? So, suppose this is z axis and this is x axis, and this is y.

And, suppose this z axis separates 2 media of refractive index n 1 and n 2, ok. So, if a light is incident like this at an angle theta 1, then it will get partially reflected and partially refracted at, say, angle theta 2 and will get reflected at the same angle theta 1.

So, this we will prove, actually, that, this angle and this angle is equal, but for now let us say that this is the case when light propagating in this direction k 1 gets partially refracted to this direction and partially getting reflected. So, it will have the same wave vector. What, we see here is that this plane, which contains the interface and the plane of the incident ray and the reflected ray- it forms a plane this is called plane of incidence.

So, if your light is such that the electric field component falls in the plane of incidence, while the plane of incidence intersects both the media, then the magnetic field component is perpendicular to this plane. So, you will have E x for example, in this particular case, H y, E z. This is called transverse magnetic polarization or T M or p polarized.

So, what it essentially means, that you can have a set of solutions for this configuration, where the electric field component lies in the plane of incidence, while the plane of incidence sees the change in reflective index and the magnetic field component is perpendicular to this plane. So, it does not see the change in reflective index.

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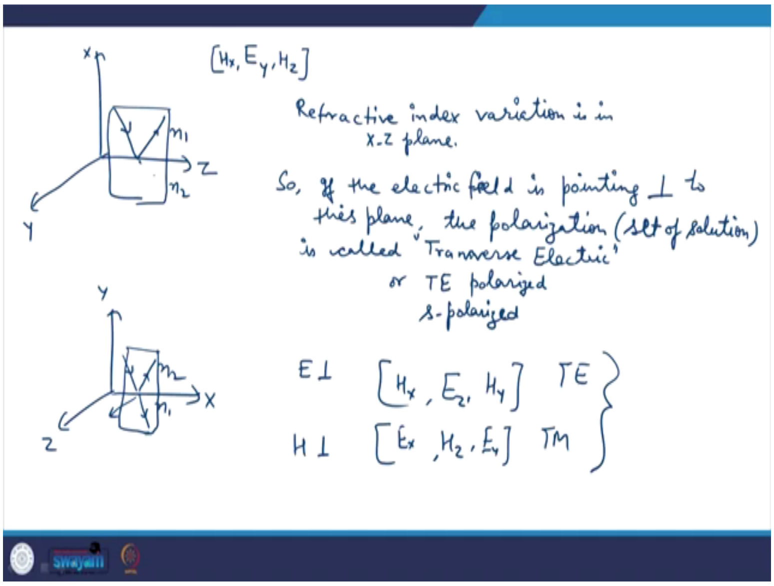

Similarly, one can have another. So, this was your structure - you had y here, you had z and x here. So, you can have H x, E y, H z. Again, the reflective index variation is in x z plane. So, if the electric field is pointing perpendicular to the interface - this plane, the polarization is called, polarization means actually the set of solution, set of solution; I told you about 2 independent set of solutions, this is called Transverse Electric or T E polarized or you can say s polarized.

So, you have this configuration where the incident ray & reflected ray, they are in one plane such that this plane intersects. This interface - it sees the change in reflective index then if the electric field is perpendicular in one set of solution then it is called transverse electric. So, all we want to find is the transverse direction of the electric field and magnetic field. And, what is this transverse direction?

This transverse direction is the direction perpendicular to the plane of incidence subject to the condition, that this plane of incidence sees the change in reflective index. So, that is how you define transverse electric or transverse magnetic. Please see, that in various cases students make errors if I simply switch these axes. Suppose I put it x y and z. And, then you remember all this and then suddenly you get confuse. And, if I change it say n 1 and n 2 - suppose it is n 1 and n 2 then what will be TE and T M components.

So, people get confused. So, do not just remember, try to understand it. So, if the wave is incident like this and getting transmitted like this, you make a plane of incidence and the component of electric field, if it is, if that is perpendicular to it - if the electric field perpendicular, then you can have E z. What are the components remaining- H x and H y. This is TE. If magnetic field is perpendicular, then you have to have H z and what is remaining here is E x and E y. This is transverse magnetic.

So, if I switch the axes or if I switch the interface of the refractive indices, do not get confused. Then, there is some other configuration in this one, you see, that light was intercepting the interface like this.

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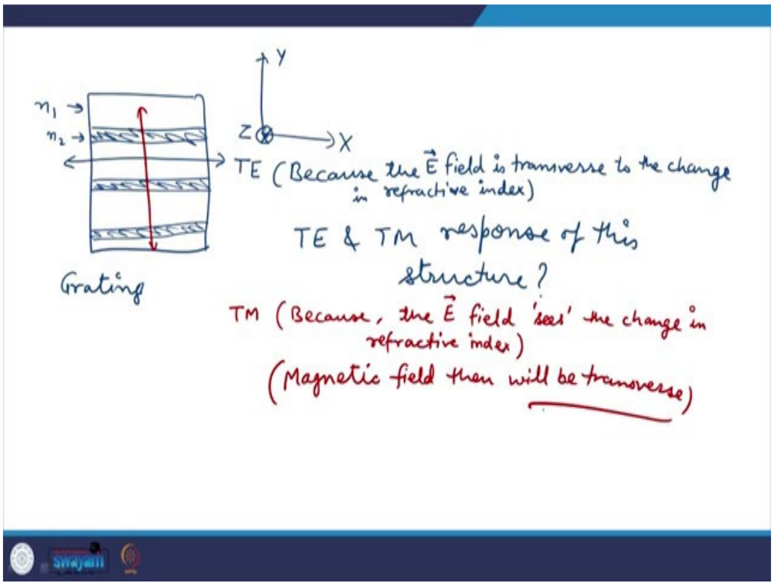

Now, suppose I have a structure made on glass, which has this kind of variation of refractive index. Suppose this region has refractive index n 1, this region has refractive index n 2 and this is periodic, and light is incident from the top. So, you have, suppose, x, y, z like this. So, z is the direction of propagation. You can think like this. Suppose, z is pointing down to the plane.

So, light is incident on these. These are, actually, grating structures. Suppose, you have a grating based sensor. Light is falling on it from the top and you want to know the T E and T M response of this structure. How do you study this? What will be the polarization of light, which will give you the T E response and T M?

So, how do you define T E and T M in the case of this kind of structure? So, you see that if you remember - I told you that when the electric field component is in perpendicular direction; suppose it is incident normally, so how you define the plane? it is difficult right -plane of incidence.

So, what you do is that you take a polarizer and if the electric field vector lies like this, then it is T E polarized because, the electric field is transverse to the change in refractive index

Electric field of the incident wave is transverse to the change in the refractive index. And, suppose if you have this kind of polarization. So, it is T M, because the E field sees the change in refractive index. So, in practical when we define TE and TM, you are not considering the magnetic fields actually, but what you consider is that, if the electric field vectors sees the change in refractive index, then the magnetic field will not see the change in refractive index and then that is why you call it actually T M polarized. So, magnetic field, then will be transverse. So, that is how you define TE and T M for different structure ok.

Suppose we want to make a sensor and we want to see its transverse electric and transverse magnetic response; it is very important for one to know which way to put the polarizer.

So, you have a sample like this, where refractive index variation is like this. If the electric field components intercept through- this is transverse magnetic. If the electric field vector either falls in crest or the trough then it is transverse electric. It does not see any change in the refractive index. So, that is how you find out whether it is transverse electric or transverse magnetic.

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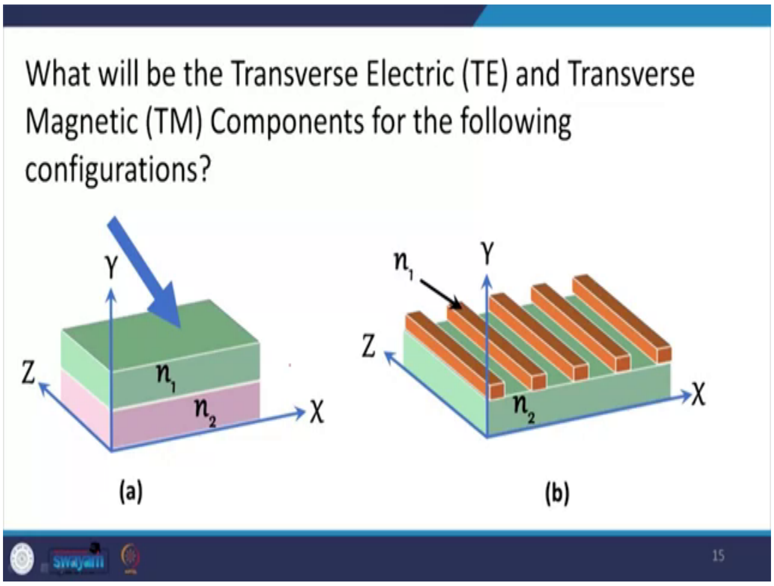

So, this is kind of a homework for you. There you have to tell me that what will be the transverse electric and transverse magnetic components for the following configurations. So, in this particular case you have z axis here, y axis here and x axis here. And, in this one is the same and it has different refractive indices n 1 n 2.

So, that is how you have to find out what is the particular direction. This is something very important which you will be using throughout the course. For example, when we come to plasmonic bio-sensors, you know, that this kind of variations will make different excitations and this kind of polarizations, which is transverse electric will have different implications. To summarize this - polarization of light plays an important role in direction of propagation and scattering and it is useful in determining the optical properties of any configuration.

So, if you are having a system which is oriented in a particular manner, then you have to choose a polarization in such a way that you obtain the desired optical properties. So, as this course progresses, we will see that different polarizations give different optical results.

Thank you.