Course Name- Nanophotonics, Plasmonics and Metamaterials

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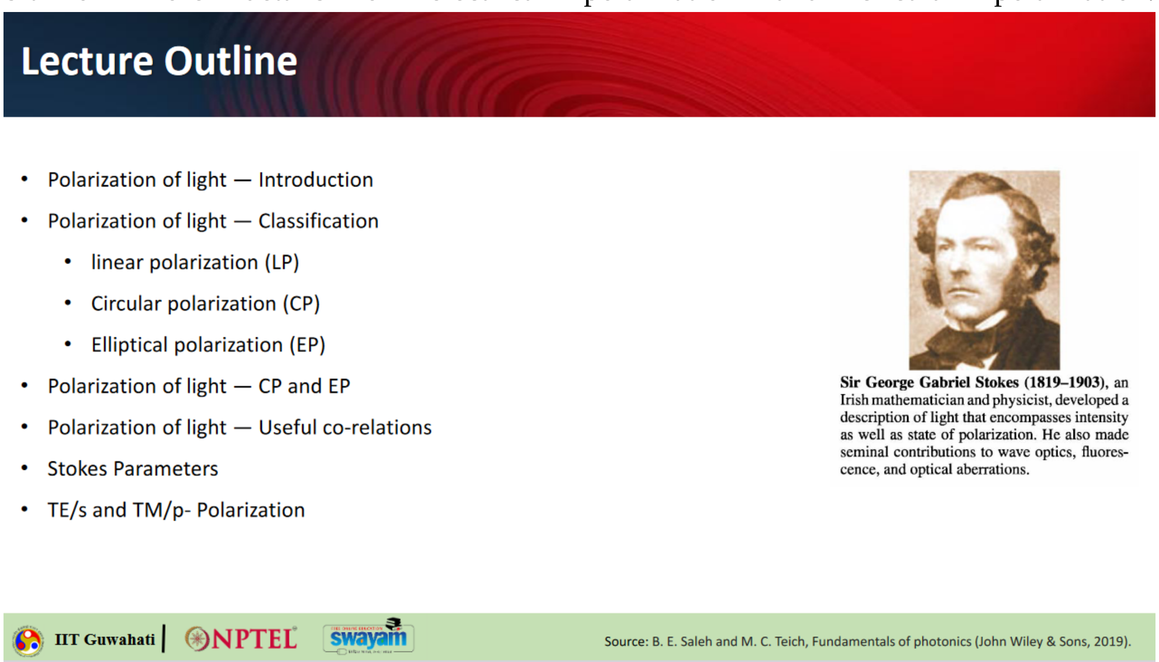
Week-03

Lecture -07

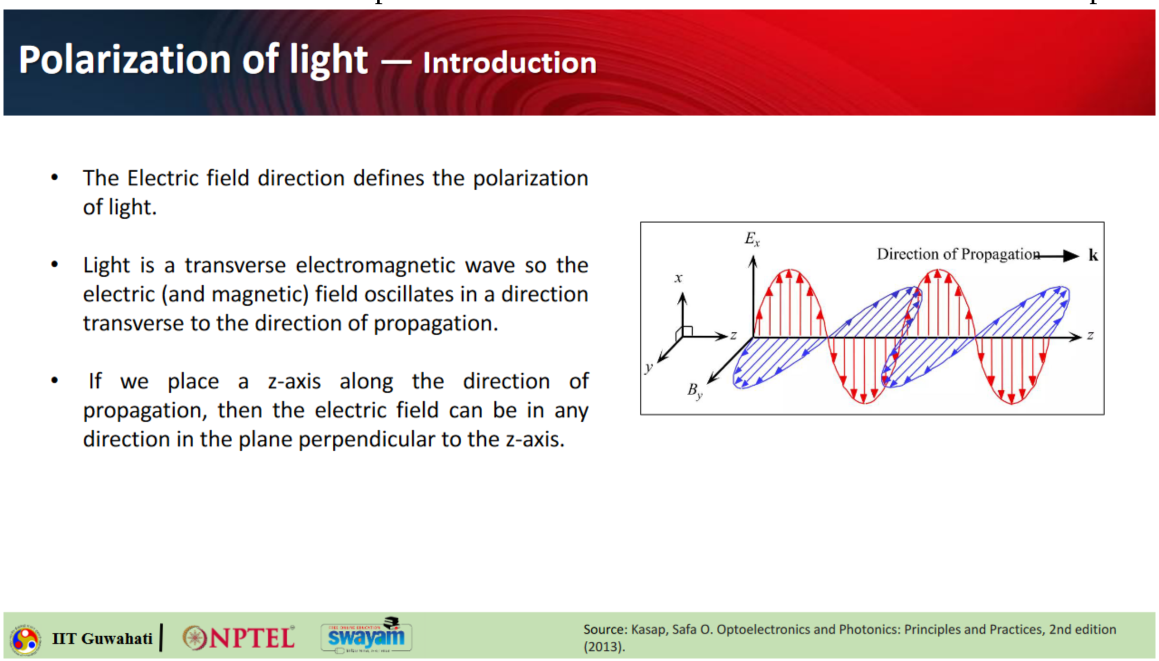
Hello everyone, welcome to lecture 7 of the online course on Nanophotonics, Plasmonics and Metamaterials. Today's lecture will be on polarization of light. So, the lecture outline is as follows. We will first introduce what do we mean by polarization of light and then we will go into the classification. So, light can be classified into linear polarization, circular polarization or elliptical polarization. And we will look into little bit of more details of electrical polarization and circular polarization.



Also we will see the useful correlations between different polarization states. After that we will study the Stokes parameters and introduce the concept of TE or s polarization and TM or p polarization. So, here is a photograph of Sir George Stokes. So, he was an Irish mathematician and physicist who developed a description of light that encompasses intensity as well as the state of polarization.

So, he also made seminal contribution to wave optics, fluorescence and optical aberration. So, we will also study Stokes parameters which are basically named after him. So, let us introduce this topic called polarization of light. So, when we talk about polarization we are mainly concerned about the electric field direction. So, you can say the electric field direction defines the polarization of light.

So, we all know that light is basically a transverse electromagnetic wave. So, the electric and magnetic field they oscillate in a direction which is basically transverse to the direction of propagation. So, if you assume here that you know the light is propagating along z direction in that case the electric field is assumed to be along x. So, that is orthogonal to the direction of z and in such case the magnetic field will be in y direction. So, how do you classify different polarizations? So, a polarization of light is conventionally defined by the time variation of the tip of the electric field vector E at a fixed point in space.

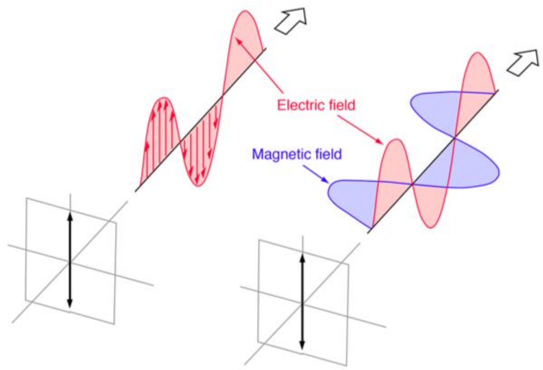


So, that brings couple of possible states of electric field polarization. Let us look into them one by one. The first one is linear. So, it means if the tip of the electric field vector moves in a straight line like this or this whichever way it is a straight line we can call this wave as linearly polarized. So, here is an example.

So, you see that a plane wave is said to be linearly polarized. So, this is how the electric field vector changes with time. This is the positive cycle and this is the negative cycle, but if you draw how the electric field vector is changing on this plane you will see it is changing linearly. So, this is how the electric field vector is oscillating while it is propagating along this direction. So, once again polarization only concerns about the electric field.

Polarization of light — Classification

- The polarization of a wave is conventionally defined by the time variation of the tip of the electric field vector **E** at a fixed point in space.
- Possible states of electric field polarization are:
- **Linear:**
  - If the tip of the electric field vector moves along a straight line, the wave is linearly polarized.
  - A plane electromagnetic wave is said to be linearly polarized.
  - The transverse electric field wave is accompanied by a magnetic field wave.



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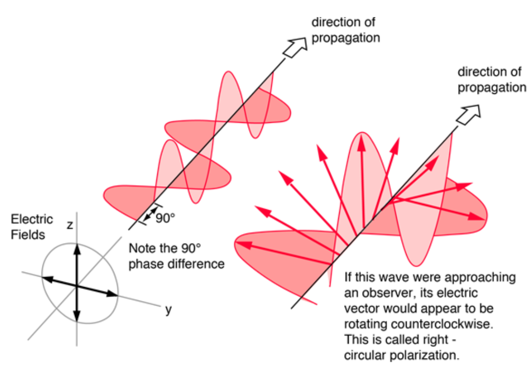
Source: http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html

However, in a plane wave we can also show this is how the magnetic field will be oriented, but polarization only bothers about the electric field direction. So, electric field here oscillates along this up and down. So, you can actually see that this is basically a linear polarization. The next one is circular polarization. So, obviously in circular polarization the locus of the tip is a circle.

Polarization of light — Classification

Circular:

- When the locus of the tip is a circle, the wave is circularly polarized.
- Circularly polarized light consists of two perpendicular electromagnetic plane waves of equal amplitude and 90° difference in phase.
- The light illustrated is right- circularly polarized.



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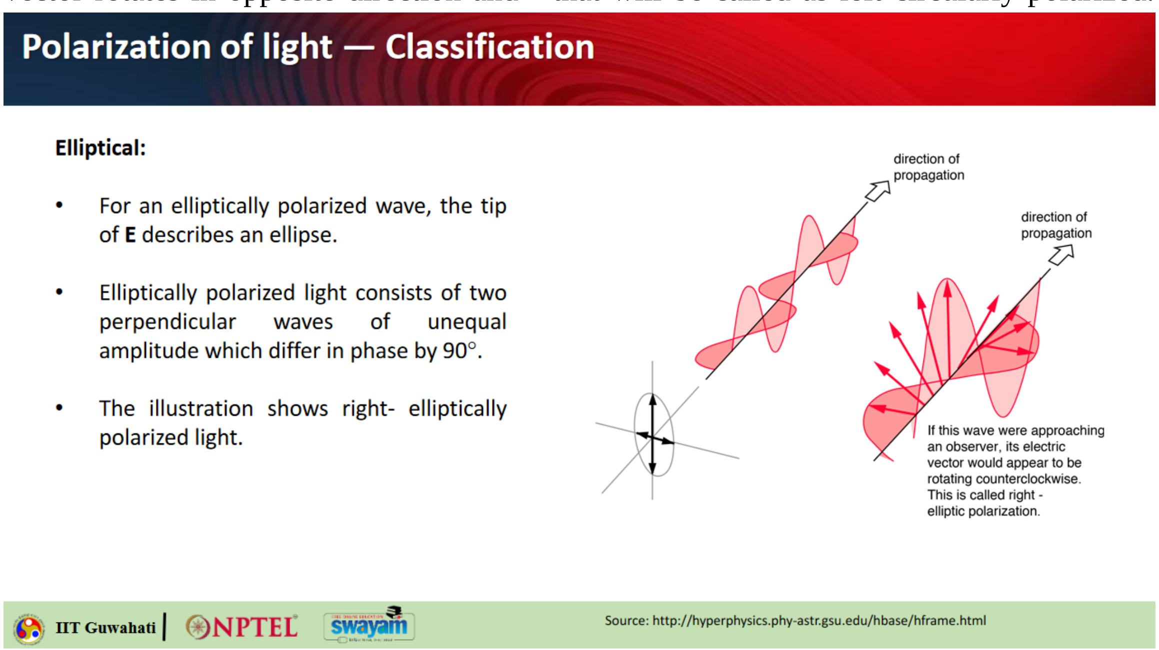
It means if you plot the trajectory of the electric field vector while it is propagating along z direction you will see that the electric field vector draws a circle on a particular plane. In that case we consider this wave as circularly polarized. So, here is a notation that shows that, So, a circularly polarized light basically consists of two perpendicular electromagnetic plane wave. And another important condition is that they should be of equal amplitude and there should be 90 degree phase difference between them. So, here both in red are basically electric field.

So, this is one plane wave and this is another plane wave. So, there are two plane waves adding up, but then there is a phase difference of 90 degree. So, in that case you will see that you know this is how the electric field vector will move when the wave is propagating. So, from this direction it goes like this and like this and like this. So, this is how it will move while it is propagating forward.

So, this is the direction of propagation. So, if you are an observer if you stand here ok, you will see that the wave is basically coming towards you in counterclockwise manner. In that case you will call it as right circular polarization. Similarly, if the phase difference is other way that is this wave is starting early. In that case you will see that the vector rotates in opposite direction and that will be called as left circularly polarized.



There is another type of polarization which we call as elliptical polarization and it is obviously, a special case of the circular polarization. So, where the amplitude of the two plane waves are not equal. So, obviously elliptical polarization is nothing but where the tip of the electric field vector describes an ellipse. So, you will get an ellipse when this vector is basically drawn on a particular plane. So, here what happens? it is basically two perpendicular waves of unequal amplitude and there is a phase difference of 90 degree.

So, that will give you elliptical polarization. Again when you stand here and if you see that the vector is rotating counterclockwise in that case it is a right elliptical polarization. So, there is a convention this is a convention difference. So, once you look at from the source the rotation will be in one direction either clockwise or counterclockwise I will summarize it later on. But here you remember that when you are standing at the observer end and if you see that the electric field vector is rotating in counterclockwise direction we call it right handed polarization.

So, it can be elliptical or circular depending on the amplitude. If the amplitude of both plane waves are same then it is circular polarization, if they are different then it is elliptical polarization. But what is important is the phase difference between the two plane waves should be 90 degree. Now, let us look into little bit of more details of linear polarization. Suppose that we arbitrarily place x and y axis and describe the electric field in terms of its component Ex and Ey which will be along x and y direction.

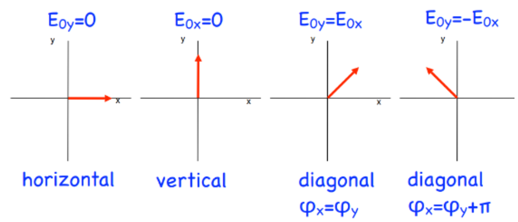
Polarization of light — linear polarization (LP)

- Suppose that we arbitrarily place *x*- and *y*-axes, and describe the electric field in terms of its components E_x and E_y along *x* and *y*.
- Any polarization state can be described as the sum of two orthogonal linear polarization states

$$\boldsymbol{E}\,(z,t) = E_x + E_y = E_{0x}\cos(\omega t - kz + \varphi_x) + E_{0y}\cos(\omega t - kz + \varphi_y)$$

where, E_{0x}, E_{0y} are the magnitudes of E_x and E_y components, respectively, and ϕ_x, ϕ_y are corresponding phases.

- Then, if field oscillations are confined to a well defined line, then the wave is **linearly polarized (LP).**
- **Some cases:**
  - (i) 0° linear polarization along x-axis: $E_{0y} = 0$,
  - (ii) 90° linear polarization along y-axis: $E_{0x} = 0$
  - (iii) 45° linear polarization: $E_{0y}/E_{0x} = 1$



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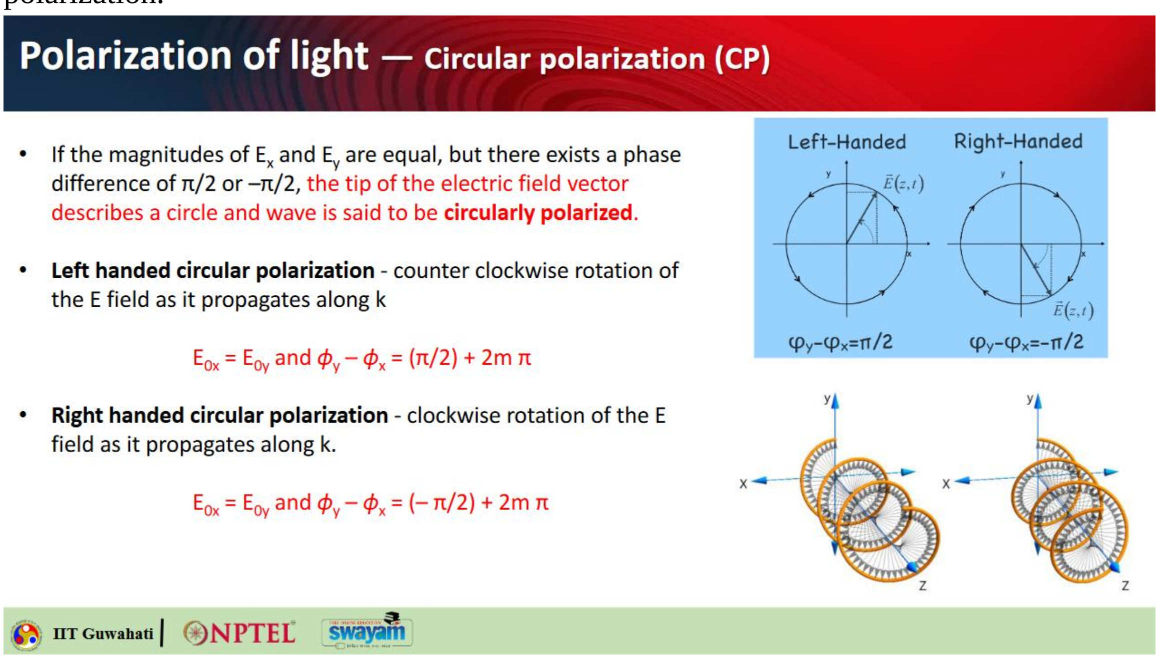
So, that you can do for any electric field direction you can basically take out the components along x and y direction. And then you can describe any polarization state as E(z,t). So, z is the propagation direction, t is the time dependence of that electric field. So, this any electric field polarization state can be essentially split into the two orthogonal linear polarization states Ex and Ey. So, if you write it in details it will look like E0x that is the amplitude and then there is a you know plane wave is varying.

So, let us take cosine function to describe that we can write it as cos(ωt), omega is the angular frequency $-kz+\varphi_x$. So, phi x is basically the phase with this electric field component along the x direction. Similarly, you can write for the Ey you can write E0y that is this the basically amplitude or the peak amplitude and this is $\cos\left(\omega t - kz + \varphi_y\right)$. So, E0x and E0y are nothing but the magnitude that is the maximum amplitude you can say of Ey, Ex and Ey component and phi x and phi y are nothing but the corresponding phases. Now, if you know we have seen that the field oscillations are confined to a particular line we call that wave to be linearly polarized wave.

When the field is only lying along x that means, Ey component is 0 in that case we call it as horizontal polarization or x polarization. So, that is 0 degree you can if you measure the angle from x axis you will say that this is 0 degree linear polarization along x axis. So, that is given as E0y equals 0. So, obviously, 90 degree polarization from x axis will be along the y axis. So, that can be also called as vertical polarization that is E0x will be 0 in that case.

There are other cases also possible where the polarization vector is making a 45 degree angle from the x axis. In that case E0x and E0y both components will be equal. So, in such case also if you have the phase to be same. So, you have the electric field polarization along this one. So, this is called 45 degree linear polarization.

So, in linear polarization the amplitudes are same here and also the phase. There is another case which is also possible that is called diagonal case where the phase difference is integral multiple of pi. So, if that happens you can actually have E0y which is basically minus E0x in that case the polarization will be along 135 degree or you can say it is minus 45 degree that is in this direction. So, these are the typical cases of linear polarization. You can have linear polarization along any of this angle as long as the electric field vector oscillates or dances along a straight line it will be called linear polarization.



Now, let us look into little bit of more details of circular polarization. So, here we have already discussed that Ex and Ey will be equal. So, these are basically two plane waves which have equal magnitude or amplitude, but there is a phase difference of $\pi/2$ (90 degree). Now the phase difference can be $\pi/2$ or $-\pi/2$ and that will decide whether it is a left handed circular polarization or right handed. So, one can be this way another can be opposite ok, that way.

So, in both cases as the amplitudes are equal the electric field vector will describe a circle and that is why we call it circular polarization. So, here you have you can see that if $\phi_y - \phi_x = (\pi/2)$ we see that the electric field vector goes in counterclockwise direction. So, this is also where you can see that it is basically going in counterclockwise direction when it is coming towards me. So, look into the screen you stand here and you see that the wave is actually going in this direction. And this is right handed circular polarization when $\phi_y - \phi_x = (-\pi/2)$.

So, in this case you will see that the electric field vector propagates in clockwise direction while going to the observer. So, mathematically you can see that left handed circular polarization we consider counterclockwise rotation of the electric field as it propagates along k. So, that is better. So, we take the direction of wave propagation as k. So, wave is propagating along z direction.

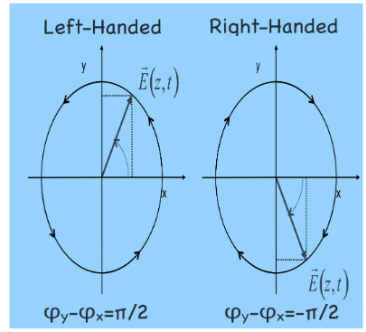
So, we can say that the rotation is happening in counterclockwise direction. So, that is another convention. Let us stick to one particular convention. So, that you do not get confused ok. And we will write that E0x is equal to E0y.

So, the amplitudes are same, but the phase difference $\phi_y - \phi_x = (\pm\pi/2) + 2m\pi$. It means m can be integer starting from 0, 1, 2 and dot dot dot. So, can have 90° phase difference or 2 pi times integral multiple of 2 pi can be added to that in all these cases you will get left handed circular polarization. On the other hand if you see the clockwise rotation of the electric field along the propagation direction we can call it as right circular polarization.

So, that is a easy notation ok. So, E0x and E0y are equal obviously, but then the phase relation $\phi_y - \phi_x = (-\pi/2)$. And you can also have $+2m\pi$. So, this is the phase relation that should be satisfied in case of right handed circular polarization. Obviously, the same thing will apply for elliptical polarization as well only difference that here the amplitude E0x and E0y are not same.

Polarization of light — Elliptical polarization (EP)

- Assume that the magnitude of one vector component in **E** is larger then the other (i.e., $E_{0x} \neq E_{0y}$).
- Instead of a circle, the wave generates and ellipse as it propagates along k in the z direction
- An elliptically polarized light has the tip of the E-vector trace out an ellipse as the wave propagates through a given location in space.
- **Right handed elliptical polarization** - clockwise rotation of the E field as it propagates along k.
- **Left handed elliptical polarization** - counter clockwise rotation of the E field as it propagates along k



So, I will not repeat this again. So, you can actually use the same concept that we have seen for circular polarization you can apply for elliptical polarization just that the amplitude of the two components will not be equal ok. So, here is an example let us take this example it says show that if Ex is given as $A\cos(\omega t - kz)$ and $E_y = B\cos(\omega t - kz + \phi)$ the amplitudes A and B are different and the phase difference phi is equal to $\pi/2$ in that case the wave is elliptically polarized. So, let us start doing that. So, Ex is already given to you Ex is this. So, let us find out what will be $\cos(\omega t - kz)$.

Polarization of light — CP and EP

Example:

Show that if $E_x = A\cos(\omega t - kz)$ and $E_y = B\cos(\omega t - kz + \phi)$, the amplitudes A and B are different and the phase difference ϕ is $\pi/2$, the wave is elliptically polarized.

From the x and y components we have

Solution

$$\cos(\omega t - kz) = E_x/A \qquad \cos(\omega t - kz + \pi/2) = -\sin(\omega t - kz) = E_y/B$$

Using $\sin^2(\omega t - kz) + \cos^2(\omega t - kz) = 1$ we find,

$$\left(\frac{E_x}{A}\right)^2 + \left(\frac{E_y}{B}\right)^2 = 1$$

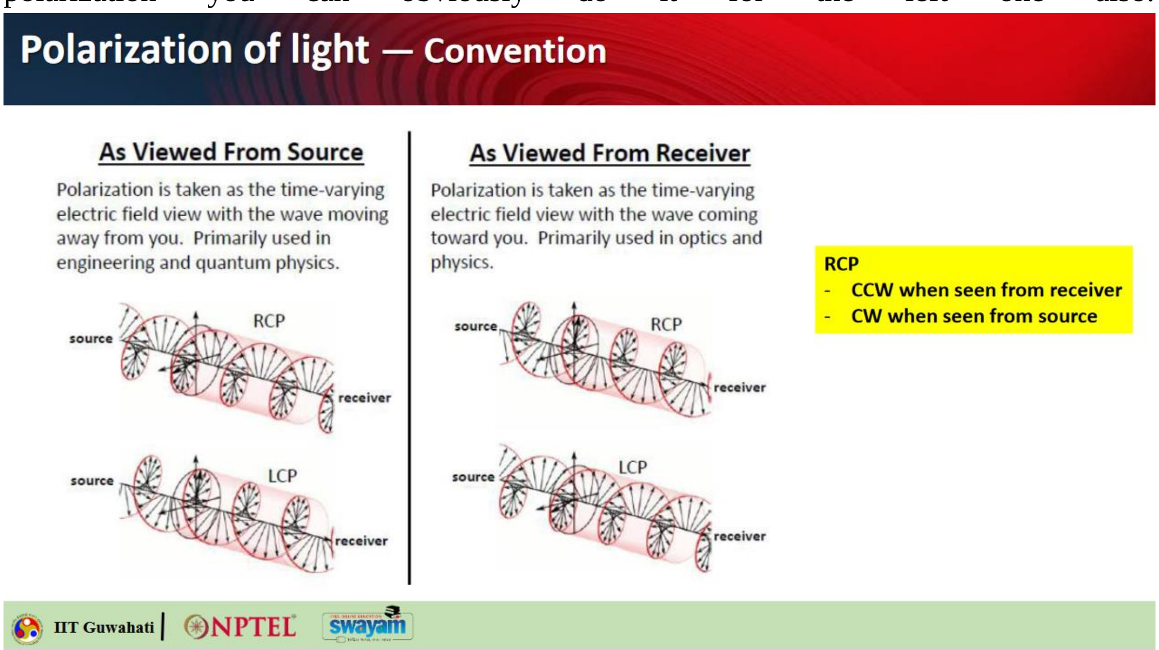
- Equation for an ellipse if the denominators do not equal
- Further, at $\omega t=0$, $E = E_x = E_{xo}$ and at $\omega t=\pi/2$, $E = E_y = E_{yo}$

The equation is a circle when A = B. Hence, circular polarization is a special case of elliptical polarization

So, that can be written as Ex over A. Similarly from this one phi here is already given that is phi by 2. So, from this equation you can write $\cos(\omega t - kz + \pi/2)$ which can be also written as $-\sin(\omega t - kz) = E_y / B$. So, you have got cos term you have got sin term if you square them up and add them up. So, you get $\sin^2(\theta) + \cos^2(\theta) = 1$. So, this will be the equation there you put these values $\left(\frac{E_x}{A}\right)^2 + \left(\frac{E_y}{B}\right)^2 = 1$.

So, that is typically an equation for ellipse right. So, in this case if A and B are not equal then only it becomes a elliptical polarization right. If A and B will be equal it becomes a circular polarization fine. So, it is a very very simple thing.

Now this we have already seen. So, there are different conventions people follow from book to book it changes. So, it people can take it as viewed from source if it they have a perception of right circular polarization or left circular polarization when viewed from the receiver end there is one convention. So, we can actually take this that we can say that when seen from the receiver end that is the wave is coming towards you. If you see counter clockwise rotation you call it right circular polarization and when seen from the source that is you are looking in the direction of the wave propagation that you should see clockwise rotation or clockwise rotation of the electric field that will be the right circular polarization. So, you just remember this one what happens for the right circular polarization you can obviously do it for the left one also.

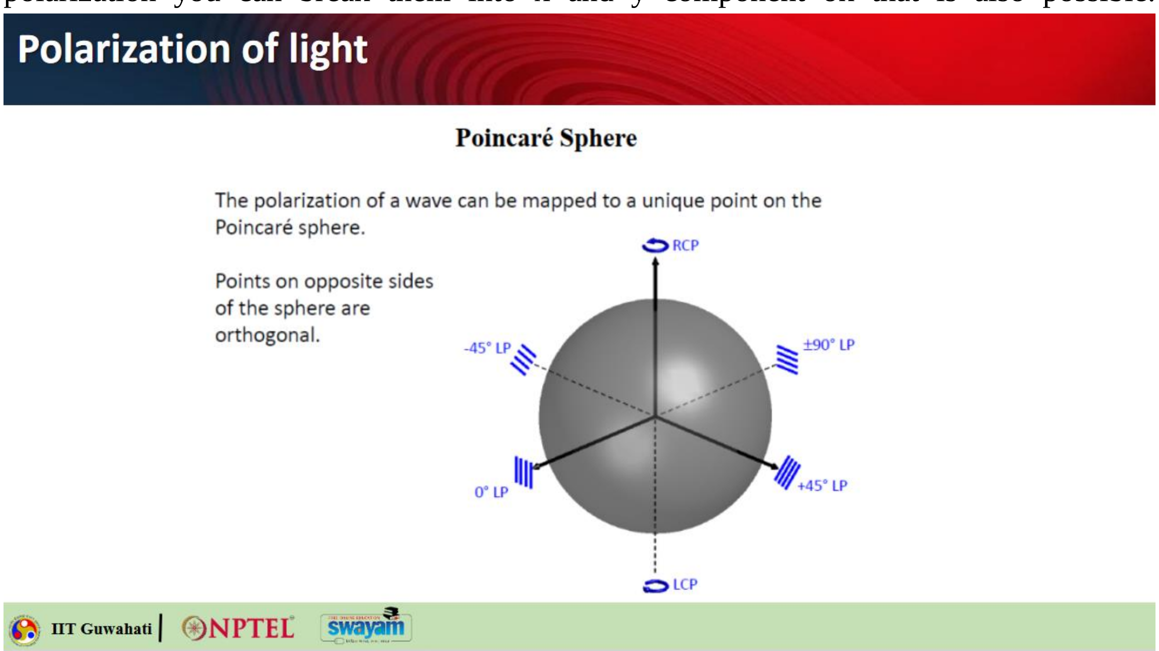


Now why we study polarization of light in so much details because in optical communication we can actually use polarization division multiplexing. If we choose two polarization states which are orthogonal to each other then the signals can actually have the same wavelength or same frequency still they will not pollute each other because they will be orthogonal to each other. So, that is why knowing the polarization state of light is very important and for that this particular sphere which is also known as Poincare sphere is very important. So, in Poincare sphere you can actually map the polarization of a wave to a particular unique point on this sphere and the points on the opposite side of the sphere will mark the orthogonal polarization. Something like say if you have this point as linear polarization like this that is 0 degree linear polarization on the opposite side that is shown by the dotted line you see this is vertical polarization.

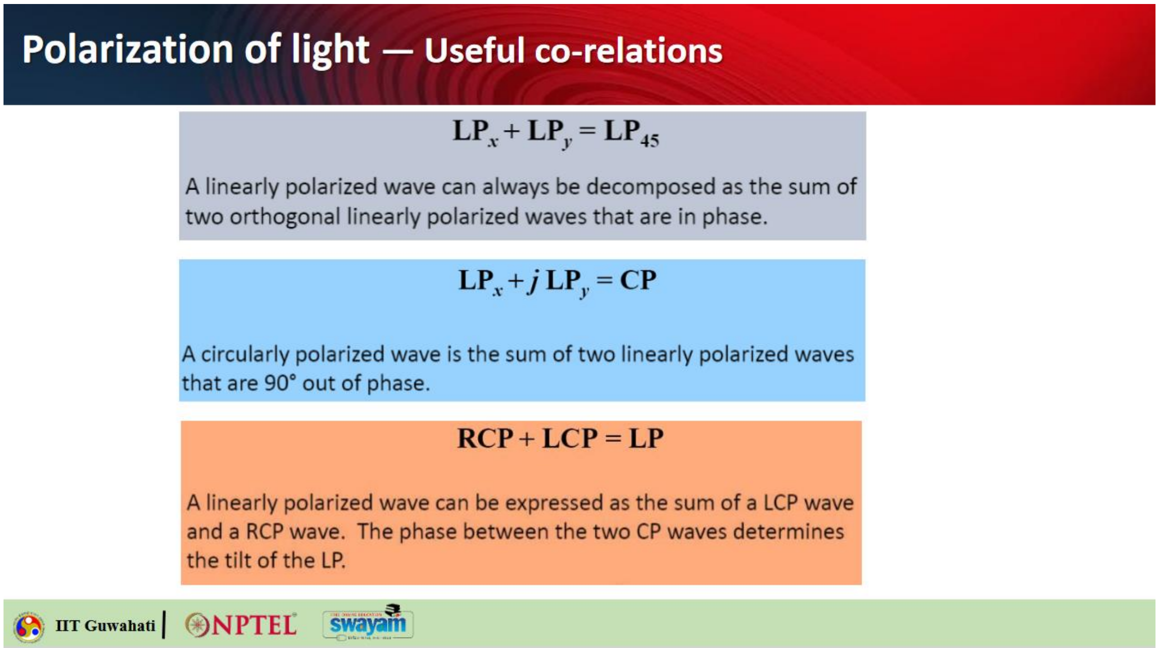
So, this becomes horizontal polarization ok. So, that is nothing but plus minus 90 degree rotated ok. So, this will be the orthogonal polarization to 0 degree polarization it can be plus 90 or minus 90. Similarly, if you take plus 45 degree linear polarization has one state. So, this is plus 45 degree from x axis.

So, this is my x axis this is plus 45 degree. So, on the opposite side you will see you have minus 45 degree polarization. So, these two states are orthogonal to each other ok. Similarly, if you have right circular polarized light ok, the orthogonal polarization state to this will be left circular polarized light and so on. So, this is where the Poincare sphere can help you find out the orthogonal states of a particular polarization. Now, let us look into some useful correlations between these different polarization.

The first one is that if you take linear polarization Lp means linear polarization ok. So, Lp along x and Lp along y if you add these two plane waves you get a Lp along 45 degree ok. So, it means a linearly polarized wave can always be decomposed as sum of two orthogonal linear polarized wave that are in phase. So, this is other way. So, any polarization you can break them into x and y component ok that is also possible.



And if you take x polarization, x polarization and y polarization you get a 45 degree polarization. So, it actually gives you idea about both. Next thing if you take you know one x polarized light and another y polarized light of equal amplitude and if they are 90 degree out of phase you get circular polarized light. Now whether they are you know plus j or it is minus j that will tell you whether it is right circularly polarized or left circularly polarized. And when you add up you know left circularly polarized light with right circularly polarized light you add up you get linear polarization.

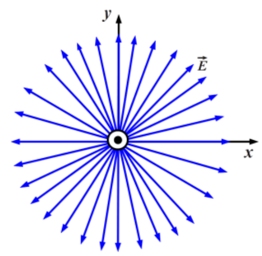


On the other hand you can say that a linear polarization wave can be expressed as sum of LCP wave and a RCP wave. The phase difference between the two circular polarized waves will decide the tilt of the linear polarization. If these two polarization have any phase difference that will tell you whether it will be a 0 degree or whatever will be the degree ok. If they are in phase you will get a 0 degree linear polarization, if they are 90 degree out of phase you will get a 90 degree polarization and so on ok. So, the phase between the two circular polarized wave will determine the tilt of the linear polarization.

So, when you have all these prescribed format of polarization it is also possible to have unpolarized light where there is no specific direction of electric field oscillation those are called random polarization ok. So, we can say if the plane of the electric field changes its orientation randomly, but the magnitude is constant ok. So, it is in the same plane the magnitude is same it is like a circle, but it can be in any direction ok. In that case we can call it as randomly polarized wave or unpolarized EM wave. So, what are the properties here? So, the plane of the electric field and also for the magnetic field will have random you know the plane becomes random as a function of time ok.

Random Polarization

- If the plane of the electric field changes its orientation randomly but the magnitude is constant, it is known as **randomly polarized or unpolarized EM wave**.
- Properties:
  - The plane of the electric field (and so of the magnetic field) are random functions of time.
  - The probability of orientation of the electric field in any direction in the x-y plane is same.
  - The magnitude of the electric field (and so of the magnetic field) at any instant of time is always same.



So, they are random function of time. Second thing is that the probability of orientation of the electric field in any direction in the xy plane is same. So, it can actually lie in any direction and the magnitude of the electric field and so of the magnetic field as well because they are anyways related. So, they are always same at any instant of time. So, this is unpolarized light. So, usually when you get light from any source that those are basically unpolarized light something if you take a LED light source you will get unpolarized light and then you can use polarizer to get polarized light.

Stokes Parameters

- In 1852, Sir George Gabriel Stokes observed that any polarization state of electromagnetic wave can be defined by four parameters, referred as Stokes parameter, and given as

$$S_0 = E_{x0}^2 + E_{y0}^2 = |E_x|^2 + |E_y|^2 \qquad S_1 = E_{x0}^2 - E_{y0}^2 = |E_x|^2 - |E_y|^2$$

$$S_2 = 2E_{x0}E_{y0}cos\varphi = 2\,Re\{E_xE_y\} \qquad S_3 = 2E_{x0}E_{y0}sin\varphi = 2\,Im\{E_xE_y\}$$

where $\varphi = \varphi_y - \varphi_x$ i.e. phase difference between E_y and E_x

- The Stokes vector (**S**) can be represented in terms of **unpolarized (S^n) and polarized (S^p)** parts of light wave as

$$\boldsymbol{S} = \boldsymbol{S^n} + \boldsymbol{S^p} = \begin{bmatrix} S_0 - \sqrt{S_1^2 + S_2^2 + S_3^2} \\ 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} \sqrt{S_1^2 + S_2^2 + S_3^2} \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} = \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix}$$

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Next thing we will try to study here is the Stokes parameter. Now as discussed initially the Stokes parameter has to do something with the polarization as well as the intensity of the light. So, in 1852 Sir George Gabriel Stokes he observed that any polarization state of electromagnetic wave can be defined by four parameters. So, he actually figured out four parameters with which you can describe any polarization state and he named those parameters or those parameters were basically named after him as Stokes parameter. So, they are given as S_0, S_1, S_2 and S_3. So, you see $S_0 = E_{x0}^2 + E_{y0}^2 = |E_x|^2 + |E_y|^2$.

The addition of that S1 is basically the difference between the magnitude square that is basically the intensity you can say, $S_2 = 2E_{x0}E_{y0}\cos\varphi$, phi is basically the phase difference between Ey and Ex. So, you can also write this as twice real of this vector and multiplied by this vector that is Ex multiplied by Ey and $S_3 = 2E_{x0}E_{y0}\sin\varphi$. So, that can be written as 2 imaginary of this product of Ex and Ey. So, these are the 4 vectors which Sir Gabriel Stokes figured out and with that the Stokes vector can be represented. Now Stokes vector can be represented in terms of unpolarized which we write as Sn and polarized Sp parts of light wave.

So, you can say S equals Sn plus Sp and this is how he has defined the unpolarized part and this is how you define the polarized part. So, when you add them together you will see that these are the basically four Stokes parameter S_0, S_1, S_2 and S_3. So, this represents unpolarized light and this can represent any polarization of light. So, let us see the significance of the Stokes parameter. So, as mentioned S_0 gives you the total irradiance, total means polarized plus unpolarized.

S_1 gives you the intensity of the horizontal or vertical linear polarization. So, S_1 is related to the linear polarization which are horizontal and vertical. S_2 gives you the intensity of the linearly polarized waves with an angle of ±45° to the previous orientations and S_3 is related to circular polarization. So, that way he is able to handle all the different types of polarization using these four parameters.

Significance of Stokes Parameters

Stokes Parameter	Optical observation
S_0	The total irradiance (polarized+ unpolarized)
S_1	Intensity of horizontal or vertical linear polarization
S_2	Intensity of linear polarized wave with an angle of +π/4 or -π/4 to the previous orientation
S_3	Circular Polarization

Examples:

- **Linear Polarization along x- or y-axis:** If $S_1 = +1$, the reflected light is horizontally polarized i.e. x-polarized. whereas, $S_1 = -1$ represents y-polarization states of the wave.

- **Linear polarization with an angle of ±π/4:** The parameter S_2 describes the linear polarization in **± π/4** ($S_2 = \pm 1$) with respect to the x direction.

So, let us take some example how it works. So, if you take linear polarization along X or Y. So, you can say that $S_1 = +1$. So, when you say $S_1 = +1$it means the reflected light is horizontally polarized that is X polarized and when you will have $S_1 = -1$ you can say it is vertically polarized or it is Y polarized. On the other hand, if you consider linear polarization with an angle of $\pm 45°$ or $\pm \pi/4$,same thing you only talk about S_2 parameter.

Stokes Parameters

- The ellipticity (χ) can be defined in terms of Stokes parameters as:

$$\chi = \left(\frac{S_3}{S_0}\right) = \begin{cases} 1 & \text{for LCP} \\ -1 & \text{for RCP} \end{cases}$$

- Degree of Polarization (DoP):

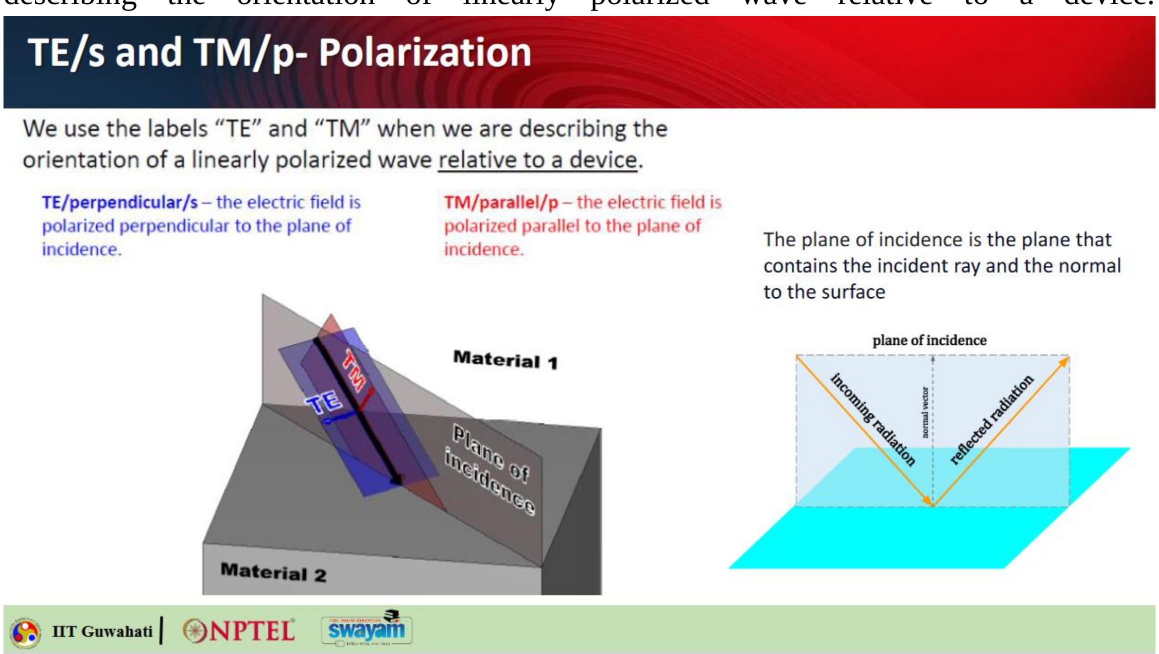
  Stokes parameters can be used to describe to calculate how much the portion of light wave is polarized i.e. Degree of Polarization (DoP), and given as:

$$\text{DoP} = \frac{I_{\text{polarized}}}{I_{\text{total}}} = \frac{\sqrt{S_1^2 + S_2^2 + S_3^2}}{S_0} = \begin{cases} 1 & \text{for fully polarized light} \\ 0 & \text{for unpolarized light} \end{cases}$$

In that case other parameters will be 0. So, the parameter S_2 will describe the linear polarization in $\pm\pi/4$. So, in case in that case $(S_2 = \pm 1)$ with respect to X direction. It means S_2 =1 will tell you it is a linear polarization of plus 45 degree minus 1 will tell you that is a linear polarization of minus 45 degree and so on. There are other terms which also can be you know extracted from Stokes parameters which is ellipticity. So, ellipticity is defined as chi parameter which is the ratio of S_3 over S_1 and when you compute this you can either find ± 1 .

If you find +1 it tells you it is a left circular polarization, if you find -1 it is a right circular polarization. Also you can find out what is the degree of polarization that is it is a Stokes parameter that allow you to calculate how much portion of the light wave is basically polarized ok. As I told you light can have polarized as well as unpolarized components ok. So, degree of polarization basically quantifies how much portion of the light is polarized and you can calculate DoP as intensity of the polarized light over intensity of the total light. So, that you can write as intensity of total light is S_0 and intensity of the polarized light is $\sqrt{S_1^2 + S_2^2 + S_3^2}$.

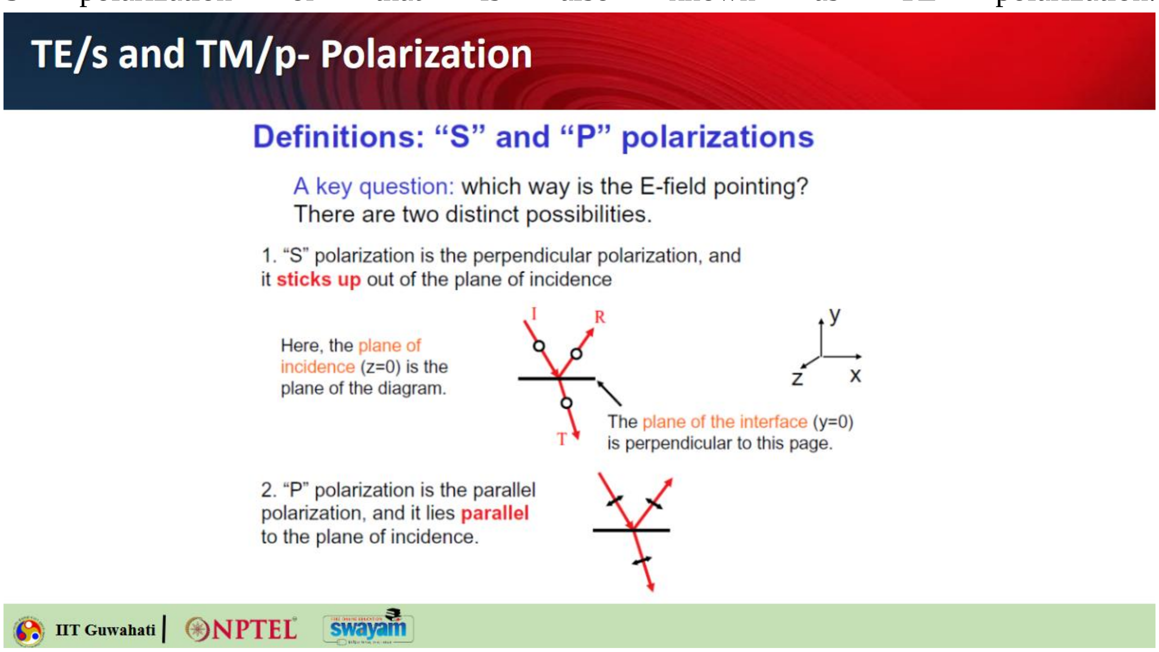
And when you get 1 it means it is a fully polarized light means the entire portion of the light is polarized. And when you get 0 it is a fully unpolarized light anything in between tells you the degree of polarization. So, the last topic of today's lecture will be regarding TE and TM polarization which are also known as S and P polarization. So, let us try to use the labels TE and TM transverse electric and transverse magnetic. And we are describing the orientation of linearly polarized wave relative to a device.



Now let us consider that the wave is basically traveling in material 1 and it is going to enter material 2. So, there is a boundary. So, this is the interface this particular plane is basically the interface. So, the wave is basically incident on this interface.

Now there are two ways the electric field vector can be polarized. So, if you draw the plane of polarization. So, plane of polarization is basically the plane that contains the incoming radiation and the normal to the surface as well as the reflected radiation. So, if you draw a plane like this that is your plane of incidence. So, here this particular one is the plane of incidence. We are not showing the reflected beam, but then reflected beam will also lie in this plane of incidence.

Now in this plane of incidence when the wave is impinging in this way the electric field vector has got two choices. Either it can be polarized along the plane of incidence or we can say parallel to the plane of incidence that is why it is called P, P stands for parallel ok. In that case we call it as TM polarization. The other choice is that the electric field vector can be striking out of this plane. So, we can call it as perpendicular polarization or S polarization or that is also known as TE polarization.



Just to you know tell it with more details. So, S polarization stands for sticks up or sticks out like this. So, you have incident light and this is the interface. So, this screen becomes this screen becomes my plane of incidence. So, incident light is falling in this way it is getting reflected some part is getting transmitted. So, in this case what is happening the electric field is in and out of this particular screen.

So, this one we will call as S polarization. And the other possibility is that when the electric field or any plane wave is falling in this direction getting reflected here some part is getting transmitted the electric field polarization can be along the plane of the incidence that is along this particular screen. So, in that case you see that the upon reflection there is a change in the polarization angle. So, this particular case is called P polarization or parallel polarization because the electric field is parallel to the plane of incidence. This one is called S polarization because it sticks up out of the plane of polarization. So, with these basic concepts here we will stop today and in the next lecture we will study more about reflection and transmission and introduce the Fresnel equations to you.

So, any questions you can drop me an email to this email address deb dot sikdar at iitg dot ac dot in. So, with that I will stop here. Thank you.