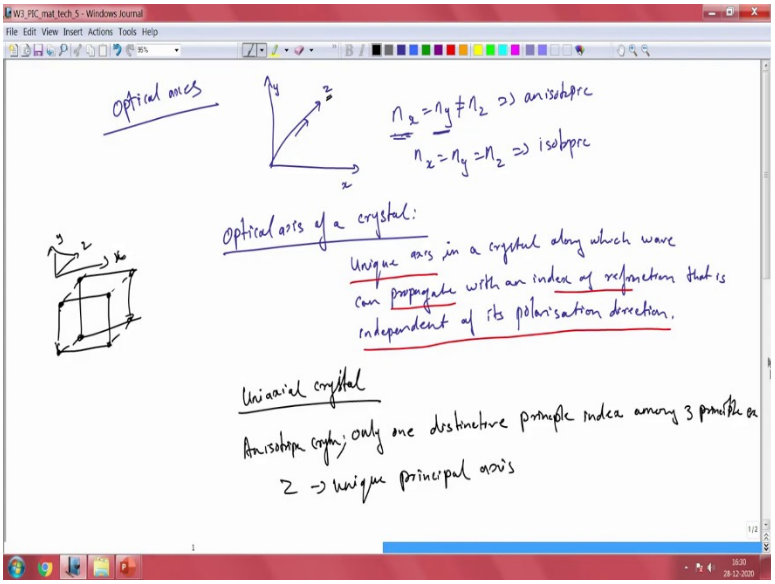
Photonic Integrated Circuit
Professor Shankar Kumar Selvaraja
Centre for Nano Science and Engineering
Indian Institute of Science Bengaluru
Lecture 13
Optical Axes

Hello everyone, let us continue with discussion on the anisotropic medium. So, so far we understood what are the implication of having anisotropy. So, how the dielectric constant the susceptibility influences light propagation. Let us now look at how one can utilize this first of all but before understanding how one can could utilize it, let us look at some of the important concepts in defining the optical axes and light propagation in this anisotropic medium.

So, the way that we do this is by taking the crystal, the material crystal and then defining the axes. So, the coordinate system that we all are comfortable with the Cartesian coordinate system x, y, z, so, it is three dimensional space. And then we are going to convert that into something optical. So, when you move along z, when you move along x and when you move along y. So, how the optical constant of this material is going to change. So, by definition we saw anisotropy. So, that means the material is not uniform with respect to space. So, there could be change in the refractive index when you go along x or when you go along y.

So, based on the direction of propagation your light is going to experience a difference. So, we need to understand how to define this optical axes. So, we know simple coordinate system but then how do we translate that into optical axes and understand the implication of those optical axes on the light propagation. So, particularly we will look at how the polarization will be affected and if a light has mixed polarization what will happen to that propagating light. So, those are the things that we are going to look at in this section.

(Refer Slide Time: 2:45)



So, let us go back and then look at how we can understand this. So, we need to define the optical axes of the material. So, a simple system is something that we all know of this z can define this as x and this as y. So, when we say anisotropy, the anisotropy can be of different kind. So, anisotropy just tells us that there is some direction dependent property change. So, that is all we understand, but in which direction we are, we cannot say. For example, you could have a system where n_x and n_y are equal but it is not equal to n_z let us say.

So, in this particular case the material is anisotropic by definition it is anisotropic the reason for that is not all three are same. So, when you say isotropic this is what isotropic means but then this is anisotropic by definition, but then if a light is propagating along z, along the z direction here, if the light is propagating through this axis that means your electric field is between x and y. So, if it is propagating through z, your field is between x and y, x and y plane.

But when light is propagating through this particular medium by definition it is anisotropy but then when the light is put along z axis it will not feel anisotropy at all. The reason for that is your refractive index along x and y. So, that is where your electric fields are going to be distributed between x and y. So, that electric field will not see any difference. So, the light will feel this medium as if it is isotropic. So, it is very important to understand the situation where the material anisotropy will affect the light propagation.

So, you need to define the direction and so on that is why defining optical axes are different. So, the moment I said okay n_x and y is equal. So, the light that is propagating along z direction will not have any anisotropy effect. But then the moment I said x and y, it is in x, y plane then you would have already guessed that the polarization of light becomes very important here. So, whether the light is E_x polarized or E_y polarized, in this particular case it does not really matter because n_x equals n_y.

So, let us take a scenario where n_x is not equal to n_y in this case you will the light that is propagating will experience anisotropy. So, normally we define this through giving principle axes. So, let us look at what that is. So, optical axes, what is optical axes of a crystal. So, what is this? So, optical axes of a crystal is nothing but a unique axis, it is unique axis in a crystal along which wave can propagate with a refractive index wherein with an index of refraction that is very important that is independent, independent of its polarization direction. So, this is how we define optical axes of a crystal.

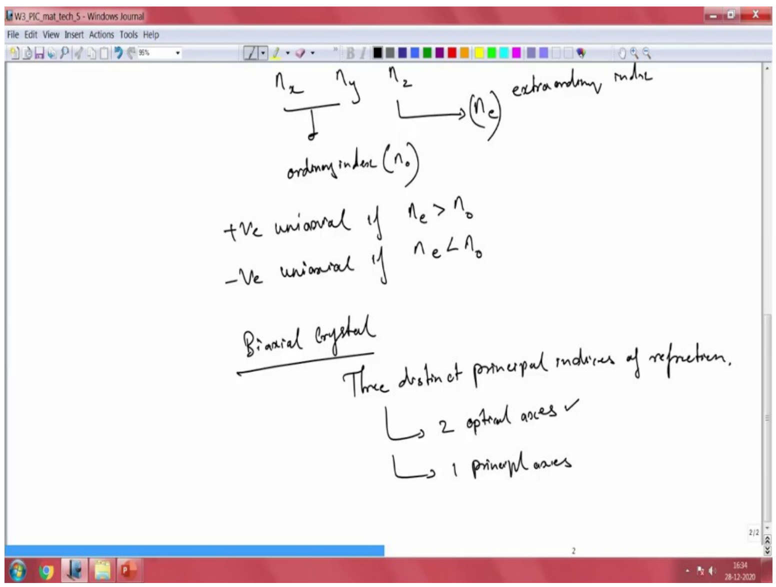
So, optical axes of a crystal is a unique axis. So, it is, it has to be unique axis in a crystal along which the wave can propagate. So, the wave can propagate with an index that is independent of its polarization direction. So, this is how we define an optical axes. So, we cannot randomly choose any orientation, that is a big difference between choosing a coordinate system to represent a crystal. So, when you take a crystal, so you take all these atoms here and perhaps and you will use the position of this atoms and then the orientation in order to define whether this is x, y and this is z direction and so on.

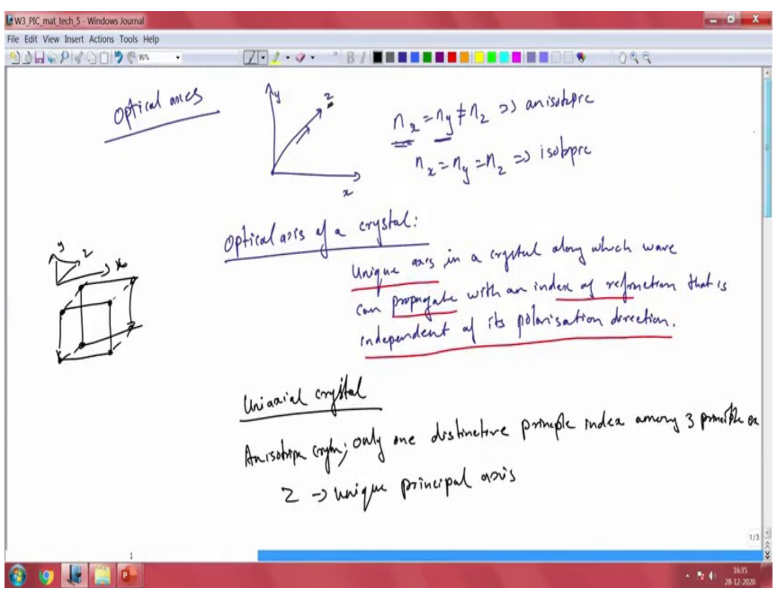
So, this is rather physical in nature but when it comes to optical axes our definition is slightly different, it is not any axis, it is a unique axis that has an index of refraction or refractive index is independent of the polarization of light that is propagating through and when we define this we have different axes, you have three systems here x, y and z and if you have only one distinct principle index let us say.

So, we call that uniaxial crystals. So, what is uniaxial crystal, you only have one distinct principle axis or principle index let us say. So, principle index among three principle axes. So, it has only one distinctive principle axis we call this as uniaxial crystal only one. So, this is material is still anisotropic, any anisotropic crystal, again I should say an anisotropic crystal only one distinct principle axis principle index among three principle axes.

So, this is how we can define a uniaxial crystal. So, you do not have distinct indices in other directions. So, normally this unique direction the principle axis we take z as the unique principle axis, normally z is represented as a unique principle axis. So, now let us look at once we given unique axis z the identical principle indices of the refractive refraction they are called ordinary and extraordinary. So, once we have given define this z as the principle axis we can now define the other.

(Refer Slide Time: 11:52)





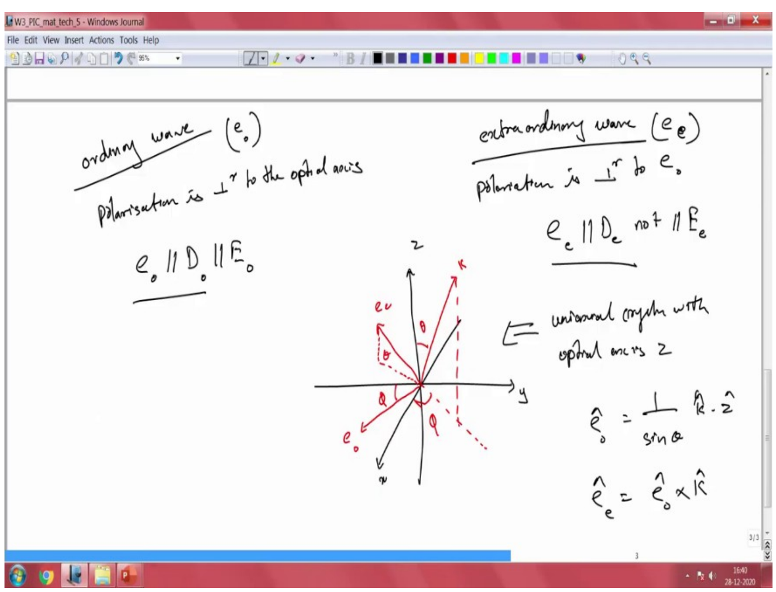
So, now let us look at n_x now n_y and n_z. So, n_z what we call the extraordinary index, this is extraordinary index, both n_x and n_y we call this as ordinary index. So, we can call this as n_o and this is n_e. So, the crystal will have positive uni-axis, this is positive uniaxial, we call this as positive uniaxial if n_e is greater than n_o; we call this as negative uniaxial if n_e is less than n_o.

So, based on the refractive index along the principle axis here that is z, you can define either it is positive uniaxial or negative unique axial. So, here you have to go back and look at the definition here there is only one distinct principle index here, there is only one that is different from the other because n_x and n_y are equal let us say in this case, only n_z is different.

So, the ordinary and extraordinary here is reasonably easy to understand but there are crystals where we could have three distinct indices. So, n_x, n_y and n_z all are different. So, then life is going to be even more interesting. So, you have all these unique coordinates here. So, then we call that as biaxial crystal. So, in uniaxial we only had one unique principle axis, in biaxial we have three distinct. So, you have three distinct indices of refraction.

And out of this we have two optical axes and then we have one principle axis. So, that is z and I know none of these two will coincide with any of the other principle axes. So, that is what this biaxial crystal are about. So, they are all unique in nature. So, once we have this ordinary and extraordinary planes that we defined we can also understand, try to understand how light would propagate in this coordinate system. So, let us try to understand, we call those as ordinary and extraordinary waves.

(Refer Slide Time: 15:40)



So, in a linearly polarized wave, the two normal modes could exist both in ordinary wave or in extraordinary wave. So, let us look at what is an ordinary wave and then we will look at extraordinary wave. So, ordinary wave is nothing but the wave where the polarization it is perpendicular to the optical axes.

So, here the polarization is perpendicular to the optical axes. So, this is called an ordinary wave and we use e_o for this. And here the polarization is perpendicular to e_o here. So, here this is the polarization is actually perpendicular to e_o. So, this is e_e. So, this is your extraordinary wave. And here the direction of these waves, when we say direction of polarization we primarily mean the e, the electric field e here and the direction of this D is also very important that we will just shortly see.

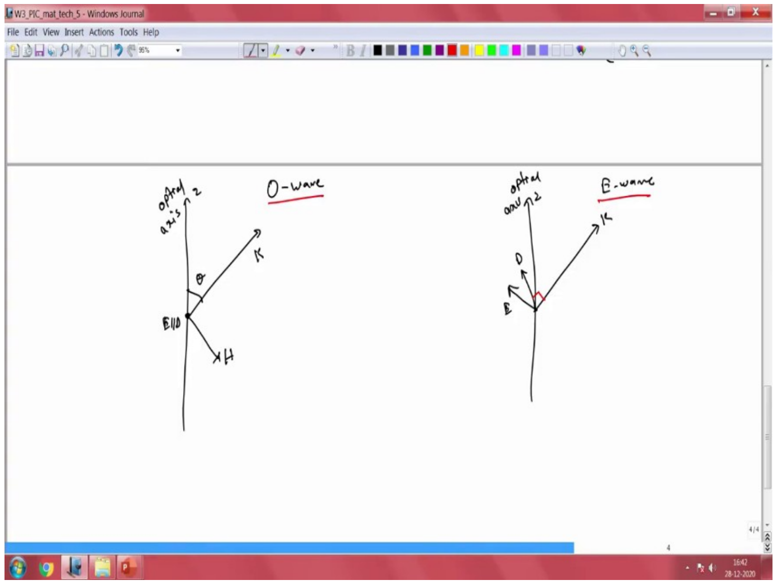
So, the easiest form to write this is e_o is parallel to D_o which is parallel to e_o. So, for an extraordinary wave, so your e_e will be parallel to D_e but not parallel to E_e. So, this is something that you should try to understand. So, both e_o and e_e being the unit vector. So, they are nothing but unit vectors of D_o D_e.

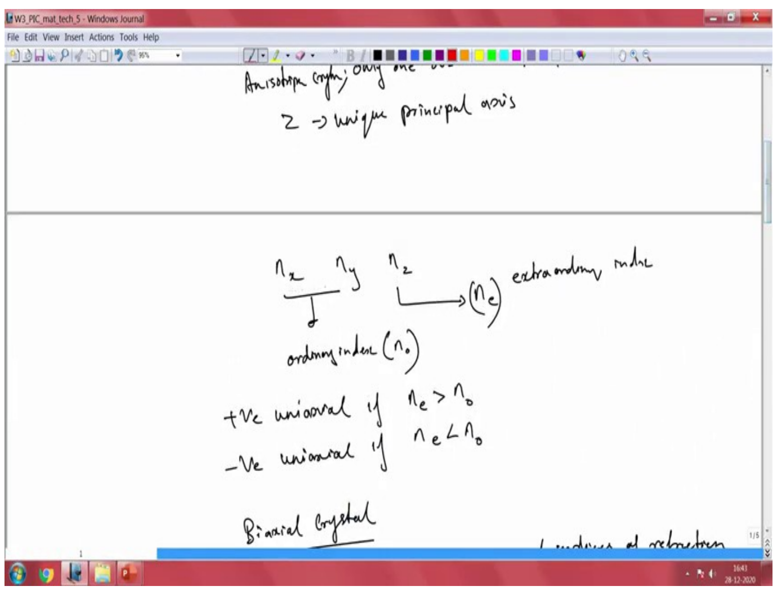
So, that is why they are perpendicular to the direction of propagation here. So, that is why they are parallel all the time but they are perpendicular to the propagating vector or propagation constant, direction of propagation that is k. So, for a uniaxial crystal let us try to map this how one can understand this let us say this is z and let us say this is y.

So, an ordinary wave. So, this is say x. So, your ordinary wave is here let me pick a different color. So, this is your ordinary wave that is having an angle ϕ and then you have an extraordinary wave that is your c and this has an angle Θ to this and we all know that it is the propagation direction k here and this angle is again Θ and this is perpendicular, this angle which is between this is nothing but again ϕ. So, this is ϕ let me take this out, this is ϕ.

So, this is for a uniaxial crystal with the optical axes z. so, this is nothing but uniaxial crystal with optical axes along z. So, now the unit vector e_o as you can see, you can write it as $e_o = \frac{1}{\sin(\Theta)} \hat{k}\, \hat{z}$. So, that is hat and we all know one can write at this way. So, both the ordinary and so this is extraordinary, ordinary and extraordinary wave can be found if both k and the optical axes are known. So, if the k and if the direction the optical axes then we should be able to find e_e and e_o . So, that is rather straight forward.

(Refer Slide Time: 21:24)



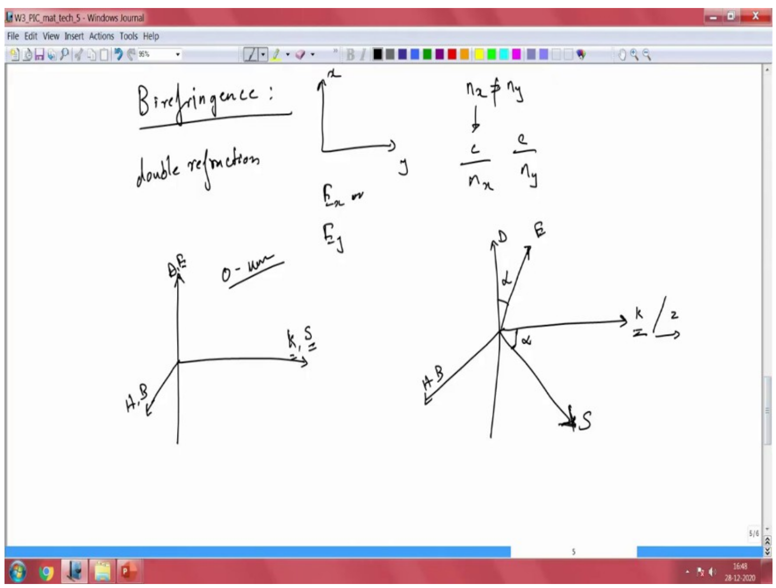


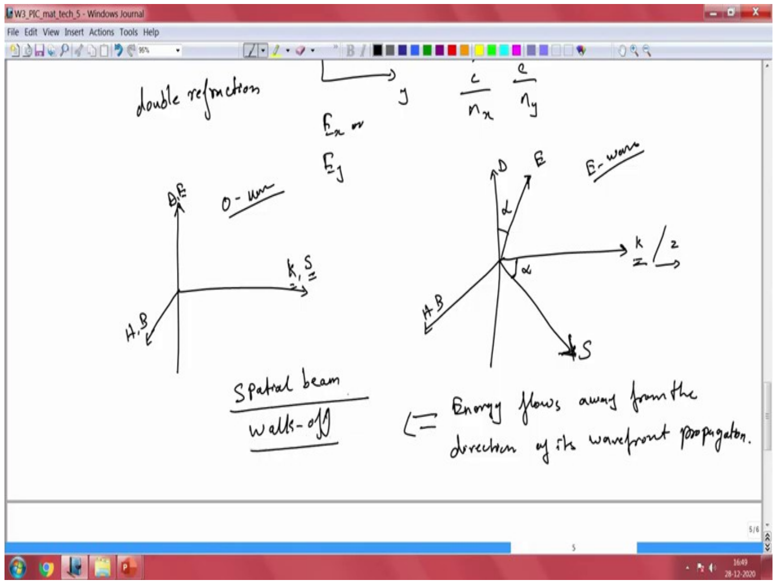
So, let us look at little bit more here you can use this to understand the two waves here. So let us take a plane. So, this is your optical axes z here and then you have another for ordinary optical axes z. So, we have O wave let us say this is E wave. So, now for O wave so, this is, so E is parallel to D but then perpendicular to here and it makes an angle **ϴ** and this is your k and this is our H.

And then if you look at the extraordinary wave the direction of propagation is all fine this is again the same, but then the electric field is in this way and you can see D is not parallel. So, it has a certain angle to it. So, extraordinary wave has a vector D that is normal to k. So, this is the D is normal to k and lies in k-z plane but H-E is not parallel to D in a extraordinary configuration. In ordinary wave configuration both E and D are parallel and H is perpendicular to your k.

So, that is something that we should keep in mind when we are talking about ordinary and extraordinary waves in uniaxial crystal. So, let us move on and then see what happens if you have a more interesting biaxial crystals or the refractive index of n_x and n_y, that we saw here are equal but then let us look at situation where you have three different refractive indices.

(Refer Slide Time: 23:50)





So, we call that as double refraction. So, let us look at material where you have two modes or two different refractive indexes. So, we call that as material with birefringence. So, birefringent material. So, birefringence is nothing but it is an anisotropic medium that supports two distinct axes where you could have two different phase velocities for example.

So, if the light is moving in x and y, so you have n_x and n_y. So, you have n_x is not equal to n_y. So, this will eventually result in let us say speed of light is going to be different here. So, n over n_x and n over n_y now. So, because of these two different phase velocities you have two different refractive indices which causes two refracted waves and the polarization of your electric field whether you are in E_x or E_y that we discussed earlier will have a very strong interaction and effect on this wave propagation. This effect of having two refraction, it is called birefringence or you call it as double refraction.

So, either you call it as birefringence or double refraction both are necessarily the same. So, now let us look at the field vectors that we introduced in anisotropic medium. So, we can take D E this direction. So, light propagating here. So, the pointing vector S is here and then the perpendicular is H and B. So, this is ordinary configuration. So, why we call it as ordinary? The propagation direction is where the wave is propagating through. So, k is the propagation here S is the pointing vector, where the energy is going.

So, let us look at the extraordinary k's here. So, this is k. So, this is D and you have H and B will not have an effect but we already know from our earlier understanding E and D are not going to be parallel. So, you will have a certain angle to your E. So, they are not going to be the same direction. So, because we have E having not aligned with the principle axis here what you expect to see, so this is O.

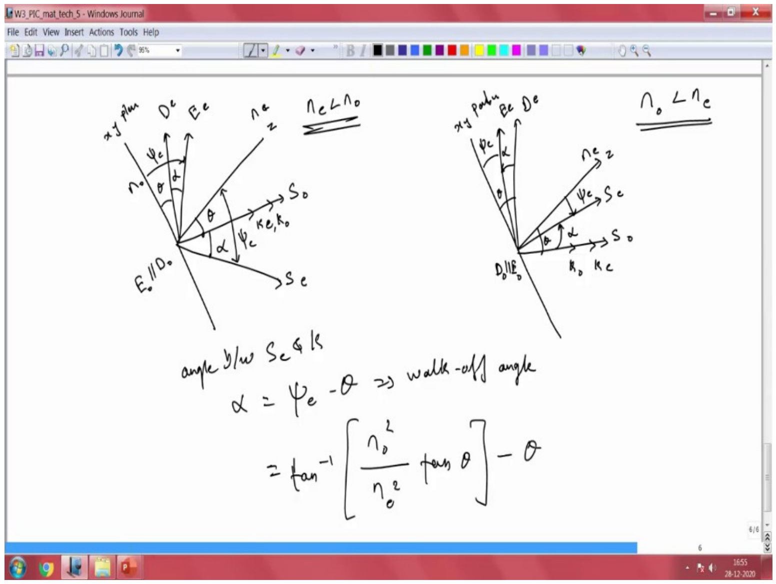
So, what you expect to see is your k, or sorry your pointing vector will have again an angle alpha with respect to the direction of propagation. So, now you can see the direction of propagation is along this k, in other words you can also call this as z if that is giving you some imagination here. So, the direction of propagation is along this z but then look at the energy. So, the energy is not flowing in the direction of propagation.

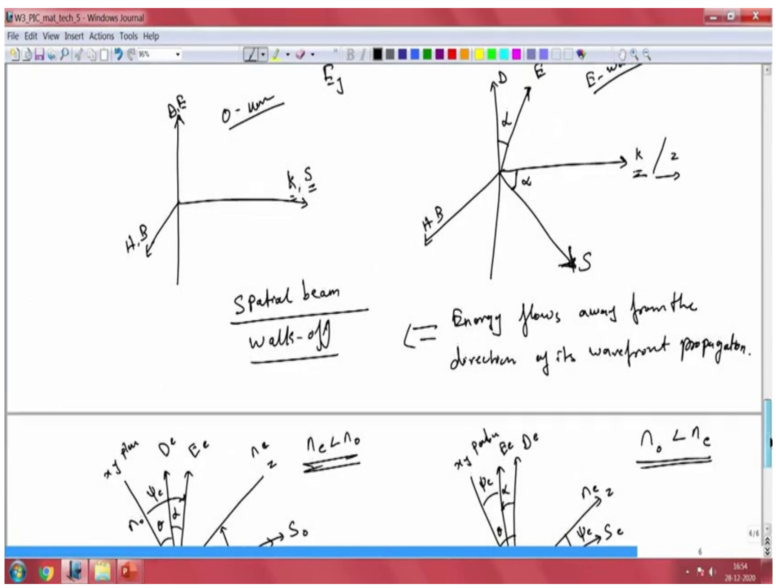
So, the energy is now propagating at a certain angle alpha, it is deviating from the actual propagation direction. So, this is something very interesting and this could give rise to some interesting application. So, one can exploit this angle with respect to your principle axis to create polarization dependent propagation. So, let us look at what that is, if the electric field of an extraordinary wave is not parallel to the principle axis, if it is not, its pointing vector will not be parallel to its propagation direction that is what we are trying to say.

So, the energy is going to go away from the direction of its wave front propagation. So, to summarize this the energy flows away from the direction of its wave front propagation. So, these phenomena of moving away from the direction of propagation is called spatial walk off, spatial beam walk off or a spatial walk off, because it is moving away.

So, if this particular separation happens in an anisotropic crystal then the optical waves will split into two different beams one of the, one in along the propagation direction one coming out at a certain angle alpha. So, what will be that alpha is the question here. So, let us look at how one can arrive at this particular alpha again I will go to this similar to what we saw in for the uniaxial crystal let us look at the spatial walk off in this birefringent material.

(Refer Slide Time: 31:00)





So, we can take this as x, y plane, so, you have z. So, this is your n_e, in this case n_e is less than n_o let us say and we have extraordinary here and D_e here and it has as I mentioned. So, here we have S_o and this is S_e. So, k_e and k_o are all same. So, they are in the same line. So, this is nothing but Θ that we have and this is our α. So, the same thing here this is Θ and this is α and the angle between this n_o that is what we have and our e is ψ_e and here this angle that we have is ψ same thing and this is nothing but your D_o which is parallel to E_o.

So, this is the condition when the extraordinary refractive index is less than n_o. So, if we take another scenario where your n_o is less than n_e. so, the positive and negative uniaxial crystal we saw that. So, here the situation slightly changes x, y plane here again you have z and extraordinary is here and then we have S_e and then S_o. So, here k_o k_e along the same line.

So, here this is Θ and this angle now is α and this is nothing but ψ_e. So, now since we have moved this way you have D_e and then we have e_e again same thing. So, ψ_e here. So, this is Θ and then this is α and here D_o parallel to E_o . So, this is positive and negative crystal planes that you can have whether it is n_e is greater or n_o is greater. So, this gives us how our electric field is oriented with respect to the crystals that we talked about now one can actually find the walk-off.

So, the angle α between S_e and k. So, S_e and k which is defined as α. So, that alpha. So, this is angle between S_e and k. So, alpha is nothing but ψ_e - Θ. So, this is what we call walk off angle we saw this α here. So, how far this energy is going to deviate from where you from the propagation direction. So, that is our α. So, α is also angle between e_e and D_e. So, α is nothing but angle between D_e and e_e.

So, let us look at what this actual α is. So, this is nothing but $\alpha = \tan^{-1}[\frac{n_o^2}{n_e^2}.tan\Theta] - \Theta$. So, your

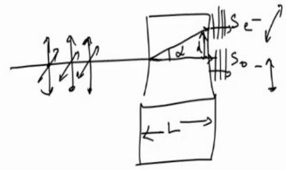
ψ_e = $\tan^{-1}[\frac{n_o^2}{n_e^2}.tan\Theta]$. So, let me write it again tan theta. So, this should give us how far the spatial walk off will be. So, why this is interesting, why are we interested in understanding this deviation we can actually exploit this difference in the propagation direction for polarization splitting.

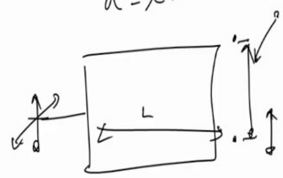
(Refer Slide Time: 36:30)

Polarization beam splitter

Beam separation

$$d = l \tan \alpha$$

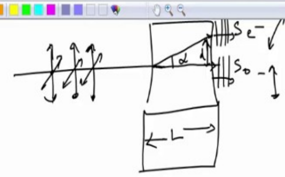


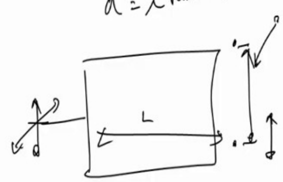


- → Wollaston prism
- → Rochon prism
- → Glan-Thompson prism

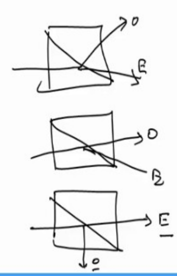
Beam separation

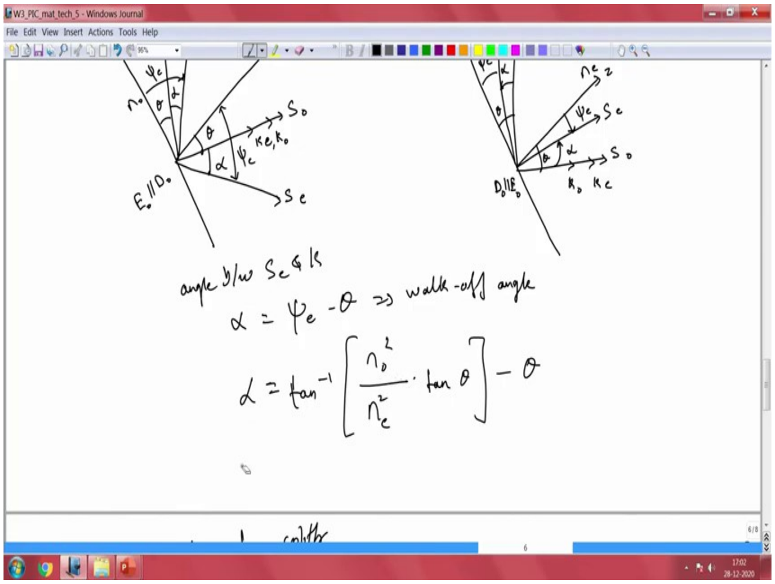
$$d = l \tan \alpha$$





- → Wollaston prism
- → Rochon prism
- → Glan-Thompson prism





One interesting application is so polarization beam splitter. So, what a simple block diagram would be. So, I have waves that are polarized in a certain way and when I go through this based on the polar, the angle at which I hit I could have a light that is passing through that is the ordinary. So, that is S_o and then I could also have a light that is coming out that is S_e. So, you will have this splitting of this.

So, this is the polarization beam splitter, at what angle it is going out is basically defined by the alpha that we just saw. So, it has to move a certain distance L in order to do this spatial movement but based on the length you can spatially segregate these two waves separately. So, this is used in lot of quantum photonics implementation of lot of gates and information processing where you want to take a photon and then you want to split it.

So, you have a bunch of photons coming in with a certain polarization then you want to split it. So, the how do we split it is by using this particular technique of spatial splitting and the wave fronts are coming here and in this case it will be aligned in plane and in this case maybe I should put it like this and like this. So, vertically aligned and also horizontally aligned. So, you can have waves like this. So, there are two polarization coming in and you can split this polarization based on this.

So, how far you can split them, let us say d is the distance between the two waves and the distance between or let us say beam separation is nothing but $d = l \tan\alpha$ here. So, if you want them to be separated reasonably far enough then you have to increase the interaction length. So, if you increase the length of interaction we should be able to separate the two polarization. So, you will get this polarization here and get this polarization here.

So, this is how you can exploit the property of this anisotropic crystals for multiple application. There are few specific crystals and geometries one can use based on the material. So, you can you must have read something called Wollaston prism is one, Rochon prism and then the other one is some more famous Glan-Thompson prism.

So, all these prisms configurations actually split the polarization, for example, the WP, it is a prism configuration like this. So, where you will get an ordinary wave here and extraordinary wave like this and then in the other configuration again you would have ordinary wave here and then the extraordinary wave here and in Glan-Thompson configuration perhaps you must have done this in introduction to photonics or optics courses.

So, you have very large difference. So, this is ordinary and this is extraordinary. So, this is Glan-Thompson at the bottom, then you have Rochon and then you have Wollaston. So, you can see here why Glan-Thompson is much popular, the reason for it is I know there is 90 degree shift in the direction of propagation. So, it is orthogonal. So, when you are putting a beam splitter, polarization beam splitter it works reasonably well when you are organizing your optics.

So, here you have to rely on the distance. So, you have to put your detector or next optics far away to have the required spatial separation, but in a Glan-Thompson prism it is much simpler because it is inherent to it to divide the light and divide the polarization orthogonally. So, one can use this beam walk-off technique or phenomena in order to split the beam and we saw what affects the splitting, it is primarily the difference in the ordinary and extraordinary refractive index.

So, the larger the difference, the better your splitting angle is and for a compact device you should be able to have larger walk-off. So, with that we came to an end to this particular topic of understanding anisotropy in materials and how one can understand this anisotropy and use this anisotropy for our own good, various interesting application one can develop but that is not the end.

So, we are going to use this in our integrated optical waveguides and devices an exploit these properties. So, right now we only saw the passive properties. So, once you bring in the electrooptic properties of this material it becomes even more interesting which is something we will discuss later on in the other sections of this course. Thank you very much for listening.