Introduction to Photonics
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Light manipulation-Birefringence

Okay good morning welcome to introduction to Photonics, so in our last lecture we were talking about finding ways to manipulate light, properties of light and before we did that we said okay let us first understand how light propagates through a medium, so we went through this mass spring model and came up with picture of how the permittivity or how does medium respond to an incidental electromagnetic wave, so the response we saw could be complex in nature and it is also something that is frequency dependent.

So we identified that the real part of the permittivity which provides the refractive index of the medium is not constant and it goes through certain resonances and those resonances we saw that the imaginary part actually becomes maximum, so that provides absorption is in the material and then we went on to look at what are the possible ways that we could manipulate light that this propagating through a medium and the 1st one that we were considering is polarisation.

So we went through just brief introduction of what polarisation of light means that we could have in linear circular or elliptical polarisation and then we took example of 2 crossed polarisers or rather polarise and analyser which is rotated around its axis and we said that actually goes through a cos square function, the transmitted light goes through a cos square function with respect to the rotation angle and that is what we call as Malus law and one example of where this could useful we said was in liquid crystal displays and the said liquid crystal display are such that when you apply a voltage it rotates the polarisation of light and then your analyser could be set such that the rotation corresponds to maximum transmission right, so initially you may not have any cancellation but upon voltage to this liquid crystal cell you could rotate the polarisation and you can maximise the transmission, so you can turn light on or off in a voltage controlled manner with this simple.

So we will move along today and we will consider ways of manipulating the polarisation of light itself.

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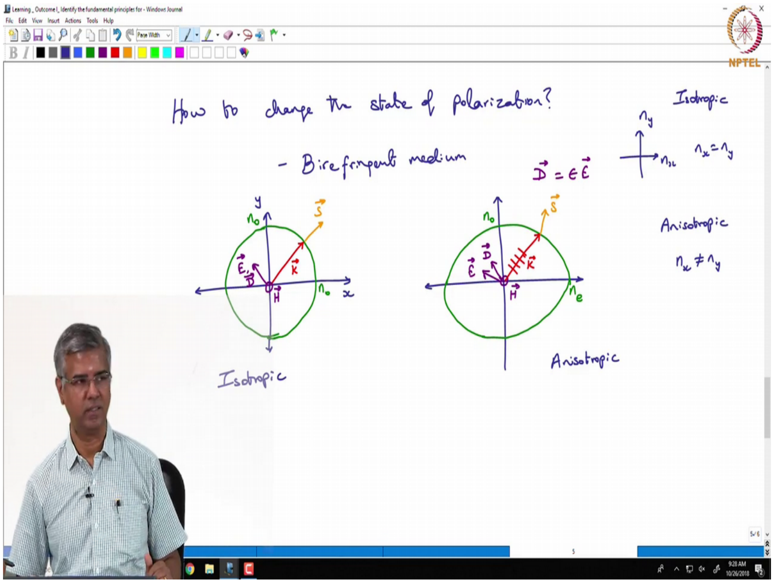

So let us look at how to change the state of polarisation of light? So is it possible to convert say linear polarisation to circular polarisation or can rotate the polarisation of light if we have a liner polarisation at a particular angle can you actually rotate it to 90 degrees and so on, so how to change the state of polarisation of light? To do that what we need to consider is Birefringent medium, so what do I mean by Birefringent medium? So far most of whatever we have considered we said that our response of the medium to an electromagnetic wave is isotropic in nature, so what does that mean? If it is isotropic then if you say this nx refractive index and this is and ny.

For isotropic medium nx equal to ny n equal to nz if z is the direction of propagation, so the refractive index is the same everywhere but a Birefringent medium is actually anisotropic medium in which case nx is actually not equal to ny okay, so when nx is not equal to ny the light that propagates through the material depending upon the polarisation of the light whether it is oriented along way x direction or y direction it is actually going to go through different phase change or it is actually going to go at the different velocity right, so what happens in those cases? You know there is some interesting propagation in the principles that we can study with this sort of material.

So if you go back and look at once again an isotropic material say this is along the x direction, so this is x and this is y direction and if we consider the refractive index, the refractive index is uniform everywhere, so that the refractive index we can call n naught no okay and in this sort of a case if we consider wave vector like this okay, wave vector will be supported by certain electric and magnetic fields right so let us say the magnetic field is perpendicular to that so the electric field will be perpendicular to both the magnetic field and the direction of propagation and if you consider the displacement vector which is Epsilon times e that will also be in line with the electric field, both of them are parallel to each other and in this sort of a case if you look at both the k vector as well as your pointing vector, pointing vector denotes the direction of energy propagation right.

So the k vector and the pointing vector are one and the same that is what we have been looking at all along in electromagnetics and so far in Photonics also so they are all lined up with each other okay. So this is for a isotropic medium but when you consider and anisotropic medium okay the refractive index is not the same everywhere, so the refractive index would be different along different directions okay and it may be a long one direction, it may be with the same refractive index as the other case but in the other direction the refractive indexes is different we call that ne.

Now in this medium if you look at let us say once again the magnetic field is like this and if you look at the electric field let us say this like this but when you look at the displacement vector, the displacement vector depends on the relative permittivity of the material okay along that particular direction and that relative permittivity gives rise to the refractive index of the material right, so the refractive index is different and as a result of which because it is actually sort of an index ellipsoid that we have the displacement vector is not parallel to the electric field vector okay because the response of the medium is different, there is a question.

Student: (())(10:30)

Professor: Sorry d?

Student: (())(10:33)

Professor: No, so the question is, is it not d independent of the material, d is defined as Epsilon times e right and Epsilon is Epsilon naught, Epsilon r is the relative permittivity which is given by 1 plus susceptibility and that susceptibility is proportional to the displacement that is what we saw yesterday, so de is actually dependent on the medium, the response of the medium, e is the applied electric field but b depends on the medium. In this case what is interesting is the k vector is given by d cross h, so the k vector will be like this okay but your pointing vector is e cross h conjugate to be specific.

The pointing vector is actually slightly off, so your pointing vector is like this that corresponds to the energy propagation whereas your k vector which talks about how the phase fronts are moving in the direction in which the phase fronts are evolving that is different, so this is a key point to note in an anisotropic material. In an anisotropic material the direction of energy propagation and direction of phase evaluation is not the same, may not be the same I will come back to specific cases where they are saying but it may not be the same.

The specific cases where they are the same is probably if you are going against the…if you are going along the axis then you can say either the major axis and the minor axis then you can say that both k and s are oriented along the same direction but if it is going at some other angle k and s need not be the same okay and that is giving rise to some interesting effects okay which is not so intuitive, so one of the effects is now we need to go back and look at Snell's law. Sorry there is one more question.

Student: (())(13:26)

Professor: Okay.

Student: (())(13:31).

Professor: No, okay so he is talking about for coulomb's force it is dependent upon Epsilon, right? Yes in the coulomb's case it is dependent upon the medium but… Electric field could be anything that you apply to the medium, right? Electric field is an independent parameter that is your cos, the effect is d okay. The cos could be because of you know the specific case where you are talking about coulomb's force there are actually 2 charges that are interacting and the force between them defined by the coulomb's force and that coulomb's force may be dependent upon Epsilon okay. Please do not confuse that with what we are talking about here, here we are talking about electromagnetic wave being the excitation and the response of that medium is this quantified through d which is again quantified through Epsilon. Is there some other question?

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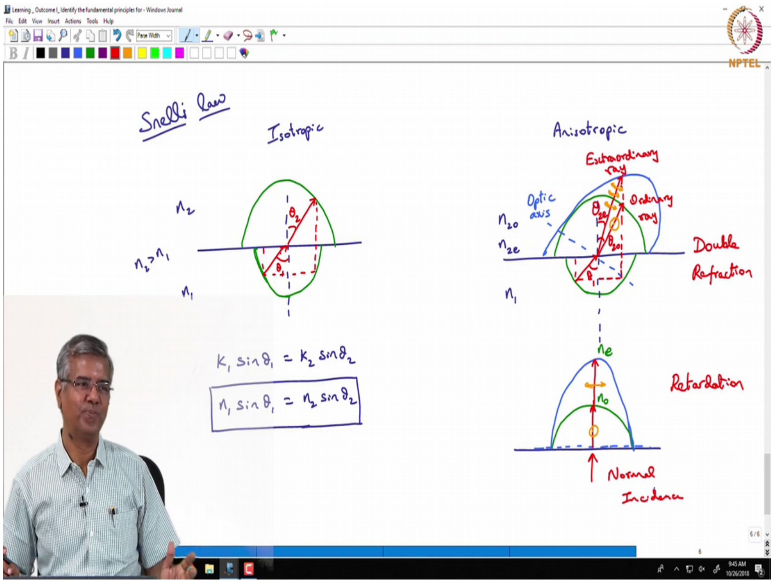

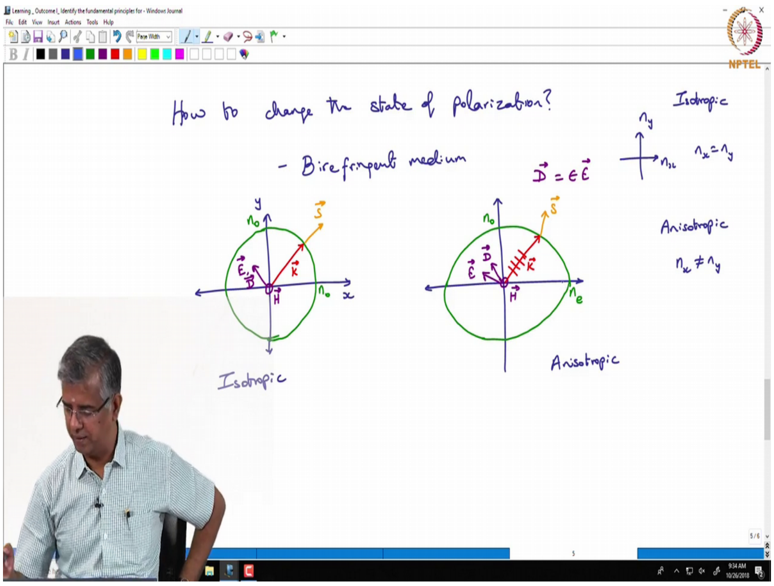

Okay so let us actually revisit Snell's law okay and we did not quite have this picture of Snell’s law when we originally talked about it but let us just look at this picture, it says you have light going from one medium to another n1 to n2 and let us say n2 is greater than n1, so in this medium if I define the constant phase fronts and let us say a normal is somewhere over here.

If I define the constant phase fronts then this medium that is actually a spherical way front right if you have a point excitation then the wave actually spreads out in a spherical manner right it is a isotropic material, this first material and let us say to start with that the 2nd medium is also anisotropic medium, so in that case also you expect to have a sphere but in this case if the sphere will have a larger radius because n2 is larger right, so this k value, the momentum actually is larger in that case.

Now if I have wave that is incident on this medium at an angle let us say theta 1 okay, how do you figure out theta 2 to basically say okay this is got to have a component along the surface that is what you call as a tangential component, so the tangential component on both sides have to be equal, so which means that if I project this to the 2nd medium then you have… where it needs this constant phase front right that defines your data 2 okay, so you write this as k1 sin theta 1 equal to k2 sin theta 2 okay and because those represents the tangential components and then that gives you n1 sin theta 1 equal to n2 sin theta 2 right. That is the Snell's law that we took up right up front this is what we use across interfaces.

This is what we use across interfaces separating isotropic material, rights so that is okay so this is isotropic material. Now consider the same for a anisotropic material, so you still have n1 representing isotropic material but n2 now is characterised by 2 different refractive index right, you can have n20 which corresponds to an ordinary wave okay and you also have n2e which corresponds to an extraordinary wave meaning if in one direction it is seeing just an index in isotropic material that corresponds to an ordinary wave but now we have this other case that in the other direction it might have a different refractive index and in that direction you were actually have this extraordinary wave come into the picture okay.

So if you draw the phase fronts once again this is for the 1st medium and then this is for the 2nd medium along one direction okay but in the other direction you have refractive index that is changing, that is changing with respect to the different access. Now for that direction you have essentially an index ellipsoid that is defined by this, so the index ellipsoid is such that in this case you have what is called the optical axis, the optical axis in this picture corresponds to the watercolour line okay it is the optical axis will be perpendicular to the direction of the extraordinary refractive index okay.

So let us say the optic axis is like this so my extraordinary index at this point is corresponds to ne, so in this case if you do the same thing that we did before right you have basically a wave that is incident to this material, so you project the tangential components. You find that the tangential components you know it needs this phase front, the two different points in 2 different directions. So in this case you have one wave that needs one wave front in one direction okay that we can call it as…this angle we can call theta 2 O okay but that is one more in a perpendicular axis okay that…the perpendicular polarisation sees a different medium effectively okay.

So if I have this polarisation it sees this normal medium but if I have this polarisation, this polarisation sees a medium which is Birefringent which actually has that index ellipsoid, so that medium will satisfy Snell's law in a different manner okay. If you project the tangential components then you have this angle which we can call it as theta 2e okay which is also called the extraordinary ray, so this is called the ordinary ray because it acts in the same way as you would expect any isotropic material to respond that is called an ordinary ray but the perpendicular polarisation will actually correspond to this extraordinary ray okay, so octagonal polarisation will corresponds to the extraordinary ray okay.

So you have 1 wave hitting that interface and that actually gets split into 2 waves okay each of them having a different direction okay you understand that. Now of course if you have a case where the optic axis, the optic axis is like you take a material and you define in to the Birefringence, so you say okay in this axis is n naught in this axis is n naught in this access it is ne okay it is up to you as to how you cut that material, so the optic axis is defined and then depending on how you cut that material, that material will have an interface like this.

To give you an example you can cut the material such that that interface where you have cut corresponds to your optic axis, so it is basically parallel to the optic axis right both the optic axis and how you have cut are essentially parallel to each other. Let us see how things work in this case, in this case you basically have your ordinary wave experiencing something like this but for your extraordinary ray that would be something like this right it will see a different refractive index but in this case quite interestingly if you look at wave that is going straight down right.

If you have this condition your extraordinary ray will be aligned with your ordinary ray both of them are going through the same direction because you cut your optic axis such that extraordinary ray is actually passing through one of the axis of your crystal okay and so both the ordinary and the extraordinary rays they go through the same direction. They go through the same direction but what happens in this case? What can you say about the speed at which light propagates for the 2 different polarisations?

Student: (())(27:19).

Professor: They will be different right because one is seeing this n naught and the other one is seeing ne as the effective index, do you understand that? So depending upon how you cut the crystal whether you cut it along the optic axis or at an angle with respect to the optic axis. In this case if you have cut it at an angle with respect to the optic axis you have phenomena call double refraction meaning you come in with one-way but you go out with 2 ways right so you have double refraction happening in this sort of case whereas if you cut it across the optic axis then you have only one direction of the way but in this case you have what is called retardation happening meaning the phase between the 2 polarisations let us define the polarisation.

So the polarisation is such that your vertical polarisation will be your ordinary ray and your horizontal polarisation will correspond to the extraordinary ray okay. So here again this is your vertical polarisation whereas horizontal organization correspond to the extraordinary ray and that sees a different refractive index. So you have retardation happening between the 2 polarisations components. In the 2nd case if we have…you are asking if…

Student: (())(29:36)

Professor: Yes this is actually only for the…so the question is whether the direction would be the same irrespective of the incident angle. No no this is actually the direction for normal incidence, if you have for oblique incidence you have to go back to this picture and then say okay where does the tangential components, where does the momentum matching happen and you draw that line corresponding to that you will actually find that it corresponds to 2 different points at which they meet, so you will have double refraction for the case of oblique incidence but the case of normal incidence and if the optic axis is aligned with the things so that ordinary and extraordinary refractive index they are different but the orientation is actually the same. Then you have this retardation…you do not have double refraction but you have retardation. Now you may want to ask what happens if you have normal incidence but your optic axis is at an angle with respect to the interface, what do you think will happen?

Student: (())(31:19)

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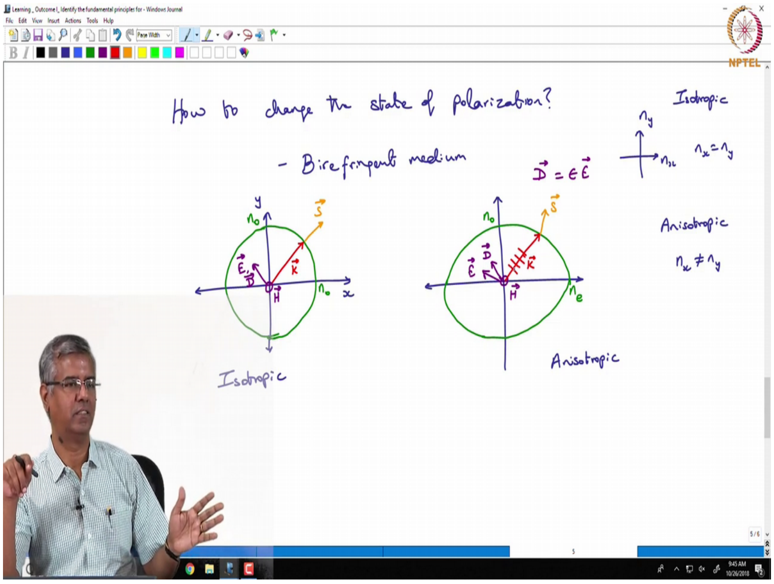

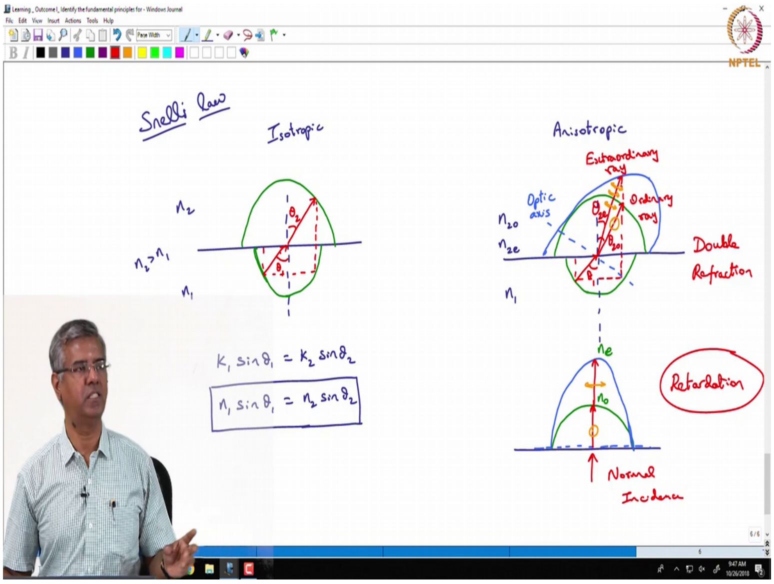

Professor: So what we talked about here is that the k vector will be aligned right the k vector will be aligned so it is all normal but since the optic axis is at an angle your energy direction your pointing vector will be of axis, so in the case where you have a normal incidence and the optic axis not aligned like this, optic axis making an angle with respect to the interface you would still see double refraction that is actually not very intuitive right to say normal incidence Snell's law tells me that I should have only normal beam going out but because of the fact that the extraordinary ray your energy vector the pointing vector is not aligned to the k vector right you have phase front that are aligned in the direction of the normal incidence but your energy direction is off from that.

So you will actually see if you see a dot through one of these materials right you will actually see 2 spots 1 spot in the centre corresponding to the ordinary wave and the other spot corresponding to the extraordinary wave and you can actually rotate that crystal we will show that in the lab today. You can rotate the crystal and you can see that extraordinary…the dot corresponding to the extraordinary ray will actually rotate, so there will be one central dot which will not rotate but the other dot will rotate.

So that corresponds to normal incidence but you have a condition where the optic axis is cut at an angel with respect to the surface okay. Now let us quickly look at one example and then we will stop, so based on this principle based on this retardation principle you can actually make components which changes the polarisation of light okay and that is what you wanted to look at.

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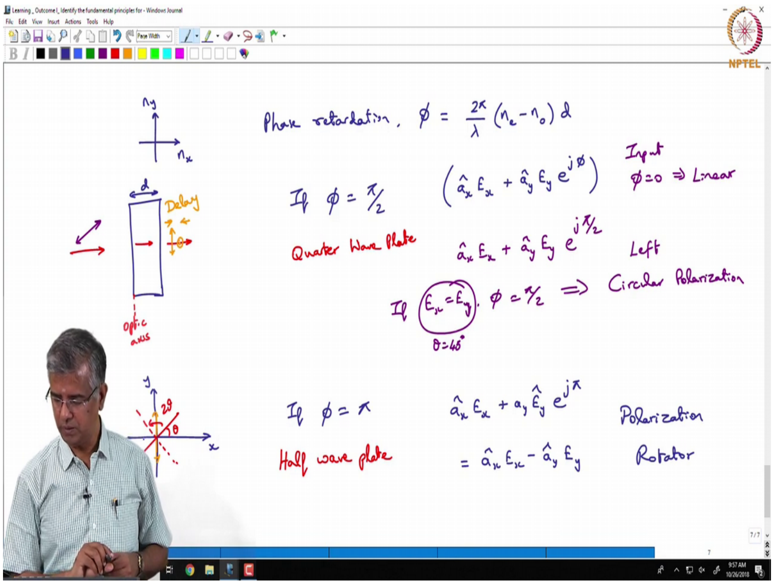

So now you have let us say…now what we are saying is you might have nx like this ny is like this, if nx is not equal to ny then the polarisation components aligned across the x and y direction they are not propagating with the same velocity, so that means there is actually a phase retardation between them let us call it 5 and this is going to be defined by 2 pi over lambda ne minus n naught multiplied by how much it propagates right, so if you have let us say a material like this right and if you have a wave that is incident on it normally and let us say the optic axis is like this has been cut like this.

So we expect both the ordinary and extraordinary ray to go through this directly straight but in this case they are saying to different refractive index okay let us say the thickness is d, so as it propagates through this it is going to accumulate phase difference that is given by this. Now for a given material ne and n naught if you say calcite is an anisotropic crystal, now for that ne and n naught are fixed then lambda corresponds to the wavelength that you are coming in by changing d you can change the phase delay between the 2 polarisations components okay so in this case what we are saying is your 2 polarisation comments are going to be like this they are actually delayed there is a phase delay between the 2 okay because of the propagation they both come out in the same direction but there is a phase delay between them.

By changing the thickness you can change the phase delay, so for example you can design it such that phi equal to pi by 2 okay that is one thing that you can implement right so you cut the crystal you know with a particular thickness such that phi equals pi by 2, if phi equals to pi by 2 then what happens to the polarisation that is going through…we talked about representing it as ax Ex plus ay Ey e power j phi right that is the general description of the wave. The incoming wave is linearly polarized okay, so the incoming wave is polarized linearly but let us say it is a 45 degree angle with respect to the crystal axis then for the incoming wave phi equal to 0 but for the outgoing wave you have ax Ex plus ay Ey e power j pi by 2.

You have a phase difference of pi by 2, so if you have a phase difference of pi by 2 if Ex equal to Ey and phi equal to pi by 2 what does that mean? That corresponds to circular polarisation and since phi is positive you say this is corresponds to left circular polarisation, so you came in with linear polarisation input phi equal to 0 that implies linear polarisation and you came in such that it is at 45 degrees, why is 45 degrees important?

The Ex and Ey component are equal in that case right, so this will be the case if data equal to 45 degrees right, so this is what you call as a quarter wave plate okay, so a quarter wave plate if you have you know 45 degrees polarisation coming in then it goes through that material what comes out is actually circular polarisation, so linearly gets converted to circular polarisation. If you come back that circular…it is all reciprocal right so that circular polarisation will go back to the original linear polarisation okay, so that is one thing the other condition is if phi equals to pi which you call as a half way plate because phi phase difference corresponds to half a wavelength right so it is called half wave plate.

If you have this case then you have ax the outgoing polarisation will be ax Ex plus ay Ey e power j pi, e power j pi is minus 1, so this is basically ax Ex plus sorry minus ay Ey, so whatever was the incoming polarisation whatever was the y component of the incoming polarisation that y component got flipped right, so when we look at that so we will say that okay if you have your x and y let us say you have a linear polarisation like this then the x component remains the same but the y component will get flipped right so what you will have is a polymerisation that is…it will still be linear okay because it is just giving you a pi phase shift right that means it just flipped one of the components.

So the phase difference still remains linear but it gets rotated okay in this case what you will find is if theta is your incident angle you will find that it gets rotated by 2 theta the output will be rotated by 2 theta, so this is actually… you can call this as a polarisation rotator okay, so half way plate can be used as a polarisation rotator. You put a half way plate between 2 crossed polarisers okay, so it is a vertical polarisation coming in you go through a half way plate at 45 degrees that vertical polarisation will become horizontal polarisation right and that horizontal polarisation now can go through the analyser, so you can actually rotate the polarisation using a half way plate.

So quarter wave plate is used to convert linear to circular polarisation, half way plate is use to rotate linear polarisation. So I mean if you consider theta equals to 45 degrees that is the easiest example right, if you say 45 degrees then this will be the mirror image of that along the y-axis, so we will find that, that corresponds to a 90 degrees rotation okay, so that is what we are talking about, so we are out of time so let us stop here.