Introduction to Photonics
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Light manipulation-Mallus' Law

Welcome to intro to Photonics, so far we have been talking about semiconductors light sources and detectors, so you go back and see how we progressed in this course we started with characteristics of light, light propagation we started with ray optics went in on to wave optics and then we talked about the statistics of light the random properties of light and we found that photon optics is a nice way of capturing all those characteristics and then we looked at interactions of photons with atoms which was the basis for understanding processes like absorption and emission.

We looked at absorption and emission in atomic systems where we are considering these bosons because it actually follows Bose Einstein statistics and then we went on to look at absorption and emission in semiconductors where we are dealing with fermions because it follows Fermi Dirac statistics right and so now we know how to generate light, how to amplify light and in general what are the characteristics of light?

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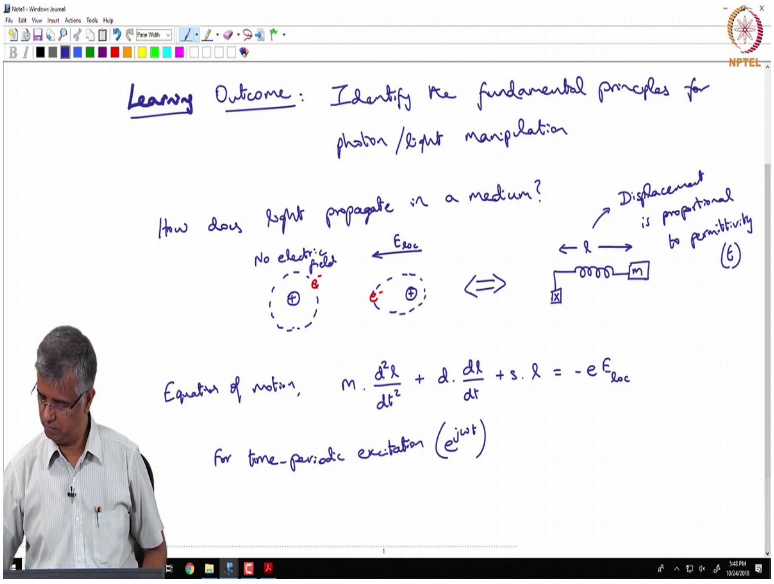
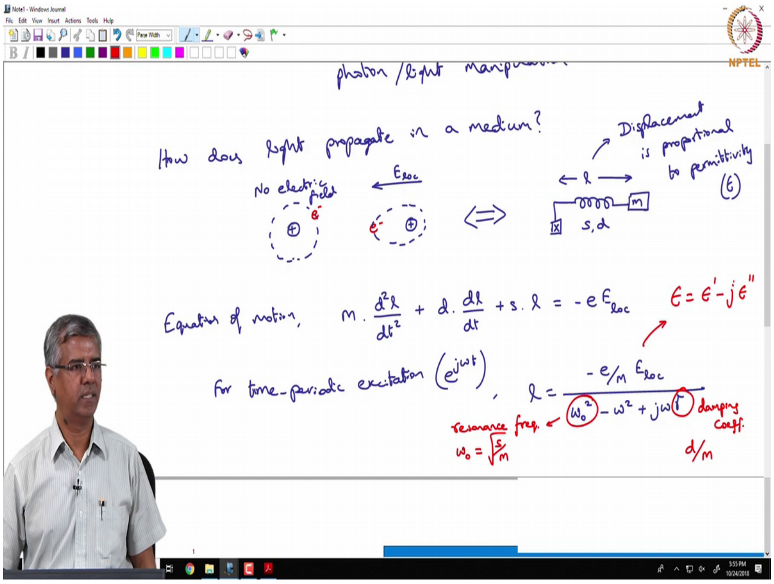


Learning Outcome: Identify the fundamental principles for photon / light manipulation

How does light propagate in a medium?

Equation of motion, $m \cdot \frac{d^2 l}{dt^2} + d \cdot \frac{dl}{dt} + s \cdot l = -e E_{loc}$

For time-periodic excitation $(e^{j\omega t})$



photon / light manipulation

How does light propagate in a medium?

Equation of motion, $m \cdot \frac{d^2 l}{dt^2} + d \cdot \frac{dl}{dt} + s \cdot l = -e E_{loc}$ $\quad \epsilon = \epsilon' - j\epsilon''$

For time-periodic excitation $(e^{j\omega t})$, $l = \frac{-e/m \, E_{loc}}{\omega_0^2 - \omega^2 + j\omega\Gamma}$

resonance freq. $\omega_0 = \sqrt{s/m}$

damping coeff. d/m

Okay, now the last module that we are going to be discussing in the next few lectures is…just put down the learning outcome. The learning outcome is identify the fundamental principles for photon or in general light manipulation okay, so how can we manipulate light? How can we change the properties of light that we have, so for example how can we change the intensity of light, so you light emitted from a source but suppose you want to modulate that light externally right you want to block the light sometime and let the light go for some time, of course you can do this you can block it manually and then take it out and you can do that but are there any other faster ways of doing that light modulation okay.

So those are the kind of things that we are going to be discussing in the next few lectures and before we go into some of the specifics let us actually go back to some fundamentals, something that you already know but nevertheless I will just for the sake of completion in this course I will go through that. Question is how does light propagate in a medium? We talk about light going through let us say an optical fibre right, how does light actually propagates through that medium, what exactly is happening?

To answer that we will have to actually look at microscopic picture, let us just look at the picture of an atom right, so you have basically a positively charged nucleus and then you have these electrons that are orbiting around it. If you this is when there is no external field, no electric field but if you have an electric field okay that is oriented like this what happens to this atom or what specifically happens to this orbital is that the orbital is now going to get influenced by that external by the electric field, the field that this atom is experiencing especially the valance electron right, the valance electron the orbital is going to get sort of polarized okay.

Now that essentially means that there is actually displacement of an electron in its orbital, it is still orbiting this positively charged nucleus but there has been a displacement. Now this displacement can be modelled in a classical mechanical system where you have a mass attached to a fixed point through a spring okay and upon application of an external force there is actually going to be displacement that is happening, so you would essentially displace the mass from its rest position that displacement we will notify we denote as l okay so what is that corresponding analogy in the electrical sense is that there is a displacement of electron in its orbital and says you are talking about an electromagnetic wave that is propagating through a material right.

You are talk about an electric field that is oscillating okay and so the electric field is actually changing sign, it is pointing this way at one instant and the another instant it is going to 0 and another instant it is pointing the other way and corresponding to that the orbital basically sloshing around okay and when this happens at 1 atomic location it influences the neighbouring atomic location also, the valance electron in the neighbouring atomic location, so when we are talking about and electron sloshing this way that will actually pull the neighbouring electrons like this, so the entire you know orientation or the entire material has this orbital that is moving this way and with the electric field going the other direction it is going to go like this.

So it is going to slosh back and forth okay and this is as if you are taking one charge and moving to another point and that is why you call it as displacement current okay, so when you talk about an electromagnetic wave propagating through a pure dielectric right you talk about a displacement current that is happening, that displacement current is nothing but the moment or the displacement of an electron in its orbital okay it never gets unbound. In a conductor you would say that there are bunch of a sea of free electrons.

So when you apply an electric field it is actually you know move these electrons across but here it is not a free electron it is still abound electron but you know it responds to an applied electric field and that responses quantify through this displacement and this displacement is what gives you the response of the material which is recognised in terms of is represented or just say this displacement is proportional to the permittivity of the medium, the permittivity which you call as Epsilon, so all along you have been taking some value of Epsilon for a material and that permittivity is nothing but the response of the medium to an applied electromagnetic field okay electromagnetic wave okay.

Now what we want to know is what are the characteristics of this displacement? How does the displacement behave as a function of frequency and how does a displacement behave as a function of magnitude of the electric field that is applied? So why is that part important? All along so far in this course we have been treating the response of a medium to an electromagnetic (())(11:38) response of a media to light as a linear response and that linear response is good only for a certain level of a certain range of electric field values.

When you go to electric field values beyond that range as in the case of this mass spring model you are pulling you pull a little bit there is some displacement, you pull a little more there is some more displacement this displacement if your pulling force is twice as initial pulling force then this twice the displacement, you go thrice it goes thrice, you go to thousand times the pulling force the responses not going to be the same it is going to start not giving you a linear response okay, so that is what we are talking about that it would get into a nonlinear response beyond a certain point. We want to understand all of that, so to understand all of that let us look at this model…there is a question.

Student: (())(12:46)

Professor: Yes so the question is, is there an exchange of energy which cause the material to heat up we will go into the specific little bit in a few minutes but suppose it is not able to respond as quickly as your excitation there is a delayed response in the medium right, so if you pull and this speed correspondingly the spring is displaced the mass is getting displayed at that speed.

Now my excitation is like this that mass may not be able to follow that excitation, so it will there will be a delay in the response and whenever there is a delay in the response you are essentially saying that there is some energy loss that is happening okay. That energy loss can correspond to one way of the energy can be lost through heat in the medium right, so one way of explaining that is through absorption of that energy in the medium and that absorption can generate heat okay we will come back that but whatever is happening in an atomic scale we are actually considering a classic mechanical model because that model is probably fairly well-developed okay so that might give us little more insights about what is happening here.

One other thing that we know as far as a model like this where you have a mass connected to a fixed point through a spring is the displacement is govern by the equation of motion and the equation of motion says that the mass multiplied by the acceleration plus b which is the damping coefficient multiplied by dl over dt plus s which is the spring constant multiplied by l is given by or equal to the excitation. In this case the excitation force can be denoted as e times e loc where e loc corresponds to the local electric field that this atom is subjected to right, so on the right side is your excitation on the left side is the response of the medium to that excitation, the mechanical response of that medium to excitation that is the field that is existing that the atom is subjected to that field okay. That field is essentially the external field that is your electromagnetic wave that is your light wave.

Student: (())(16:29).

Professor: That whatever external field that you giving there is a component of that presented at a particular location that is what we are denoting here okay but we know we are interested in the propagation of an electromagnetic wave and electromagnetic wave is nothing but…it can be represented in terms of time periodic function right, so for time periodic excitation which means that I am expressing the oscillation of my electric field in terms of e power j Omega t. So d is your damping coefficient and s is actually your spring constant, so what does it correspond to as far as this picture is concern you have a certain restoring force, what is the restoring force as far as an atom is concern?

Student: (())(18:00).

Professor: There is actually a force of attraction towards the nucleus right that is your restoring force okay, so that is actually acting like a spring and that restoring force it may not respond in a linear fashion, so there could be some damping involved in that and that is what, so this spring has got a spring constant yes and there is actually a damping constant also that is denoted by d, so for time periodic excitation I am assuming that is of course it is a wave that we are talking about but also it helps me get rid of all those differentials, so d square over dt square I replaced by minus Omega square and d over dt I replaced by j Omega right if I do that then I can get what I am interested in is an expression for l okay.

If I divide this entire equation by m I can actually find…and do that substitution for time periodic excitation I get an expression like this e over m multiplied by E loc divided by there will be an omega naught square I will come back and explain what this is there is an omega square this omega square coming from that 1st term right because d square over dt square we are replacing by minus Omega square, so that is what is coming here plus j omega let us say gamma so in this I have introduced 2 new terms so what are those this actually corresponds to resonance frequency.

Every spring that you take has got a particular resonance frequency, if you pull the spring and you let it go it is going to bounce around and come back to rest and it is going to bounce around at a particular frequency right that is going to be resonance frequency and that resonance frequency is given by root of S that is spring constant divided by m the mass, the mass of the particle that we are talking about in this case the mass of an electron right, so omega 0 is given by this omega 0 equal to root of s over m that is why s over m we are representing as omega naught square and this gamma is called the damping coefficient and that is given by this damping constant divided by m okay.

So that is the expression for the displacement and you can say that is with a proportionality constant that also denotes the permittivity of the medium but what you see from that is that the permittivity or the displacement is actually a complex quantity right it has got a real part and an imaginary part, where does the imaginary part comes in the picture, it is because of this damping term and what does that damping term indicate?

It indicates the fact that as you go to higher and higher frequencies that damping term become more and more significant edge means that it is actually not able to…the displacement is not able to follow the rate at which your excitation is changing right higher the rate at which excitation is changing more will be the damping okay or in this case you know when you look at it actually an imaginary, bringing in an imaginary term so that is actually the permittivity becomes imaginary quantity, so what is that in a complex number what is the imaginary component indicate.

If you are looking at the response of a medium and you have a complex response, so that imaginary component corresponds to a phase delay, if you do not have an imaginary component there is no phase delay there is only the real response right there is no phase delay in your response. The moment you bring in an imaginary component you are essentially saying there is going to be a phase delay in the response and that phase delay is now dependent on frequency, so this is an important part both your real part of permittivity as well as the imaginary part of your permittivity they are both functions of frequency, we loosely say you know this material has a permittivity of 4, we loosely say this material has a refractive index of 1.5 right, does that characterise a material completely?

No it does not, we are saying those values at a particular frequency this picture tells you that all these numbers are a function of frequency. If you go to a different frequency that value will be different okay both Epsilon prime as well as double Epsilon prime, I can basically say because this quantity is imaginary I can say that Epsilon can be written as real part and an imaginary part. Do not pay too much attention to that minus sign is just the convention but the key part is that there is an imaginary…the key thought is that there is actually an imaginary part to this okay, so the permittivity is typically a complex quantity.

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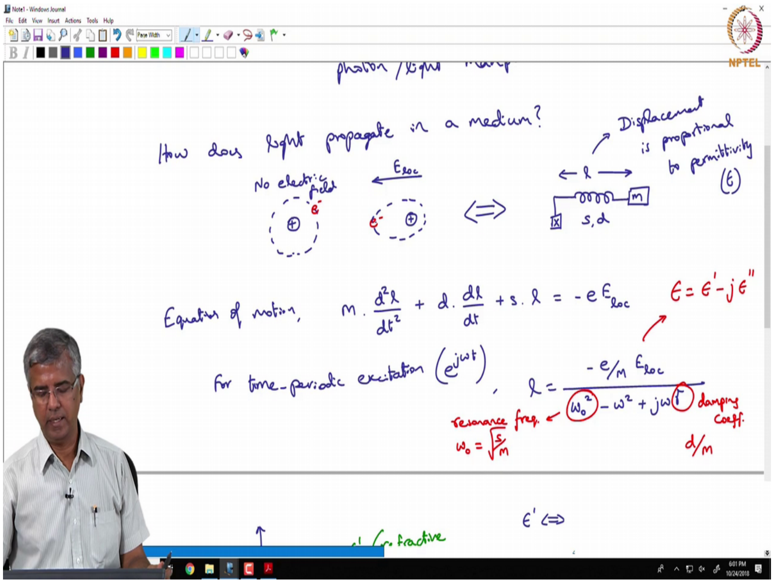

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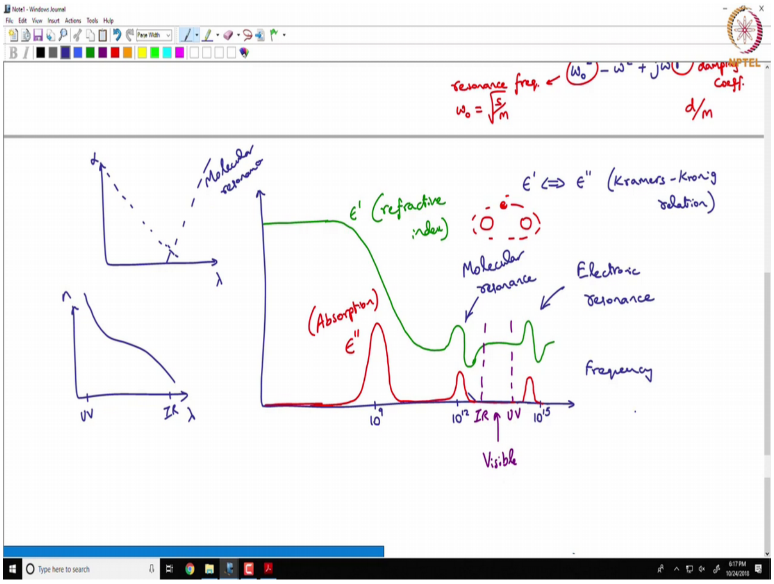
$\epsilon = \epsilon' - j\epsilon''$

For time-periodic excitation $(e^{j\omega t})$, $x = \frac{-e/m \, E_{loc}}{\omega_0^2 - \omega^2 + j\omega\Gamma}$

$\omega_0 = \sqrt{\frac{s}{m}}$

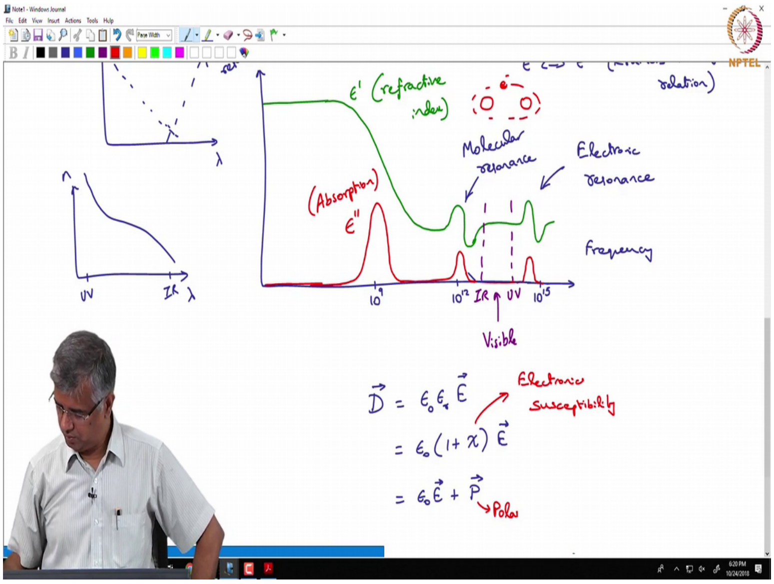
d/m



$\omega_0 = \sqrt{\frac{s}{m}}$

d/m

$\epsilon' \Longleftrightarrow \epsilon''$ (Kramers-Kronig relation)



$$\vec{D} = \epsilon_0 \epsilon_r \vec{E}$$
$$= \epsilon_0 (1+\chi) \vec{E}$$
$$= \epsilon_0 \vec{E} + \vec{P}$$

Now if I plot the real part and the imaginary part as a function of frequency let us see how that looks? So I am plotting the real and imaginary parts of my permittivity, real part is I am just mathematically plotting it as a function of frequency okay in the x axis is the frequency okay, so if you plot is then it is going to exhibit some behaviour like this something like this okay and similarly if I plot my imaginary part it is going to be like this and then it is going to go through a peak here and a peak here and a peak here okay and if I were to give some specific numbers to this…so this is in the order of 10 power 9 herds this is the order of 10 power 12 hertz this is about 10 power 15 hertz okay.

So what I plotted here this is Epsilon double prime and this is epsilon prime. So interesting thing is epsilon prime and Epsilon double prime are related to each other okay the specific relationship is called the Kramer's Kronig relation which essentially says that whenever there is a change in Epsilon prime that is a real part that is going to be a corresponding change in the imaginary part and vice versa okay. All that is just coming from the expression for the displacement, yes there is a question.

Student: (())(27:48).

Professor: So I am not putting down the…the question is how are we going to Epsilon from displacement, Epsilon is actually proportional to displacement. Epsilon specifically Epsilon r the relative permittivity is proportional to the susceptibility one plus susceptibility is Epsilon r that stability is directly proportional to this displacement okay. So that is how we are tracing our way back to the permittivity.

Student: (())(28:27).

Professor: Susceptibility is a function of…?

Student: Frequency.

Professor: Yes that is what we are saying susceptibility is actually a function of frequency but susceptibility we always or we typically deal with only the real part what I want to point out is there is also an imaginary part at certain frequencies, so what is the real and imaginary parts means? The real part actually the root of Epsilon r real part of your permittivity, relative permittivity that corresponds to your refractive index okay and the imaginary part…

This corresponds to a lost term (())(29:17) term okay so one thing we say is that the refractive index is a function of frequency and also there are specific frequencies at which material will exhibit losses okay and we see that there are 3 loss peaks over here okay out of which 2 of them are showing certain resonance, so why is this resonance because your omega naught and omega around these points that actually changes sign okay, so that is why it is actually going up and coming down.

These things will change sin but we are talking about not just one omega naught we are talking about 2 different omega naught, so what does that represent? Now this actually represents the electronic resonance which is what we have been talking so far we have been saying that you know this electron displacement in its orbital right that actually corresponds to a certain omega not right that gives you what is called the electronic resonance, so then the question is what is this resonance? What does this indicate? Any guesses? What could this be? Mind you this is happening at a lower resonance frequency compared to the electronic resonance, that is the clue.

Student: (())(31:30).

Professor: Yes this is the characteristic for a particular material, any material that you take is likely to have these 2 resonances.

Student: (())(31:45).

Professor: 1st one is atomic that is what we are…well first one as in the one on the left side you are saying that is atomic resonance okay, well it involves atom so what we call it as a molecular resonance, so you know molecule is made of atoms and you said 2 atoms there could be modular 2 springs and you know let us say if it has a covalent bond it shares an electron between those 2 atoms okay, so that electron orbiting is essentially like a spring, so 2 masses attached to a spring and that has its own residence okay.

In this case, in the electronic resonance case we are talking about mass of an electron but here we are talking about mass of an atom right because we are talking about 2 atoms they are connected by a spring okay, so in this case we are talking about mass of an atom which one is heavier? Atomic mass is obviously heavier than electronic mass, so that is why the resonance frequency which corresponds to root of s over m is inversely proportional to root of the mass right that resonances is going to be on the lower frequency side okay so you have a molecule resonance and then electronic resonance happening for any material.

Where they happen may change…a material can have more than one type of molecule, so correspondingly you will have multiple resonances, multiple absorption peaks right, so a material so we talked about silica sio2, sio that is a molecule right, so there is a molecule resonance corresponding to this. Now you may have germanium also presented that, so germanium with oxygen bond there is another molecule that might have a different resonance, so when we talk about… remember when we talked about atomic levels and we said is atomic levels could be signatures of the absorption spectrum can actually be a signature of a particular molecule, we talked about absorption spectroscopy remember that?

We said absorption spectroscopy is a powerful way of determining what is the constituent of a material right, so what we were talking about there each of those absorption peak corresponds to one of the resonance peaks okay so if you have multiple resonance peaks you say there are multiple molecules, different molecules inside that material okay, so you can identify them based on these peaks.

Student: (())(35:33).

Professor: Right, so when we talk about vibrational frequency that is the resonance frequency of a molecule that corresponds to absorption at that particular wavelength because when you give a bit of energy to that it is actually…it amplifies that energy to a point where it cannot follow…it cannot keep on amplifying it has to damp and that damping happens in terms of heat, so you lose energy through that okay, so all these absorption peaks all these loss peaks are talking about losing energy at those particular points.

Student: (())(36:22).

Professor: So what is the significance between electronic resonance and molecule resonance? It is basically saying there are 2 species where this mass spring model is valid. 2 species which respond to an applied lecture field, 2 species which respond to an applied electromagnetic wave.

Student: (())(36:47).

Prof: The absorption is essentially lost term…is what we calling as a lost term, so I should not actually called it a lost term because it is not like every time it gives loss, so I should just in general mention it as absorption. It basically excites that molecule and gets that to a vibrational state, from that vibrational state it can actually give rise to light emission also right which is what we were talking about previously, so you could actually have other energy sources coming out of that absorption but Epsilon double prime corresponds to absorption.

Student: (())(37:46).

Professor: Yes, so the 1st absorption peak is corresponding to the fact that your response… it is not able to keep up with the frequency of excitation there is a phase lag that is coming about and because of…so typically when you talk about a coaxial cable one example we say the coaxial cable exhibits high losses beyond hundreds of megahertz of frequency and gigahertz of frequency, so what are we talking about? In a coaxial cable your field is confined between the 2 conductors, so the field is actually propagating through that dielectric material between the 2 conductors that dielectric material is similar to this, it is not able to respond to high frequency excitation in the order of gigahertz okay so you have that loss that comes about. Yes there is a question.

Student: (())(38:59).

Professor: So the question is what is that we showed before, is it electronic or molecule resonance or this entire picture that we developed based on this electronic resonance. So the molecule (())(39:18) is essentially 2 atoms right, so you basically have one atom here another atom here sharing an electron right and this can be once again modelled as you know 2 masses attached to spring so that is going to have a characteristic resonance.

Student: (())(39:48).

Professor: This graph is I am just plotting directly from that expression for l.

Student: (())(39:56).

Professor: That is what you get that other extra molecule resonance over here you would have to have one more extra term right, so in this equation I have just add a term for the mass of an electron but if you add one more term for the mass of the atom right you are taking the displacement of the atom also, so we are putting both those pictures together here.

Student: (())(40:31).

Professor: 1 power 9 actually sorry.

Student: (())(40:40).

Professor: No that just comes directly from this…so you can just say even before it approaches omega naught your response is actually scaling down by omega right. Higher the value of Omega higher the frequency your response is already starting to come down.

Student: (())(41:09).

Professor: Yes it is all coming from that expression there.

Student: (())(41:15).

Professor: Exactly, so let me give you a picture here and then you can ask a question, so this is in frequency right? This is actually our visible region right we talk about infrared that means it is inferior to the red frequency, the lower to the red frequency so that infrared edge is over here and ultraviolet or superior to the violet frequency is over here okay so now you can go back and see what is the dependence of the reflective index as a function of wavelength, so remember initially when we were drawing the expression by looking at the curve for refractive index we said it is something like this.

So along UV wavelength it is actually higher and along ir wavelengths it is lower that is just tracking this curve over here okay and remember when we are talking about loss in an optical fibre as a function of wavelength we said it is (())(42:51) scattering over here at shorter wavelengths and at longer wavelengths we said it is molecule resonance. Remember that when we are talking about optical fibre (())(43:08) an optical fibre we were talking about that, that resonance is over here as you go into infrared region you are starting to climb up this molecule resonance over here okay, so you can understand a lot of behaviour of material by having this picture, so the term where we said we have material dispersion.

Why does material dispersion happens? Because the medium responds differently for different wavelengths that is because of the n versus lambda it is not uniform, so material dispersion can be explained this all the losses in the medium can be explained in this. So this is something that you should have in your mind whenever you talk about light going through a material what is happening to the light?

You have absorption you have absorption or attenuation and you have dispersion in the medium which actually the reflective index also governs the speed at which light actually propagates in that medium all of that is coming from here okay, so it is not like the photons are tunnelling through this medium without interacting with the medium at all it is more like the photons corresponds to an electromagnetic wave that electromagnetic wave interacts with the medium and the medium response and that electromagnetic wave is carried through the displacement that we are talking about here and that is how the electromagnetic wave propagates.

Student: (())(45:11).

Professor: Y axis is just magnitude of Epsilon prime and Epsilon double prime.

Student:(())(45:22).

Professor: Yes, so we have to stay clear of that molecule resonance if you want to you know make sure it is…so if you are transmitting something you want to be missing those peaks right where Epsilon double prime is 0 is where you want to transmit information. Glass is transparent (())(45:52). Epsilon double prime is 0 at visible wavelengths. Glass in opaque as you go to (())(46:06) it is opaque when you go to infrared wavelengths okay, so you can… that glass as an example but you can take another example also okay really stretching my time here so I should wrap up.

So let me just finish with this note over here so when we talk about the response of a medium right, the response of the medium we express as d vector the displacement vector which we say is Epsilon naught, Epsilon r multiplied by E for an applied electric field you get a response as D and that response is through this Epsilon r, so this can be written as Epsilon naught multiplied by 1 plus chi times e where chi actually is called the electronic susceptibility okay and this can be written as Epsilon naught e which does not have anything to do with the medium right and whatever response of the medium you denoted by this term p which is a term that we call as polarisation, so why are we calling this polarisation?

It denotes the polarisability of the medium, if I apply an electric field how well does that medium align to that electric field right or how well does these orbital aligned to that applied electric field. This final term is representing that okay and what we will see is that response can become non-linear beyond certain values of e so we will come back and look at those details later. So what you are going to be doing in this week's experiment is actually manipulating polarisation of light. I was hoping to give you some background on that before you go in to that experiment. How much time do you have, do you have any time at all? Another 10 minutes is that okay? Yes okay.

Student: (())(49:31).

Professor: P? Polarisation is basically a response term, the response to that…so that is essentially Epsilon naught chi times e right where chi corresponds to the displacement, chi is proportional to the displacement of the (())(49:55). Okay 10 minutes is what I have, so let me just quickly go through this.

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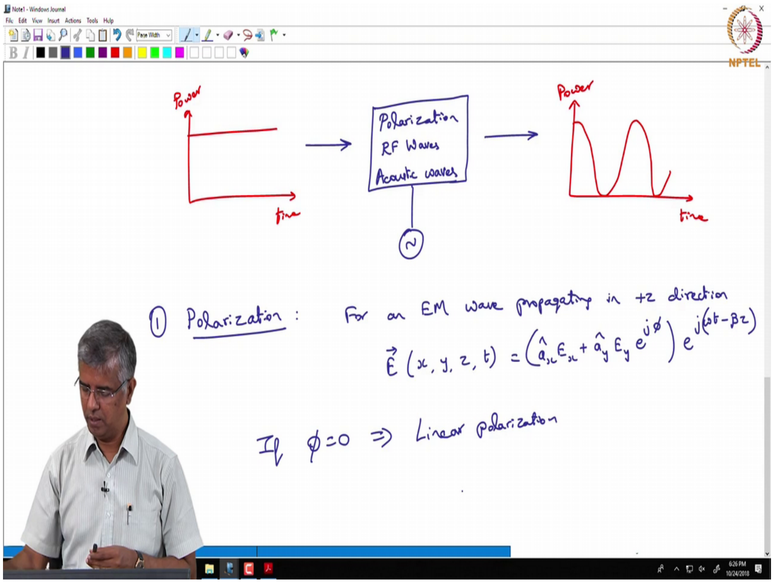
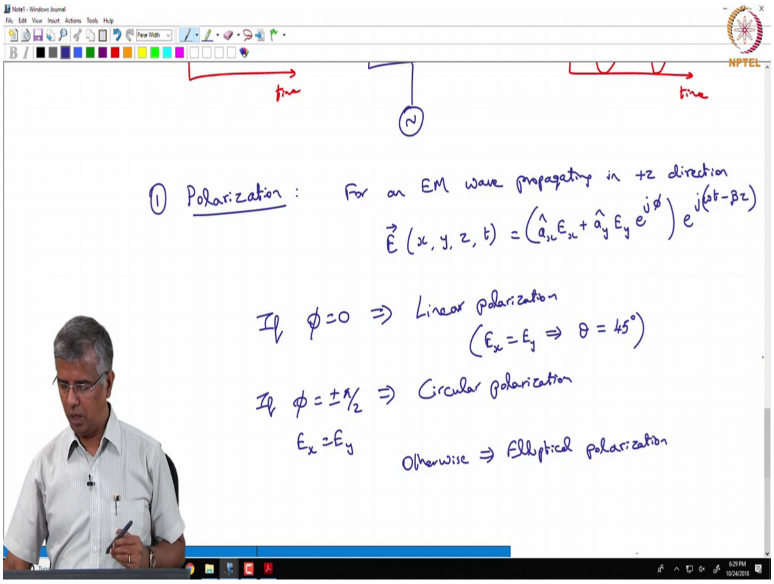


① Polarization : For an EM wave propagating in +z direction

$$\vec{E}(x, y, z, t) = \left(\hat{a}_x E_x + \hat{a}_y E_y e^{j\phi}\right) e^{j(\omega t - \beta z)}$$

If $\phi = 0 \Rightarrow$ Linear polarization



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If $\phi = 0 \Rightarrow$ Linear polarization

$(E_x = E_y \Rightarrow \theta = 45^\circ)$

If $\phi = \pm\pi/2 \Rightarrow$ Circular polarization

$E_x = E_y$

Otherwise $\Rightarrow$ Elliptical polarization

So what you are going to be looking at is how do you manipulate light? That is what we started with right so we say okay you have light beam coming in to this black box and your light beam is going out. Let us say the incoming light beam has got a power as a function of time like this it is uniform power as a function of time. Can you convert it to something like this?

Can you modulate this power or light intensity, the number of photons that are going thought this black box, how can you modulate that and what we are going to see is that modulation can happen through manipulation of the polarisation of light or you can actually manipulate this by an external signal applied to this through RF waves, radio frequency waves right you could have radio-frequency waves interacting with that light allowing you to manipulate the property of light or you could have acoustic waves imagine that by using a sound you can change the property of light okay.

So we are going to go into details of each one of these but the first thing that we will talk about and this is what you are going to be doing in your experiment is by manipulation of polarisation of light, so very quickly… this is something I expect all of you to have come across in electromagnetic course at some point in your student life right, so we say for an EM wave propagating in positive Z direction, so how can you represent that?

This electric field let us say corresponding to the electromagnetic wave can be represented in let us say (())(53:19) x, y, z and t as if you are propagating the positive Z direction all your electric field components are in their transverse direction, transverse to their propagation direction, so it is basically in the x, y plane right so you can represent this as ax Ex plus ay Ey and you could have a phase difference between the x and y components. That phase difference I will represent it as e power j phi okay.

That characterises the transverse components and then it is going to have e power j Omega t minus beta z right omega t corresponds to the time variation and beta z corresponds to the phase accumulated during propagation okay. That phase is different from phi here, phi I am talking about this is my x component this is my y component, phi corresponds to any phase delay between these 2 components okay both these components are travelling and it is accumulative phase that is at the rate of beta z right but these 2 can actually have slightly different phase with respect to each other which we are trying to denote by phi.

Now if phi equals to 0 then what you will find is both your Ex and Ey components are travelling together and depending upon your relative magnitude of Ex and Ey you would actually have an electric field that is tracing a line as it is propagating. If both of them are equal Ex is equal to Ey then it will actually have a 45 degree line that is tracing, so that is what you call as linear polarisation right, so phi equal to 0 then you have linear polarisation of light and specifically when Ex, if Ex equal to Ey that means the linear polarisation as an angle of 45 degrees right it is that is a specific condition okay and of course if Ey equals to 0 then it is x polarised if Ex equal to 0 then it is why polarized right it is basically tracing a line in the y plane as it is propagating okay.

Now if phi equals to plus or minus pi by 2 while Ex equal to Ey what you will find is that your electric field vector is going to trace a path that is going to be a circle as it propagates in the Z direction that propagates in this direction, it traces a circle so this you would call as circular polarisation and in circular polarisation if it is phi equal to plus pi by 2 you call it as left circular polarisation and phi equal to minus pi by 2 you call it as right circular polarisation okay but then otherwise if it does not satisfy any of these you have what is called elliptical polarisation, so the electric field vector traces an (())(57:47) as it is propagating in this direction. So those are the polarisation states of light, now what can we do with this? Yes.

Student: (())(58:04).

Professor: Yes then it is basically an orientation, if Ex is predominant compared to Ey then it is an orientation like this right, if Ey is predominant with respect to Ex it’s orientation is like this the orientation changes but it is always remaining linear, it always traces a line as it propagating okay only if there is a phase change then there will be this circular or elliptical (())(58:38) okay.

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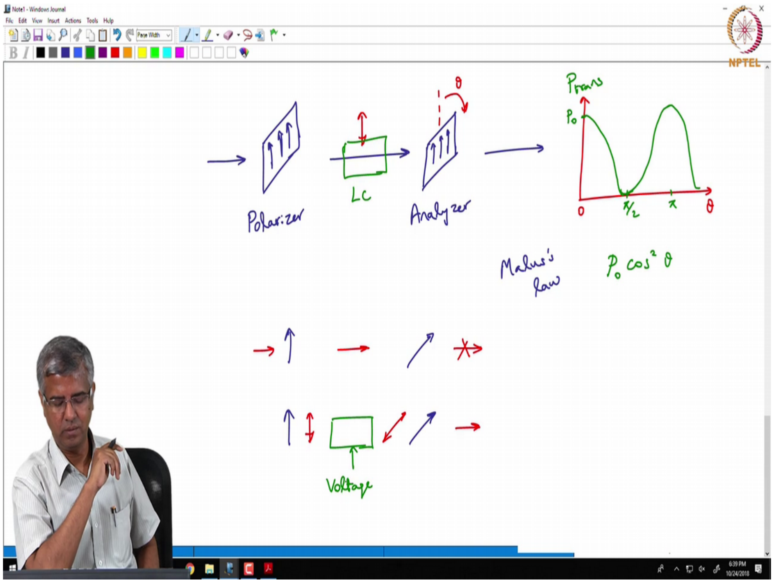

So the specific experiment that you are going to do is this, suppose you have a light source okay and you send that light source through an element called a polariser okay. The property of the polariser is such that only that polarisation component that you have aligned to that access…it is like basically you have some molecules that are stretched in this direction okay. Only this polarisation will go across those molecules, if you have a crossed polarisation that will be extinguished by that molecule right so it is basically…that is what you call as polariser, so what you expect coming out of this is actually light with vertical polarisation okay.

Now suppose you have another polariser over here and you have the same orientation then what you expect all of that light should come straight through, so I would draw this as a function of theta, now let us say that theta is 0 initially and then I rotating that, I am basically rotating that other polariser okay, so what do I expect to see? When theta equals to 0 when I get to see maximum light but when theta equals to pi by 2 90 degrees it will extinguish that light and then if theta goes to pi that will go to maximum again and then extinguishing and so on okay.

So this is basically the transmitted power p transmitted it goes like this, this is basically pi by 2 and this is pi, so the power that is transmitted can be represented as p naught cos square of theta right because you basically this equal to P naught and theta equals to 0. When theta equals to pi by 2 it goes to 0 and then pi once again become P naught right. So this is what we call as Mallus Law. Mallus Law says that if I take a polariser through which I am actually a polarising any light source okay and then this is my polariser and then I use another polariser which I will actually call as an analyser okay.

If I have an analyser and I rotate that analyser then I would actually plot this cos square function okay so I can use this now as a variable optical attenuator. Remember in one of your experiments you used a variable optical attenuator as part of your kit, this can be your variable optical attenuator by orienting, by changing the angle of the analyser orientation of the analyser with respect to the orientation of the polariser you can control the amount of light that is transmitted okay, so we can use this as variable optical (())(63:17) so you would be given to polarisers and light source and detectors, so you will be actually proving Mallus Law and then what if you introduce a component in between?

How does your liquid crystal display work? You know…you have a light source your LCD display you have your light source at the backhand and then you have a polarisers sheet, so what comes through that is polarise light then it goes into each of those pixels, each pixels has got a liquid crystal element okay and then you have another polariser at a different angle okay. Now without any signal applied to the liquid crystal, the orientation of the liquid crystal can be changed depending upon voltage supplied to it okay.

So without any voltage you set up the 2 polariser such that it is all dark okay there is no light that is coming through but then in here you put your liquid crystal and you actually change the polarisation state of light that is going through you rotate that polarisation okay so let me just draw that so initially you have polarized light coming in and you have a crossed analyser, so light that comes in here goes through here and it cannot go through here because it is all absorbed by this material okay it cannot go through here but now I put my liquid crystal over here right such that I have once again polarised light but that light polarisation.

So this is my polarised light after this but after going through the polarized liquid-crystal suppose I am able to twist the polarisation, rotate the polarisation so that it lines up with this analyser over here then I have maximum transmission, so I can turn light on or off by changing the voltage applied to this liquid-crystal okay, so that is essentially what you are doing in your display or even in your projector certain parts it is white light that means light is going straight through right, certain parts there is a particular color, red color so that actually goes through a red pixel which is turned on which means that there is a voltage applied to that red pixel such that it is transmitting and all the other color.

So you basically have RGB pixels, each pixel that you are defining has got RGB sub pixels and each of those sub pixels has a liquid crystal element which is individually controlled by this voltage that is applied right, so by turning on only the red pixel, red transmission you are going only the red color is let through and the other blue and green are dark basically there is no voltage applied to those liquid crystal, so they are blocked but if you want to get orange what you do is you turn on both red and green they mix together and they look orange over here right so that is how you are generating all those color but essentially you are manipulating the light transmission through your liquid-crystal display by manipulating the polarisation of light okay, so that is what you are going to actually see in the lab this week.

Student: (())(68:32).

Professor: Yes normally it is linearly polarized light because they polarisers that pass this linear polarisation is easy to achieve it is actually naturally occurring but there are some very specific application where you need to go to circularly polarized light and you can generate circularly polarized light from a polarisation through a process called retardation. I think we are running out of time now so I will not hold you guys very much but we will talk about it in Friday’s lecture.