Nanobiophotonics: Touching Our Daily Life

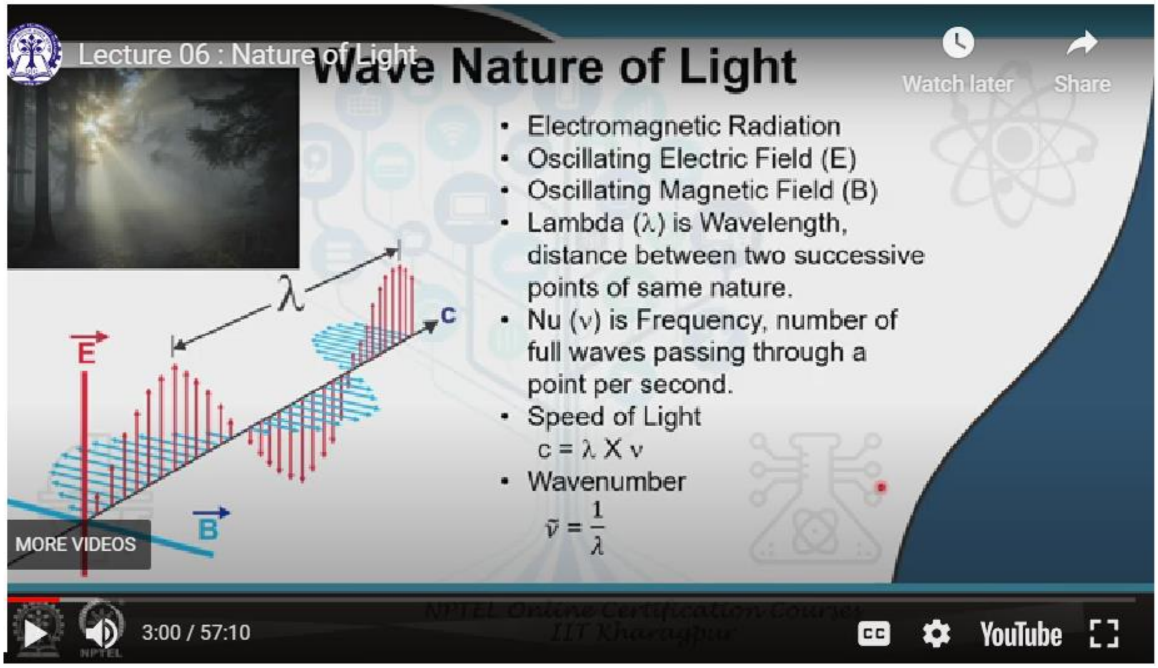
Professor. Basudev Lahiri
Department of Electronics and Electrical Communication Engineering
Indian Institute of Technology, Kharagpur

Lecture No. 06

Nature of Light

Hello and welcome. This is week 2 of the Nanobiophotonic course. This is the preliminary chapter in which we are going to discuss about the nature of light. Now, before I go any further let me just make this declaration that since preliminary this is very common meaning chances are you have already learned this most of you already know this most of you have the in and out information regarding this. However, I am doing it to refresh some of the old revised concepts or revise some of your old concepts that you may have forgotten. Students who are coming after the biophotonic course the my previous biophotonic course may find some commonality.

In any cases if you think that preliminary is something that is not so exciting or that does not generate enough interest in you by all means skip it. You can join us from chapter 4 onwards when we are actually going to the real part of the problem, but for first chapter which is merely introduction the second and third are preliminaries mere revision of concepts that all of you most of you should already know right. But it may so happen that you have lost touch with it say for example, you are medical students you have lost touch with your physics background or you are a physics student you have forgotten in about biology. So, these two chapters I will try to encompass that. However, if you are a physics student if you are doing a masters or doctorate in quantum mechanics and then I talk you about nature of light chances are you have already understood known and even played with some of the concepts yourself. So, this will not serve any purpose to you again feel free to skip it.



Having said that let us go further and let us try to understand the wave nature of light. As I said light is simultaneously wave as well as a particle. When we are talking about the wave nature of light usually a particular electromagnetic wave, light is a part of electromagnetic wave as we have discussed previously Maxwell proved it can in its bare minimum form can in its simplest form could be described something which has an orthogonal, orthogonal means perpendicular oscillating electric and magnetic field with respect to it.

Meaning if a light is travelling in this particular direction with a velocity c this direction suppose is the z direction in x y z Cartesian coordinate this is the z direction then the electric field will have to be perpendicular towards it. It could either be in the y or in the x direction and the opposite is also true for the magnetic field. The magnetic field will also be perpendicular to the direction of the propagation of light perpendicular to the z direction it will be either in x or y. There is no restriction that electric field has to be in the x direction this is also perpendicular this angle is also 90 degree. So, the electric field can also be in this direction the magnetic field can also be in this direction as long as they are orthogonal they are perpendicular to one another in its simplest barest minimum form I will start with high school physics and take you slightly above.

So, again if you think that common sense everybody knows it just give it give it some time you will probably find something that you do not know. So, an electromagnetic wave has a direction and it has two hands consider this to be the direction this to be my weak hand and this to be my strong hand I have a strong hand right hand and weak hand left hand. So, light contains two hands similarly light contains two hand strong hand which is the electric field the weak hand which is the magnetic field and these two fields are constantly oscillating among each other they are constantly oscillating with a particular frequency oscillating means vibrating it is going up and down up and down coming back to its original position up and down in a wave like manner. Whenever light tries to enter a particular medium light is travelling in vacuum and electromagnetic wave in particular cases you can consider a single photon a photon is travelling in vacuum now it tries to enter a particular medium the medium could be glass the medium could be solid liquid gas anything different than vacuum anything other than vacuum anything other than simple free space anything which is made up of atoms matters per say normal matters per say I will say normal matter because there is something called dark matter, maybe I will discuss it later very fascinating, but let us talk about the matter which is around us something that is comprising of atoms. Light first want to ascertain whether it can sustain inside that matter by first trying to ascertain whether its strong hand and weak hand can survive inside it what does that mean meaning if this propagating wave if this propagating photon is entering a medium first the electric field and the magnetic field would like to see if it can survive if it can sustain itself into the medium. The medium is made up of atoms, the atoms contain charge particles electrons and the nucleus, charge particles have their own electromagnetic field yes charge particles which are also not static even if they are static they will have their electric field they will have their magnetic field. static charge does not produce magnetic field I have to be careful what I say, but electrons and electrons are constantly moving around the nucleus moving charged particles produces electromagnetic field those electromagnetic field will interact with this particular electromagnetic field this electric field and the magnetic field of the electromagnetic wave upon entering a medium will interact with the matters with the atoms with the electrons electromagnetic field.

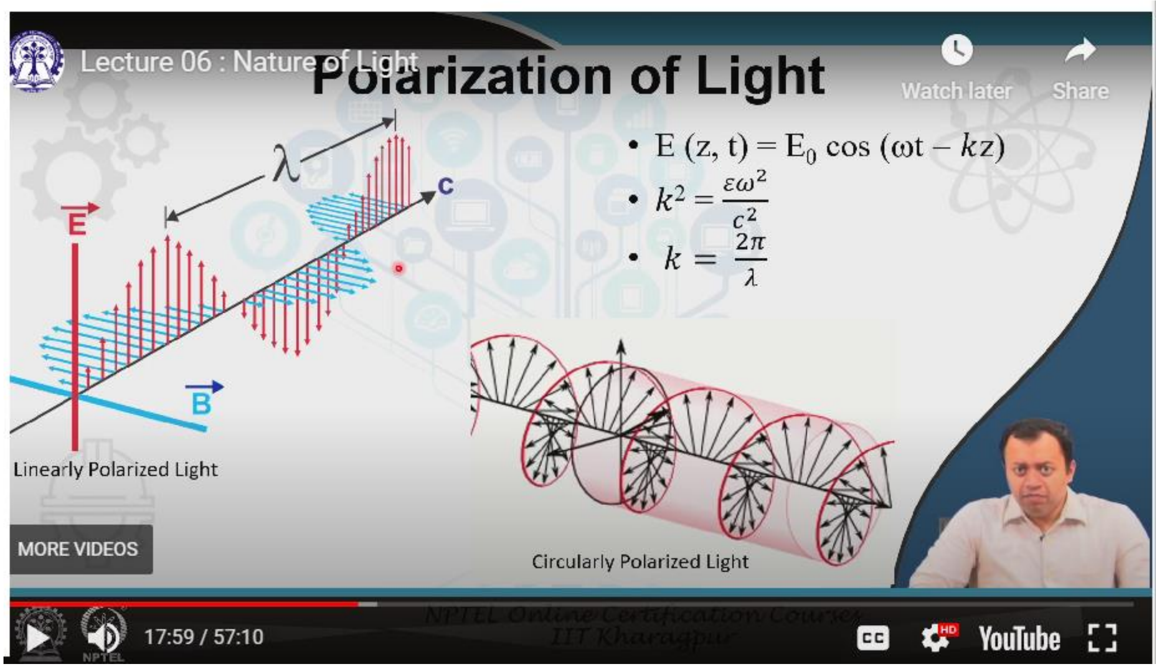
The overall interaction between the matters electromagnetic field versus the photonic electromagnetic field will overall determine the propagation of the light inside the medium right of course, it depends on frequencies of course, it depends on energy of course, it depends on intensity, but overall this is the idea as soon as the photon or electromagnetic wave enters the medium as soon as it enters the medium the electric and magnetic hand interact with the existing electric and magnetic field. If the result is complete cancellation of one another at a particular frequency at a particular frequency then light will not go inside light will simply reflect back if there is slight modification slight modification the light will be refracted and if there is very little modification it simply will pass through like visible light passes through glass then that is it the electromagnetic field of glass silicon dioxide has very little interaction with visible light. So, this this overall interaction of the electromagnetic fields inside and outside is the basis for refractive index all of you know about refractive index, but overall refractive index is based on that. Now, these are the formulas or frequency every high school child knows ν is the frequency number of full waves passing through point per second whereas, λ or the wavelength is the distance between two cone successive point of nature. So, if you are taking this as a reference if this is 0°as wave needs to come back to 360° which is equivalent to 0° and that this entire distance where it has started from 0 and return back to 0 is a full wavelength. A wavelength is start to finish if it has started from this stop then it will have to go here not here not here this is opposite direction if it has started from here if your wavelength is starting from here then it has to go up till, here if it is starting from here it will go here yes this this this point if it is starting from here then it will go from go to here where it has started from angle wise because it is a full circle if you start with 0 and this is 360◦ everything in between falls with 0 to 360 this is 180◦ this is 90◦ this is 270◦ as such it is a full circle.

You can of course, describe it in radians 2 πradian is the full wavelength π is the half wavelength and so on and so forth. Wave number on the other hand is 1 over λ wave number simply describes. So, wave number is usually in centimeter inverse which basically is a fancy way of trying to say that how many waves how many of this full λ 1 λ is generally called 1 complete cycle and if we understand 1 complete cycle of the wave we can understand because waves keeps on repeating itself the same thing is repeated unless otherwise stated, how many of this wavelength can be occupied can be packed can be compact inside a centimeter. So, wave number is per centimeter. So, 600-centimeter inverse or 600 per centimeter which means in 1 centimeter 600 of such wavelengths of that light could occupy without having any distortion without having any non-rational number.

So, 600 full wavelengths can sit within 1 centimeter 1000 full wavelength can sit within 1 centimeter and hence the wave number is centimeter inverse given in centimeter inverse. We need it because when we are dealing with spectroscopy usually the units are in wave numbers rather than wavelengths, but obviously, if 1/ lambda is centimeter inverse you just reverse it you get lambda anyways. Now, this electric field is the strong hand why do I say strong hand because mostly you see a static charge produce electric field a moving charge produces electric as well as magnetic field a magnetic field or magnetism per say has no independent existence of its own you see electric current you do not see magnetic current. The movement of charge particles or movement of electric field associated with the charge particle manifest itself into magnetic field thereby magnets can only exist when electric field is present. A static charge produces electric field you can get away without having any magnetic field around a static electric charge. Exceptions are there I understand I fully understand, but since I am making controversial statement let me make myself absolutely clear.

Electric field is independent electric field can exist by itself a magnetic field cannot exist without having an electric field somewhere nearby. A magnetic fields entity is associated with the electric field that is making some sort of a movement a charge particle is moving it gives rise to electric field moving electric field moving gives rise to magnetic field moving. A magnetic field a magnet therefore, cannot exist without the dipole without south and north pole you cannot have magnetic monopoles yes I am quite aware even sitcom such as the world famous big bang theory I am not talking about the theory I am talking about the famous sitcom the famous serial they wanted to Sheldon went to find magnetic monopole in north pole, but thus far in real life we have yet to find evidence of existence of single south pole or single north pole of magnet. If we find some part of science some part of physics some part of electromagnetism have to be rewritten, but positive charge can exist by itself there is no requirement for a positive charge to be present always in proximity with a negative charge a single electron can simply move through vacuum there is nothing preventing it from going around a single electron exist a single electron exist which is just a negative charge and the negative charge produces a negative electric field around it.. So, moral of the story it is independent and thereby it is stronger thereby the electric field associated with a photon or associated with any charge particle is far more stronger than the magnetic field.

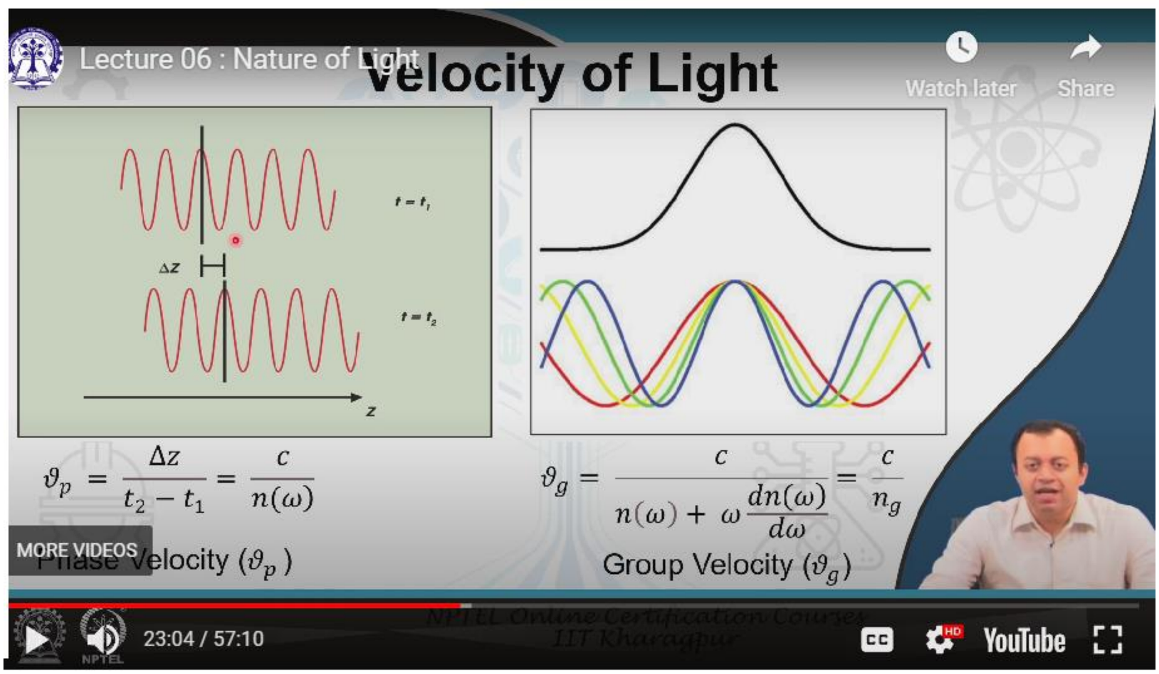
We in optics business we in photonics we in electromagnetism try to ascertain this oscillating electric field all of our instrument by which we measure light per say or the properties of photons per say is tuned to understand ascertain to be sensitive towards this electric field associated with light. And perhaps some of you know Maxwell's equation have stated that if we are able to mathematically calculate the electric field associated with an electromagnetic wave we are automatically able to calculate the magnetic field associated with the wave right or vice versa is also there if you are able to calculate B you are able to calculate E, but mostly when we are looking for a photon we are trying to ascertain its electric field, that electric field gives us information about the magnetic field gives us information about the wave vector the speed by which the light is the photon or the wave is moving around in a particular medium we are able to ascertain it with understanding with having a proper knowledge of the electric field associated. So, this oscillating electric field this electric field is not static when your photon is moving when your electromagnetic field is moving we try to understand we try to ascertain the stronger hand and once we have able to understand the stronger hand we are more or less able to resolve or we are more or less able to understand the wave or the photon.



Now since based on this in which direction the electric field is determines the polarization of light in which direction of the incoming light you will have the oscillating electric field determines the term polarization of light. Polarization can be roughly divided broadly divided into linearly polarized light and the circularly polarized light what exactly it means I will explain it to a moment as I said the electric field has to be perpendicular to the direction of the propagation if the wave is propagating in z direction the electric field has to be either in x or in y direction in Cartesian coordinate.

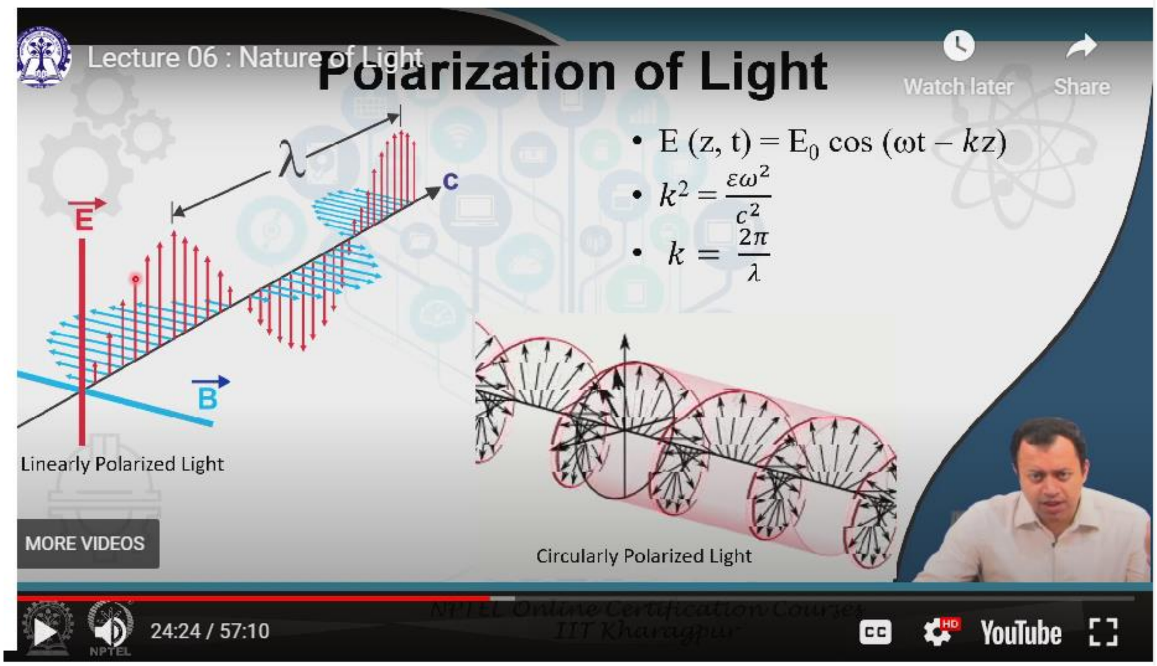
Suppose in this particular case the electric field is in y direction this is y this is z as the light propagates in a particular direction if the simultaneous direction of the electric field mark my word if the direction of the electric field remain exactly the same. So, we have previously considered it y it remains in the y direction remember it has a flexibility it has the freedom to go in the x direction as well x is also perpendicular this angle is also perpendicular this angle is also perpendicular, but the E field the electric field remain fixated to the direction it has started with it remains fixated in the y direction its intensity increases and then decreases does not matter at all, but as the light keeps on propagating it remains fixed in one particular direction say in y direction we call it linearly polarized light we call it linearly polarized light, light is giving in this direction electric field is through. So, throughout the journey the electric field remains in this direction it can go up it can go down, but it can never go this direction this is also allowed this is also perfectly allowed, but it will always remain it will always remain in this particular direction if it is so then it is called linearly polarized light. In linearly polarized light the intensity of the electric field the intensity of the electric field reduces crests ebbs and flows increases or decreases reduces and then increases again, but the direction remains constant. Compared to that we have a circularly polarized light in circularly polarized light the direction of the electric field constantly changes between two orthogonal polarities meaning if the light is moving in the z direction if the light is moving in the z direction the electric field constantly direction changes between x and y x and y x and y the direction changes, but the amplitude the overall intensity remains exactly the same.

So, the fundamental difference between linear and circularly polarized light in linear polarized light direction remains same intensity changes in circularly polarized light let us call it amplitude, amplitude is a far more scientific term. In linearly polarized light once again direction is constant amplitude is changing in circularly polarized light amplitude is constant direction is changing. There are others other type of polarization elliptical and what not there are exception into these two, but remember this is preliminary if you want to go detail on to this I ask you to go into a course of electromagnetism. I cannot go further detail into it because then it will be instead of a nano biophotonic course electromagnetic theory course there are several of them I have to do something separate from them, but I am forced to give you some amount of basic idea these are very generic very basic ideas all of you must know about it this is high school physics I am simply doing it as a revision as a refreshment.

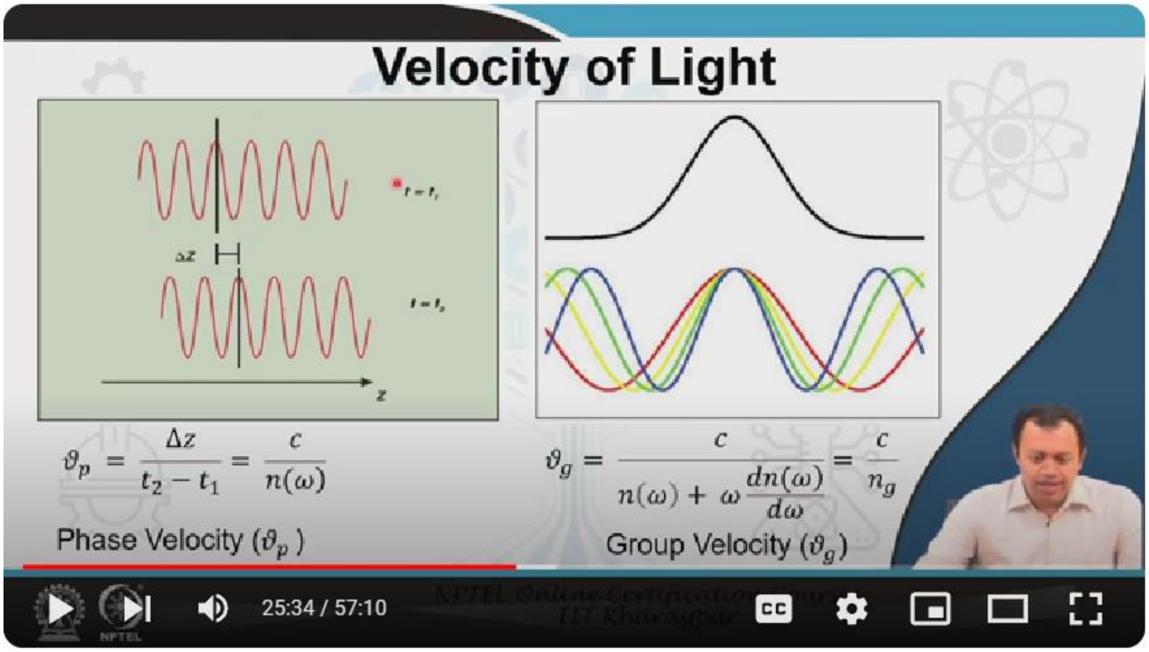


Now velocity of light usually is given into two different formats phase velocity and group velocity what does phase actually means phase is the angular component it is basically a point of the wave that is propagating.

Now wave is propagating in z direction if it is a linearly polarized light. So, these points these points can be considered as individual phases those radians that I talked about it starts from 0 comes back to the same position. So, you can say it has gone through a 360◦rotation it has gone through a 360◦rotation. So, this end within that entire complete 360◦ rotation in within this entire complete 360◦ rotation a particular point at this particular coordinate in x y z direction at a specific time $=t_1$. The electric field had this much intensity we have considered arbitrarily per say that this is 0 and this is 0 360◦ this is entirely a wavelength. So, one of these point the angular position of this particular point of wave mark my word the angular position of a particular point of a wave in a specific space and time coordinate is phase that is it, this is a phase define it π/2 π/3 what not π by ¼ π anything of that sort is particularly a phase.



So, when the wave propagates if we have you know fixed to a particular point if we have tracking this particular point how is it moving how is this moving after you know 10 cycles 4 cycles this is one cycle and then there is another cycle starting. So, if we are tracking this particular point with respect to this this distance that it covers at a particular speed that speed is the phase velocity difference between speed and velocity is one is scale and one is vector velocity is direction associated with it.

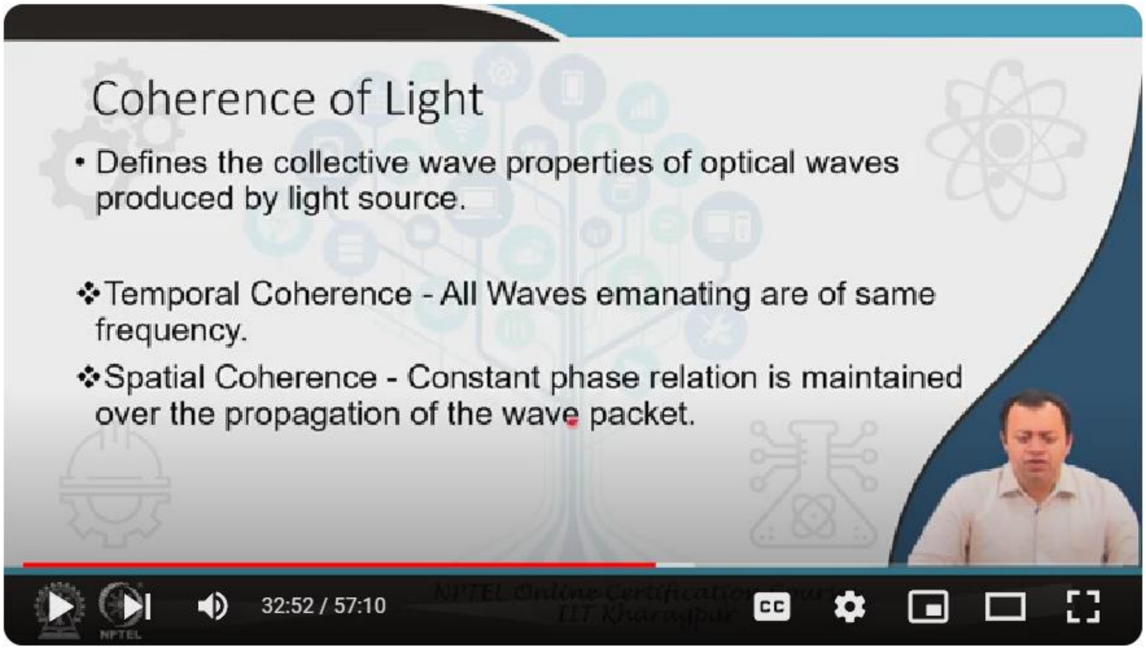


So, phase velocity is simply a particular point it is at a specific point at t equal to t at t equal to t_2 it has moved the distance moved is z_1 minus z_2 which is Δz. So, Δz by Δt is the phase velocity and this phase velocity is something that we talk about as $3X10^8$meter/second for electromagnetic wave for light in vacuum. However, that is the phase that is usually light or electromagnetic wave per say I will use both interchangeably when I am talking about electromagnetic wave in your mind imagine visible light because photonics mostly deal with as I said visible light infrared and ultraviolet and of course, we are more susceptible to visible light than any other form of light per say our eyes are more tuned to it.

So, it helps you to understand visible light. Now, visible light as you know does not have one particular wavelength one particular frequency, but it has large number of frequencies large number of wavelengths all travelling at a slightly different speed. At crest and trough, crest is the stop top part and trough is the bottom part they usually sometimes coagulate they sometimes come together, but overall, they do not. Light electromagnetic wave more or less does not travel as individual wavelengths with individual frequency, but as a large packet large packet containing different wavelengths different energy different frequencies of light. Again, one more thing when I am talking about light or when I talk about energy within your head you should always be trying to calculate E is equal to is equivalent to λ is equivalent to frequency is equivalent to electron volt what not.

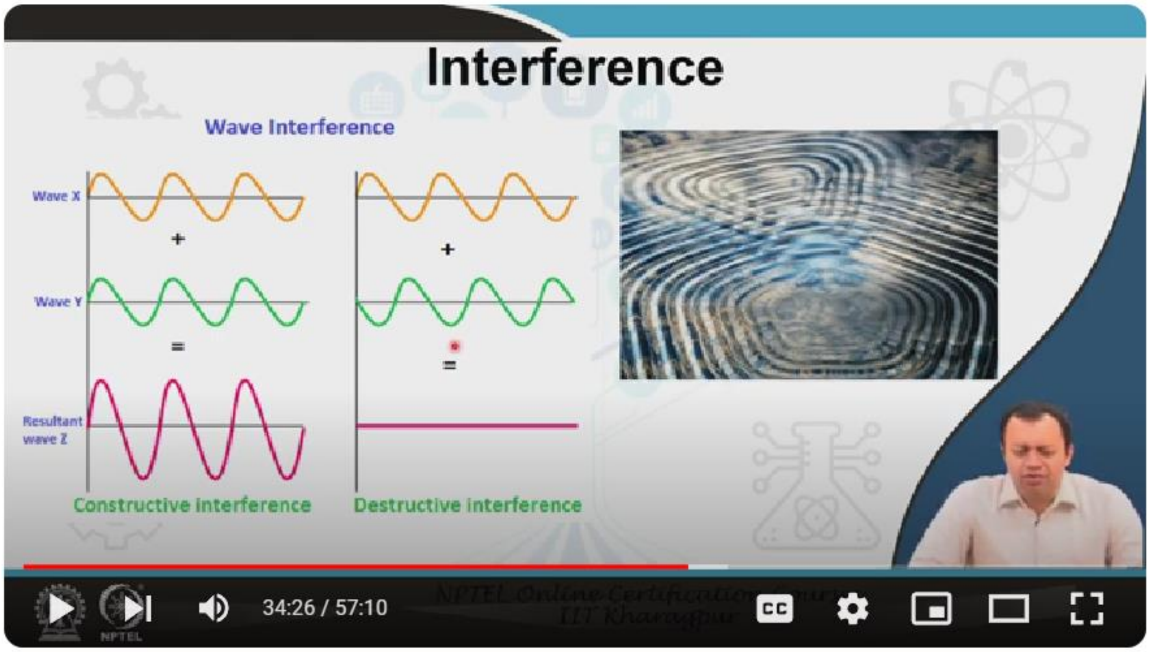
So, the chain goes like this. Coming from speaking about chain you can imagine this to be a train to be a train moving from point A to point B. Now, what does train contain so many different bogies so many different bogies. So, each of these bogies might have their slightly individual speed, but overall the train contains all of these bogies going at a specific speed so much so as an average speed moving from one point to another point. So, again waves travel in groups waves travels in groups visible light contains 7 specific frequencies I do not want to tell you what are they you should know by this time any middle school student know what are those 7 frequencies yes I heard you they all travel together and a combine is white light that we see we do not usually see individual frequencies of light one after another we see a combination of all of them traveling together only in specific condition by passing that light through certain type of material certain type of object certain types of mechanism can you see this white light breaking down into 7 lights and interesting phenomena such as rainbow comes up.

Now, the average speed of this group velocity average speed of this wave packet the overall all of these are having a slightly different frequency and thereby they have a slightly different energy. $E = h\nu$ energy is associated with frequency if they have different λ i.e. different color they have different wavelengths they have different frequencies and thereby they have different energies if they have different energies they also have different velocities. Overall the average velocity of all of these packets which are traveling together which have you know similar frequency similar energy, but not same, same and similar are different. They travel with a speed which is called the group velocity this is phase velocity one individual point traveling group velocity is overall the group the wave packet all the 7 lights of wave VIBGYOR traveling together and is given by this particular formula this particular formula depends on something called group index not the refractive index, but the group index group index just like refractive index is overall how much there will be a modification of the how much will be the average modification of the electric field when all these waves with their slightly different intensity of electric and magnetic field enters a medium a complex medium which have electrons charged particles which are also producing its own electromagnetic waves the average the overall change is given by the group index. Now for all intent and purpose understand this that if we are trying to do something meaningful like communication we have to deal with a packet of wave very few actual information could be sent through phase velocity we have to do with group velocity per say we have to deal with group velocity because group velocity is the entire packet several waves and that is something that is allowing us to take information from point A to point B usually information. Usually information cannot be sent using phase velocity or using a particular point of the wave. Group velocity is different than phase velocity sometimes you see bizarre things keep on happening with group velocity especially with this particular formula with refractive index changes with respect to frequency and if this thing rapidly changes then this group index become very high group index become very high your group velocity can be very low inversely proportional right meaning the light which is traveling from the medium acquires a very low speed. We call those those typical phenomena as slow light the frequency of the light or the speed of the light or the velocity of the light reduces very significantly slow light phenomena. Anyway, that is a discussion for another day we will not discuss slow light we just go through couple of definitions more.



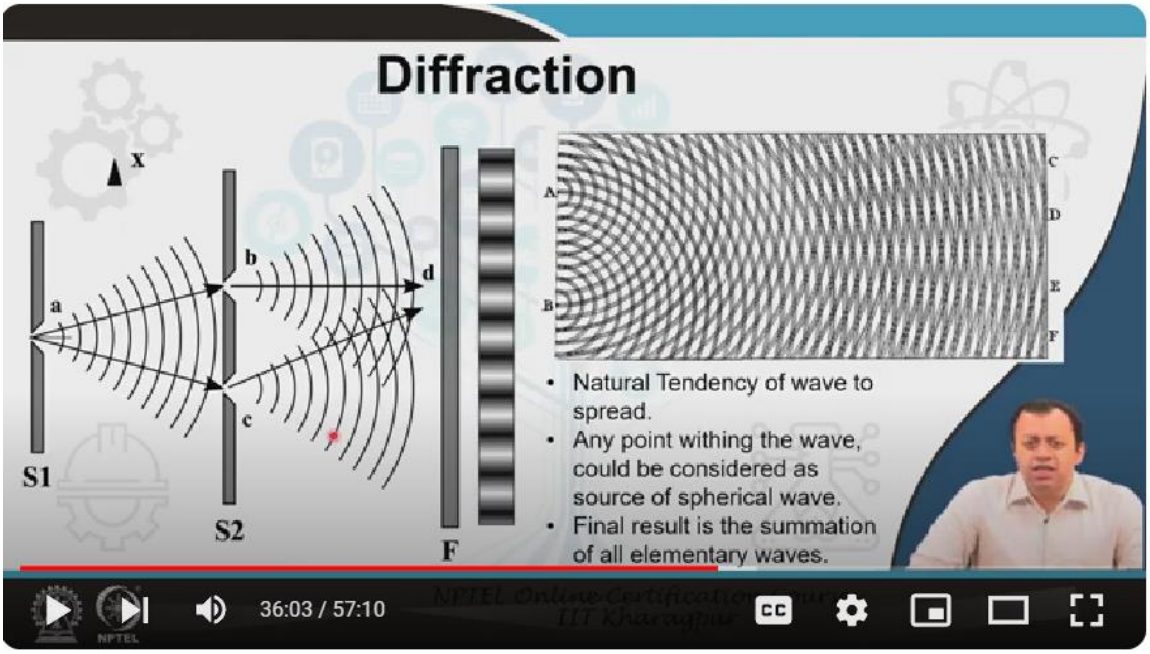
Let us talk about coherence of light coherence simply defines the collective wave properties of optical waves. So, you are sending bunch of frequencies bunch of light bunch of wavelengths going through one medium to another medium if they remain as they have propagated through a medium point A to point B all the waves are of the exact same frequency we call it temporal coherence, time wise they are coherent or if this gap this phase difference this difference between them the spatial temporal difference between them remain as it is here it is most definitely not, but if suppose it remains the phase difference between wave 1 versus wave 2 versus wave 3 remain as it is then we call it spatial coherence. We will require this when we are talking about imaging. We are sending light through a turbid medium trying to see a cell or a biological molecule the light that is coming out after passing through the turbid medium and how much it has remained itself coherent with respect to its previous case determines several properties of the image that we are planning to get. So, coherence is an important phenomenon of light which we require in when we are talking about imaging of a particular biological matter.

So, two types of coherence temporal and spatial.



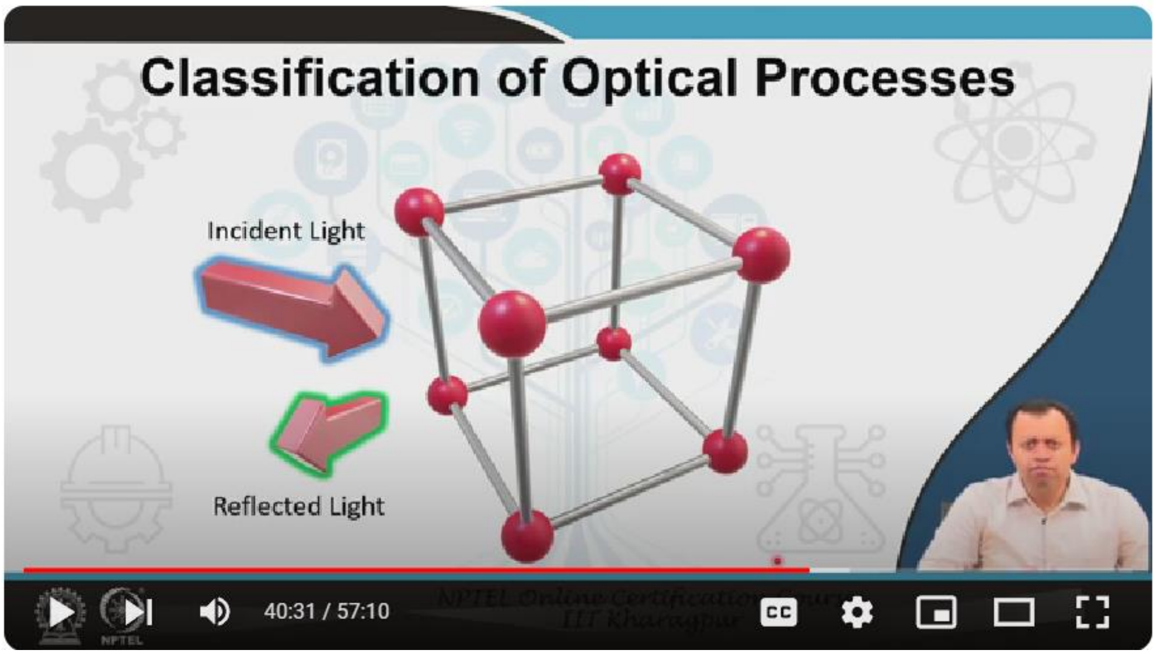
I would very quickly go through interference because all of you know what interference is, interference is basically couple of waves combining together there is a linear superposition between them there is a linear addition you can say linear summation rather than addition summation of them. So, if wave x and wave y have same phase difference between one another this intensity and this intensity are same they have same energy similar energy let us say similar phases they can simply add up. So, this is one this is one they add up linear superposition they become 2 or if they are 180◦phase shifted this is 1 and this is minus 1 they can cancel each other with destructive interference causing you know bright and dark fringes as we have talked about in Young's double slit experiment. So, wave interfere among each other their phases their electric field intensities can combine like these two waves are combining with one another they can combine with one another and the overall result is a linear superposition.

These are maxima and minima and everything in between will give you shades of grey this will be very bright this will be very dark and anything in between obviously, these are the two extreme cases 180 degree phase shift whereas, this is 0 degree phase shift anything in between 0 to π anything in between $\pi/2$, $\pi/3$ anything in between will give you shades of grey.



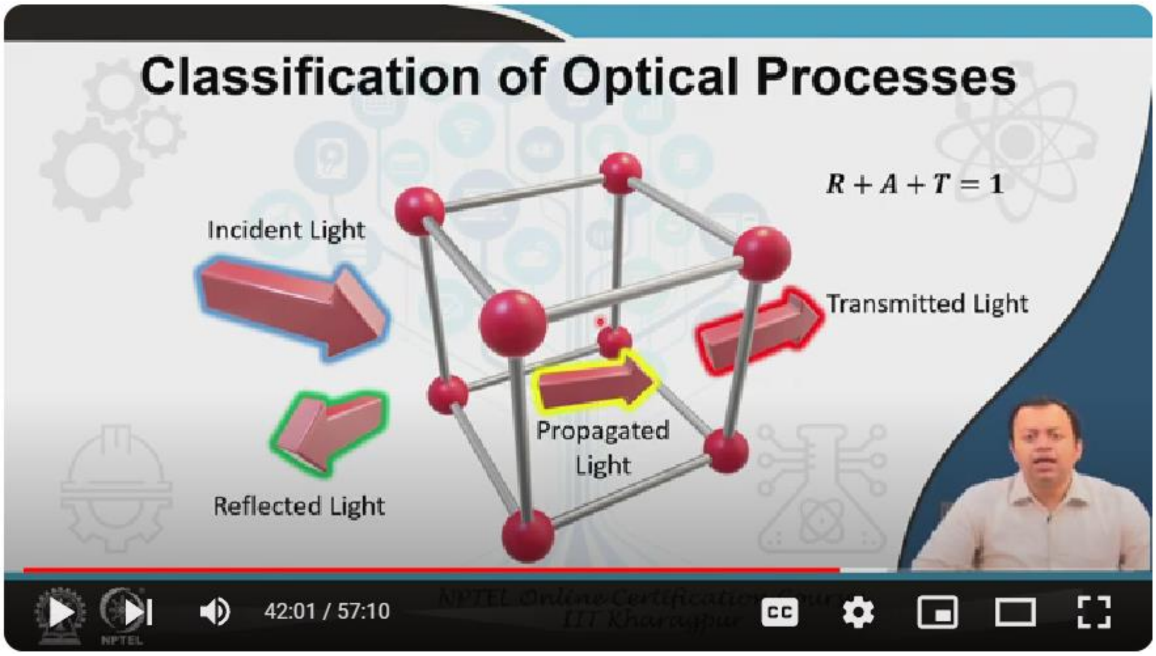
Diffraction is similar phenomena with respect to interference and many books consider them as completely same some books have a confusion stating that no they are fundamentally different phenomena. I would like to quote an authority here Richard Feynman. Richard Feynman's book describes diffraction and interference as very similar phenomena diffraction is combination or interference of several different waves simultaneously together. When we are talking about interference and here I am quoting Richard Feynman when we are talking about interference it is usually couple of waves combining together linear superposition between couple of waves one or two more can come in. Diffraction by definition has lots and lots and waves they are combining together they are producing secondary waves those secondary waves then combining with their primary or other secondary waves it is a interference manifestation in a large matter along with along with and here why certain books consider the diffraction is completely different.

Diffraction can also or usually need some sort of a physical boundary some sort of an obstacle in between their path these obstacle helps break one particular wave or create large number of secondary wavelengths. So, light basically in this particular case because if the wavelength of light is closer to the sharp corner closer to the distance closer to the length closer to the geometry of these obstacles they can simply bend through it they can simply bend around sharp corners it is not only straight away go some part can also bend around this bending of light around sharp corners is diffraction and that require a object that require an obstacle that require something else. Again do not get confused interference is two waves interfering here also large number of waves are interfering here large number of waves are interfering they are spreading around as they moving every single point can be considered as a source of wave every single point of this could be considered a source of wave they are creating their own waves they are creating with their own waves and a combine effect because of the presence of interference of large number of waves because the waves which were probably moving in this direction had to change its direction because of the presence of an obstacle a massive scale interference happened a massive scale interference happened between large number of waves secondary primary this that etcetera and that is diffraction. Final result is also the summation of all elementary waves interference usually one or two in a simplistic case that interference when you become manifest it to a larger extent becomes diffraction.



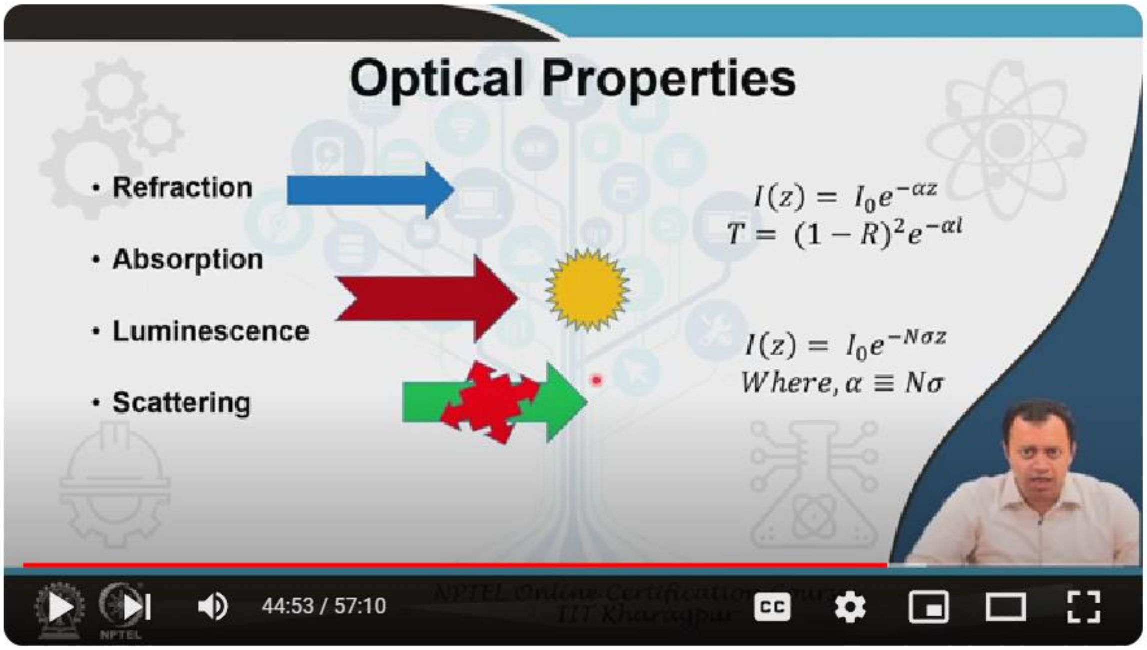
Things starts getting interesting things starts getting interesting when this light enters matter and when I am talking about matter I will usually talk about solid matter yeah it is a whole different ball game lights interaction with liquid or turbid media or fluid media we are not into that you will have to go to the opto fluidics class for this here we stick to solid material.

When light is entering a medium say for example, incident light a substantial portion can get reflected. Now reflection usually of two type specular reflection and diffused reflection specular reflection is just like that what you heard at a particular angle the light is coming hitting the surface and with the same angle it is reflecting back. So, this if it has come at a angle θ 60◦ it is returning back with an angle θ 60◦say specular reflection nothing happened simply the direction of the light changed the light remain as it is. Polished surfaces usually mirror gives us specular reflection. However, most objects that we see around non-mirror you me table chair etcetera gives us diffused reflection i.e. the incident light comes and because of the surface roughness of the material because of the property of the material the light that reflects that reflects in different direction different angle. Bunch of photons come different frequencies wave VIBGYOR is coming and hitting a particular say a butterfly wing or precious stones like gems and jewels etcetera some of them are absorbed some of them are reflected, but they are reflected in different directions and overall that makes you visible. A particular light is from a bunch of photon bunch of wavelength wave VIBGYOR some of them are absorbed some of them are reflected. In a ruby just, primary example red color ruby blue and green light mostly are absorbed red light is reflected.



So, a ruby looks red simple phenomena. Red light is the interesting bit which we will be discussing mostly is the light which is inside propagating inside the medium whatever filters out is transmission. So, we can more or less classify interaction of light of matter into this simple formula, reflection + absorption+ transmission = 1, 1 is 100%or whatever the incident light. You send bunch of light into a material some amount gets reflected some amount get absorbed some amount is transmitted the total is the incident light. Interesting thing actually happens this is the last one I know my lecture is going little bit longer just bears with me I will explain very clearly just two slides I will finish immediately. Interesting phenomena happen when light is in inside the medium when light is inside the medium what happens all of you know refraction the direction changes why is the direction changes the speed changes why is the speed changing the velocity changes why is the velocity changing because energy is changing why is the energy changing the frequency is changing why is the frequency changing because the electromagnetic field of the incoming wavelength incoming wave is interacting with the electromagnetic field of the material which is inside.

These are atoms they have their own electromagnetic field they will interact with them the modification of the electric field will result in change in the property of the wave that is travelling through overall understanding of refraction.

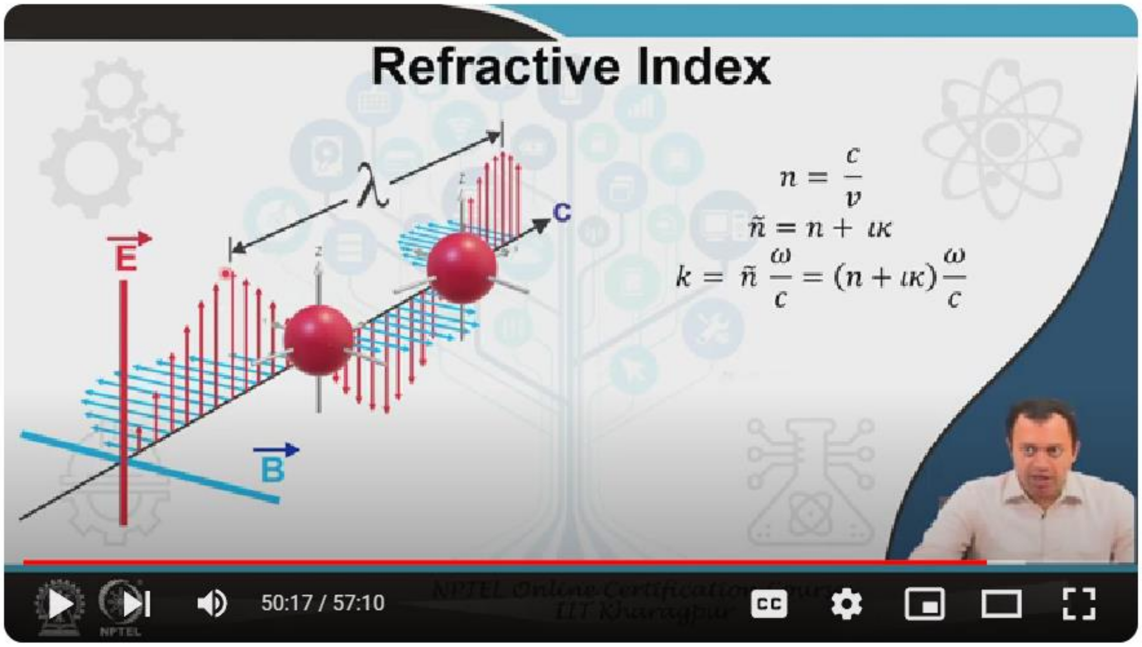


Absorption is when the wave or the photon that is going through is simply consumed is eaten up there are two basic ways in which photon or electromagnetic wave light can be eaten up absorbed consumed inside the material. Inside the material which is made up of atoms and molecules they exist in discrete states. Electrons exist in orbits around sorry orbitals orbits is for planets orbitals is for electrons SP and all of that 1s 1 2s 2 you know those orbitals and they are discrete electron can absorb light go from one orbital to another similarly molecules they have their own modes own vibrational modes they can absorb light and go at a higher excited state. In these two ways light can simply be absorbed light could simply be absorbed consumed eaten up destroyed by something that is inside the material there are two basic ways electronic absorption or molecular absorption. What happens after absorption is that either the electron or the molecule which has eaten up this light has gone into an excited state cannot stay in an excited state it has to return back to its ground state sooner or later high energy is not sustainable high energy is not stable it needs to return to its lowest energy state ground energy state ground state which is much more stable it returns back it can return back it will return back with spontaneous emission at a random time.

We have not able to we have not yet been able to calculate the time by which the spontaneous emission will take place we can give it only a time frame a probability distribution. So electron was there light came it absorbed it went to upper level after some time if it is not disturbed it will return back to its original position this returning back is random spontaneous emission and it will emit photon or the equivalent of photon back sometimes it emits heat sometimes it emit vibration sometimes it emits photon that photon could be of a completely different energy than it has consumed depend or it could be of the same energy as well elastic as well as inelastic. If photon is given out emitted out we call the phenomena luminescence. Now remember luminescence does not necessarily means that absorption has to happen just before absorption could have happened at a long time ago it is spontaneously returning it back luminescence does not mean whatever frequency of light has been absorbed the same frequency is returned back some frequency can be converted into heat some frequencies into light. So incoming light and outgoing light is of a different frequency right and then come scattering.

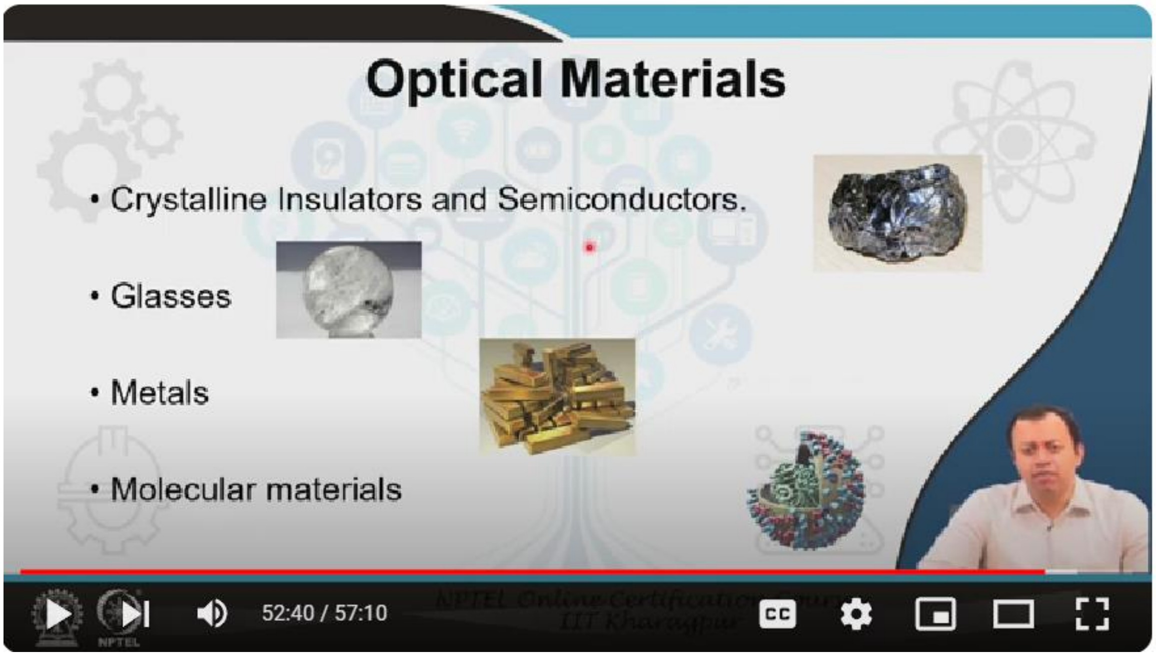
Scattering is the phenomena where light which is propagating inside the medium which is propagating inside the medium encounters different refractive indexes different refractive index because of presence of impurity because of presence of scratch because of presence of some doping material as such the impurity centers are far smaller than the wavelength of light. So, there is a constant zigzag pattern the direction of the light will constantly change thereby the forward propagating light bunch of photons which were forwardly propagating will get zigzagged away from one another will get zigzagged away from one another and the transmission light the light that is transmitted out will be reduced. So, you can see that scattering and absorption though different are analogous formula in absorption light is consumed in scattering light is deflected in both cases in both cases the transmission the direction of the propagation the light filtering out has reduced in one case light has lost light has gone in different direction which can again get scattered again get absorbed in a different direction or in absorption, but the light has simply been destroyed simply been consumed. So, we can define it like that if intensity of light in z direction can be given by intensity of light with z = 0 the maximum intensity when it start with$e^{-\alpha z}$, z is the direction alpha is the absorption coefficient this is intensity of light after it has moved in z direction. When we are talking about scattering center this n versus sigma, sigma is scattering center how many of these scatters are there how many of these scatters are there and n is well by sigma I means the n is the number of the scattering centers and the scatterer are what are the properties of these scatters you know how much of this light they are able to deflect.

So, you can see absorption coefficient is quite equivalent not equal equivalent to the number of scatters centers with their scattering parameters this is the scattering parameter associated with it. Refraction, absorption, luminescence is scattering all results in reduction in transmission. Only non-absorbed non scattered light is transmitted there are exceptions of course, you can get scattered light from some place which is going transmitting at a different direction etcetera, but overall I am talking not of exception I am talking about general formula refraction absorption luminescence and scattering all can result all can result not necessarily they always 100 percent of the time will result, but they can result in reduction in transmission. And by understanding these phenomena we understand the interaction of light with matter.



Refractive index I have actually gone through the incoming electromagnetic field agitate this charge particles inside the medium which is electrons in the nucleus they produce their own electromagnetic field those two electromagnetic field interact with one another resulting in reduction in speed.

The speed reduces why would the speed reduced simply because of that. Now, the refractive index is not simply reduction in speed, but can be given in a complex phenomenon with respect to an extinction coefficient this small k is extinction coefficient and it is complex it is a complex number and this is the wave vector the propagation of the wave vector do not confuse between this k and this k this is extinction coefficient whereas, this is wave vector and this wave vector can thereby give with respect to this formula ω is obviously, the angular velocity c is the speed of light n is the complex quantity and that can help you give rise to understand the propagation of the light in a particular direction.



Now, when this is the last slide I promise no more when we try to classify solid materials in terms of their optical properties. Electronics engineers you classify materials in terms of their electric properties right metals insulators semiconductors we can differentiate materials according to the optical property as well why not optical materials can be classified roughly into this three you also roughly differentiate into semiconductors metals and insulators there are other categories as well trust me what have you heard of metalloids what is gallium is it metal is it semiconductor gallium .I am not talking about gallium arsenide. So, come back to optical materials optical materials can also be roughly differentiated into crystalline or insulators as in semiconductors glasses metals and molecular materials optical materials are differentiated as such.

Crystalline and insulating semiconductors are basically something that has a lattice you know semiconductors have a particular lattice there is a unit cell there is a unit cell in which the atoms are arranged in three dimensional space and that particular arrangement is called lattice that is repeated throughout light passes through it has its own property depending on whether the light is absorbed by the electron or molecules it will propagate further, glasses see around you where you see glasses in your window pane in your spectacles I will soon require a spectacle as I have been prescribed they are transparent why because the visible light is neither absorbed by the molecules of glass silicon dioxide nor by the electrons of glass electrons SiO_2 electrons absorbs ultraviolet light the molecules of glass absorbs infrared light both of them are transparent to human eye the middle between ultraviolet and infrared is visible frequency that simply pass through nobody likes it in glass neither the electron likes to absorb it nor the molecules like to absorb it so it simply pass through. So, it is neither absorbed nor if you have good enough structures nor scattered then what do you get full transmission full transmissions makes it almost invisible hence we put it in spectacles we put it in windows etcetera. Metals are entirely different ball game metals have an electron cloud moving through them at a particular frequency that is called plasma frequency this plasma frequency is usually an ultraviolet. So, any light any wave any electromagnetic wave any photon that has frequency less than ultraviolet light will be screened will be screened by the insides electron cloud and they will be scattered away. Since the plasma frequency the frequency the speed by which the electron cloud under them travel is in ultraviolet any wavelength higher than ultraviolet is simply scattered visible light is above ultraviolet wavelength wise it is scattered and hence metals are shiny and resulted in wars and genocides and murders because simply bunch of light is getting reflected out of it.

We will be mostly dealing with molecular materials molecular materials technically every material is molecular materials, but here molecular materials means large number of molecules have come together a variety of molecules different types of molecules have come together they have formed close bonds among each other, but intramolecular bond is generally very strong, but intramolecular bond is weak they formed a unit type of thing with a variety of molecules carbon hydrogen oxygen nitrogen etcetera glass is silicon dioxide metal is just gold etcetera semiconductor is also one or two molecules, but here plethora of molecules plethora of elements have combined together carbon hydrogen oxygen nitrogen sometimes metal sometimes this that etcetera they have combined together and made something very very complex much much more complex organic matter for example, a biological matter for example, therefore, we call them molecular material they have strong intermolecular bond, but one unit is very weakly associated with the other unit they are there by soft matter very low melting point very low boiling point any biological entity for example, yourself how much heat your body can tolerate as compared to glass or metal or semiconductor. We will be mostly dealing of lights interaction with this complicated molecular material.

I know I took more time than expected I apologize. Next class I will try to wrap within 30-35 minutes.

So, these are my references. Thank you very much. Thank you.