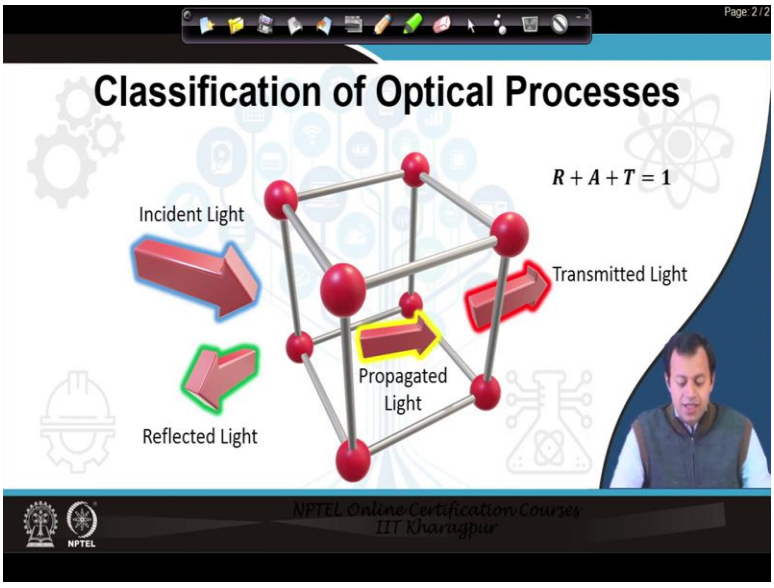
Biophotonics
Professor. Basudev Lahiri
Department of E and ECE
Indian Institute of Technology Kharagpur
Lecture No. 08
Light Matter Interaction

Welcome back, so we shall continue our discussion on various topics of biophotonics for the past few lectures as such we have been discussing the basic very-very basic of light and very basic of matter high school stuff. Today we will continue on that phase, this is just a revision or refresher course for those of you who might have forgotten this for a pretty long time. So, let us continue with that. Previous lectures we discussed about the basic of light, what is the dual nature of light, wave properties as well as particle properties and after that we discussed the basic of matter, how atoms come together, how the state of electron around the nucleus in an atom is quantized and we also discussed why atoms forms molecule and we discuss a little bit of matter as such.

Today we are going to continue in the same tone in the same manner and revisit or revise the other topic which is basically fundamentals of light and matter. Here we are going to discuss mostly how light interact with matter you have already known light you have already known matter now, let us combine these together and let us see how these two interact with one another and what are the manifestation of such interaction after all the manifestation of light and matter is what makes this world go around what makes everything beautiful and we going to discuss that.



So, let us start with the very-very basic not even high school middle schools. So, you have a atomic arrangement, some kind of a structure where atoms are arranged here it is in a crystalline structure, in a periodic structure it need not be you have an incident light, light falls onto it, some part of it gets reflected, some part of its gets propagated through the medium, through the material, through the matter and then the remaining part gets transmitted, we know it from a I think even if not primary school, secondary school we know this topic as nicely as it could be done.

There is also this angle dependence on the incident light and reflected light according to specular reflection laws, we know that the same angle in which the light has incident it will be the same angle in which the light will be reflected. But, most of the time which we are discussing this type of reflection we are talking about specular reflection, specular reflections where the wave front simply changes its direction. Specular reflection is mostly achievable by mirror polished mirror polished surfaces.

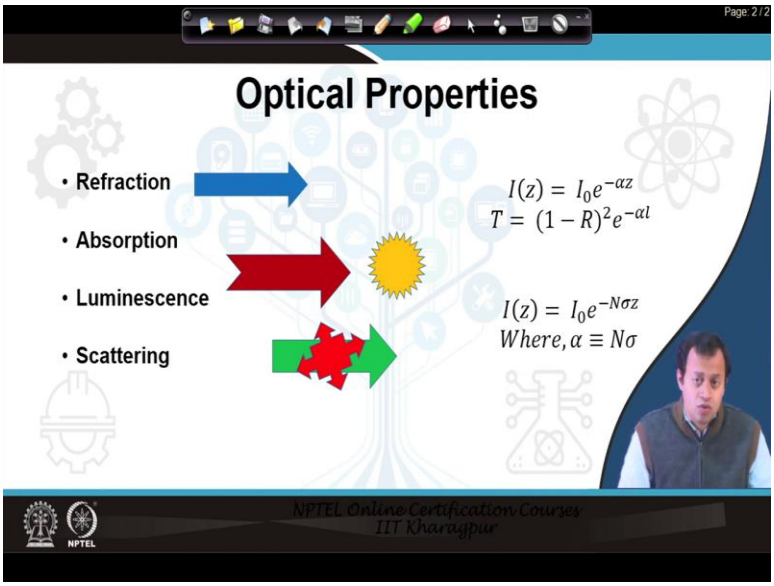
Usually reflections are bit more complicated they are diffuse reflection so, if the surface in which the light is falling is not as smooth or as polished as mirror, it has some amount or roughness, then the light which will fall onto it will get scattered in different directions apart from mirrors or the highly polished surfaces this is the type of reflection that is the diffused reflection that we generally encounter. Then there is this very-very interesting topic of propagation of light, what happens to light when it is inside the medium, what happens to the light when it has entered the matter per say what exactly is going on?

There are several different processes that goes on when light has already entered the inside of a matter you have obviously absorption, you have scattering, a manifestation of all of this can give rise to luminescence, emission per say and finally whatever remains whatever have not been absorbed or scattered or anywhere else get transmitted out get transmitted out. So, we can say that reflection plus absorption plus transmission is equal to 1, 1 as in 100 percent the overall incident light gets manifested or get trifurcated differentiated into reflection absorption you can also use the term attenuation per say.

But, attenuation generally means that almost substantial portion almost entirety it has been attenuated. So, let us call it absorption but the absorption here remember mostly talks about this propagated light i.e. what happens to the light when it is inside and then whatever remaining is

filtered out its it comes out as a transmitted light. So, the overall process is reflection plus absorption plus transmission it gives rise to one it might seem very-very intuitive and you might think that this is very natural very easy we know it pretty well but, as I said basics if you know probe a little bit you start seeing that maybe some part is still missing.

So, let us for the time being concentrate on this propagation of light inside the material inside the matter what exactly takes place when you have light interacting with atoms molecules electrons what are present inside the matter per say.



We can classify the processes optical processes into these 3 or 4 categories refraction absorption luminescence and scatter there are some other properties as well but, let us stick to these forms the most important one. Refraction any school going child will know this is the reduction in the velocity of the light we will discuss it very much what happens to refraction when there is no light inside the matter what happens to that but, for the time being accept that refraction is basically the direction of the light changes from one medium to another medium. Snell's slow and all you have known.

Although here it needs to be accepted that in refraction the intensity of light per say does not change intensity of light per say under normal circumstances perfect circumstances does not change. What is absorption, absorption is when the light wave is absorbed by either the molecule that makes up the matter the atoms that makes up the matter of sub atomic particles like electrons. Now, remember these are two slightly different phenomena though we categorize them

as absorption, we will in next classes see the difference in absorption but, for the time being consider the part of absorption.

So, light enters the light the electric field and the magnetic field of the light most importantly the electric field of the light interacts with the charge particle the change particle is basically the nucleus as well as the electron surrounding the nucleus the charge particles gets agitated by the presence of electromagnetic field electric field you can think for simplicity and the change particle starts vibrating, vibration of charged particles in turns produce its own electromagnetic field that electromagnetic field basically interact with the incoming light.

We will discuss that little bit in bit more detail in the refractive index but, understand what is absorption or where absorption is coming from. Absorption simply mean very easily very simplifiedly that the light is eaten up, it is being consumed where is the energy going, most of the time the absorption or the light energy is going to either vibrate the molecules, the molecules are arranges in a particular way more complex molecules more complex arrangement they can be vibrated in different directions, they can move and inside that atom which forms the overall molecule, inside individual atoms, the electrons can also absorb the photon, can also eat of the photon, can also absorb the wave and jump from lower energy level to higher energy level.

We discussed about the energy levels in electrons around the nucleus is quantized they have discrete values. So, they can jump from one level to another level lower level to higher level by adding or eating up the photon the light that has come to it, thereby halting the propagation thereby, reducing the propagation and this is usually given by this particular formula this is the Beer's law in which the intensity of light moving in z direction inside a medium is given by this particular formula why I_0 is the initial intensity the maximum intensity at direction z equal to 0 given by $e^{-\alpha z}$ where alpha is the absorption coefficient it is power loss per unit length

So, this is the formula and we can therefore from the absorption part and the reflection part figure out how much amount of light needs to get out that is filtered out that is finally transmitted. So, transmission of light can therefore also be described according to this formula where l is the full length the full length of the matter that the intense light has covered this is again the propagation constant and $(1-R)^2R$ is the reflectivity T is the transitivity.

So, transitivity actually is determined by well t+ a+ r = 1so, t = (1-a+r) in a fancier way I can describe it in this exponential term because, it incorporates losses, absorption has to have some amount of losses. Now, let us discuss absorption a bit more, what happens to those electrons which has eaten up the photon and gone to a higher level?

So, electron around the nucleus was moving closely attached with the nucleus moving depending of course of the molecule and depending of course on the atom per say but, say it is very closely moving around the nucleus, photon has come it has energized, it has been absorbed, the electron has eaten up the photon and it has gone back one level extra, it has jumped from ground floor to say first floor that is an unstable state.

Remember, we discussed about bonding and anti-bonding anything wants to lose energy and comes back to the minimum energy value available, so minimum energy value it will go to by doing the so called spontaneous emission i.e.; the electron which after consuming the photon has gone from ground floor to first floor will return back to ground floor the return back into the ground floor will result in emission of photon. A photon will be removed out will be removed we call it emission.

If the energy of the photon that is removed is within optical ranges, we usually call it luminescence. So, sometimes you can things glowing after hitting it with light we will discuss it in detail in fluorescence and phosphorus that chapter is coming up but, after absorbing some amount of photon after absorbing some amount of light energy, some different frequency of light energy is also emitted it is not always that if, x is absorbed x is emitted there is a gap usually when x is absorbed y is emitted usually the frequency or the energy of y is less than x. Today we are going to discuss why it is less than x.

So, not necessarily though that luminescence is having to be followed by absorption it is no guarantee or not at all necessary that every time there is an absorption happening you will see light coming out that is not the case, absorption as I said several times the photon is not actually energizing the electron it may be simply vibrating the molecule per say or even if the photon is energizing the electron.

The electron may come back to original ground floor in a non-radiative manner meaning the electron can return back from higher energy level to lower energy level without emitting photon

per say, it can simply return back there are several other mechanism there is something called phonon based propagation or phonon vibration in which it simply shakes or vibrates, the lattice vibration is how the electron loses its energy you can consider it as heat you can for the time being for sake of simplicity consider it as heat some sort of a vibration. So, not just light gets emitted when electron comes back to original position from upstairs to downstairs, it can also come back to the downstairs by simply dissipating heat.

So, be absolutely aware that luminescence is not necessarily a compulsory phenomenon and every absorption does not give you luminescence. I understand some of you might be chuckling that this is common sense but, common sense is not that common. Then comes the topic of scatter what exactly is scattering basically means that the light encounters different refractive index that the refractive index change is at an order smaller than the wavelength of light. Scattering strictly speaking, the perfect answer here is that the light is encountering different index, different indexes of refraction before it can complete a total wavelength let us understand a little bit.

So, say you have impurities or say you have defects or say you have lots of scratch mark and these impurities these defect these scratch marks are at an order are at a length scale smaller than the overall wavelength of light. If the wavelength of light is 1 micrometer, you have random arrangement of atoms each having their different electromagnetic properties, each haveing their different electric and magnetic susceptibilities, each will react differently variedly to the oscillating electric field before the overall oscillating electric field can take a full turn.

That make sure that the light or the electromagnetic field of the light, the electric field of the light is going through constantly varied and random fluctuation in contract with these different periodic, different scattering, different scatterers. Once again there are defects or there are scratches there are impurities which are present at the length scale smaller than the wavelength of light. So, before the wavelength before the electrical magnetic field can compile come back to its original position, have a 360-degree phase, it has encountered many different random charge particles which is going to scatter or which directs the wave or which is going to scatter the photon in different direction.

As a result, the wave front that is travelling or if you say bunch of photons that is travelling maybe the overall photon is not absorbed eaten away but, it is deflected in different direction. So,

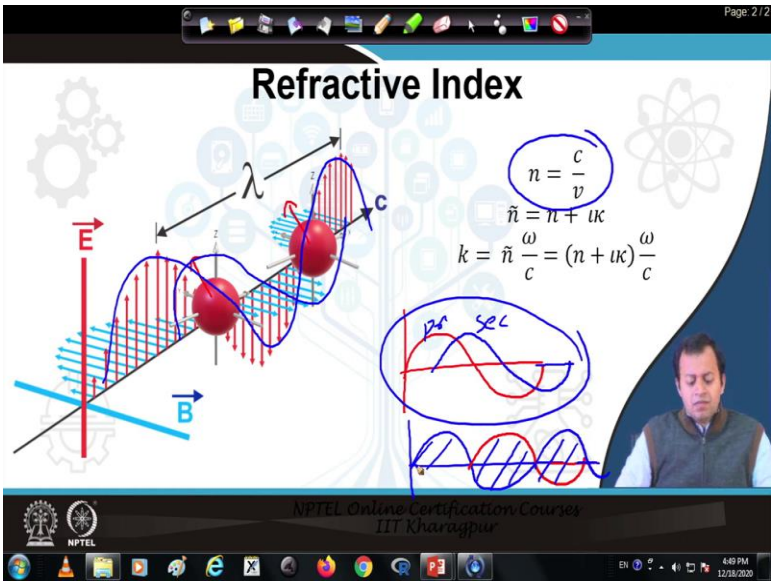
the number of photons that is propagating in straight line propagating in the z direction gets reduced, as a result the transmission also gets reduced. Remember the fundamental difference between absorption and scattering, it is not an intuitive as you might have thought earlier it is not as common sense as you have thought absorption there is an actual consumption of the photon.

Whereas scattering there is no consumption per say but, there is deflection of the photon in different direction. Here, the overall intensity might also remain same there may be some amount of frequency changes but, overall because of the change in the direction the forward propagation of the number of photons gets reduces significantly. So, you can say absorption and scattering though different phenomena are analogous to one another resulting in loss of transmission; one directly consumes the photon one deflects the photon in another direction.

So, if it goes in 10 different directions, 100 different directions you have to calculate all of that and combine it together, overall if you take one-one single direction of transmission then you will see the transmission has reduced because, the scattering is very high you can think of several different materials which scatter more, I have couple of those in mind maybe you deal with gold jewelry think about it metals are quite good scatterers.

So, here also if we are looking for the intensity in terms of scattering, the intensity in terms of scattering can be given by this $e^{-N\sigma z}$, z is of course the direction of propagation n and σ n is the total number of scattering points how many scatterers there are and σ is the overall cross section of each scattering point. So, one determines how many scatterers is there and σ determines the average cross section of each scatterers. If they are randomly distributed, if they have different cross section, then obviously this formula becomes much more complicated.

But, you can see here α is equivalent to n σ α is the propagation constant loss of power per unit length at the same time you see that is equivalent to the n σ the scattering parameters associated well technically parameters is not the right word. But, cross section and the number of scatterers per say so, if you want to get the gist of it absorption and scattering though not the same phenomena are analogous to one another resulting in somewhat of a similar outcome.



Now, let us see what refractive index is there was a beautiful animation that I did here but, unfortunately this version of power point is quite old so, maybe it will not work. So, now let us discuss refractive index per say. You need to understand this very-very carefully because, the whole basic of refractive index is whole basic of optics is based on refractive index.

So, any school going child will tell you refractive index simply means the how much the velocity of light gets reduced when it is propagating through a medium. So, the velocity of light the maximum velocity of the light in vacuum $3X10^8$ meter/second as soon as light enters a medium, it undergoes because, the medium is optically dense it is obviously denser than vacuum any matter is denser than vacuum so, even air, so there is an optical density change this optical density change make sure that the light propagate slowly and refractive index is overall c/v c being the velocity of light in vacuum without any medium and v is the velocity of the light in medium.

But, see herein lies the problem, if you think that there is a specular reflection is happening i.e.; light has completely been reflected by a polished mirror surface have we thought about that. So, there is no light which is propagating through the medium, there is no light which is propagating through the medium the light got simply reflected back look at a mirror look fine you will say it is not 100 percent perfect but, say 90 percent light is reflecting back only 10 percent is travelling through the mirror granted.

So, the velocity is very-very less so, if light does not travel inside the media, will the refractive index become infinite? Because, then it will be c divided by 0 but that is not the case why because, refractive index is a complex phenomenon it is a complex quantity it is given by this term n + ik where n is the real part of the refractive index and k is the imaginary part of the refractive index the k basically determines all these extinctions, all these coefficients, all this absorption all these losses associated with it.

So, when people mostly talk about c/ v they are actually talking about the real part of the refractive index and after doing few amount of mathematics you finally can correlate the wave vector of the propagation of the light with respect to the complex refractive index as such but, it does not explain you still what refractive index is, what exactly is refractive index if, it is not loss of velocity, velocity getting less than what it is well to tell you the truth in order to fully understand refractive index you need a rigorous quantum mechanical treatment.

A quantum mechanics has to come in and you have to go through several you know detailed mathematical calculations and thereby determine the actual nature of refractive index which I will not do here because that is not the scope or the aim of this particular course I will try to teach you what microscopically is happening when we talk about refractive index without touching maths that is the goal.

Let us see, so suppose you have a medium suppose and these two are the two atoms that I have described they are arranged in whatsoever manner periodically aperiodically, crystalline whatsoever. When there is an electromagnetic wave falling through it, whenever there is an electromagnetic wave passing through it, whenever there is an electromagnetic wave propagating through it, the electric field, the oscillating electric field will agitate the positive and negative charges electrons and the nucleus, electromagnetic field agitates or vibrates or it can make sure that the charges particles get vibrated.

Whenever a charged particle vibrates, it produces its own electromagnetic wave whenever the charge particle vibrates, it produces its own electromagnetic wave. As it happens if, we are comparing like with like if well obviously, here the concept of susceptibility, electric susceptibility has to be taken into account electric susceptibility simply means the ability susceptible we say a person is susceptible to bad advice a person is susceptible to bad judgment susceptible here means electrical susceptibility means how quickly or how strongly a particular

atom or a particular molecule can react to optical can react to dipole formation, can react to an electric field, how quickly it will rearrange itself in the presence, how quickly the material will modify itself, polarize itself in the presence of an electric field.

So, assuming these are susceptible materials, assuming some amount of susceptibility is going on i.e.; these atoms are actually affected by the light we have to assume that if there is no interaction, there is no effect, then none of this makes sense. So, light has entered into a matter, the atoms which contains nucleus and the electrons gets agitated by the presence of the electric field of the electromagnetic wave. This will only happen at certain specific frequency you cannot send any random wave and think that any atom whatsoever of the vast array of molecules will get agitated. But, assuming that this particular case has happened, the electric field is agitating the charge carriers, agitating electrons and agitating the protons.

Agitation of charge carrier will produce its own electromagnetic field and this electromagnetic field will be compatible will be comparable will be similar to the original electromagnetic field, electromagnetic wave agitates charge carriers, charge carriers getting agitated generate their own electromagnetic wave, the first electromagnetic wave, then interacts with the second electromagnetic wave and the overall response of the final electromagnetic wave is superposition, remember, we discussed in the previous case of all these waves that is primary and secondary as such.

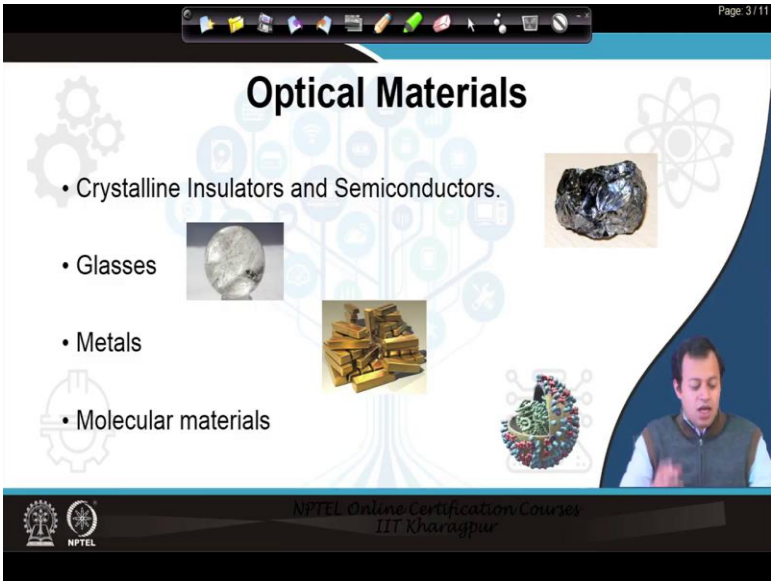
Though the frequency might not charge the wavelength does change inside as I said we need a very-very complex procedure complex quantum mechanical understanding to get this but, understand this the wave that is generated by the atoms here are maybe of the similar nature, similar amplitude as that of the primary wave but, it is still lagging behind phase wise from the primary wave because it started later. So, if this is primary wave you can have this as the secondary wave so, this is primary, this is the original and this is the secondary the overall results are a combination of all of this the overall result refractive index is a combination of all of this.

Now, I understand this is not a proper and proper definition of refractive index, refractive index is basically how much the measure of how much the electromagnetic field this electric field per say gets modified in the presence of the electromagnetic field that is generated by the charge carriers overall, it is not a complete understanding but, it is a better understanding than simply saying that reduction in velocity we have to understand that.

Now suppose, interesting phenomenon comes out of this suppose you have an original wave like this and you have a secondary wave like this 180-degree phase difference what do you think might happen? They can simply cancel each other out you know crest and trough so, if the electric field get cancelled out, do you think the light can propagate? Remember in the very first class I discussed that the light has two hands; electric hand and magnetic hand and only if they can sustain inside the medium light goes otherwise, reflected back So, think about it this is a primary case what happens in case of metals, in metals the generation of the secondary wave is 180-degree phase shift.

Now, some of you may still be wondering that I get it we have interference between primary and secondary waves and remember it is not just secondary there are millions of atoms here and randomly oriented but, it still does not take care of the speed per say. There is this theory of extinction, theory extension theory or extinction coefficient theory which actually says that whenever an atom is agitated by an electromagnetic wave it produces two waves first is the original fast wave that is same but, exact opposite to the incoming primary wave and it cancels each other and there is a secondary slower wave and that finally propagates through it.

I will not be discussing more on it. I will simply tell you that the overall understanding from a microscopic point of view is whenever light enters matter, matter itself produces its own wave or itself produces its own light, whatever comes out whatever propagates is a combination of the light that originally has entered and what matter itself has produced upon excitement original light a superposition happens and finally what comes out is. Because, the measurement of how much it has changed from original to final is refractive index. In a nutshell I cannot explain it anymore without going into detail of quantum mechanics which I want to avoid.



So, based on the various refractive index and how light can propagate through them we can classify materials, materials can be classified according to their optical properties and thereby we can roughly classify materials into crystalline semiconductors glasses metals or molecular materials. Now, let us go through them one by one. Semiconductors such as Silicon usually whenever the electromagnetic wave that is generated from the agitation of atoms they are lagging behind the original light. So, they basically slow down the original light and therefore you have a refractive index more than 1.

Crystalline structures or semiconductors follow in that category, in that sense that they have a periodic arrangement of atoms they have a periodic arrangement of atoms they have a crystal structure and whenever light passes through, it encounters a periodic potential. So, like light has its own periodic potential because of the arrangement of the atoms in specific manner, in a crystalline manner, in a lattice which is repeated infinite number of times in x, y and z light also encounters similar periodic potential. So, the interaction is more or less smooth.

So, the light can either get absorbed by overall changing the lattice vibration or light can simple penetrate through the lattice spaces or if the light is strong enough say for example, ultraviolet, it can get absorbed by the electrons, the electrons of these crystalline insulators even up to a point semiconductors like gallium nitride and gallium oxide high band gap semiconductor ultraviolet light will be absorbed by them and the electron will go from lower level to upper level for

semiconductor electronics engineering students will know from valence band to conduction band.

Glasses on the other hand are very similar in that regard but, not necessarily crystalline they are amorphous in nature and they have a large gap they have a large gap between their atomic arrangement meaning if, there is a very high wavelength, it will get caught, it will get absorbed by the atomic arrangement. If the wavelength is very small the electrons will absorb it but, if the wavelength of light is somewhere in between in middle neither very large nor very small, it can simply penetrate through the overall atoms being arranged amorphously into the overall matter.

Have you ever wondered why glass is transparent? Glass is transparent because, this middle frequency middle wavelength that I was discussing is for them the visible frequency. Glass absorbs infrared light because it is too big, the molecules glass molecule silicon dioxide absorbs them, glass also absorbs your ultraviolet light, the electrons in silicon and oxygen starts absorbing this high energy wavelengths and start jumping to upper level but, this sweet spot of light which can simply penetrate through the overall atomic arrangement falls into the visible spectrum.

Therefore, for human eyes glass is simply transparent and therefore you will see glass everywhere so much so and since it is invisible we do not pay much attention to it. Just look at yourself and think what else is glossy that you are carrying in your position watch, maybe your spectacles, maybe I do not know a car keychain sometimes it contains the glass-based beads as such. So, the idea with glasses are it allows its arrangement it is atomic or molecular arrangement is such that that the visible light simply pass through it but, infrared light and ultraviolet gets absorbed.

Metals on the other hand are the extreme category. These are the materials remember, where the secondary wave front is at a 180-degree phase shifted. If it is 180-degreee phase shifted, it simply cancels out the electric field and thereby light cannot penetrate. There is other explanation, plasmonic explanation which actually deals with electron cloud moving in metals and that goes to screen, any light penetrating through it, the electron cloud inside the metal moves. So, the electrons in metal atoms are very-very loosely bound to the parent nucleus that are not very strongly attached they are loosely moving around. So, they belong to the entire

system and they move with a particular speed given by this frequency called plasma frequency, this frequency is usually in ultraviolet range.

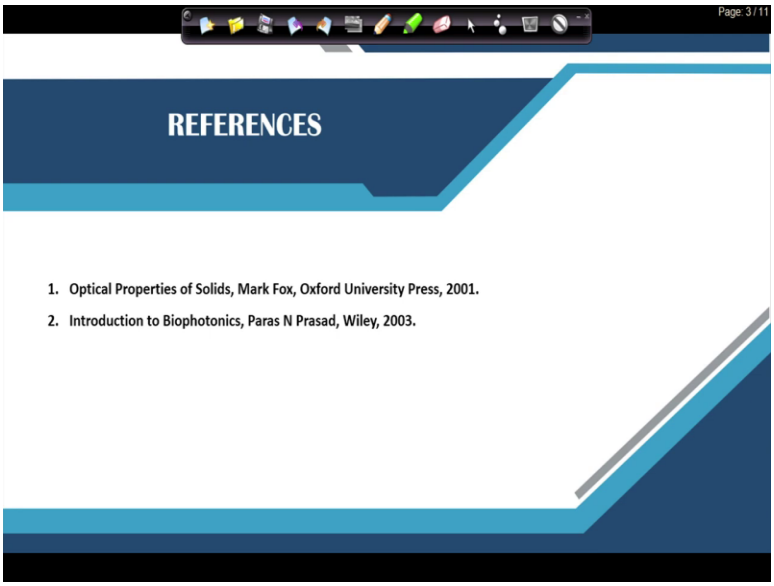
So, electrons inside the bulk of a metal is moving in ultraviolet frequencies. So, any frequency of light which is less than ultraviolet eye visible frequencies when it comes this electron tries to screen it and scatters it back. So, now you know why metals are shiny wars have been fought civilization have been lost and found because of human beings' greed for gold which is nothing but, the vibration of electrons at a particular frequency. If electrons have in gold or any other metals have been vibrating at visible frequency, it would not mean scattering this much, it would have scattered infrared light not visible light and it would have been dull and we would not have where we are now.

So, what happens to light frequency which is above plasma frequency, ultraviolet light and above can it penetrate through metal? I will hazard a guess yes but, I will ask you to do your own research. So, this is my gold and finally we have molecular materials any material can be considered as a molecular material, but here we mean a complex molecular material various different types of atoms are combining together.

So, semiconductors, glasses usually are one or two different types of atoms metals as such molecular materials are these various compounds which various atoms which are joined covalently carbon, hydrogen, oxygen, nitrogen they are joined covalently and though their intermolecular forces are quite strong different molecules by themselves are joined very-very weakly using van der Waal forces and they are usually therefore, soft to touch as well as they have very low melting point.

Can you think of any such molecular material? This is is an image of a virus that I have used as a molecular material example and we are going to discuss a lot about molecular material in the coming classes because molecular material is the biological material that we are going to discuss without introduction of light and that is what biophotonics is all about.

So, please remember the concepts that I have covered.



And these are my references, I strongly recommend the to go through the optical properties of solid by Mark Fox very-very interesting book, if you need to know more about refractive index more about quantum mechanics and more about the difference between luminescence, fluorescence excreta. So, thank you very much I shall see you in the next class. Thank you.