Nanobiophotonics: Touching Our Daily Life
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Lecture No. 36
Metamaterials

Hello, and welcome. We are almost at the last leg of our course on a Nanobiophotonics. And today we start a new module, module number 8 which talks of Quantum Biophotonics. So, what exactly is quantum biophotonics? And why are we suddenly bringing in quantum into the realm of biophotonics as if it was not complicated enough or as if it has not ah borrowed enough ideas from different fields. So, quantum biophotonics simply means that we utilize quantum technologies for biophotonic application. Biophotonic application you already know, interaction of light with biological material for either disease detection and or disease therapy disease cure.

So, what is the quantum part associated with? Quantum part means we utilizes quantum technologies into biophotonics. What is quantum technology? Well, quantum technology is those technology that follows the principle of quantum mechanics. We discussed a little bit about quantum mechanics in the beginning. Ah biology student do not switch it off.

I am not going to discuss quantum mechanics in detail. There is a separate NPTEL course specifically for quantum mechanics, but you need to understand irrespective of whatever your background is that quantum mechanics is one of the greatest theories that humankind has ever developed. It is the most experimentally proved theory. Quantum mechanics is a theory it has to be based on certain proofs certain experimental proof and of all the theories that human beings have developed from Pythagoras theorem to ah Maxwell's equations laws of electromagnetism to Ohm's law whatever you say the most proved theory in a variety of states in a variety of experiments all over the world the most proved theory arguably could be considered as a quantum mechanics. And we see quantum mechanics manifesting its properties are manifesting the more and more we go into ah nanoscale level.

Now herein lies a fundamental debate that exists between physics and biology from ah after the world war 2 or from 1930s onwards. So 1901, 1902 quantum mechanics was first developed by Max Planck you know it Einstein came in and all of those ah luminaries all of those giants of physics started working on it and physics simply took a proverbial or literal quantum leap and went to a completely new field from classical mechanics Newtonian mechanics this was quantum mechanics and so on and so forth we were able to describe the motion of electrons we were able to understand the atom and then we were

utilizing the ah energies of atom in making nuclear power plant or nuclear weapons depending on ah your your your choice and it got manifested tremendously. So whatever physics these days you see or you want or you utilize and its manifestation for example, electronics is a manifestation of the physics your smart phone utilizes quantum mechanics because your smart phone uses this silicon chip the semiconductor chip and the proper utilization of silicon chips as a nanoscale level has to have some amount of quantum technology has to have some amount of quantum mechanics associated with it. So even if you do not know if you are using a nanotechnology based equipment which is these days any electronic equipment smart phone, smart TV, smart watch what not everything utilizes some amount of quantum mechanical properties or quantum technologies more and more quantum communication is going on entangled photon is going on squeezed light are going on these are different fields of quantum technologies that are changing the game the changing the nature of human civilization so on and so forth laser is utilized everywhere else so many different thing from discotheques to laser surgery as we have seen and that is basically a quantum phenomena laser by definition is a quantum phenomena. While this advancement in biology ah sorry this advancement in physics and vis-a-vis its application of physics engineering electronics computer science mechanical etcetera were going on biology was not sitting idle biology was also growing leaps and bounds, but in it completely different direction biology was working on central dogma DNA has come up just in 1950s and then they have started understanding the gene the genetic material the mysteries of the cells opened up so on and so forth we were able to understand how the DNA converts into RNA and RNA creates protein if you can control protein what is the basic of ah cancer human genome project came up so on and so forth.

But from late 90s onwards basically the development of nanotechnology onwards the maturity of nanotechnology rather nanotechnology was developed in the 60s, but maturity of nanotechnology onwards biology started observing certain phenomena at a nanoscale level basically at a nucleic acid level where the standard explanation given by normal biological theory central dogma etcetera were failing and the better explanation better explanation not the wrong previous explanation was wrong, but whatever the previous application was it could be bettered using the theories of quantum mechanics. So, there in started this debate between a physicist and biologist, biologist started saying that quantum mechanics belong to physics or belong to even chemistry department we have made our own parallel path where we developed central dogma and what not why are we now interested to encroach change the boundary to go into ah quantum mechanics which do not even belong to us. Physics people on the other hand were of the opinion that we have to theory of relativity theory of quantum mechanics do not matches the way the universe reacts massive celestial bodies stars and galaxies work in a different way atoms and nuclei atoms and nucleus and electron subatomic particles work in a completely different way we have far more important work to do we have to combine come up with

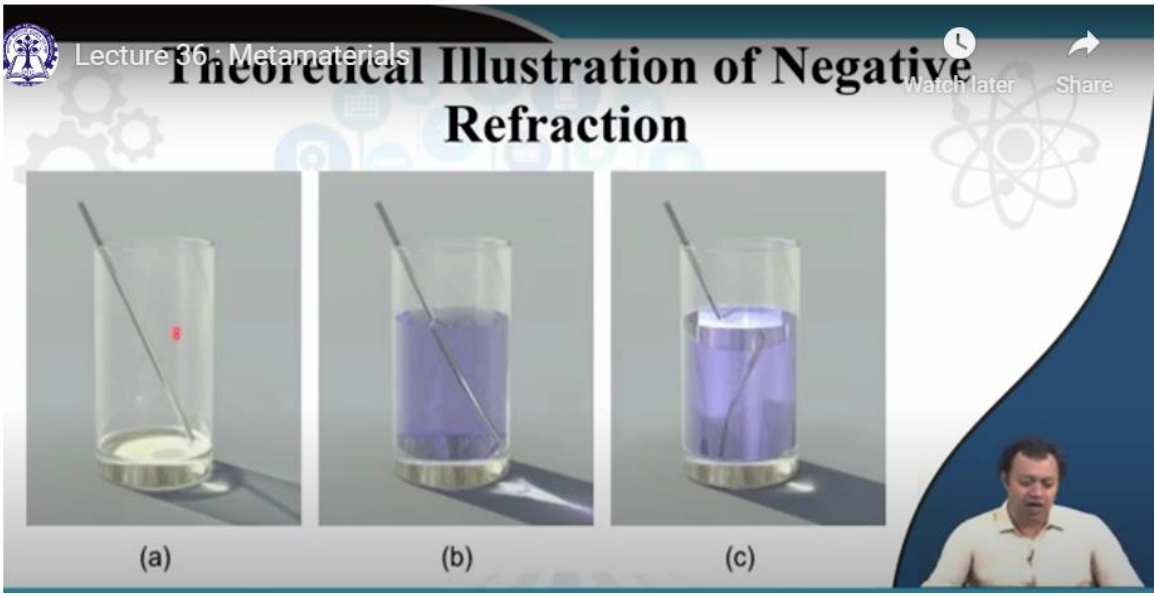
one universal theory theory of everything that you know takes care of the scale from massive black holes galaxies to electrons protons and neutrons we do not have time to go into biology and this debate is still going on this debate is still going on it is completely your option to choose which way you belong, but then there was a group of people ah both from physics and biology who said that if the explanation is better if you can understand something by applying quantum mechanics or even without applying quantum mechanics if we simply apply the technology because the more smaller you go nanoscale level atomic scale level the bulk properties do not work as such the bulk properties of the material do not work and the property of the material at a nanoscale level is tremendously different from its bulk counterpart this difference in property has to be explained has to be explained from from a quantum mechanics point of view think about it a DNA is made up of only a four bases the DNA combines and manifests itself and to produce a whole different and complicated organisms such as yourself. So, from a massive level that is the organism itself to the nanoscale level the properties are significantly different and if you want to further go below at a atomic level or a molecular level of individual genes individual DNA's then we already have a theory that describe the motions of molecules that describes the properties of atoms all of that why do not we utilize it a debate is still going on someone thinks a group of people thinks that it is useless biology and ah physics should be separate and some people think it should be combined and then there are the middle ground people who said that even if we do not understand quantum mechanics try to utilize it. So, many people these days use mobile phones yeah you have seen mobile phone in the hand of every single person that you more or less come across in your day to day life how many of them actually understand the complete technology behind mobile phone how is a mobile phone connected with satellite and how is a mobile phone without any wires is able to make you talk with the other person right knowledge has never prevented somebody from utilizing it.

So, there is another argument that even if you do not understand quantum mechanics why do not we utilize its properties nonetheless people uses computers without knowing anything much about algorithm or how the CPU the ALU arithmetic logic unit the central processing unit works people use mobile phones people watches TV all the time they do not know very few people have a understanding of how exactly a television system works the picture tube and what not how exactly works, but that has not prevented them from utilizing television utilizing mobile phone. So, same here same here we utilize quantum properties we utilize quantum mechanics theories to understand biology to try to find out the defects try to sense something try to image something using quantum mechanical properties. So, to give you a nutshell what exactly is quantum biophotonics what exactly is quantum biology or what exactly is quantum photonics for example, is simply this most photonics applications utilizes Maxwell's laws of electromagnetism, but then comes nanophotonics nanophotonics is the one where simple Maxwell's equations are not enough

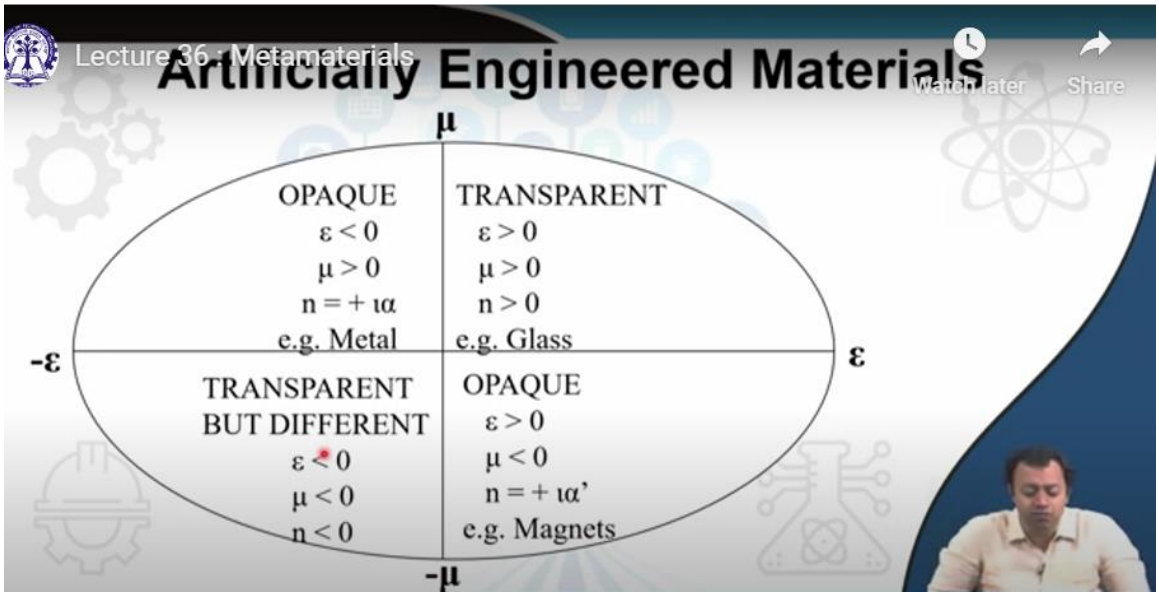
there in order to fully understand the nanophotonic part you have to use Schrodinger wave equation as well. Schrodinger wave equation plus electromagnetism combine them together you get nanophotonics. Schrodinger wave equation Maxwell's laws of electromagnetism central dogma combine them together you get nanobiophotonics simple explanation ok.

So, today we are going to learn there are several quantum technologies squeeze light, slow light, ah entanglement, communication etcetera, but today we will go ah learn something which is very close to my heart that is metamaterials extraordinary materials I am biased towards it unashamedly I am biased towards metamaterials because my doctoral work was on metamaterials there are so many other quantum technologies and I could have gone for all of them, but this is something that I do. So, subsequent results that you will see are all my results my own results. So, I am biased towards it I am allowed to have some amount of bias I cannot be neutral all the time I am not saying that this is the best, but this is something I know the best to all of it. So, I think that I should teach you metamaterials and its application in biophotonics. So, what are metamaterials? Metamaterials are artificially engineered materials whose electromagnetic properties whose electromagnetic properties are controlled or electromagnetic properties are customized or electromagnetic properties are those which are not available in naturally occurring material.

So, welcome to today's class lecture number 36 module 8 quantum biophotonics where we will discuss metamaterials. So, let us try and understand what exactly metamaterials can do the fundamental aspect of metamaterials that it can produce an electromagnetic effect that is not available in naturally occurring material and what is that that is negative refraction. Light bends you know Snell's law when light moves from rarer medium to denser medium because of the refractive index change light bends in a certain direction and you all have seen this that effect is everywhere we have discussed refractive index in the preliminary classes. So, what exactly is negative refraction? Negative refraction is produced by metamaterial it bends the light bends in a different direction bending of light is there, but it bends in a negative direction. So, you have a glass you put a steel spoon inside it fill it with water I have purposefully colored the water as blue.



So, that it is better seen. So, light now travels from in normal cases air to glass to water and then comes out because of the change in the refractive index between air glass and the water the spoon the spoon steel spoon looks bent actually it is not bent, but it looks bent try it sometimes if you have a ah you know glass tumbler or something like that a cup glass cup something like that like this drop a steel spoon and fill it with water you will see that the spoon looks bent you can do it any time. If we now change the glass or change the water of the material with a metamaterial you will see that the bending of the glass is in a completely different direction 180-degree phase shift if the bend previously in a positive material was in this direction the bend is now in a negative minus theta direction. So, Nels law sin theta 1 by sin theta 2 is equal to your refractive index now it is sin minus theta 1 divided by sin theta 2 yeah that is the overall refractive index giving the refractive index and negative connotation a negative value and this opened up the whole area of electromagnetism in a different perspective people started looking into electromagnetism in a completely completely different perspective where the refractive index where the refractive index of a material became negative.



So, what exactly are artificially engineered materials you know that materials have this epsilon and mu value the electrical permittivity and magnetic permeability I told you in previous classes if you have forgotten go and ah rewind the previous lectures where I discussed the basic of light again just for the sake of argument light has two hands right the strong hand and the weak hand the strong hand is electrical hand the weak hand is magnetic hand if light wants to enter something it first sees that if the right hand strong hand can exist can sustain itself if the left hand can sustain itself if the sustenance is good it will go otherwise it will come back that is the basic of transmission or reflection.

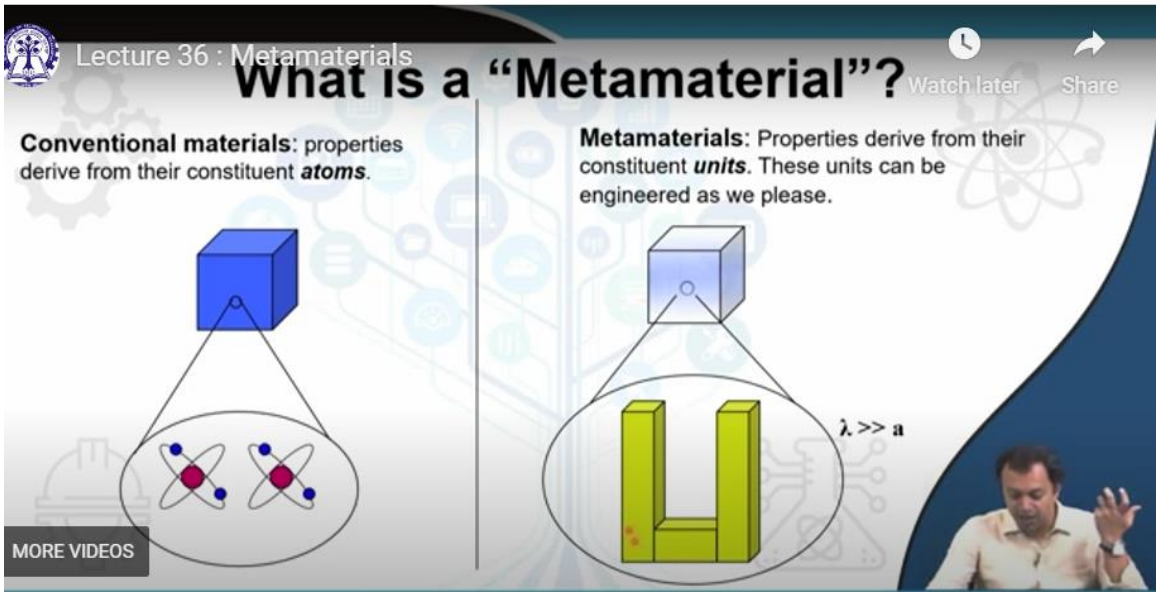
So, most material have either positive values of epsilon and mu i.e. transparent or opaque these are metals where I told you metals have plasmonic ah plasmons basically ah electron cloud moving at high speed and whenever light comes it it tries to opposes it. So, when I say negative per say I am talking about the directionality the direction is negative theta minus theta minus theta means another direction negative does not simply mean something magical negative simply means direction. So, if this is positive this is negative if the same thing.

So, in a vector coordinate in a Cartesian coordinate if this is positive epsilon mu with considering 0 this is negative this is still positive metals have this property in which their epsilon their electrical permittivity is negative i.e. whenever light comes in a particular direction the electron cloud goes in an opposite direction to prevent it from going. So, the direction of the electric field from this electron cloud is anti parallel is anti parallel is therefore, negative to the direction of to the direction of the incoming light to a direction of the electric field of the incoming light or at least a component of the electric field of the incoming light. There are certain magnetic materials ferromagnetic anti ferromagnetic probably you have heard where if the magnetic field is in a particular direction if the

magnetic field is in this direction the domains the domains that is form inside the material is in opposite direction the direction of the field the wave vector the pointing vector is in a different direction.

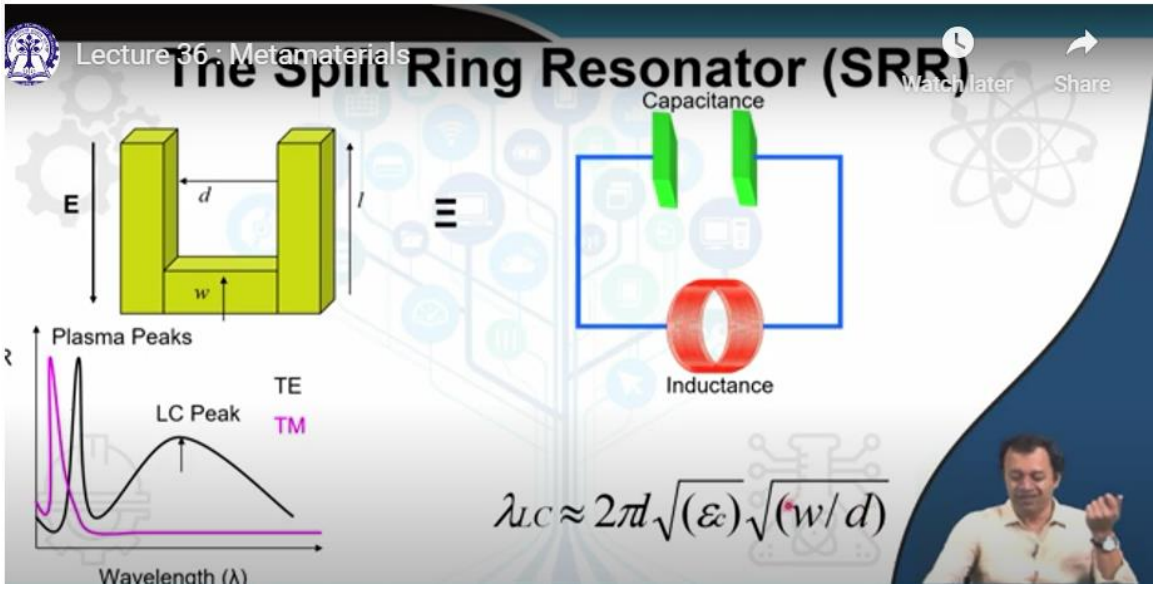
So, anti parallel to one another this is parallel this is anti parallel the direction is separate. Now, all these three exist in nature you have metals you have glasses you have magnets all of these things exist in nature though it is electromagnetically allowed, but to the best of our knowledge we have found thus far no material which can simultaneously at the same frequency same frequency range shows negative direction for both electric and magnetic field simultaneously yeah. Metals shows negative epsilon negative towards electric field for magnetic field they are positive magnets or anti ferromagnets they are negative towards the magnetic field, but they are not negative towards the electric field. In nature there is no such thing that shows simultaneous value of negative epsilon and negative mu remember this is 0. So, Cartesian coordinate if this is 0 this is negative this is positive this is negative nothing in nature exist that falls in this particular quadrant.

Artificially engineered metal artificially engineered materials are those materials that are as the name suggests artificially engineered and they fall in this particular category we engineer them we engineer them specifically to fall in this particular category to exhibit this properties of epsilon and mu simultaneously 0 simultaneously less than 0 i negative thereby making the refractive index negative and when you have refractive index negative you change the game in electromagnetism you have changed the game in electromagnetism you have changed the game in photonics. If you have changed the game in photonics try applying Schrodinger wave equation and central dogma you have changed the overall the plethora of bio photonics or nano bio photonics.



So, what exactly is a metamaterial? So, in conventional material I told you the reason refractive index exist that light with its two hands electric field and magnetic field enters inside the medium the electric field tries to couple with the constituent atoms with its oscillating charges the electrons and the nucleus the nucleus or especially the electrons have its specific arrangement the specific arrangement allows it to be coupled in a different way when a specific electric field external electric field with an external photon comes and reacts with it that results in the charge carrier the electron specifically to oscillate it is easier for electron to oscillate than a nucleus, but nucleus can also oscillate the electron couples with the electric field it can couple not always not necessarily, but the reason of refractive index is that the electron will couple with the photon electromagnetic field of the photon it will start vibrating itself oscillating or vibrating charge carriers or charge particles produce their own electromagnetic field that electromagnetic field the internal electromagnetic field will couple with the external magnetic field the result the resulting is what slows down the resulting is here is what slows down the overall movement overall movement of the electric field overall movement of the ah photon through the medium through the material and this slowing down the speed of slowing down is refractive index refractive index simply happens because of the internal electric field reacts with the external electric field internal electric field forms because an external electric field has tried to couple with it that is the overall very simplified ah explanation of electromagnetism ah refractive index beg your pardon refractive index there is too much quantum mechanics associated with it I am going to skip it because this is not a physics class, but those of you who are interested in the quantum mechanical explanation of refractive index be my guest send me ah an email I will try to explain it to you in a more in depth quantum mechanics this is not this is not the point this is not the place to describe further quantum mechanics we are here to apply quantum mechanics not go further deep into it. Meta materials on the other hand uses constituent units instead of atoms using nanotechnology you create you create individual structures nanostructures or units that have their special properties they are numerous in nature they are numerous in nature they have special electromagnetic properties light the electromagnetic field previously was coupling with electron the electromagnetic field of the photon of the incoming photon will react will couple with these kinds of nanostructures several of them numerous of them i e meta atoms artificial atoms meta atoms and their their size is far far a is the size of this ah structure far or less than the wavelength of light of what you are using light will get confused light will consider these as atoms these artificial materials as atoms and we will try to see if it can sustain its left hand or right hand if it has negative or positive refractive index based on the characteristic feature of these units since you create this units since you create this units you determine the property of the light interacting with it you determine the refractive index of the material that is what meta materials are the refractive index is controlled by you the refractive index is customizable it does not matter what this material is made up of as long as it follows a particular property particular set of rules these unit nanostructures

replaces these atoms of course, they contain their own atom, but light is not bothered with it light will consider these as atoms because its size is far far greater than the size of this far far greater than the size they are numerous they are atomic scale molecular scale you send light through them light will consider them to be atom does not decides to go further deep further deep consider these to be atoms derive its property tries to couple with them depending on whether it is successful or not it will be behaving in a particular manner. So, if it behaves in this particular manner you can not only slow down, but do the opposite accelerate the group velocity can simply accelerate perhaps think about it you know about group velocity or phase velocity we have discussed this the phase velocity can go somewhere else, but the group velocity is something else can the group velocity accelerate or forget about acceleration or slowing down of light you can simply change the phase or the direction of the light in which it is supposed to propagate the pointing vector can point at a different direction.



So, how do we do this what are the special units? So, the special units are called split ring resonators SRR the split ring resonators act as an LC circuit what is an LC circuit L is an inductor C is a capacitor medical student stay with me capacitor is just two parallel metal plates light cannot charge cannot pass through them they will simply store charge capacitor store charges and inductor inductor is basically a coil inductor is basically a coil. So, they are the equivalent they are usually metallic dielectric is also present, but for the time being consider this split ring resonator they are called ring split ring because this portion is splitted this portion is broken down. So, it is kind of a squarish U shape structure it has a width it has a distance and it has an L which is the length and it acts as a capacitor inductor circuit it is simply electrical engineering capacitor inductor circuit this part act as an inductor coiled this part this gap this split acts as a capacitor. So, whenever you shine polarized light on to it with a electric field across the gap electric field across the gap it is the property that when you have an electric field across the capacitor electric field across the capacitor the capacitor will store charged capacitor will store charged capacitor will

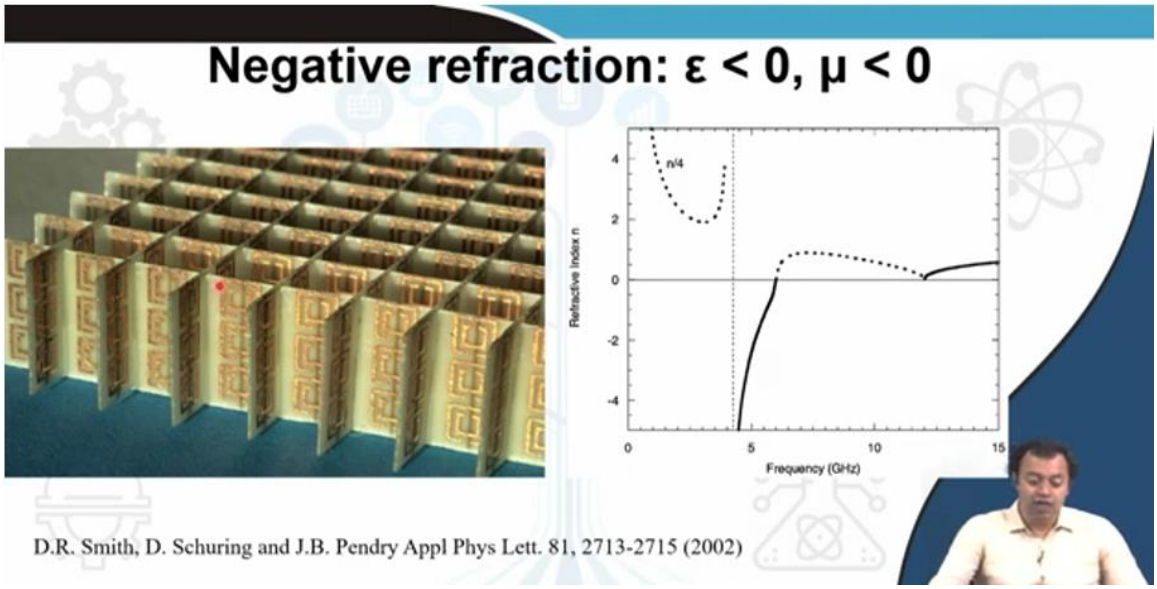
perhaps store the electromagnetic field capacitor will store the electromagnetic charge and because this is a conducting part because this is a conducting part a circulating current will flow yeah. You have a conductor you have put electric field across it there will be charge accumulating and this charge will discharge through this circuit through this particular circuit.

So, if you have a circuit like this if you have a capacitor like this if you have a capacitor like this. So, it is like this you have an electric field across it there will be a circulating electric field. If there is a circulating electric field by Lenz's law we know there will be an anti parallel magnetic field yes there will be an anti parallel magnetic field. If electric field is in this direction you know about this law right if electric field is in this direction there will be an orthogonal magnetic field. So, this circulating electric field on plane we will have an orthogonal magnetic field this magnetic field is anti parallel to the direction or at least few components of it are anti parallel to the direction of the incoming light I told you the direction is anti parallel it is considered negative.

So, you get something which we called as LC peak this LC peak is this anti parallel magnetic peak the anti parallel magnetic peak that is simply because of the structure of this unit and the anti parallel magnetic field is given by us right sorry beg your pardon. Let us go slightly a step back I will give you the formula, but in a moment, what happens when you remove the electric field across the capacitor across the gap and put it along the circuit. If there is an electric field perpendicular to the gap not across it there is no charge and discharge the current will not flow there will be simply no circulating current and thereby a parallel anti parallel magnetic field. So, by changing the direction of the electric field you can change the LC peak the anti parallel magnetic field the presence or absence these 2 peak are plasma peaks which are these are metals when light goes you know the electron will try to screen it, but this is unique this LC peak is because of the structure the plasma peak is because of the material there is a difference any material any metal will show the plasma peak, but this LC peak will be because it is in a unique u type shape it is in a unique u type shape and the wavelength lambda LC is given by this particular formula where L is this length W and D are width and this gap and epsilon c is the epsilon of the surrounding substrate not of this metal. Meaning what? Meaning try to understand this you have created a magnetic response using a non magnet you have created a magnetic response using a material which is not magnet where the material property does not matters what matters is the size and shape omega D W D and L are length breadth and height yes thickness gap etcetera are this.

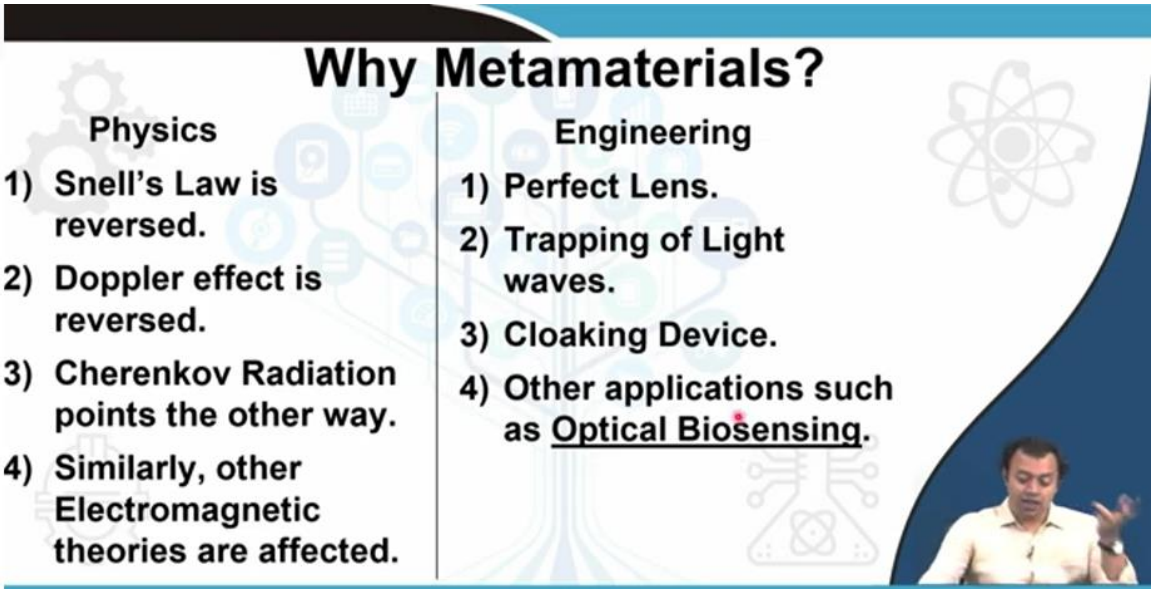
So, using nanotechnology if you reduce this to few nanometer scale 10 nanometer 100 nanometer 20 nanometer you have a lambda LC at a frequency of your choice at a frequency of your choice it depends on the shape and the size on the geometry of the

material on the geometry of the material rather than the property of the material. So, this is something fascinating and yes LC circuits have had existed for a long-time nanotechnology made this omega D and L at a nano scale level LC circuits have existed at long time, but nanotechnology has made an LC circuit in a molecular scale level in an atomic scale level in a nanometer angstrom scale level. So, the properties here the magnetic property which were previously not done like this were being achieved were seen to be possible. So, this was first time in I think 1998 ah University of California St. Davis and Duke University where they actually figured out 2002 beg your pardon 2002 they figured out that the real part of the refractive index these are experimental data please go and read this paper.

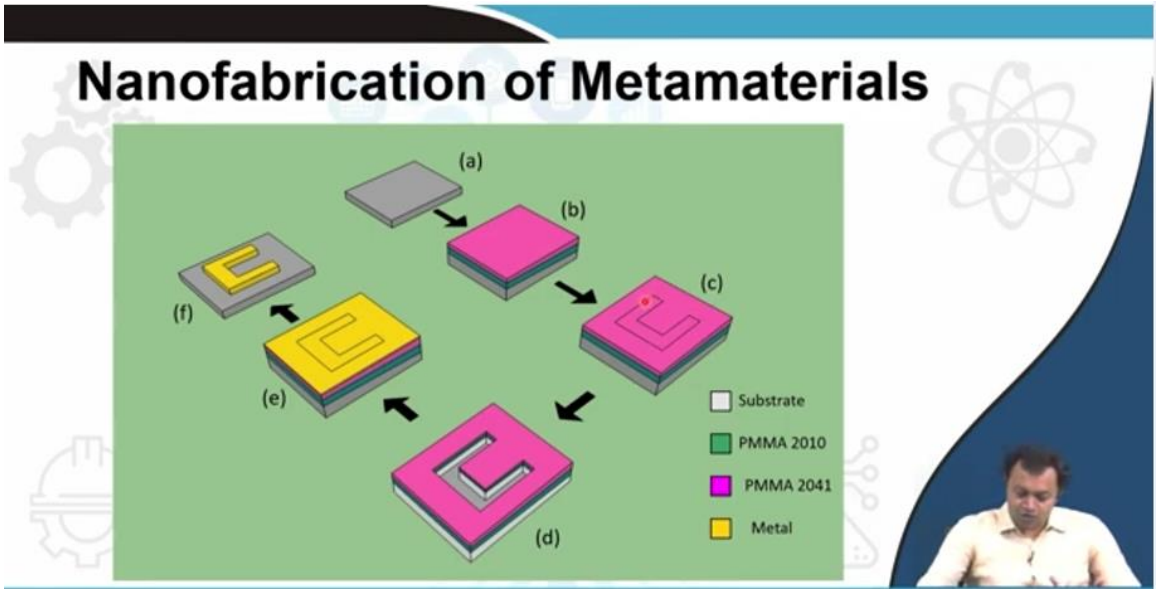


Experimentally the refractive index this is the refractive index and this is the 0th value has actually gone negative experimentally proved refractive index. So, see they have this metal hoops and plane line going through it when light passes through it the structure rather than the material this as copper copper is not magnetic this is copper on ceramic plates they were bending the light in a wrong direction they were bending the light in a different direction this material this material was trying to show. So, previously it was achieved in a frequency of gigahertz microwave frequency, but since then we have been able to I will show you my own work we have been able to get it at an ah visible frequency range at a visible frequency range. So, you can customize you can make these materials that will bend light that will bend light because of it is unique refractive index unique refractive index because you have created it you have created LC circuits at an atomic scale level at a molecular scale level at a nano scale level that produces individual localized magnetic field since they are numerous and all of them are same the magnetic field of this is equal to the magnetic field of this is equal to the magnetic field of this is equal to the magnetic field of this so on and so forth and they all combine and you see a combine effect you see a combine effect just like what you see in a normal material individual oscillation of electrons provides a proper refractive index it is the same thing simply you have created

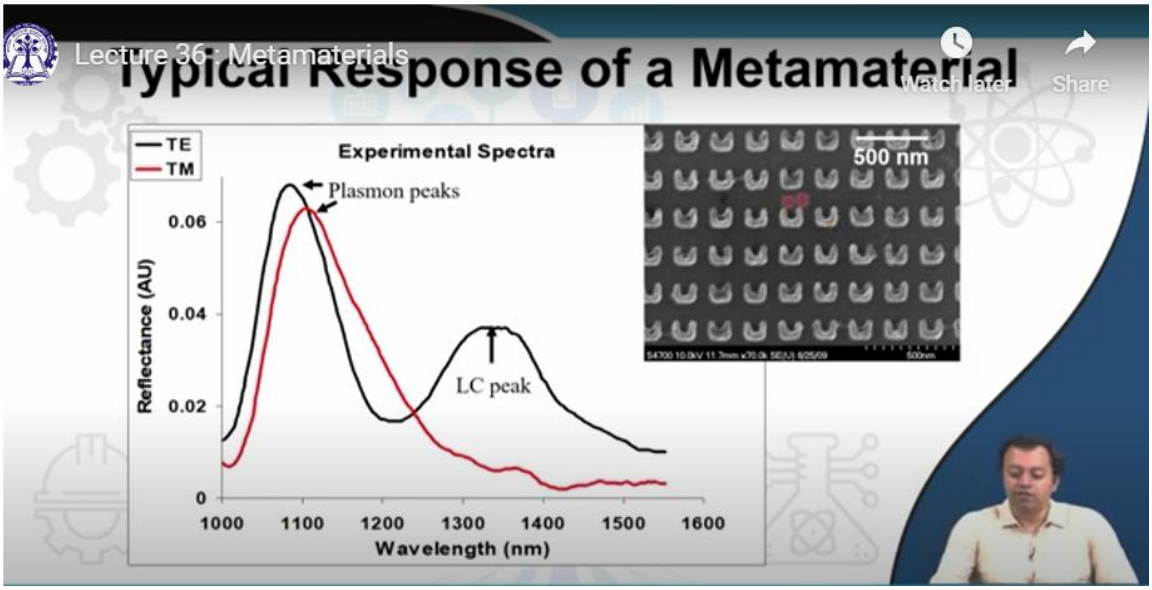
your own atoms you have created your own atoms what is inside the atom light does not care about it diffraction limit and what not light does not need to go inside light is happy with this. So, that is negative refractive index why meta material why do we need it.



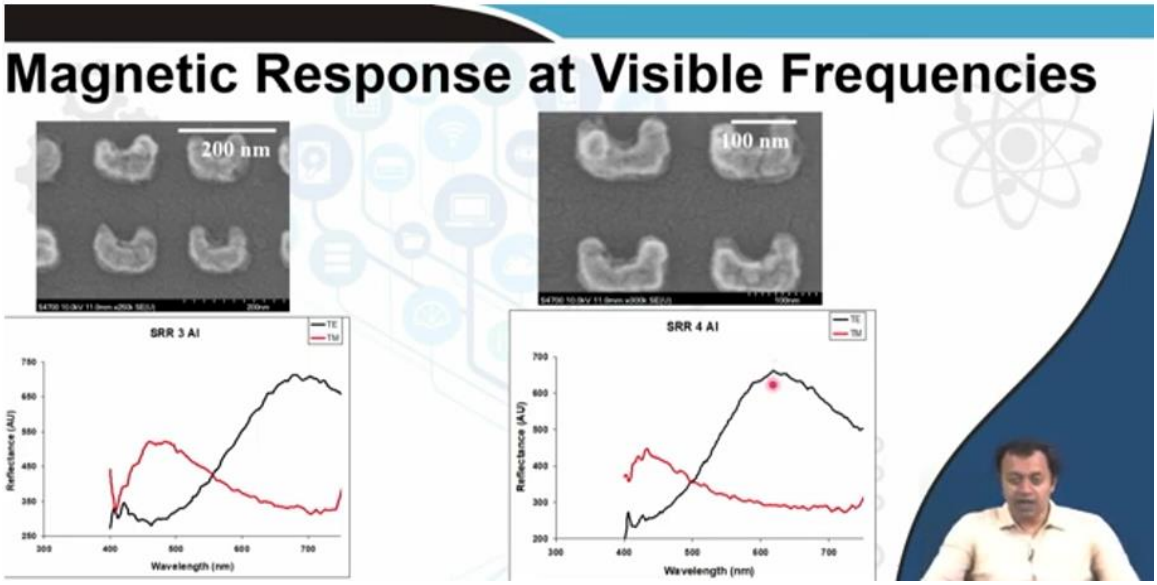
So, from a physics point of view think about it how many things will change if your refractive index any law that has refractive index associated with it which is almost several will have a negative sign associated with it Snell's law will be reversed Doppler's law effect is reversed Cherenkov radiation this is usually present in ah nuclear power plants nuclear reactors all electromagnetic theories all electromagnetic theories will be affected from an engineering point of view we can have perfect lens we can have trapping of light waves cloaking devices you can make materials invisible you have probably seen it in movies several military ah war films war movies are quite common Harry Potter has shown that predator if you have seen alien comes and hunt human beings predator it is available in I think Netflix go and watch it one of my favorite science fiction movies predator becomes invisible. So, cloaking devices we can create what we are interested in the bio photonic application is utilized it for optical biosensing is utilized it for optical biosensing how do you fabricate this is something I fabricated it I



probably have shown you I took a piece of silicon covered it with different types of photo resist or electron beam resist they are photo or electron sensitive material I make a cad like tool and ask the electron to you know break the bonds of the photo resist here electron beam resist here not here the broken parts are eaten away are developed methyl isobutyl ketone they develop it like that I cover the entire thing with gold the metal which is also non magnetic covered it with gold gold falls into the trench the hole some part stays on top and when I put it in so called warm acetone as a left of the entire thing washes away leaving little bit of gold which was directly sticking with silicon intact which was sticking via the photo resist or electron beam resist is removed. So, these are some of my ah split ring resonators that I myself long long time ago fabricated this is the scale. So, you can understand if this is 500 nanometer this entire white line is 500 nanometers tell me how small these materials these split ring resonators are and they showed me depending on ah whether I have put the electric field in this particular direction or the electric field in this particular direction the presence and absence of an L

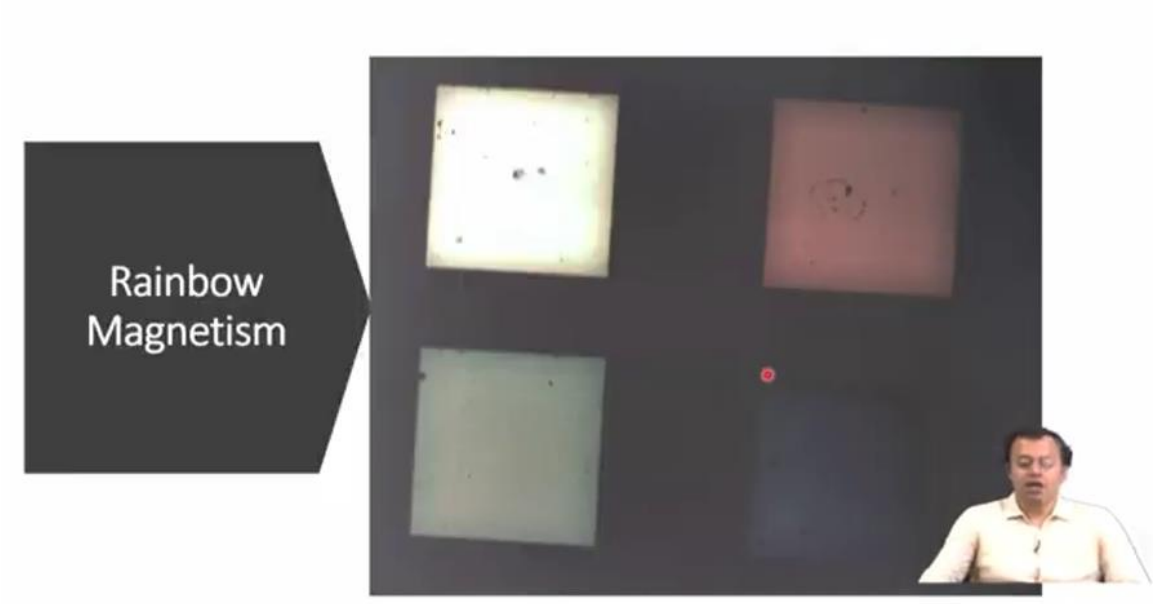


C peak ah there is something significant about the wavelength that I have used try to figure out why I have tried to put it in between 1300 to 1400 wavelength this peak is always present. So, this was some of the test cases of metamaterials that we utilize and finally, finally I told you that I can change the refractive index meaning how much material will reflect what it will reflect depending on the size basically structural color color because color is the wavelength that it is reflecting color at the end of the day ah wavelength right.



So, lambda LC I told you depends on size not on the material properties I utilize aluminum simply because it was cheaper and easier to use put their size the omega D and L their geometries using nanotechnology in such a small level what color is aluminum aluminum metal what color is this white right in quantum mechanics when you confine them when you go into a nanoscale level the bulk properties are different than the nanoscale properties example which I did this these are some of the smallest materials and they start showing

LC peak at visible frequency visible frequency can be shown by this graph or why should by graph see it from your own eyes this is what I



called as a rainbow magnetism all are made up of aluminum aluminum is white right, but I have created their structure in such a way in a quantum mechanical way that they show this individual colors and this color is because of the size the geometry of the constituent element rather than the property rather than the material property of the constituent element this is what you can do this is what we were able to do these are magnetic responses colored base magnetic responses lambda base magnetic responses at visible frequencies at visible frequencies how high does your magnetic resonance go mine goes at this frequencies you can see them you can see the magnetic resonance the color of aluminum is now changed to this particular color anything that you want basically any color you want because of the size think from a structural color point of view think what it will do to textiles displays what not it is not based on any chemical reaction no dye is combining with some cotton fabric and creating a particular color it is because of the structure that it is reflecting a specific specific light will it fade your clothes the color of your clothes fade when you put it in the sun for a long period of time or when you keep it with you for a long long period of time the color of your clothes fade right your garments fade will it fade it is because of the structure.

So, anyways I think these are the basic concept of metamaterials I will discuss some more topics in the coming class.

So, this is the references please if you have time go through it this was my doctoral thesis and I will see you in next class. Thank you very much.