Biophotonics

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

Lecture 33

Metamaterials

Hello and welcome, we were discussing optical biosensors as the next module of our biophotonics course and in the previous two lecture I gave you an introduction of what exactly a biosensor consists of, what exactly are optical biosensors and then give you an example in the second class that is lecture 32, lecture number 32, how optical fiber could be utilized as an optical biosensing tool. We also saw few examples for detection of blood clots.

Now, in the next three sets of lectures I was stuck to make a decision, I could take the lecture number 33, 34 and 35 with three different types of optical biosensor, there are several plethora of these biosensors, I could take three different examples and describe them to you at a time or I just take one specific example of an optical biosensor and describe it for the whole three subsequent lectures.

Now, I chose option number 2, why? Well there is actually a course coming up, a very interesting course on optical sensing, which will be a 30-hour course as such and that will have a complete description of different types of optical biosensing etcetera, etcetera. So, trying to compete with that 30-hour course and thereby failing to summarize all the different varieties into one hour, one and half hour lecture I thought I will take one specialized case and describe it in relative detail, go little bit deep on it. Instead of jack of all trades let us be master of one.

In previous other modules I have given you several examples, taken several examples at a time, each one has their different manifestation, here I decided in this particular case, in this particular module, specific module optical biosensor instead of giving 10 different types of biosensor, let us stick to one type of biosensor and discuss it in detail. You only will be the judge of it, you only will be able to tell me whether this experiment of mine have been successful or not, I have tried to rejig it a bit.

Now, some people will like it, some people will dislike it and whatever criticism that you might have please feel free to share it with me. I decided to explain to you or to discuss with you something very, very specific and the most specific thing that I can discuss is my own work, my own personal research on optical biosensors and I utilized nano scale meta materials. Some of you might know what metamaterials are, some of you might have had heard what meta materials are.

Today I am going to give you the concept of metamaterials, it is a very important part of photonics, nanophotonics in general, biophotonics you will see why it is important part of biophotonics as well. I will start from the basic of metamaterials and in the subsequent lectures we will describe the application of meta materials of optical biosensors. This is what I chose to do because, a, metamaterials are important and b, I have personally invested my own time into understanding metamaterials, creating them, fabricating them.

So, what exactly are metamaterials? The term meta simply means is Greek term for extraordinary, extraordinary materials, extraordinary in what sense? Extraordinary in their electromagnetic properties. Now, every material has some sort of an electromagnetic property, they reflect, they transmit, they sometimes fluoresce, they sometimes have refraction, well most of the time they have all of these, most of the time they have refraction and several other optical phenomena they exhibit.

Metamaterial has or meta material tends to have extraordinary electromagnetic properties that are not present in naturally occurring materials, thereby they are called extraordinary materials. Now, what property you ask? The most significant property that metamaterial can exhibit is a negative refractive index.

Recall your class the first few lectures where I discussed what refractive index is, the high school definition is the reduction in speed but then I also told you that there is a real and imaginary part and it is a product of the interference of the wave that comes when charge particle inside the material gets excited by incoming light wave and that if you are confused just go back to the previous lecture where I have discussed what refractive index is and then come and then you will know what I mean by negative refractive index.

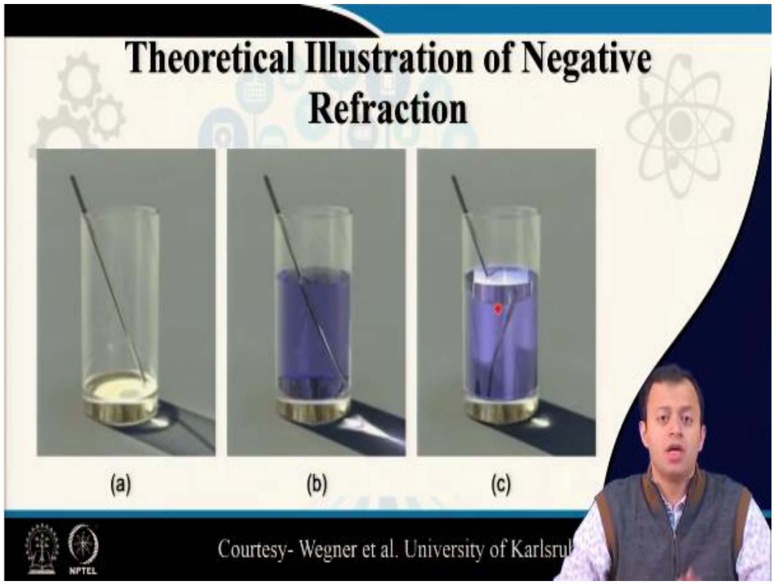
Now, what exactly does negative refractive index mean? I told you it is not simply just speed, it was not simply just velocity, refractive index according to Snell's law and every other part has something to do with direction of propagation as well. So, negative refractive index simply means that the pointing vector will point in a opposite direction light which will be refracted by going inside a material which has a negative refractive index will bend in the wrong way.

What do I mean by wrong way? So, Snell's law suggests that if light is moving from rarer medium to denser medium it will move towards the normal. In negative refractive index it will move towards the normal but at an angle of minus theta 2, so sin theta 1 by sin theta 2 is n1 by n2, you know this I am not repeating this, I am not making it here because by this time I have taught you this you should know. Here if it is minus n2, so n1 is air, n2 is material minus n2 you have minus sin theta 2 or sin minus theta 2.

So, instead of the angle moving in this direction, the angle moves in this direction there will be a 180-degree phase shift. If it was supposed to go in this direction it will now go in this direction, vector negative means opposite direction. What is the manifestation of negative refractive index?

When first meta materials were experimentally exhibited it caused a sensation that it is going to rewrite physics in general and electromagnetism and optics in particular, because remember every single optical phenomenon or optical laws or laws of electromagnetism which so ever uses refractive index and there are almost a majority of them utilizes some form of refractive index, all of that needs to be reversed because now you have refractive index which is negative.

(Refer Slide Time: 8:01)



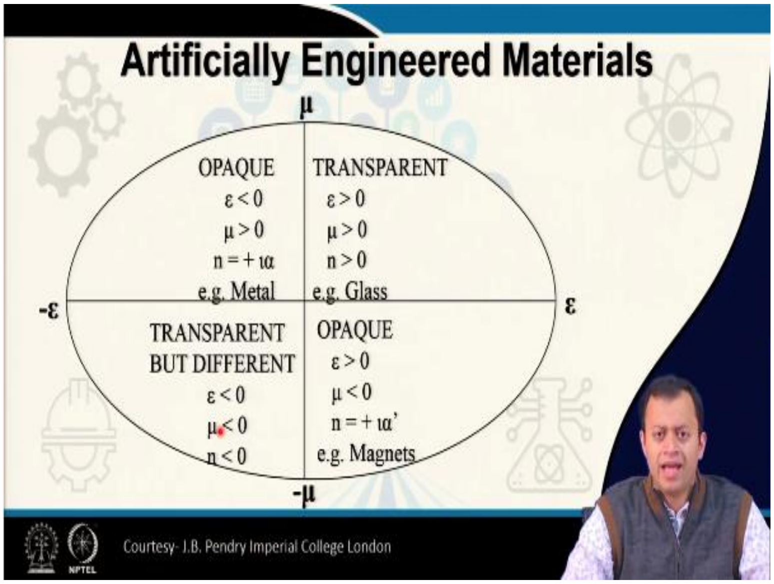
What is the manifestation of that? This is a theoretical illustration of negative refraction. This is a primary case where you have a glass and you have put a steel spoon on it, you can do it in your own home, all of you know this. When you fill the glass with water you see that you feel like the spoon is bending, it looks like the spoon is bending, why?

Because light travels from air to the glass to the water and then it comes out in the same way and there is a change in refractive index light will bend according to Snell's law from this medium to this medium to the inside medium and as a result the spoon will look bent. But whenever the water is replaced by a medium which has a negative refraction the spoon will bend, the spoon will look bent but in an opposite direction, but in an opposite direction minus 180 degree or 180-degree phase shift however you want to call it, there will be a phase shift.

And that is based on negative refraction. Metamaterials are extraordinary materials because they can produce negative refraction, no naturally occurring material to the best of our knowledge can produce negative refraction. Although, I am sure someone somewhere will prove me wrong that we have this exotic material something that has come from the depth of earth but to all intent and purpose to the best of my knowledge no naturally occurring material shows this property.

This property can only be engineered in laboratory, several people have engineered this laboratory including myself and today I am going to discuss that and what are the application of it especially to optical biosensing, how can this phenomenon be utilized for optical biosensing.

(Refer Slide Time: 10:07)



So, let us go into it, let us try to understand how you actually achieve negative refractive index. Now, you all know, you know this formula n is equal to root over epsilon by mu, epsilon is permittivity and mu is permeability, the electric field part how the electric field will get modified when a wave, when a photon comes into the system. So, if you have both positive values of epsilon and mu, you mostly have refractive index of n greater than 0 and you have more a transmitting transparent material such as glass.

Several materials naturally occurring materials falls under that this category where both the magnetic part as well as the electric part of the refractive index, remember, n is equal to root over epsilon and mu is greater than 0 both are positive, both are positive and you have a transparent medium for example, glass.

Remember refractive index is complex it has a real part and imaginary part and so does the permittivity, permittivity and permeability. They are complex quantities and for all intent and purpose several times they are also vector, i.e., they have a direction, even refractive index I told you about isotropic and anisotropic material, centrosymmetric, non-centrosymmetric especially in the class where I covered non-linearity, so you should remember this.

So, there are categories of material where which has both epsilon and mu positive and thereby n is also positive and you have transparent material glass, then there are certain materials where although the mu is positive, epsilon that is the electric component becomes negative and there is a huge imaginary part coming up in the refractive index and that is metal.

Now, you will ask me what does it physically means, what does epsilon and mu positive and negative physically means, what is the physical meaning of it, well the physical meaning is simply this and this is very rudimentary, the physics people will frown upon me but I will try to explain it as rudimentary as possible but no further. If there is an electric field, the direction of the electric field is from left to right. So, like this left to right you might in the camera see it opposite, but use your imagination.

So, there is a particular direction of the electric field left to right, you have now put a material in that electric field, you have now put a material a medium in that electric field, there will be some sort of electric field generating a modified version of the electric field generating inside the material, the material will be susceptible to the electric field depending on how much susceptible it is, depending on how much susceptible it is and how much susceptibility is given by this dielectric constant, how susceptibility is or how much it will react to the presence of an external electric field.

If the direction of the modified electric field formed inside, formed inside the material is in the same direction, how do I put it, is in the same direction, we consider the epsilon part as positive. If the field that is formed inside the material is in the reverse direction, we consider it as negative. Vector how else do you define it, so left to right outside, direction of electric field, left to right inside direction of electric field, inside the medium positive, left to right outside the medium, right to left inside the medium negative, that is how it is.

Most metal shows negative characteristics, negative epsilon, most metals show negative epsilon, why? I think I discussed it a bit in surface plasmons, most metal have, are basically plasmas, plasmas means metal nucleus the atoms the nucleus of the atoms have very little connection with or very little control over the electrons of metallic atoms, the electrons are not strongly bound by the nucleus, in fact they are very weakly bound, the metallic electrons are very weakly bound with the nucleus of the metallic atoms and they basically float around into the system in the form of a cloud.

There is an electron cloud which is floating around, roaming around inside the entire bulk of the metal with very little control by the parent nucleus, by the parent nuclei. So, the electrons do not belong to any specific nucleus but they belong to the entire system, they move around the entire system with a specific speed, a specific frequency that frequency is called plasma frequency.

Most of the metals have plasma frequency in ultraviolet, so any time an external light field comes with its own electromagnetic field, the electron cloud goes to screen, it goes to opposite. So, the electric field that is usually generated inside the medium is anti-parallel, i.e., in different direction.

So, naturally occurring metals have epsilon negative hence, it has a strong imaginary part, imaginary part basically means extinction, extinction means the light is unable to go inside as a result the light is unable to penetrate inside metal and the light is getting scattered and hence light is shiny, hence metal is shiny and hence all those wars, civilization have been built and fought on the back of back of the shininess of metal.

And it is simply because metals are having refractive index, sorry beg your pardon, the plasma frequency the electron cloud moves in ultraviolet frequencies, if it had happened, if it had been moving in visible frequencies then it would have not mattered and metal would be not this shiny but it is just the frequency of electron that changed human civilization.

There is a third case of course, where if the material is put inside a magnetic field, the magnetic field generated inside that material is antiparallel, is in an opposite direction.

So, from outside left to right, inside right to left for magnetic field and you know about this ferromagnetism, anti-ferromagnetism this, that different types of magnets and they also produce extinction and they also have opaqueness, light is unable to penetrate thereby they are not transparent they are reflected back.

Most naturally occurring material are a combination of these three, most naturally occurring material or a combination of these three, that is what you see, either it is transparent or they are opaque and opaque depending on different types of properties, they are opaque at certain frequency, they are not opaque at certain frequencies all of this depends on epsilon and mu, how the field is generated at a particular frequency antiparallel or parallel.

Metamaterials are those which can show both epsilon and mu, both the negative field, negative direction antiparallel for both the electric field component as well as magnetic field component. Now, see here, here though epsilon is negative, mu is positive. Here mu is negative, epsilon is positive, naturally occurring material falls in these three categories, either you have both positive or only one negative.

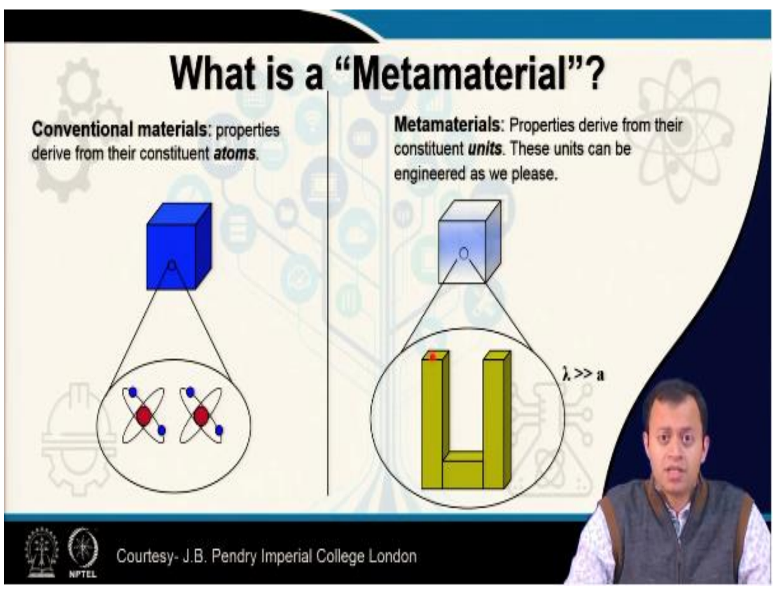
We created artificially engineered we made material in our laboratory that can have epsilon and mu negative under the same frequency range. So, both fields, it will oppose both fields simultaneously in the same frequency range and thereby the refractive index becomes negative. Now before you jump that root over epsilon and mu is equal to n and if both epsilon and mu are negative then multiplication of minus epsilon into minus mu is positive, well dude, complex quantity this is complex, this is complex.

So, when we are talking about negative part add these real parts negative imaginary part negative and then multiply and then add the vector term. So, it is not simply a scalar quantity where you are multiplying minus 2 with minus 3 and getting plus 6, this is complex, complex number. So, meta materials are artificially engineered materials that can create both epsilon and mu negative, thereby having refractive index negative.

Now, it was in 1968 A Soviet Physicist Victor Veselago who thought, who made a thought experiment that what will happen if I have a refractive index negative, how can I do it? I can have epsilon and mu negative, how do I get epsilon and mu negative, he has no idea, he did not write it down, he thought, suppose I have this what will be the manifestation, it is a favorite pastime of several scientists, suppose the sky is green what will be the manifestation, suppose the planet earth had two moons what will be the manifestation, so, a thought experiment, that is it.

Suppose we have an artificially material that happens to have negative values of refractive index, what would that be what, would be the manifestation of such a thing? And he came up with certain examples, but since it was a thought experiment and since there was no way to achieve this, at least in 1968, no one paid much of an attention to it, fine, yeah, okay there is a manifestation, there is a thought experiment minus n and yeah it will have some manifestation, light will move in backward direction or a different direction or going the wrong way, so what yeah, and it was left at that 1968.

(Refer Slide Time: 21:05)



Cut to 1998 there was a famous physicist Sir John Pendry at Imperial College London who was working in microwave, who thought, yes, I think I know how to make this practically experimentally. How he did it? Well he went into the root of the system, he thought that the conventional materials properties, by properties I mean refractive index, electromagnetic properties, transmission, reflection, epsilon, mu, the properties are derived from the constituent atoms you know this I have discussed this.

So, light goes inside again I have made train tracks remember I scoffed on into it but old habits die hard these are train tracks, no atom is like that but I am creature of my habits. So, there are charge particles and when a photon comes with its consequent electric and magnetic field it agitates the charge particles, the charge particles move it produces its own electromagnetic wave, that electromagnetic wave interferes with the primary photon and interference pattern comes up.

And the overall interference pattern, either frequency is changed or wavelength is changed, thereby usually the frequency is kept constant, wavelength is changed but there are exceptions usually because of the interference of the two waves, the primary wave and the secondary wave you have reduction in speed, the reduction in speed gives rise to refractive index.

So, basically the properties are derived from the constituent of atoms, how much the atoms will generate, whether the interference pattern will be in phase, out of phase, 180-degree phase shift, completely destructive interference, constructive interference, partially constructive and overall this generates the refractive index, you know this I have discussed this at length in lecture number I think 3 4 whatsoever.

This gentleman professor Pendry, Sir Pendry actually, he got knighted by the Queen, thought what if we replace the atoms, what if we create, we create artificial atoms? Well artificial atoms in from an optical point of view, from an optical point of view, he was not creating electron, neutron, protons just out of thin air. He thought if we can create something artificially. How?

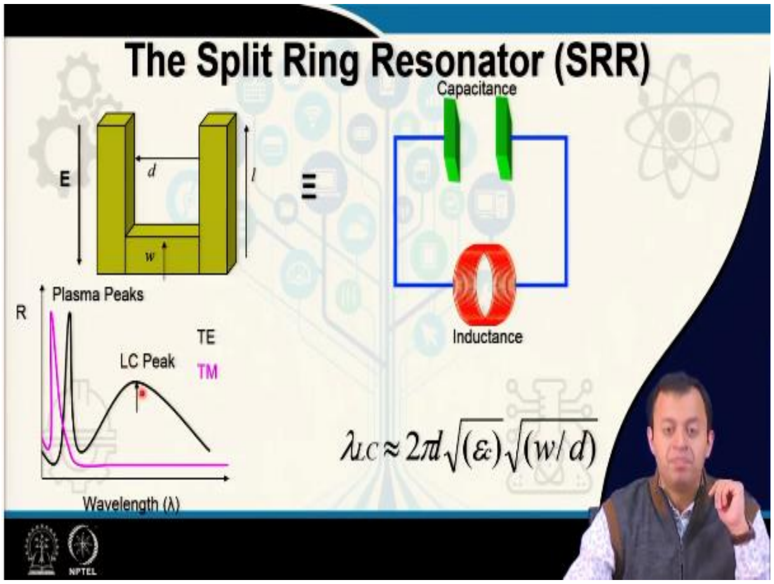
Well he designed that we can create constituent units, units such as these kinds of structure, these structures he called split ring resonator, why? Because this looks like a ring minus this part, hence it is called split, the ring is like that you split it open, it can be u shaped, c shaped whatsoever and they will be arranged in an array, numerous millions of them and their dimensions has to be much smaller than the wavelength of light, a is the dimension, any dimension length, breath, height whatever.

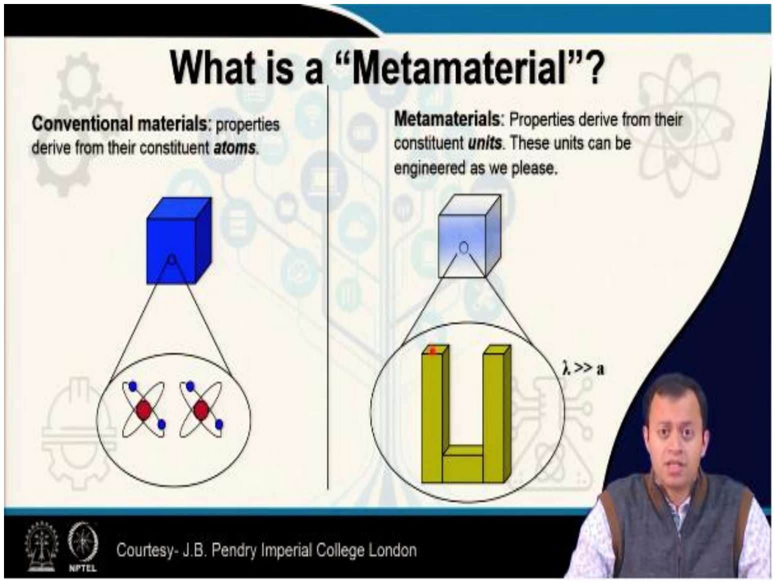
Wavelength of light is the light that it is exciting, so can we replace this by this? Turns out that we can, if they are numerous in nature, have a dimension very much smaller than the light which is exciting it, light will simply determine just like here, the total refractive index depends on the property of this so-called split ring resonator.

Same thing that this is doing, it is generating its own wave which is interfering with the incoming wave and thereby reducing the speed, refractive index whatsoever, it can do the same thing here, you have simply replaced like by like, atom by atom into something like this, very small in structure, the light is big enough. So, light consider these as atoms, light consider these as atom they are called meta atoms or units split ring resonators.

And depending and these units behave in a specific way, like this they generate a particular wave and that particular wave interferes with the incoming light and the same phenomenon happen, only difference is this is natural, this is artificial, we cannot control this, we can control this, we make our own split ring resonator and this split ring resonator could be customized to produce negative refraction. How do you ask? Well, let us investigate, remember this thing is called split ring resonator, SRR.

(Refer Slide Time: 26:11)





So, a split ring resonator in essence is an LC circuit, oh joy for electronics and electrical engineers, finally something that is coming in their comfort zone, ask them to resolve it and they will be more than happy, biotechnologist or life science background bear with me I will tell you what this is. So, a split ring resonator in a sense is a miniaturized LC circuit with a gap as a capacitance, a capacitor and the base as inductor.

Now, when you shine polarized light into it, polarized light again, remember polarization with a specific direction of electric and magnetic field, onto it say normal, so this is your split ring resonator you are sending light directly onto it, these are the lengths, width and the gap etcetera, do not worry. If you shine light, polarized light with an electric field across the gap, across the capacitor what happens?

Well, electronics or electrical engineers will tell you that when you have an electric field across the capacitor there is obviously charging and if there is obviously charging there will be discharging, if there is a discharging and if this medium is conducting these are usually metal structures, metallic loops, I am discussing metals meta materials are usually, usually not always there are dielectric but usually made up of metal.

Victor Veselago discussed these structures as metallic hoops, so I will continue with metal. So, this is a metallic structure which represents a LC circuit capacitor and inductor it has to be conducting. So, if you shine electric field, if you shine light, beg your pardon, I am missing today. If you shine electric, if you shine light onto it a polarized light with electric field across the gap, if there is an electric field across capacitor there will be charging and discharging.

And if there is charging and discharging electronic student or electrical engineering student will tell you there will be a current flow into the circuit. If there is a circulating current flowing across the circuit in this particular direction. Remember, Lenz's law from your high school physics, if there is a circulating electric field like this there will be an orthogonal magnetic field, orthogonal 90 degree, there will be an orthogonal magnetic field generated in orthogonal direction, if this is the direction of the flow of the electric field, electric current which generates it will generate an upward magnetic field.

The most interesting thing is that magnetic field is dependent on the value on the property of this electric current and this electric current is not so much so of a material property as long as this is conducting and as long as you have been able to put an electric field across the capacitor this will work all the time, every time, what happens when you have moved or when you have changed the polarization. Meaning, you have removed the electric field from across the gap and here you have put the electric field in this direction.

So, if the electric field is in this direction, there is no circulating current, there is no current, there is no electric field across the capacitor. So, there is no charging and discharging happening and if there is no charging and discharging happening, there is no circulating current, if there is no circulating current there is no orthogonal magnetic field, if there is no orthogonal magnetic field this peak, this resonance peak is gone.

Two things you need to be absolutely, absolutely clear here, just go back couple of times to see to repeat what I just said, but understand this. First and foremost, this is an LC circuit which is not connected with an external voltage or current source, the only thing you are doing is shining light onto it, because of the presence of the electric field across the capacitor and the presence of the electric field is coming from your photon, it is the electric field of the wave, it is the electric field of your light wave, it is the electric field of the photon current is generated.

So, light is generating the electric field which is generating the electric current which is in turn generating the magnetic field and they are perpendicular to one another, they are orthogonal to one another. The magnetic field that is generated is antiparallel now to the direction of the incoming light and thereby several of the components of the generated artificially created magnetic field is also antiparallel to several components of the incoming photon.

And that magnetic resonance, that magnetic field that is generated by the circular current is structure dependent given by this particular formula w, d, l is the length, width and this gap, this d and epsilon c is simply the surrounding refractive index. Plasma peaks are the peaks that whenever you shine light, light gets reflected this is because of this is the electrical resonance, this is because the electrons present here, the electron cloud present here in this metal is opposing it and that will happen in any case and this is not polarization dependent.

The polarization dependent is this part and this is something that you have created and this polarization, this LC peak is frequency is the frequency of this LC peak depends on the dimensions, depends on the structure not on the material property, that opened up a whole new generation, that opened up a completely new form, why? Because as I told you light is basically one handed the electric field is the one which strongly proves a material, whenever the wave, whenever the photon is entering a medium is the electric field part that is agitating the electron or the charge carriers.

Magnetic field is very weakly able to couple with the material, you know that the dielectric constant epsilon r or epsilon per se is quite significantly different from epsilon naught in most materials but mu r permeability is either same or very, very similar to the permeability of free space, mu r is very, very small so most of the time refractive index is instead of root over epsilon and mu, the mu part is neglected and you call it epsilon. Why?

Well, again because the magnetic field of a system is because of the mu part is basically because of the Bohr magneton, Bohr magneton by definition is weak. So, we see most of the magnetic resonances happening at a very low frequency. Have you ever wondered yourself why do not we see magnetic current? You have electric current, why not a magnetic current, because it is not an independent phenomenon, magnetism is directly dependent on the movement of charge carriers, movement of electric charge it is a derived effect, it is a derived effect it is not an independent effect.

And hence you do not see monopoles, you do not see south pole separately, north pole separately you can say see positive charge is separately and negative charges, electric charges separately but you cannot have magnetic field separately. Why? Because it is dependent on the movement of the electric charge, this is what is happening, this is what is happening. So, they are usually at a lower frequency because coupling and what not because of Bohr magneton just investigate that I do not want to go too much at this stage into atomic physics.

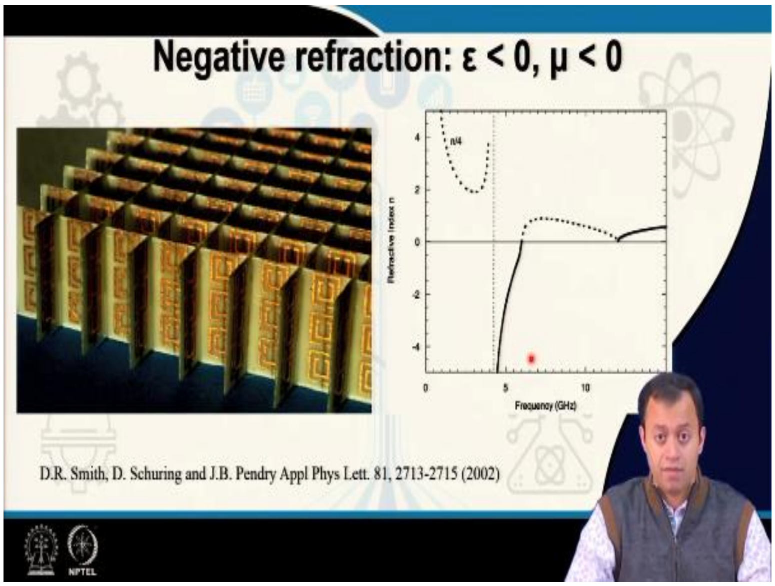
But you know, you can see magnetic field is generally a weak phenomenon, we have electric current moving not a magnetic current moving. But now for the first time we are able to produce materials which are very small in nature, which are very small in dimension, which are very small in size. How? Nano technology, nano technology was not available in 1968, nano technology is available in 1998 Sir John Pendry knew it, Sir John Pendry utilize it, we made several structures very, very small compared to the wavelength of light.

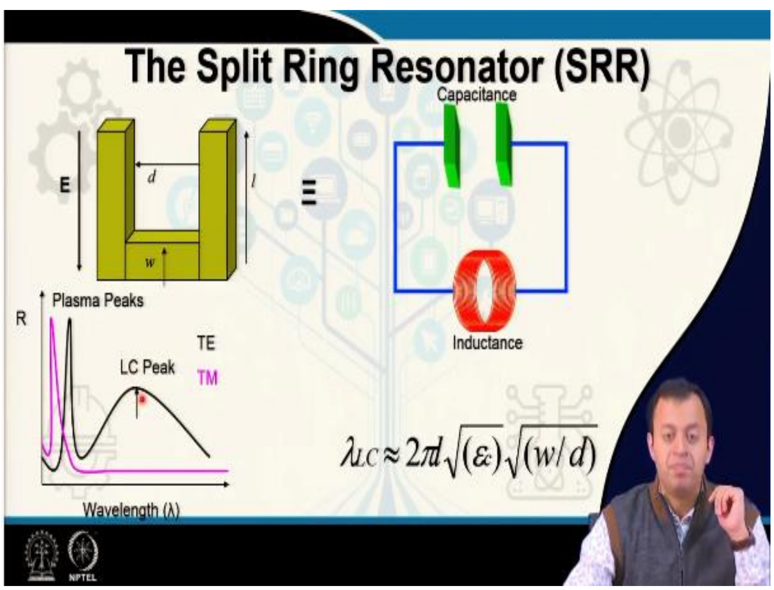
Shine light into them they generated circulating electric current, the circulating electric current without any external voltage source it was simply by putting electric field, the electric field has to be compatible to the size of the structures as well, you cannot simply excite electric current in any material you please, it has to have certain properties into, it has to have certain dimensions etcetera.

As long as this is conducting you will see an opposing magnetic field and opposing magnetic property which will be polarization dependent, it does not have to be a magnetic material, it can be any material which has conducting properties, mostly metals and by shining light onto it in a special direction you can have a peak, a magnetic peak at dependent upon its dimensions.

You control the dimensions, you control the dimensions by nanotechnology so you control the frequency, you control the energy, you control the wavelength previously we used to have magnetism at very low frequency gigahertz. Now, if you are using nanotechnology with dimension in the nanometer scale, can you calculate roughly what this LC peak is supposed to be?

(Refer Slide Time: 37:20)



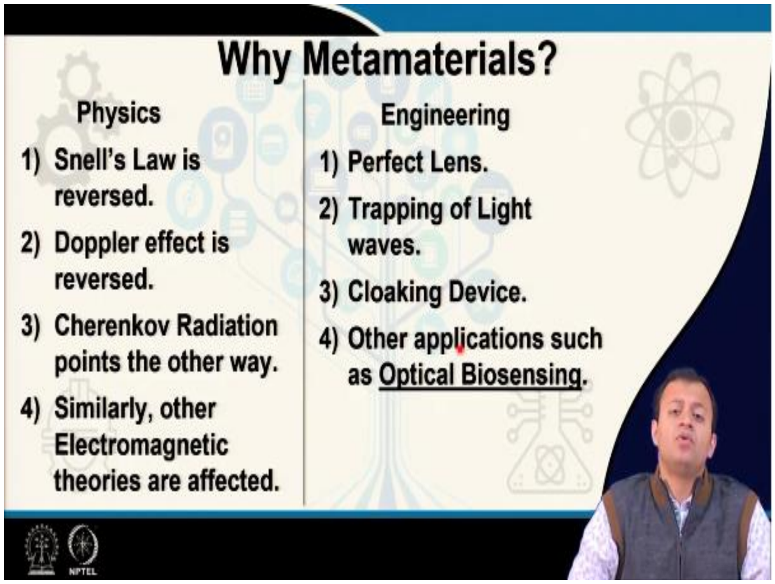


What he did, he made structures such as these, he made structures such as these, these are ceramic tiles and these are copper plates and he was, these are still millimeter size but he was using microwave, you know the wave wavelength of microwave as compared to millimeter. So, he experimentally proved it, please go through this paper Applied Physics letter in 2002, where the overall refractive index turned out to be negative because this could produce negative mu and by putting wires through it, metallic wires through it which automatically have epsilon less than zero.

This is the metal property, this is the artificial hoop property he combined both of them in this kind of format and produced, so, this is the refractive index, this is the real part of the refractive index and this is the imaginary part of the refractive index, you see the real part of the refractive index going below 0 at a microwave frequency. And this opened up a whole plethora of antennas and perfect lands and this invisibility cloak came up very, very strongly because at that time Harry Potter got released and Harry Potter has an invisibility cloak.

Predator movies were coming up, so they thought that we can utilize because we have complete control, we have complete control over the property of light here, we can ensure that having negative refractive index we can make it transparent. Remember the quadrant that I showed you the final fourth quadrant where you can make something transparent if something is transparent in front of you, maybe it is invisible, so invisibility cloak was coming up.

(Refer Slide Time: 39:09)

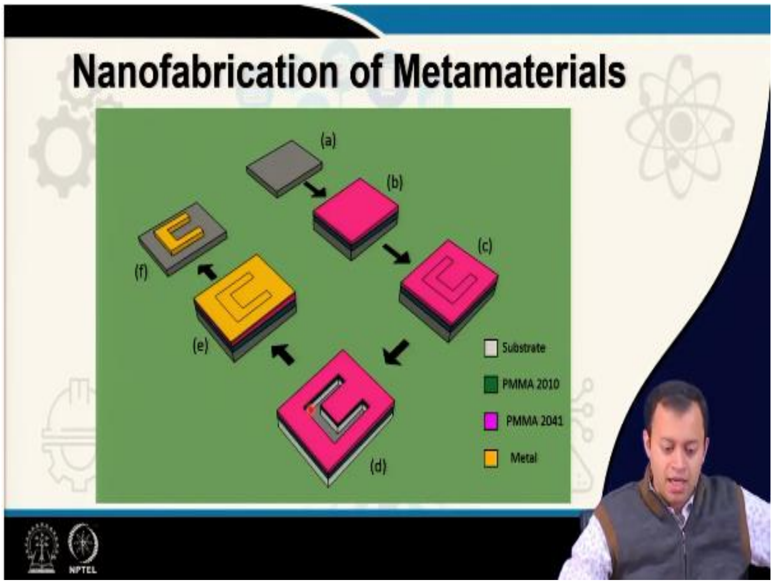


So, why exactly we do utilize metamaterials for? Well anything that thus far has a negative refractive index like Snell's law, Doppler's effect, Cherenkov radiation all other theories are affected, from a physics point of view electromagnetism has to be rewritten, now let me be absolutely clear, none of the laws are actually getting violated it is simply getting modified, you previously have put the absolute value of n now you are putting the negative value of n, what has it resulted?

It resulted in the light bending in a different direction, the light bending in a different direction. From an engineering point of view, they discussed making cloaking devices, trapped wave, perfect lens, but a group of scientists thought that we can utilize it for optical biosensing. How? Well, let us see.

Remember now, the property of the resonance which it will reflect the magnetic field will depends on the circulating electric current and it all depends on the dimensions, not on the property of the material, not how the atoms are arranged inside the material but how the materials dimensions are and how smaller they are than the wavelength of light. So, if we are trying to see some kind of an effect in the visible frequency range where light is the wavelengths are 400 micro, 400 nanometers to 800 nanometers roughly, then we have to make materials of sizes smaller than that. Well, how do we do it?

(Refer Slide Time: 40:53)



We utilize nano fabrication, nano technology. In the I think imaging part I did not show you how to do nano fabrication but this is the particular case where I can give you a glimpse of how nano technology is being used to make ultra-small structures. So, what you do, you take a particular substrate, say silicon, substrate which is silicon, you cover it with some kind of a polymer, this polymer is electron sensitive, the polymer is electron sensitive and then you subject this polymer into something which we called as electron beam lithography.

Lithography you know basically printing its cheap method of printing. To understand lithography, consider your home computer connected with a printer, all of you have a printer, you know there is a paper, you send information to the printer’s head, the printer moves in a scan either a vector scan or a raster scan wherever it has information it will drop ink wherever it has no information it will move a blank space and finally when it has done you see a letter a, b, c, d or an image or a combination of that is coming up.

The same thing in electron beam lithography, electron beam lithography the electron is made to fall according to a particular pattern on top of a substrate which is covered with electron sensitive polymer. Other way of looking into it is cathode ray oscilloscope, all of you know what cathode ray oscilloscope is, cathode ray oscilloscope utilizes the electrons the beam of electrons utilizes magnetic plates and what not to make the electrons fall at a particular place of the screen, the phosphor screen and thereby you see some kind of a pattern generated into the screen depending on the signal that it is connected it, depending on the signal that is put into its input.

So, consider an electron beam lithography as a sophisticated miniaturized, well not technically miniaturized it is quite big but a sophisticated and much powerful with 100 kilovolt, 50 to 100 kilo volt version of cathode ray oscilloscope, where you can pin point where the electron beam is falling, instead of the phosphor screen you have a substrate, you have a substrate.

And you can make the electron fall at an area which is roughly of a resolution of 10 nanometer, well this is nano technology so it has to be at that particular scale, how small is 10 nanometers compared to the width of your hair again? Remember, I gave you the formula. So, whenever the electron falls on top of that PMMA polymethyl methacrylate substrate, the bonds break and this part becomes weakened.

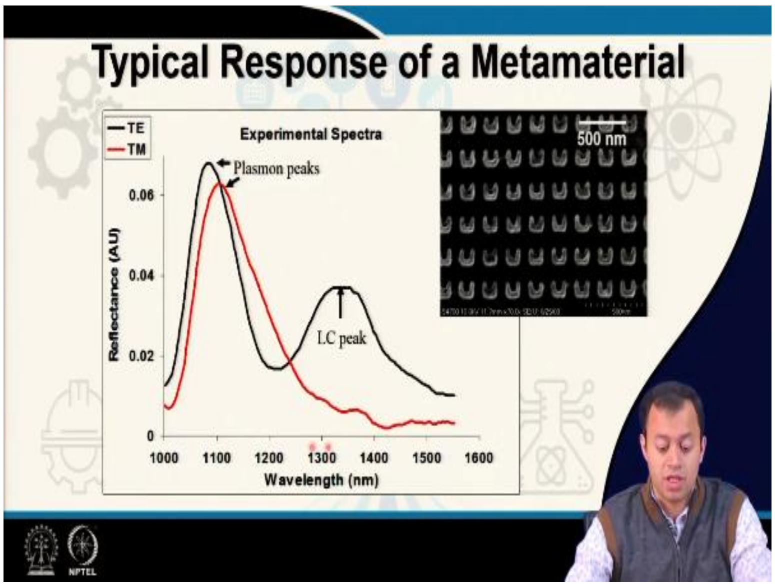
When this part becomes weakened we can simply dissolve the weakened part by putting it in some kind of a solvent, when that solvent has put a hole, put a trench into the system it simply is dissolving the polymer, the PMMA not the substrate. We cover the entire thing with metal, in this particular case gold or aluminum. So, the metal falls on top as well as into the hole and then I put the entire thing into a very strong solvent, something that dissolves PMMA.

So, it will dissolve the entire PMMA part, so if the PMMA is dissolved whatever was on top of PMMA which is the gold or metal will be agitated away as well but that part which has fallen into the trench, so you have structures like this with holes in between, gold is here and gold is here, gold is here and gold is here, gold is here and gold is here this gold top and bottom are no longer connected.

It is no longer connected there is some amount of gold here and some amount of gold here, try to do it you take some kind of a water filter or something like that and put some amount of powder on it and some of the powder will fall through onto the nearby surface, we do it during decoration.

Remember we take a stencil and put some different kinds of paint, some amount of paint falls on top of the surface, some amount falls in the bottom and then you remove this and then there is a pattern forming at the surface, you have a stencil like thing and you have the surface below, through the stencil you are throwing metal or powder or something like that, some amount will pass through some amount will stay on top when the stencil is removed what is left is a pattern and this is the pattern.

(Refer Slide Time: 46:02)

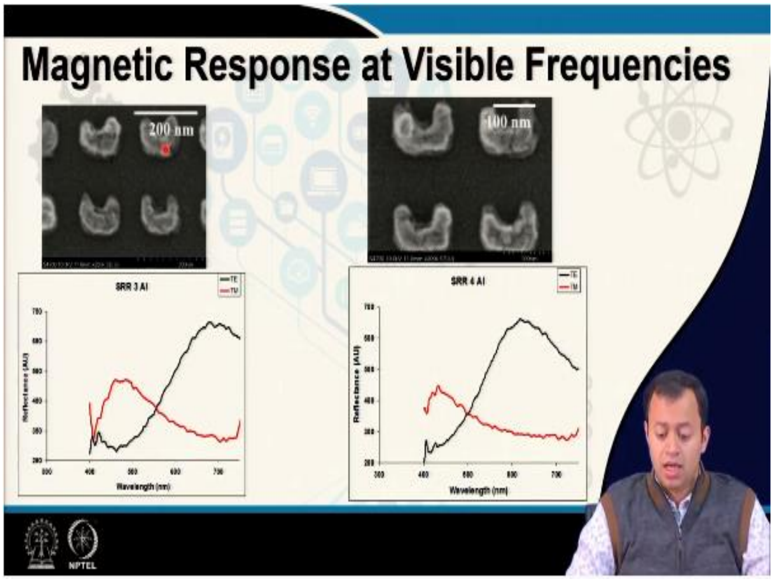


This is the pattern that I made, look at the scale here 500 nanometer, I made it, this is my personal work, you can look it at the date, these are the dates when I first made it, it was how many years ago when I used to be 50 years old, now I am 60 and you get experimental spectra of Plasmon peak and LC peak.

So, when light is in, light is thrown into it with electric field in this direction, circulating electric current will form that will oppose magnetic field in this direction, negative antiparallel to the direction of the incoming light several of its component will be antiparallel to the magnetic field component of the incoming light as well and you have an opposing field which is the LC peak.

These are experimental spectra I made it, I personally made it, so this is not simulation, this is not computer generated and this is simply gold or aluminum-based structure, this small and whenever you change the polarization there is no peak and look at the wavelength these are the telecom frequency range telecom frequency is here and here we can utilize it its telecom.

(Refer Slide Time: 47:19)

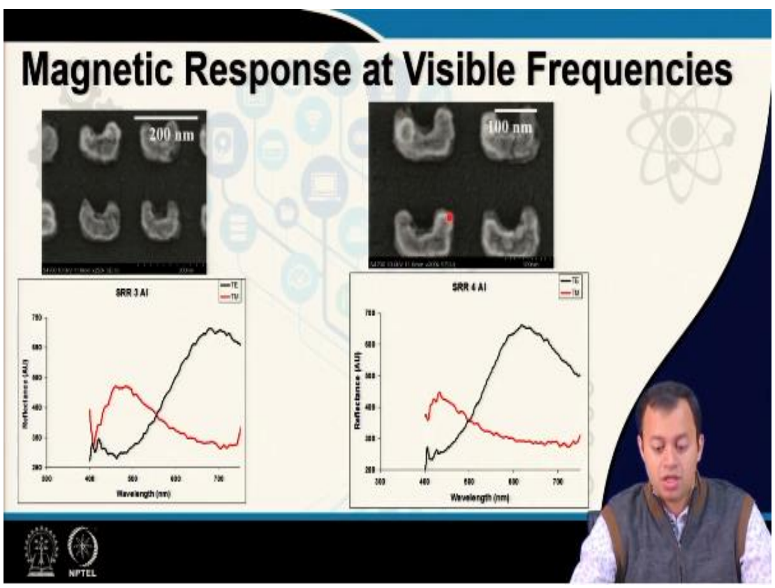


But I wanted to go further so I made this smaller 100 nanometer these things are 20, 25 nanometers. Again, think how small I can go as how many of these structures, these metallic split ring resonators, I know they are not as sharp but just appreciate how small they are. So, how small I have made them and now they are opposing TE and TM are simply two different polarization.

Transfer electric and transverse magnetic when the electric field is in this direction it will show this, when the electric field is in this direction it will not show and these are in the visible frequency range. So, you are seeing magnetic effect at a very, very high frequency range.

So, the question comes that if the response, if the resonance response, if the whatever the reflection, whatever the antiparallel field happens to be at an area in a region which is susceptible to our eye, which our eye can detect, then if I put this material under microscope large number, large sections, so though they are 100 nanometer they are putting arrays, you saw the previous arrays, I make a whole box containing several like of these like atoms, like atoms, atoms contains the bulk material. Can I see them?

(Refer Slide Time: 48:52)



And, yes, you can see them, these are the different color, I do not know if you are able to see this color, this is actually visible blue, this is dark field microscopy, recall what dark field microscopy is, why I have used dark field microscopy is the next question but the beauty of this is, this structural color, the color is happening because of the size usually the color is because of the how the atomic arrangement is basically a material property but all of these are aluminum based structure.

And you know the color of aluminum, the color of bulk aluminum is whitish, but I have made them in a such a manner, I have patterned them and made them in such a manner that they are able to reflect or oppose in this particular case light at a particular frequency and that frequency is manifested here, that frequency is manifested here and I call it rainbow magnetism.

You can create structural color using metallic nanoparticles, the metal the property of the metallic color itself gold or silver they have their own internal color but structural color depends on the structure not on the material properties. So, imagine what this could happen what this could bring in the area of textile, usually the colors are from dyes and they fade after washing and after what not.

But if I make them because of the structure what will be the manifestation of it, but that is not what I want to discuss here, you must be asking what this has to do with sensing. Humor me this, they have a particular color, so for example, green you can see this, now I have immobilized antibodies on top of this, these antibodies the paratope of the antibody is specific to the spike protein of a coronavirus.

I am now putting some patients nasopharyngeal swab or oropharyngeal swab, if it has coronavirus it will attach, if it does not have coronavirus after some amount of agitation it will wash away. So, if it gets attached to these structures the overall refractive index will change. Remember the formula where you have the lambda c, the response depends on the refractive index of the surrounding material.

If the refractive index of the surrounding material has changed, changed because it is getting attached to another foreign body which is not air, will the color change? If lambda is color or if color is wavelength or frequency or light. if lambda changes upon contact with coronavirus, will you be able to see it at the privacy of your own home, if I give you structure such as these, so this is 1 millimeter by 1 millimeter and they have calculated how many 100 nanometers by 100 nanometer array structures.

So, these, these 100 nanometers by 100 nanometers numerous of them, if you zoom into that you will see this you will be able to see this. Now, I have connected this with specific antibodies that antibodies only will attach to coronavirus, no other virus will be attached to it. If it is attaching there is a change in the local refractive index, if there are change in local refractive index there will be a wavelength shift.

If there is a wavelength shift you can detect it and if that wavelength shift is specific to a specific antibody capturing a specific antigen, can you detect it, is it not like your home pregnancy detection kit, have anybody of you seen or used home pregnancy detection kit? After you put few drops of urine and if you happen to be lucky enough to be pregnant, the color changes you see two blue lines. So, from white the color changes to blue and that is the indication that it is present, can we not utilize it here? Just think about it and we shall meet in the next class.

(Refer Slide Time: 53:50)

So, these are the topics that I discussed, go through a little bit on the split ring resonator part, there are beautiful articles here, I know maybe some part I was unable to describe properly but just go through it a bit and then return back to me we can have a proper better discussion, I have to finish the syllabus at a specific time.

(Refer Slide Time: 54:18)

So, these are the references and you could see what this reference is, this is my own work I made them. so, if I can so can you, in fact I am counting on you to do a far, far better job than me and come up with something even better and thereby change how physics is seen, why not. I shall see you in next class. Thank you very much.