Biophotonics
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Lecture 34
Metamaterials as Biosensors

Welcome back, so we will continue with our topic on metamaterials. One thing I forgot to mention how are we measuring the spectra, you saw those spectra that is coming up at what particular frequency, what kind of signals are coming up, can anyone tell me how I am measuring those optical properties, the spectra, electromagnetic spectra?

There is a possibility that I am using FTIR, you now know what FTIR is, if I can utilize FTIR to look into vibration of molecules, these are meta atoms, these are artificial atoms, these are artificial molecules why cannot I see their vibration, what are vibration? Well when light is coming they are behaving in a particular way like your molecules. So, I use FTIR, I forgot to mention how that measurement is done but now you know that FTIR is used.

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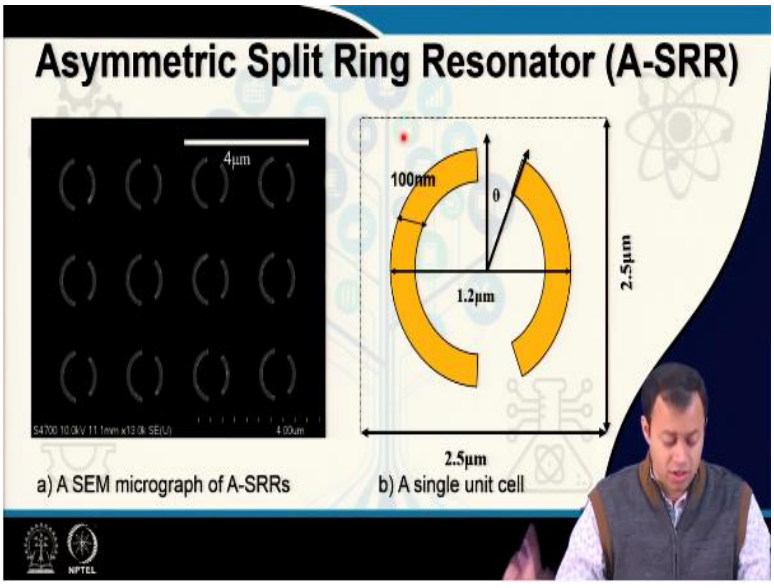

So, let us continue with our topic on this time, previously I gave you a glimpse of what metamaterials can do but how to utilize metamaterials as biosensors. so, I made asymmetric split ring resonators, previously you saw u shaped now I made asymmetric c shaped split ring

resonators, why do you ask well there is a very good example or very good reason for that. So, let us understand what asymmetric split ring resonators are.

Asymmetric split ring resonators are two c shaped metallic structures, they share the same center of curvature but they have asymmetric arc length. So, this is a left-hand arc, this is a right-hand arc and there is a gap between them, the length of right-hand arc and the length of left-hand arc are dissimilar.

However, they have the same center of curvature, they have the same center, the circle, the arc has the same center, why make this and these are slightly bigger, this is 5 micrometer, so this is 2.5 micrometer, meaning they will resonate in the infrared region, you can using that calculation using the formula that I gave you, you can calculate where roughly the lambda their response is going to be.

However, that formula has since then been made much more complicated because there was accuracy problem like any other formula but still we use this formula as a rough ballpark. So, whenever we design something to understand and this strip length, the thickness the length here is 100 nanometers. So, why make this kind of a complicated structure and what does it has to do with biosensing anyways.

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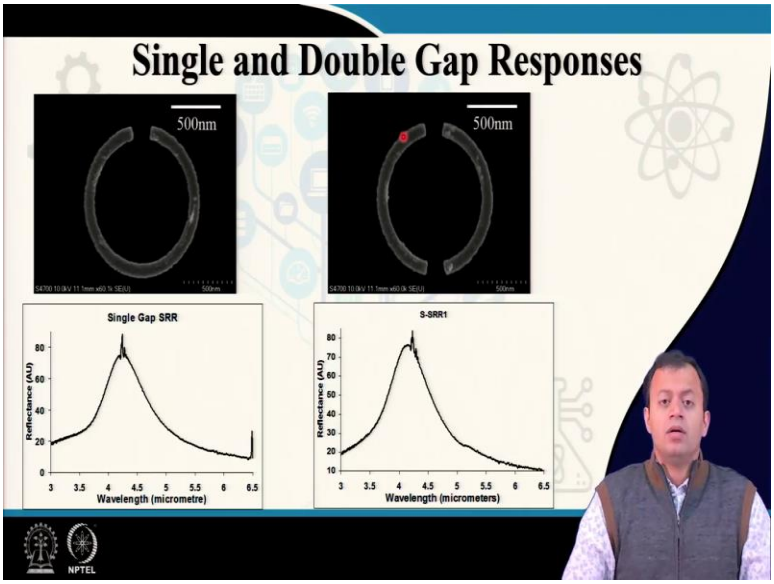

The response, the resonance response, magnetic response, the LC response, however the optical response of these structures depends on their size, you know this already we described this lambda c is equal to that omega LD that hideous formula. So, we can tune this frequency range you can tune this wavelength range by changing the size, I have shown you that I have changed the sizes a bit and I have made it resonate at yellow, red, green, blue whatsoever I can similarly do it here. Why? Because this has a resonance and this has a resonance.

This is one particular system and when I have shown light with electric field in this particular direction it will resonate circulating electric current, magnetic field is forming and this is the response that you are getting. When I have split these two apart, then this is resonator 1, this is a resonator 2, these are optical resonators why not, metamaterials as optical resonators because when light falls into them they react, they response and their response is depending on their size rather than material property.

Always remember material property in this particular case is immaterial, pun intended material is immaterial, so it depends on the size. So, if left hand arc has a resonance and the right-hand arc has a resonance, if the size of left-hand arc and the size of the right-hand arc is same, their responses are also same and they overlap nicely, no problem whatsoever.

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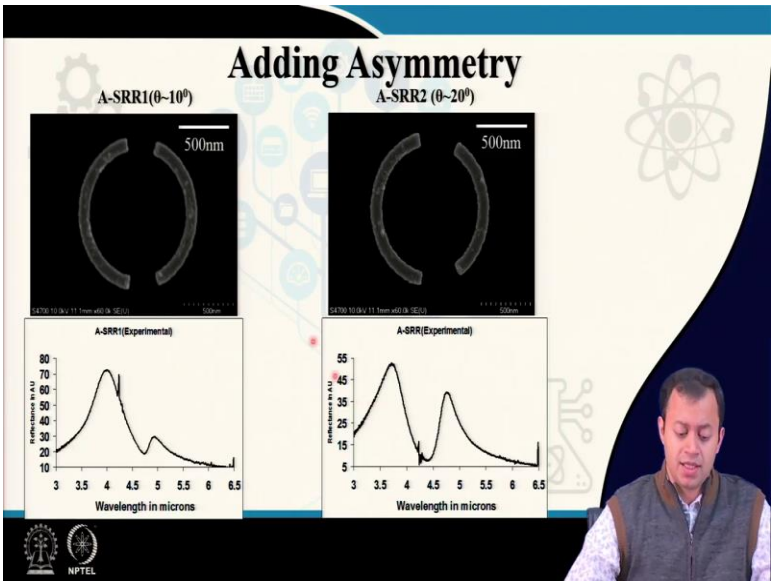

Things starts getting interesting when you keep the size of the left-hand arc constant and start to slowly reduce the size of the right-hand arc. I increase the angular gap between them theta is equal to 20 degree, here is equal to 10 degree. What happens then, remember the resonance or the response the lambda c, lambda LC, depends on their dimensions depends on their size.

So, this has a response of its own, this has a response of its own. Now, you are seeing a coupled resonance effect, the resonance is similar but not same, the resonance is similar but not same. So, there will be some kind of a mutual effect on to one another, there will be some kind of a mutual effect into one another.

We see as soon as a small gap starts appearing the two resonators, their response starts diverging, bifurcating. Previously they have overlapped with one another now they are startly showing to diverge because their dimensions, their sizes are no longer same. But since they are very close to one another the response of this will be modified by the presence of this and the response of this will be modified the presence of this.

Electrical engineers can think of it as two inductors carrying current are brought very close to one another, so there is mutual induction happening, mutual current flowing. It is a coupled resonance system, the resonance of this is getting modified by the resonance of this and resonance of this is getting modified by the resonance of this and they are brought very, very close to one another and because of their closeness, because of their proximity they can interfere into each other, each others affairs, each others resonance.

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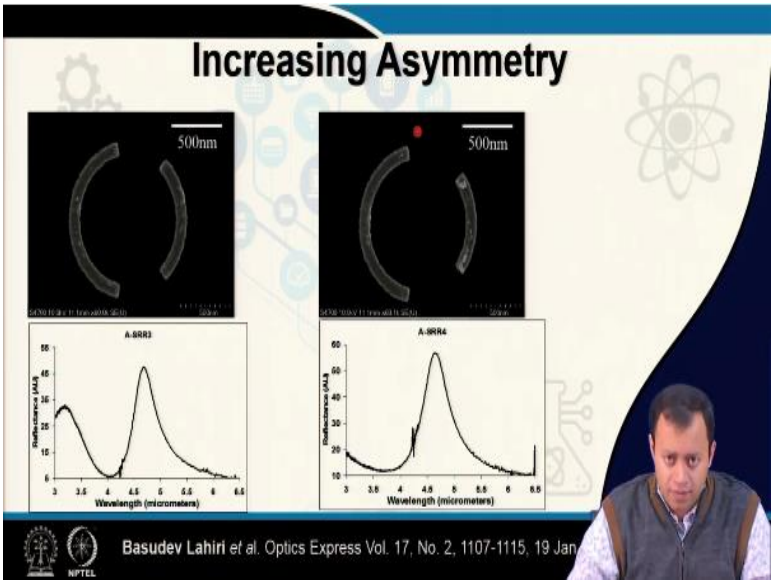

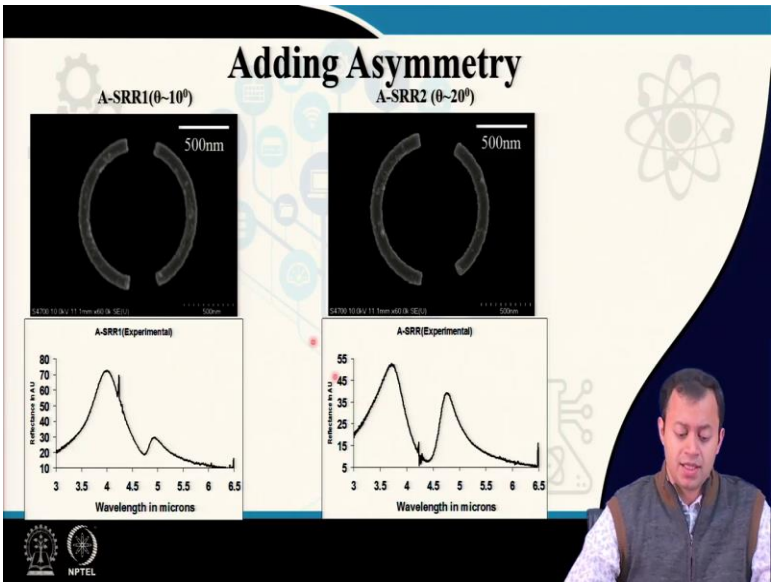

When you further start reducing the size of the right-hand arc keeping this constant you see the two resonators are no longer talking among each other, they are decoupled, they are so far away from each other that either you see this and in a separate manner you see the other one and they are no longer, they are decoupled, this was coupled, this is decoupled.

So, what is the significance of this? If dimensions are very close to one another they will overlap, if they are either very dissimilar to one another or very far away from one another they will also decouple, but there will be a sweet spot where the sizes are similar, not same and they are also

close to one another, so there is a coupling effect going on between the response of one resonator with the response of another resonator and they are both mutually interfering on to one another.

Just take two inductors, two different kinds of inductors with similar electric current flowing through them and bring them very close to one another and you know keep doing that and you will see that mutual current keeps on flowing, the mutual current formation the coupling is a phenomenon. So, what is the point, why are we doing this?

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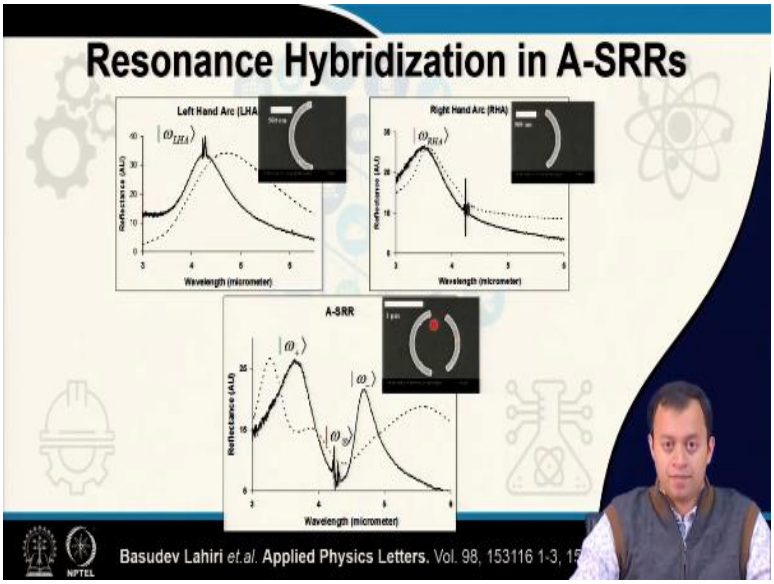

The fact of matter remains that when such kind of a system, a coupled system comes in where the sizes are similar as well as they are close to one another, their resonances hybridize, their resonances hybridize. So, this has a response of its own, this also has a response of its own, you combine them together the overall response produces two peaks and one trough, one valley, this valley ladies and gentlemen is very, very significant. Why?

Because when you shine light onto it, this is resonating and this is resonating, it has its own resonation, it has its own resonance, at a particular specific frequency, at a particular specific wavelength, the resonance of this will dominate the entire system the resonance of this is much more larger than this and you see this peak appearing.

At one point, at one particular frequency this will respond more because of the dimension because of the size and this will respond more and it will dominate the system and this is given

by this particular peak. There come, a particular case, a particular case in between these two resonances, in between these two resonances where the strength of the signal is similar but the direction is opposite.

At one particular case this is dominating and this is lagging, at one particular case this is dominating this is lagging but then comes a particular case where they are equal but opposite. So, the resonance strength of this and the resonance strength of this, remember it is a circulating electric current, so it has a direction, so it can have this way or this way, it does not matter if your circulating current is this direction or in this direction, a chance come where the response of this and the response of this are equal and opposite to one another.

When they are equal and opposite to one another, destructive interference they will cancel each other and you see this valley, this trough. What does that mean, what does that represent? That is something that we call as trapped mode or the North American called it dark mode these days it is being called as bound state continuum, though the definitions are not same, they are quite a difference between them but what does this actually mean?

It actually means that see all of the light that is exciting these kinds of structure are free space coupled, free space coupled you are not connecting it to some kind of an optical fiber, you are just making the structure and shining light onto it. So, this is free space coupling and since it is metal it is glossy it is scattering light you have made a special condition where it will scatter in a specific manner, granted, it will resonate in a specific manner, granted, but then you have made a special condition where the scattering of one is cancelled by the scattering of other, destructive interference is happening.

Remember in the very first class when I was talking about interference I said that at the end of the day every major electromagnetic phenomenon has something or other to do with interference, this is the interference happening, usually we have a material with very high transmission will be equated with very low reflection. Opposite is also to very high reflection i.e., gold or metal very low transmission.

Trapped mode is that one particular case where since this and this have cancelled each other, the resonances of both have cancelled each other it has simultaneously very low reflection as well as

very low transmission. Where is the light going? The light is simply trapped it is a purely absorptive mode where you are controlling the absorption.

Previously you are controlling transmission and reflection now you are controlling absorption, you have trapped the light like you have been able to trap water in a container, using this in this particular frequency it is possible to trap light, hence it is called also dark mode, a mode which is neither transmittive nor reflective because of the scattering parameters e and h field are mutually opposite to each other in this particular resonator and this particular resonator and they have cancelled each other. So, e and h are cancelled what will happen to the speed of light, what will happen to the propagation constant if e and h are both cancelled or almost cancelled?

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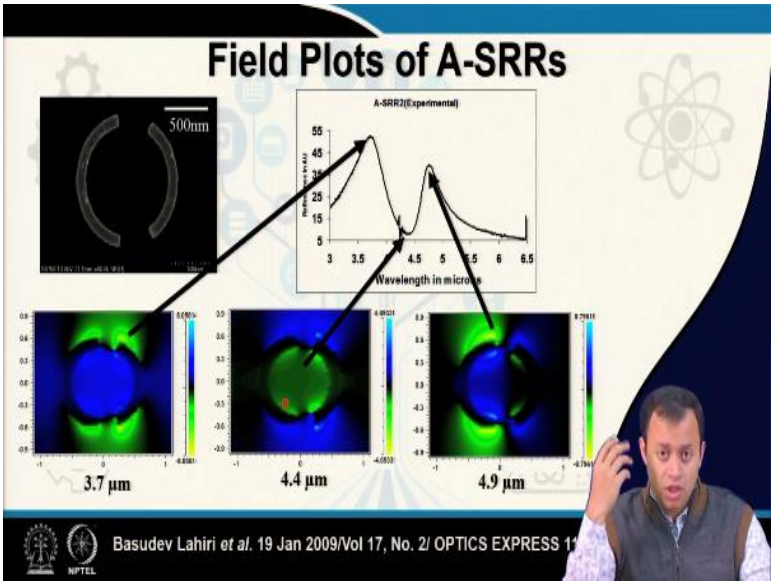

We saw that using some kind of a modeling that what I was telling you this is the particular field where this resonator is resonating, this is the particular field where most of the, well let us take this one, where the bigger one the left-hand arc is resonating and the trapped mode is the one where most of the optoelectric field is concentrated inside the contour of the system.

This light cannot transmit, cannot get reflected, it simply stays there and dissipates in a non-radiative manner, dissipates as heat or something similar vibration, phononic vibration this is what we are doing, this is a reflection taken by an FTIR, if you do a transmission you will see the

exact opposite where both the reflection as well as the transmission are simultaneously going down, absorption is going very high this is trapped mode.

The other two modes, this is dominating so this is resonating maximum, this is resonating maximum with optoelectric field very close to one another because the electrons present here, these are the plasma peaks, electrons present here are basically opposing the electric field coming, so there is a localized electric field generated here. So, this is the overall field plot of the structure. How do I utilize it?

Well I basically these things are called electromagnetic hot spots, so whenever you shine light into it there is an uneven and heterogeneous distribution of electric field around it, depending on the frequency the light or the optoelectric field or however you want to define it are heterogeneously unevenly distributed. Depending on what particular frequency is resonating at what particular structure, they are at a different area, they are different places at different frequencies and these electromagnetic hot spots are very, very susceptible to any change in local refractive index.

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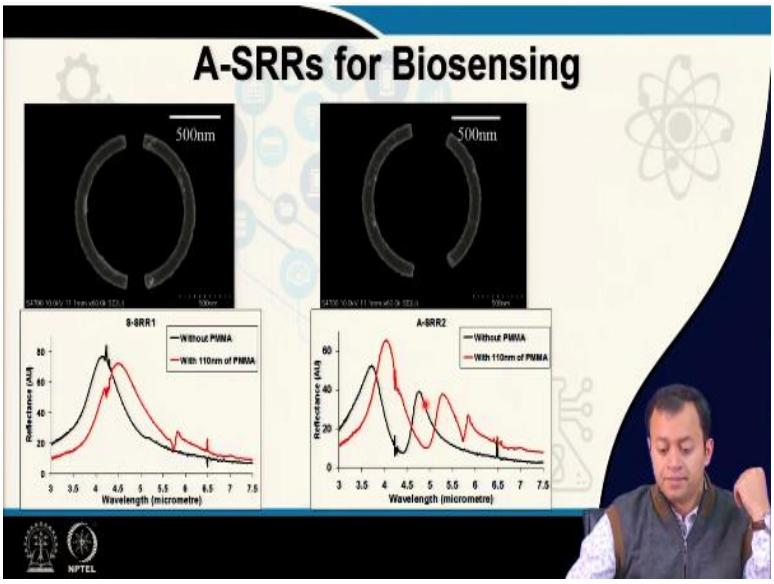

Remember from previous class the resonance depends on the local refractive index and if you change the local refractive index by covering the entire structure with some kind of an analyte you see a red shift happening, this red shift you cannot see from your naked eye because these

are in micrometer range, but using an FTIR equipment you can see this is a symmetric structure, this is an asymmetric structure and you see how much there is a red shift.

Red shift shows that the energy has been lost, energy loss is represented by higher wavelength lower frequency, e equals to h nu. So, e is equal to h c by lambda, so if lambda is increasing energy is reducing. Why is energy reducing? Previously light was coming straight from air and hitting the surface, now light is coming from air to the analyte that you have put, in our case it is very, very thin layer 110 nanometer of poly methyl methacrylate, the light is now passing from air to medium to this, just like the light is passing from glass to water to the steel spoon and then returning back it is the same thing and you see the shift in resonance.

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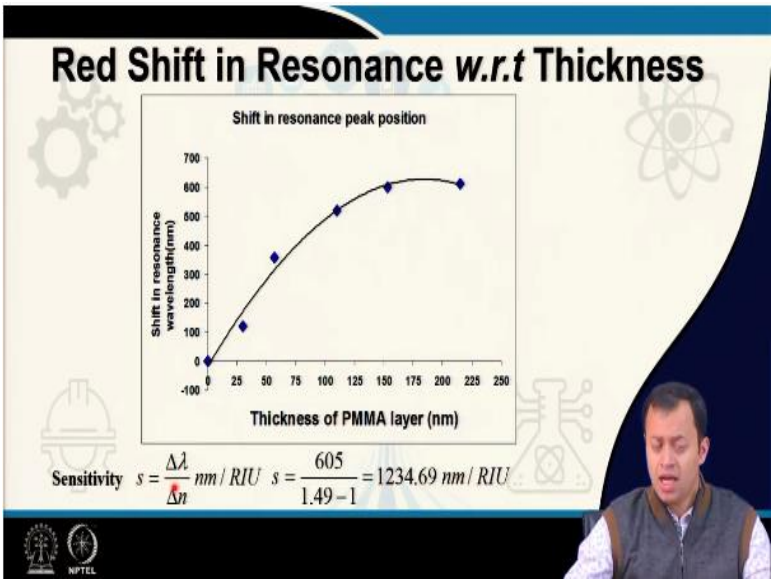

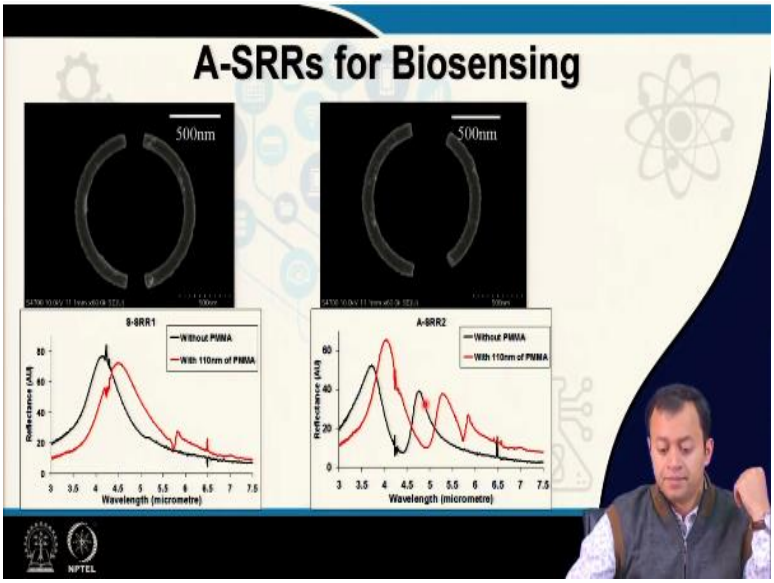

This shift in resonance is directly proportional to the thickness of PMMA layer as you go on increasing the thickness there is a shift in resonance happening. After some time obviously, you cannot infinitely increase the thickness because the photon will no longer able to penetrate but the shift in resonance is very palpably measured. And if that can happen you can measure sensitivity, remember sensitivity is delta lambda by delta n, delta lambda is this lambda 1 versus lambda 2 without analyte and with analyte and delta n is the change in refractive index, previously it was air now it is PMMA 1.49 minus 1 and this is the overall sensitivity.

This is a crude value of sensitivity there are other sophisticated formulas as well but this is a rough ballpark figure that we are generating. Can you now tell me for a PMMA layer of 110 nanometers thin how many molecules are present and if the layer is 110 nanometers thin, if the thickness of the layer is 110 nanometer what is the approximate thickness of a virus, any virus, coronavirus? Can I measure it in infrared as well using this?

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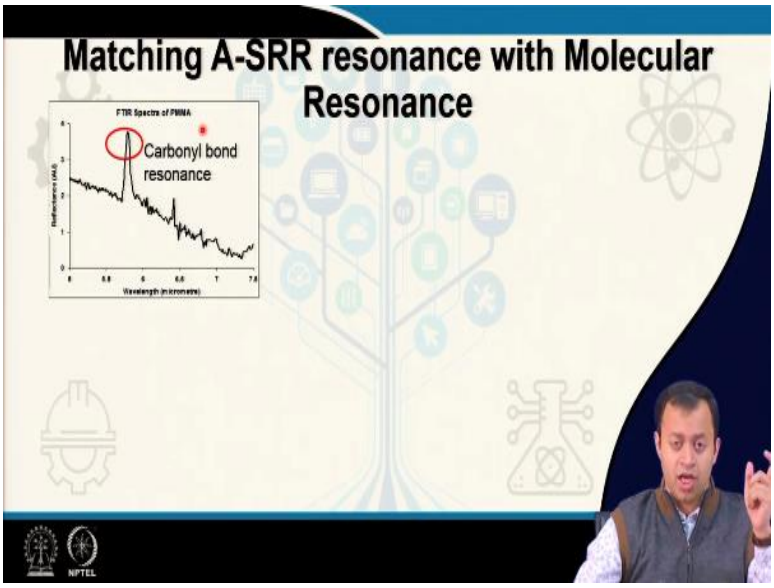

Well one more thing that came up, I told you that most of the organic molecules have their own molecular vibration in the infrared range, I discussed this, that is fixed this is how the molecules are arranged, you cannot change that. So, PMMA has a response in 5.7 micrometer which is its carbonyl bond resonance, this is the c double bond o, this vibrates at a particular frequency, this is the signature by which we identify this is PMMA you cannot change that unless you deform the molecule completely, there is no need for that.

But you can change the dimensions of your split ring resonators, you can tune that. So, this is the response of your molecule, molecule is vibrating in this frequency, the resonator that you have created is vibrating at this frequency, this is fixed, this is not, you can tune it to match here. So, the vibration of your split ring resonator is matching that of the vibration of the molecule that you want to detect.

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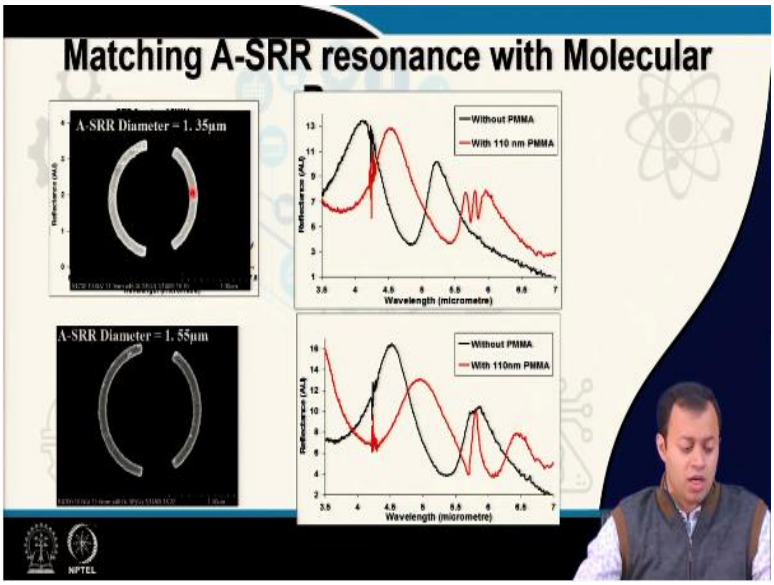

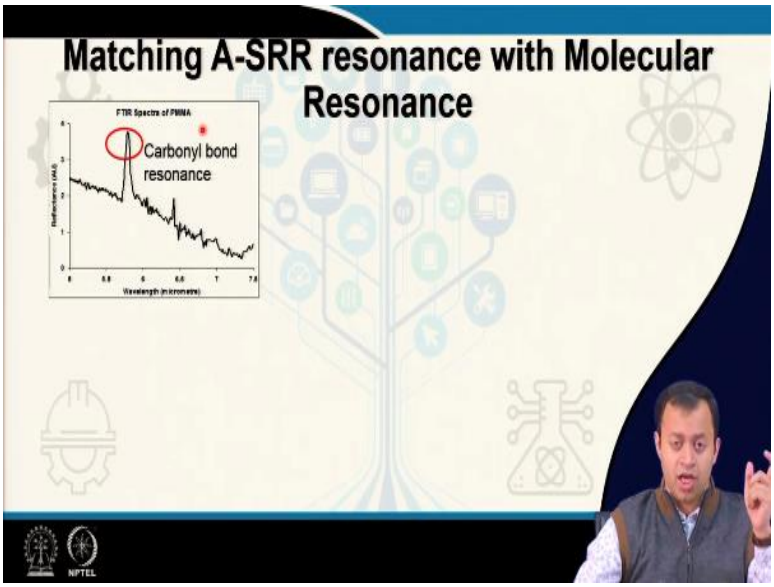

Result you change the diameter from 1 micron previously to 1.35 micron and now you have a phenotype resonance coming up here. Furthermore, you enhance the overall signature. That is simply getting amplified, previously the vibration was happening because light was falling, now the vibration is happening because the light which is exciting the molecule is also exciting the split ring resonator and both of them are resonating at the same time.

So, this is a couple resonance, this is an amplified resonance, this gap thereby delta lambda shows how much thickness, how much quantity it is and this particular signature coming at 5.7

identifies the molecule. So, you have both figured out what the molecule is and how much the molecule is, you require these two, at the end of the day these two are the most primary criteria because previously you have simply made a material of a particular thickness, material of a particular thickness that was changing the refractive index.

Now, it may happen that dissimilar materials have the same refractive index, dissimilar material there are several materials which have the same refractive index or material a of thickness say 100 nanometer is producing the same effect as material b of thickness 200 nanometer, how do you differentiate?

You differentiate by this, you target one specific molecular resonance carbonyl bond molecular resonance is the spectral signature of PMMA, you ensure that your resonance response of your split ring resonator is specific, is matching to that particular response. When those two have matched you will see a characteristic feature with a red shift which shows how much and characteristic signature which is getting amplified which is there as your fingerprint, as your identifier.

Where can I use this? PMMA is proof of concept, PMMA is not a conjugated material, it is a saturated material we have utilized it, I use PMMA because I can control its thickness 110 nanometer thin, I can control its thickness very well. So, where can I use it, can you tell me where I can utilize these materials, where I will see 110 nanometer thin layers with a particular signature? All I have to do is to customize the size of my material, of my resonator to match a specific frequency. Tell me in the comments below where I can do that.

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So, this is where I stop for today, these are the concepts that I discussed, trapped mode, dark mode, bound state continuum they are not same they are slightly different from one another, I want you to explore what are the subtle differences between each other and I have shown you thin film sensing.

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So, this is again my reference for those who are enthusiastic download this is available free of cost in from University of Glasgow's library as a PDFs file, just download it and go through it

and think what else you can do about it. Thank you very much I will see you in the next class where I am going to conclude the biosensing with metamaterials. Thank you very much.