Photon Integrated Circuit
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Lecture: 50
PIC for Sensing Applications-1

Hello, everyone. Let us look at how light can be used for sensing. This is a very familiar topic. So, you can sense whatever you want using light because light-matter interaction is very strong. For example, whether there is an object present there or not, you can sense using light. And you can sense the color of that object. And you can sense what is this object made of.

So chemically you can probe, physically you can probe. So, and also, the shapes that any object has. So, optics or photonics has this really powerful light-matter interaction that can give you variety of information that you want to get out of any matter that you are interested in. We use it every day.

For example, you are using a camera and this camera is nothing but a light sensor. So, it senses the photons and in particular it can sense the color of the photon. And also, you have opto-electronic devices that can also, can emit certain color based on the information that you give into this device. And there are lot of spectroscopic techniques that relies on light-matter interaction.

So sensing is very fundamental to light-matter interaction. So, you can do lot of interesting things. But when it comes to integrated optics, the field is very large. Perhaps, we could have one full eight-week course on this optical sensing alone. But since we have to reduce our scope to how we can exploit the photonic circuit for light-matter interaction, we are going to look at two examples here as a case study on how we could exploit the guided wave system, that is photonic integrated circuit for sensing.

So even sensing here sounds very broad. So, what are we going to sense? So, you have a light beam that is propagating through the waveguide. And as we all know that this guiding is controlled or determined by the material that you have as a waveguide and also the environment around it.

So, we have the refractive index, when I say environment, it is about the refractive index that is surrounding. And when there is a change in the refractive index in the environment, the light will actually sense this environmental change. How do we sense it? Because the $n_{effective}$ or the propagation constant will change because you are changing the environment now.

So now, all your, waveguide, when you go back to your waveguide design, we, we talked about n_1, n_2, n_3, right? So n_3, is the, the light that is, the light that is interacting with the top cladding, the top cover. And if you are going to change this n_3 then your guiding condition itself is going to change. That means your β is going to change. And we can actually measure it. So, we can measure those changes.

And similarly, when the light is propagating through the waveguide, you can have light that is extending itself out. So, there is a, the evanescent tail that you have, outside the waveguide. So again, going back to our basic understanding of waveguide design. So, you do have exponentially decaying solution outside your waveguide. So, you have very strong electric field outside. So that field is actually probing the environment. What is happening there?

And when you, when you say there is a change in the environment, it could be in two ways. One is the density change and it could be also absorption change. So, the environment is characterized by the refractive index. So, you have n and then k. So, you could have absorption because of this.

So, when you have absorption, then eventually that is going to affect the light propagation. How? It is not going to directly affect our β, but it is going to affect the intensity of light that is propagating through. Light will be absorbed by this medium that is surrounding. So, we can measure the density and we can also measure the absorption around the waveguide in the environment.

So, these are all very fundamental ways of using it, very simple ways of using this. And there are other techniques, like you can do on chip spectroscopy for example, you can do on chip florescence. So, you can have florescent molecules sitting on the waveguides, and you can excite those waves, florescent molecules using the waveguide. So, the light could excite the molecules sitting on the waveguide and then once you have excitation, you will have emission. And this emission can be isotropic. So, the emission normally is an isotropic.

So, you can collect this light either from the top or even with the waveguide. So, this becomes a spectroscopy. So, using waveguide, enhanced spectroscopy you can do. So, these are all different ways of exploiting light guiding in a, in a guided wave system for various sensing applications.

So, since we do not have lot of time to go about talking about this interesting field of sensing on chip, we are going to pick up simple examples and that is good enough for you to get motivated. So how one can easily use this concepts that we already learned throughout this course and use it for something very applied. So, we are going to look at two different things here. So let us jump into that.

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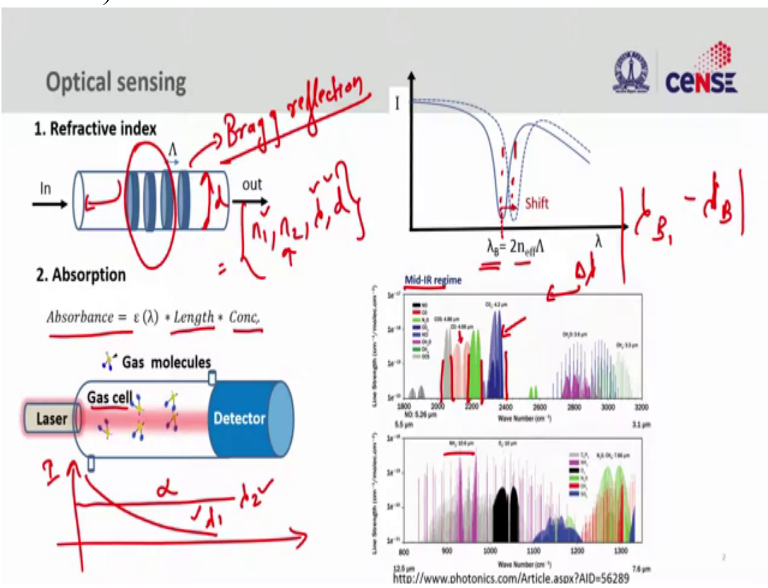

So, what can we do for this sensing? So, there are two ways. So, as I mentioned, you can do refractive index sensing. So that is the change in the refractive index. So how can we sense that? And next is the absorption sensing. So, the refractive index sensing is rather straightforward. So, you have a certain medium, you could have for example, in this case, this is a fiber Bragg grating, so we create a Bragg reflector. So, there is a waveguide, and this is a Bragg reflector.

So, this is again something we already studied in our basics, in one of the lectures. So, this is going to reflect light, and this is also going to transmit a certain amount of light. So, when you look at the light that is going through, this is the transmission that you see, you see a dip. So, this is our Bragg wavelength or the resonant wavelength here. So, this reflected, or your Bragg wavelength strongly depends on the effective index.

So, any change in the effective index will result in shift here. So, what does effective index depend on? This whole environment. It depends on n_1, n_2, λ and if this is the dimension d as well. So, all this is captured now. So, when you fix rest of the things, all these are fixed now.

But now the, the surrounding refractive index, we are going to change this. So, when there is a change in the refractive index of the environment, your $n_{effective}$ is going to change. So, the $n_{effective}$ change here would result in shift in this peak. And based on this shift between λ_{B1}-λ_B, let us say, if there is a positive shift, then this would result in some $\Delta\lambda$. And this $\Delta\lambda$ is related to the Δn, the change in the refractive index that we have in the environment.

So, one can easily find out how, how much change in the refractive index we have around your optical device, in this case, Bragg, simple Bragg. We will see whether you need a resonant device like this, like a Bragg, we can also have other kind of devices like, a ring resonator. That is what I am going to show you in the next couple of slides.

So, the next way of doing this sensing is using absorption. So, the molecules, for example, the gas molecules, they absorb a certain frequency. This is coming from your, the vibrating molecules here. So, the molecules vibrate at certain frequency and when you have a light wave of identical frequency, these molecules will absorb it. And when you have absorption, then the amount of light that you get on the detector, decreases based on the absorption coefficient, if this is the intensity.

So, if there is a molecule, if there is a, a wavelength, so let us say this is λ_1, and I send in another wavelength. It will just pass through. So, the reason for this is, your, your wavelength here is not absorbed by the, the gas that we have in the system. So, this is how you can choose the right kind of wavelength for a certain gas.

So, when λ_2 is not absorbed, then λ_1 is absorbed, so then we know what this λ_1 absorption correspond to. How do we know that? So, this is from our fingerprint absorption. Because the molecules are very sensitive to these wavelengths. So, they do not absorb any wavelength that they want. These wavelengths are very specific. They will only absorb a certain wavelength of light, or frequency of light. Because since this is a resonant absorption, you can see here, they are very specific absorption.

For example, carbon dioxide absorbs at 4.2 micron here. And then carbon monoxide here, 4.66 micron. So, you can see here, very distinct absorption band. So, this is very characteristic of optical absorption spectrum. So, this is the reason why absorption sensing, particularly when it comes to optical absorption, are very, very selective. They are very selective to the gas.

So, when I, when I see an absorption at 4.2 micron, I do not have to confuse, I know that there is carbon dioxide present in the system or present in the volume. So, if there is carbon dioxide inside the volume, then I would see the light getting absorbed at 4.2 micrometer, if I want to know whether carbon dioxide is present.

Similarly, I can do it for ammonia, I can do it for methane. Any kind of gas that you want, you can find a fingerprint absorption here. So, this is all in long wavelength range. As you can see here, this happens primarily in mid infrared range. So, this is absorption spectroscopy.

But we can also do this in, in, in combinations. We can do both refractive index and also absorption together in one single device. So that is also a possibility where you use both these modes to firm up your data. So, you are not only looking at the absorption, you are also looking at how much concentration you have and that concentration comes from this absorption.

So how much of light is getting absorbed for a particular length that you have. So that strongly depends on a concentration of light that you have, and this is a dielectric constant that we have. So based on this let us look at these two techniques that we have.

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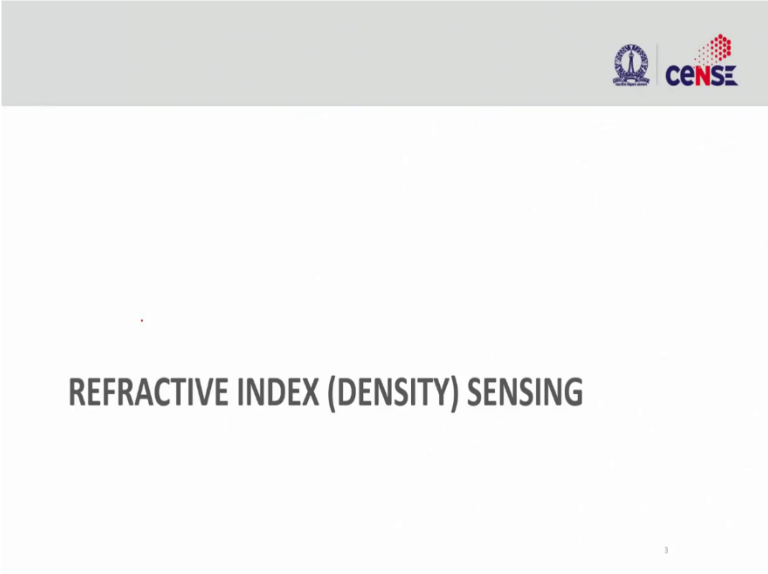

So, one is refractive index sensing. It is primarily density sensing. So, in this case, when we say density, you have, you have light propagating through the waveguide and there is an environment. And I want to sense this environment. And when you say sense the environment, what are you trying to sense? I want to sense how dense the environment is, whether it is tightly packed or loosely packed. Why would you do that?

So, the primary reason to understand the density is to understand the concentration. So, when the concentration, so we have two mixtures, let us say. So, you have a solvent and then you have some constituents there. So, when you increase the constituent, the solvent density is going to increase. So, by understanding the environment, you can say what is the concentration of this constituent present in this system.

For example, I can take any chemical, for example, I will say sulphuric acid, for example. So, what is the dilution of this sulphuric acid? So, you mix sulphuric acid with water let us say, or any kind of analyte for that matter or electrolyte for that matter. So how do you measure this concentration? So, this is by understanding the density.

When you add sulphuric acid to water, so the refractive index of water is going to change. So how much of sulphuric acid is present in this water? So that can be measured by looking at the refractive index. So, the refractive index is helping us in measuring the concentration or the density change. So how can we measure this?

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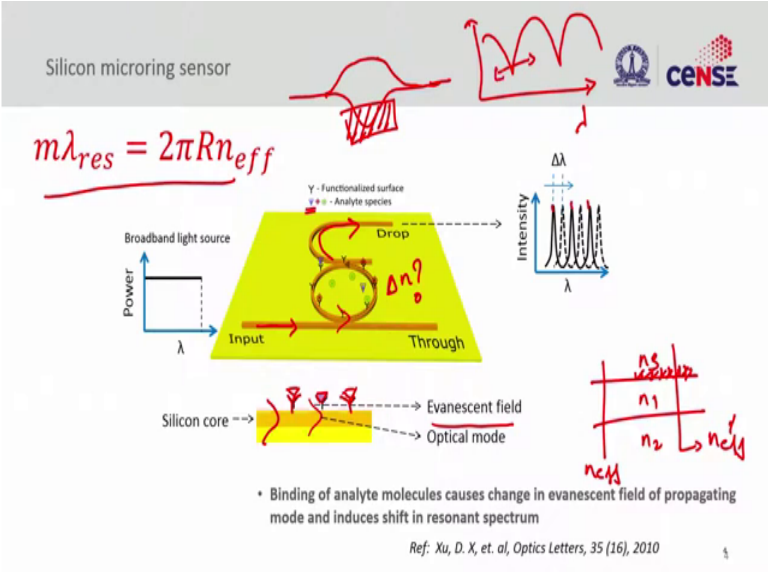

So, we are going to look at our good old ring resonator here. So, this resonator, this is something we already saw earlier, even in our communication discussion, we looked at this ring coming into play. So, this is the fundamental equation here. So, $m\lambda_{resonance} = 2\pi R n_{effective}$.

So, when the, when you put a broadband light source into the system, then the light is going to propagate through the waveguide here and then it can couple into the ring here. So, it will start circulating around this ring. And then you can get the light out with this, such a spectrum. So, you will see, these are all resonant wavelengths, what you call the drop resonances.

And what one could do is, you take this ring, so this is the surface here. The light is propagating like this. So, this is the optical mode, and this is the evanescent mode. This is something that we know. What we are going to do is we are going to add some functional groups onto the surface here. So, you see this is all functionalized surface that will attract a certain analyte species. So, you will have lot of analytes and a particular species will come and sit onto this.

When this particular species bind onto the surface, it will interact with this evanescent mode. Because of this binding, you will have refractive index change because the material density around this point is now different. So, we, we talked about n_1, n_2 and n_3. So now, there is a local n_3 variation. And now, if you look at the $n_{effective}$ around this point, it is going to be different from the $n_{effective}$ that you have outside this region.

So, wherever the molecules are sitting, your refractive index is going to be different. So, when the refractive index changes, your resonant wavelength will change. So, you can see here there is a shift in the resonance because of the analytes that we have on this surface.

By looking at this Δλ change, because we, we do not know how much change we have. So, we do not know what is Δn change or how much refractive index change we have. But what we know is this Δλ. So, we know this Δλ and we can look at our effective index here or the resonance here. From this equation we can back calculate what is the density change that would result in this Δλ shift.

So, this is how we can use this very simple resonant device. Is this the only way to do it? No. Any device that has spectral response, we can use for sensing. For example, you can use a Mach-Zehnder interferometer as well for such applications. So, you have, you have resonances, or rather the phase shift as a function of λ here.

But now when you put an analyte here, it is going to shift this peak. So, you can still use a simple Mach-Zehnder for doing sensing. So, all you need for sensing application is to have some spectral signature, some spectral response that depends on the refractive index of the environment. And when you have that relation done, then we should be able to do that.

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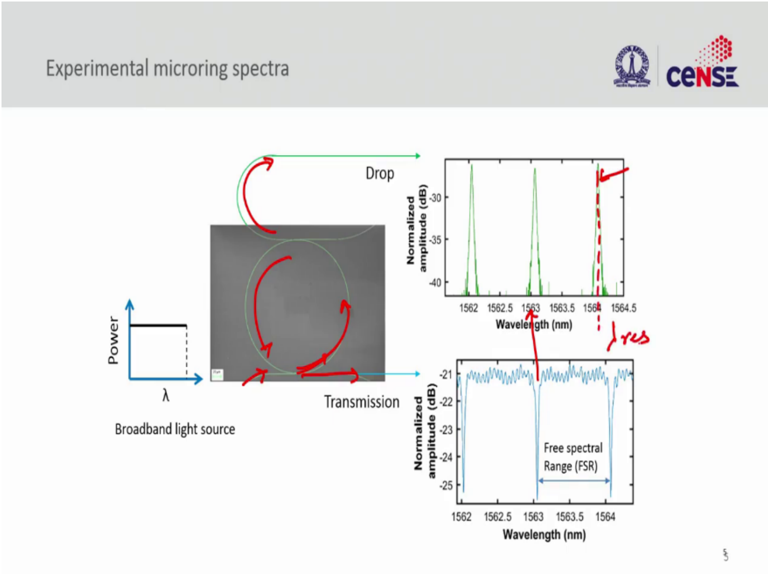

So, this is actually a, a fabricated device, what you are seeing here and their spectral response. So, we have input power, so you have a broadband input here going through the ring. And then it couples in, and it starts circulating and then a part of the light is taken out. So, what you see here is the directional coupler. So, it is something that we already saw. So based on the evanescent coupling, light will be coupled in, and some light will also leak through.

So, this is called the through port or the transmission response that corresponds to the resonance that we have here. So, we have very nice resonances coming out of the, this particular drop port. And this is exactly what we want. So, we have a clearly defined resonance here. So, this is our $\lambda_{resonance}$. Now, the question is, what happens if I expose it to a medium?

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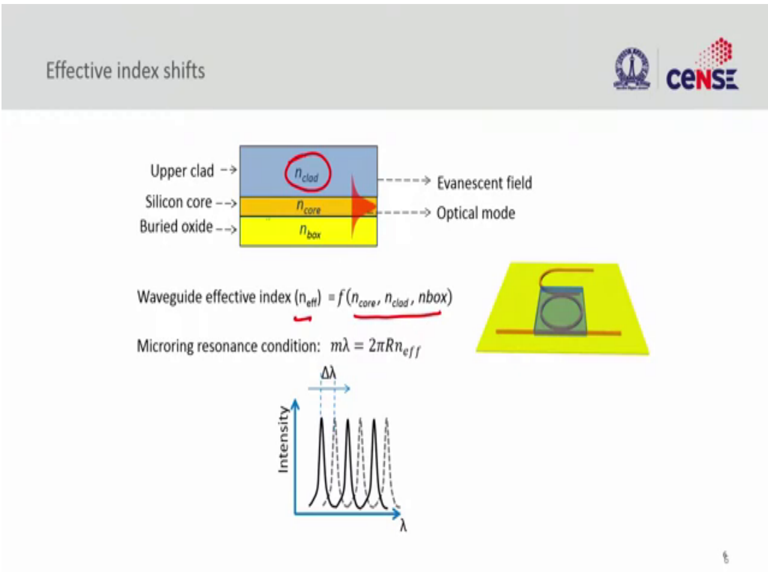

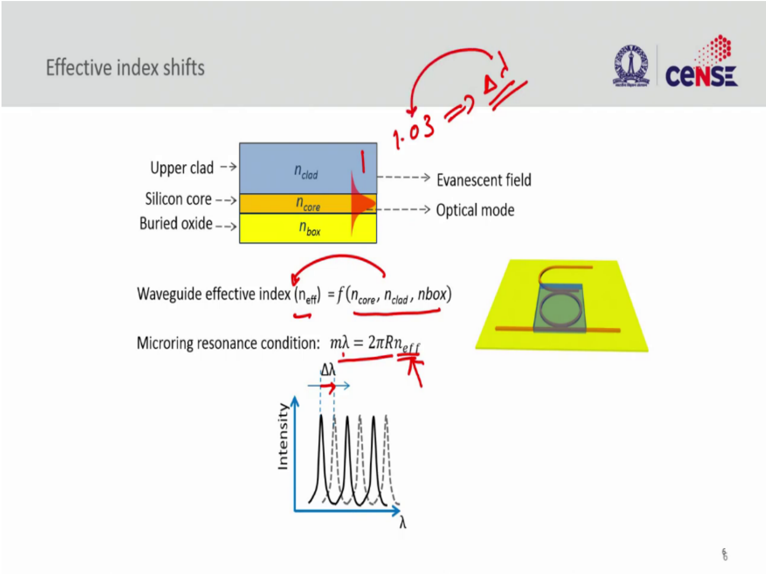

And as I mentioned, you have a cladding that is surrounding here. And that effective index depends on all the refractive index that we have, n_{box} is nothing but buried oxide layer in this case. So, when you have a thin film, this is how it is going to be. So, since you have the top cladding influencing your refractive index, change in the top cladding will affect our $n_{effective}$. So, this is what would result in this shift in the resonance. So, make sure we understand this clearly.

So, this is our resonance condition. So, we are trying to change this $n_{effective}$ and because of the change in the $n_{effective}$, your resonance wavelength will shift, and we are looking at relative shift in the wavelength and based on this relative shift, we can back calculate your change in the effective index. So, you start with some index 1, let us say and if I change 1.03, that would result in an appropriate change in Δλ. So, since we know the relation, we only need to measure this Δλ to back calculate what is the change in the index that I have.

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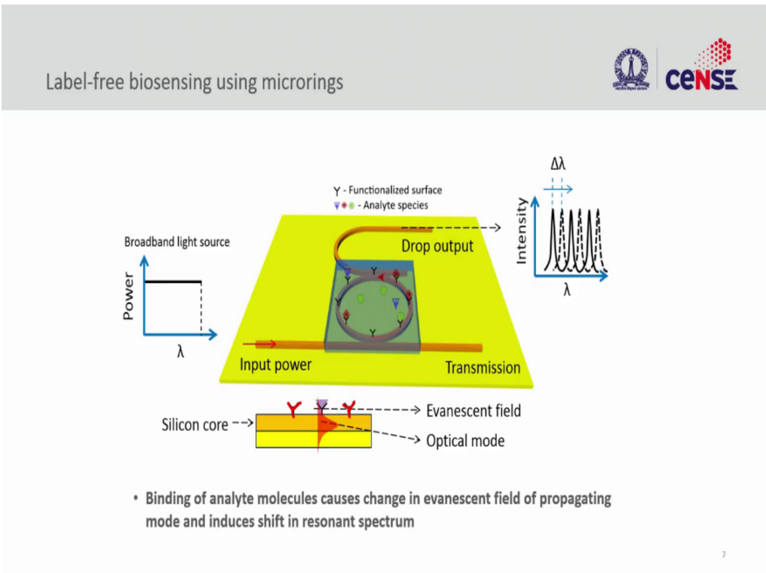

So, this particular technique that I mentioned of measuring the change in the, in the, in the response, by using this kind of receptors here, the functional, functional groups sitting here, and it will attract a particular type of analyte. And this is called label free sensing. Why it is label free?

Normally what happens in optical sensing, is if you want to sense a molecule, we are going to attach a tag to this molecule. Particularly happens in microscopy. So, you want to trace a certain cell or certain virus or bacteria, what they do is they attach a dye. So light emitting dye onto this particular biomolecule that you have. And then when you illuminate it only those attached molecules are going to illuminate. For that, you have to tag it.

So, you have to first functionalize this biomolecule with a receptor and this receptor should be very sensitive to only the biomolecule that of interest. You, you, you do not want it to stick to all the cells and other molecules that you have. You have a specific target molecule. So, this, the tag has to sit onto this, or latch onto this particular biomolecule and attract the dye, so the light emitting dye. And this is called labelling.

So, when you label this, then upon illumination, only these labels are going to illuminate. So, then you can count how many of this interesting biomolecules are present in the, the bio-fluid that you are looking at or in the mass that you are looking at. In this case, we are not doing any tagging at all. So that is why we call it as label-free. We are not attaching label.

So instead of label, what are we doing? We are doing functional groups. This is antigen, antibody type conjugate. So, you make this specific receiver molecules, coated onto the substrate. Then, when you flow all these analytes on top of it, only that specific binding will happen.

For example, if you have a certain chemical configuration, only that force or only those molecules that conjugate will attach to this binding molecule. So, the rest of the things will float around, you can wash it off. So, you can do a fluidics and then you can wash it off. And by doing this, you do not need to do any tagging, you do not need to do any labelling here. And that is the reason why we call this technique, label-free bio-sensing.

This is a very powerful and very easy technique. We do not have to think too much about whether the tagging will work and what is the success rate or the affinity or your biomolecule to a particular tag and so on. So here, it is a clear conjugate that you identify and then of course, you need to do some biochemistry, it is not just you search and get it.

One need to look at the right biochemistry between these two molecules that you are looking at and if you get it right, it works all the time. The success rate is very high. What I mean by that is the selectivity is very specific.

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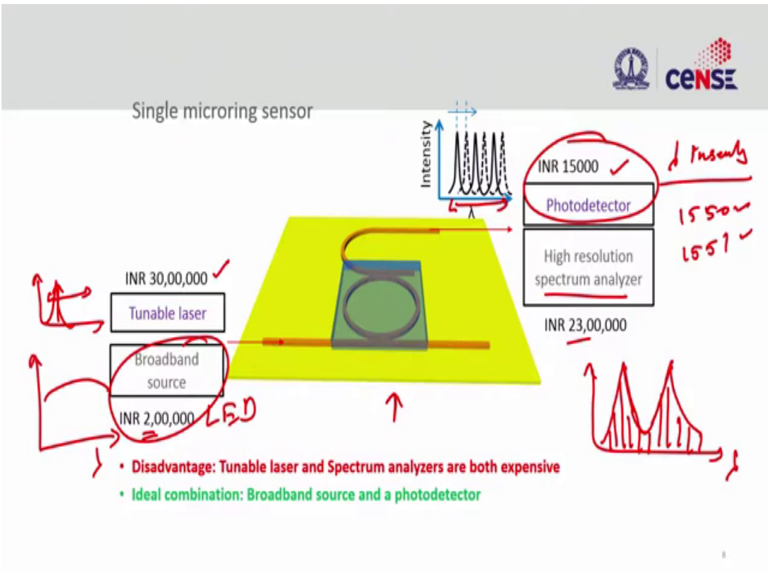

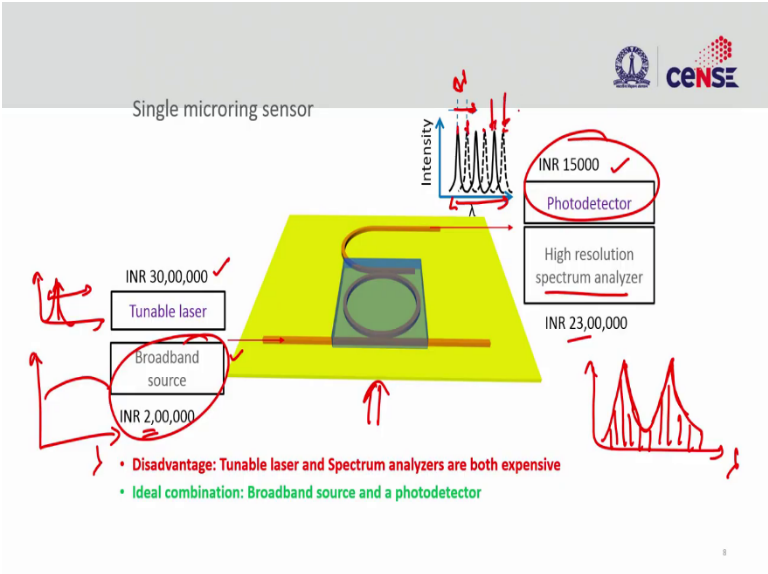

So let us look at the simple architecture here and when you have this kind of architecture, what you have is two ways of doing this kind of sensing. One is by using a tuneable laser. So, when you, when you have a tuneable laser, very expensive tuneable lasers and you can use a photodetector. So, photodetectors are reasonably cheap.

But then the lasers are very expensive because you have to traverse through this whole wavelength range. You have to sweep the wavelength in order to find out the spectral response. So, you have to have all these wavelengths available to you. So, this is tuneable laser which is very expensive.

But if you want to do any sensing kind of work, you want the sensors to operate at very minimal overhead. That means you do not want too expensive equipments to measure something very trivial. Or when you are doing point of care use, you do not want these equipments to be very expensive. In a remote place, you do not have access to this kind of equipments, let us say.

So, we can use broadband sources. This is an LED source. They are reasonably cheap. Not very expensive like light sources but you need an optical spectrum analyzer. So, in one go, you have to filter out, so you, this, this broadband light source will give all the wavelengths that you want which is a good thing. In the laser, you only have one frequency here which will be tuned.

But what we need at the output end of this broadband source is a spectrum analyzer which is again, very expensive. So, you either move your most expensive item from the input to the output. So you are, you are not actually benefiting from doing this. So ideally, what you want is a combination of broadband source and a photodetector. This will be the most efficient option.

So, this is the ideal option to make cost effective sensor characterization, or sensor measurement. The device remains the same. But it is impossible to do this. The reason for that is photodetectors are λ insensitive. So, they will measure just a photon. We do not know whether the photon is sitting at 1550 or 1551. So, it will not differentiate it. It will just measure that I have a collective this much of photons. It will just give you a total current which is not something that we are looking for.

We are looking for spectral shift, spectral characteristics. So, is there a way to solve this problem? Because for sensing, we primarily look at a very easy way, inexpensive way of doing these measurements. Is, is, is this combination going to work? A simple answer to this is, just with this particular configuration, it will not.

We cannot do photodetector measurement with broadband source with this kind of spectrum. The reason for this is, the spectral shift that we have, you can only notice it when you have a spectrum analyzer. But when you give it to the detector, the total current, the total power remains constant. It will not change. Whether the wavelength, whether the resonance is here or here.

So, it does not really matter. So, this puts a constraint here. You cannot put this two reasonably inexpensive source and detectors just with a single range. We have to think little bit more to come up with a strategy that could avoid this problem of spectral measurement.

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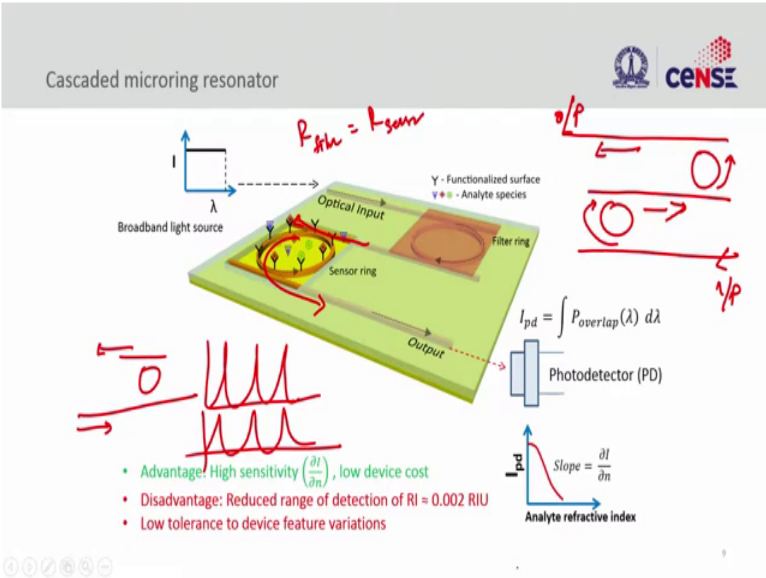

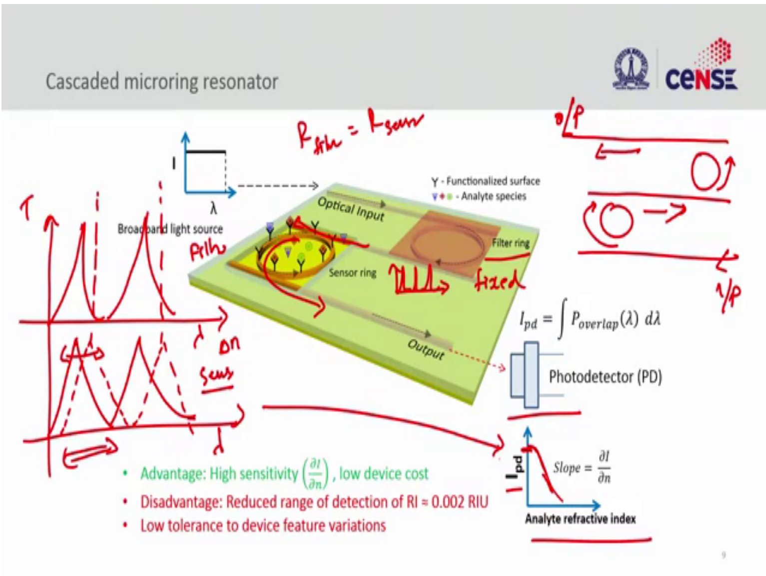

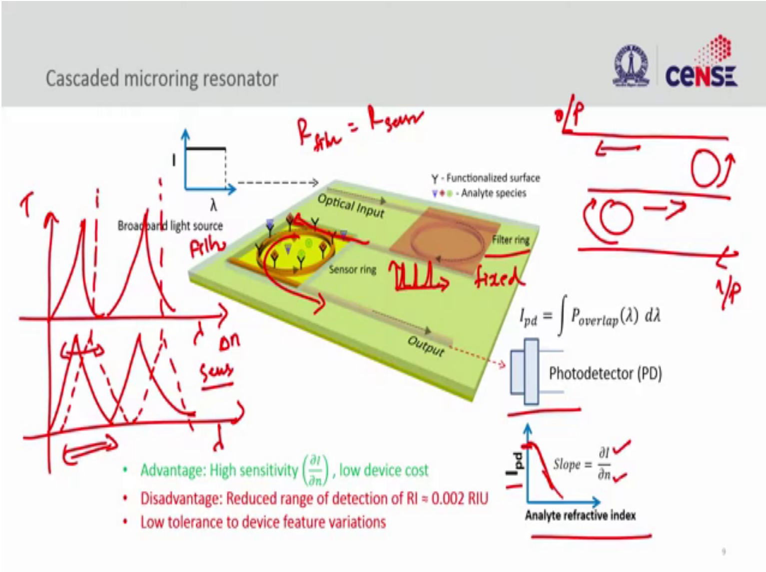

So, this is the architecture one can think about. Instead of a single ring, let us make a two-ring configuration. So, in this two-ring configuration, the light is coupled. So, what you have is, is a very simple configuration of light being coupled here. A configuration like this. So, this is input, the light is coupled into the system, goes through this, goes through this and then it is coupled into this and then it comes out. So, this is my output.

So that is what we have here. So, we have a sensor ring, and we have a filter ring. First it goes through the filter ring. And then whatever is filtered comes out to this sensor ring. So, what will be the output of a filter ring? Just look at it. You have the input, and you have the single ring. And it comes out. So basically, what you ate looking at is a, this is your input, and this is our output.

So how will it look like? It is going to look like this. This is what we saw earlier. So, this is what you will get from the first ring. And it will go to the second ring. So, the second ring will also have the same response. The second ring also, you have the input and then light is going to come back.

So, the spectral characteristics of the second ring will be also like this. Here we want this filter ring and your, the sensor ring to be identical. So, you want identical sensor ring and your filter ring. So, for example, you will have same radius, R_1, let us say R, R filter equals to R sensor. You want to have this. So that they are overlapping resonances.

So now what you are trying to do is instead of having a broadband source given as input to the sensor, you are already providing a, a filtered comb like input to our sensor ring. So now, when it goes through it, you can put it through a photodetector now. So, the photodetector, current will change as a function of refractive index here.

So how is the photodetector current changes as a function of refractive index? So let us look at that a little bit more carefully here. So, we have a filter ring. And then we have sensor ring. So, both are having same resonances. So, they should have same resonance like this.

So now, imagine that the sensor ring is put with some analyte here. So that means you will have some Δn change. The resonance is going to now change. But your filter ring is fixed. We are not doing anything to this. This is fixed. So that means your response, this is transmission, let us say, this is λ, your transmission is not going to change for the filter ring.

However, for the sensor ring, the response is going to change. So now, they do not align anymore. So now, if they do not align anymore, look at the output current that it will produce.

So, when they are on top of each other, all the light from the filter or the fixed ring will go through the sensor, and you will have maximum light.

So, when the sensor ring starts moving, the overlap is reduced and when the overlap is reduced, the current that you measure also goes down. So, this is how you can convert spectral information into just a very simple current measurement. So, you can visualize this by using two combs.

So first, we have comb 1, so that has the filter response. And there is one more comb. So, if you take these two combs, since I have a blue background, it will be much easier. So now, let us say we have such a, such a comb here. So, all the light is now passing through. So, we do not have any problem in visualizing it. So, there is lot of light going through. So, when they are aligned.

So now imagine that one of the filter is fixed, the other filter is moving now. Now, can you see any light through this? The light is now reduced through the, through my fingers. The blue screen behind me, you cannot see it through the fingers here. So, it is completely blocked. That is because one of the ring has moved. So now, this movement of one against the other changes the light that can pass through. And this is exactly we are doing.

So, we are taking one ring that has fixed response. The other ring, which is the sensor ring, we are moving it on top. So, this movement, we can clearly calculate how much power change that you will have for a certain Δλ change. So, the optical power is now related to Δλ. This is our goal. If you remember, we want to have a broadband source and we just want to have one photodetector.

So, photodetector will only measure power. Since, you have single ring moving up and down, the total power remains the same. But now, I have put two rings. So, they are going to change the amount of power that is going through, and I just need a photodetector in order to measure this power.

So now, we have a very good solution of having a very simple broadband light source, it is an LED source. And then, put a, a photodetector. And in the photodetector, we are going to just measure the current. And this current change is a function of the analyte or the refractive index change on it. So, this is, this is a very neat way of doing very efficient sensing.

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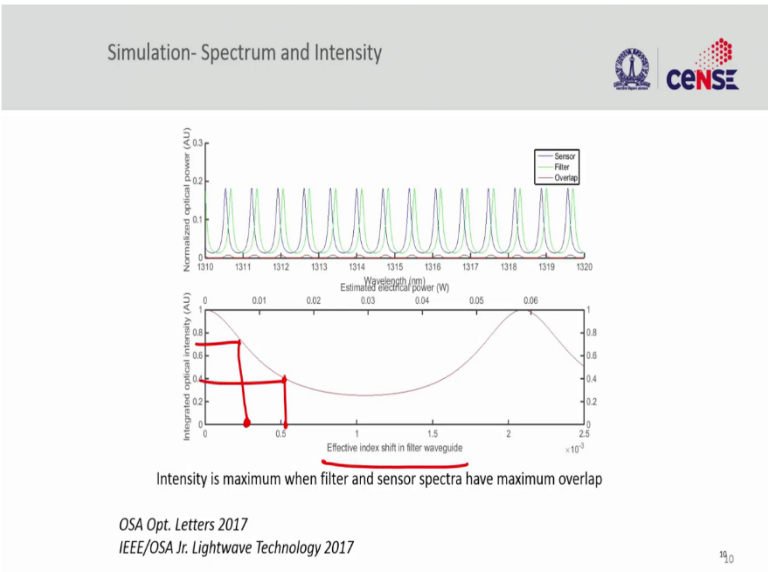

So, we will try to see if this one runs. So, this is a simulation of, of such an architecture. I will show you how the actual measurement would look like in the next slide. But this is just for you to understand how the, how it should work. Whatever I explained, this is simulated here. So, you have the sensor ring. And you have the filter ring. And what you see in red here, this is the overlap, so overlap between this.

So right now, you can, you can see here and the bottom one shows the, what is the total light intensity change as a function of effective refractive index. What is the refractive index change? So, so you can see here, the sensor or the filter in this case is moving, one or the other, it can be anything.

So, when it is moving, you can see that the power is going down from high and then once it reaches closer, the power is becoming higher. So that is what is happening here. And here, again, it is traced. So, whatever, the red curve that we had, so you can see here, it is going up and down as a function of refractive index change.

So, by using this particular technique, you can measure the refractive index by just measuring the power. For a certain power, this much is a refractive index change. For this much power change, what I have. So, this, this particular technique gives us a very interesting way of measuring just the power in order to measure the index change.

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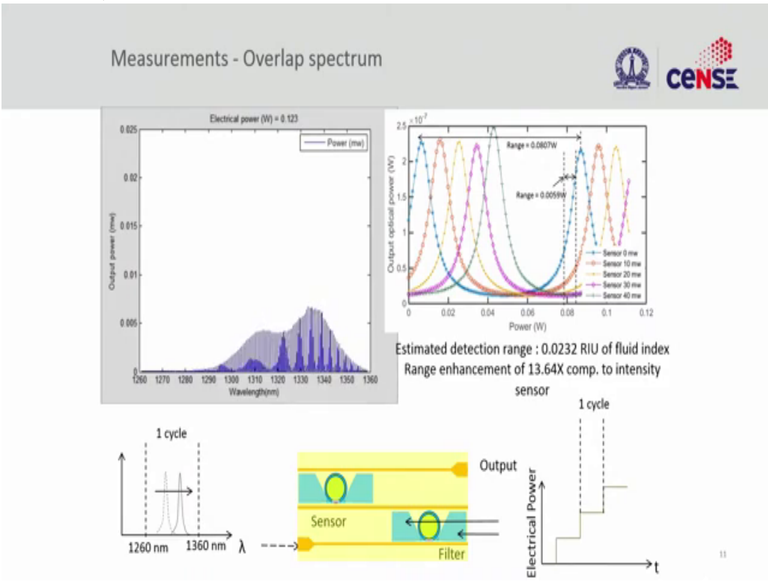

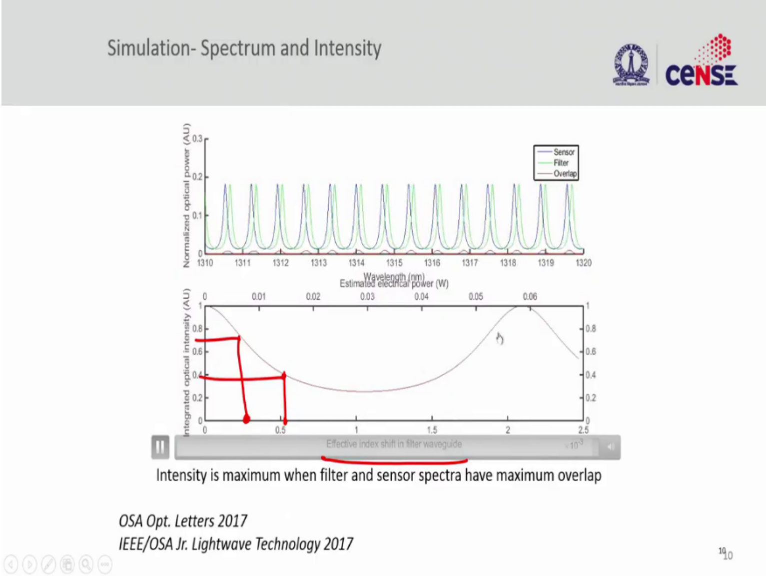

Let us look at the actual measurement. This is real experimental measurement, that you can see where you have the filter ring, and you have the sensor ring. So, one is energized, and one is moved against the other. So, you can see here, the spectrum is getting bigger and then smaller.

So, this is all happening because of the overlap between this. So now, it will again come up, when you have a good overlap between the sensor ring and the filter ring and then it will go down. So, I will play it again. You can see here good overlap, best overlap and then you are out.

And then again it will come back because this is a, a periodic function. So again, you can see here, a good overlap and then going down. And this is again coming from this particular plot here, so it is going down and then it is coming up again. So, it is high, low and high. So, this, this is what we actually measure here.

So, it is now coming closer, they are identical and now it is dying. So, this technique gives us a clear way of measuring density changes not by looking at the spectrum. So traditionally, we only looked at the spectrum. But now, instead of looking at the spectrum using a very expensive spectrum analyzer, we can just use a photodiode.

And all we need to do is measure the photo current. So, by measuring the photo current, whether it is high or low and you trace that slope and based on the power, you know that how much density change has happened. So, with that, we, we have an understanding of how density change could be measured.

But in the following lecture, let us look at how we can measure both, absorption and density change together. So that is again an evolution of whatever we are discussing now to see how we can improvise this to make it a little bit more interesting. Thank you very much for listening.