Photon Integrated Circuit

Professor Shankar Kumar Selvaraja
Centre for Nano Science and Engineering (CeNSE)
Indian Institute of Science, Bengaluru

Lecture 49

PIC for communication

Hello everyone. Let us now look at some really interesting applications. So, we would like to explore how we can exploit photonic integrated circuits for various applications. So, there are wide range of applications, but we have to confine to few, to appreciate the widespread or the versatility of the photonic integrated circuits.

Today, we are looking at silicon as a platform, but this can be extended to other platforms as well. So, one can use III-V semiconductors to realize what we are discussing today, or you could also use polymer for this or other dielectric platforms like titania or silicon nitride or aluminium oxide. So, all these possibilities are there.

But the fundamental ideas are the same. But you can choose the platform that you want, either you are doing any non-linear application or doing sensing or doing communication or just doing any passive operation for that matter.

So, it is important to keep in mind that choosing the material platform is important when it comes to the application specific requirements. So, you want to choose the material based on the wavelength you are working on and whether you are going to do any active function on this light that is propagating through the waveguide.

So, if you are not doing any active functionality, you can go with very passive dielectric platforms. And you do not need anything special there. So, on the other hand, if you are going to do some active functionalities, like, I want to control the phase of light, with very high speed, let us say. So, then you have to think about what kind of platform will allow me to do that.

Furthermore, once you have this functionality, the other question to ask is what is the wavelength I am going to use? For example, if you are going to use visible or lower wavelengths, the platform is going to be very different. And if you are going to use mid IR, long wavelengths, beyond 1, 2 microns, the platform is going to be different. And in telecom region or near IR, your platform can be very different.

So, it is based on your wavelength of interest. And also, functionality that you are going to realize, you need to choose the right platform. It is not what is available to you, in some cases, you just work with what you have but rationalize whether this is the right platform. If the other platforms are not available, then fair enough. But then, there should be a good rationale in choosing a platform for a certain process.

But platforms like silicon or III-V semiconductors offers wide range of functionalities from passive to active functionalities. But then, silicon being an indirect band gap material, you cannot realize light emitters in that.

In III-V semiconductors, you can realize everything, all kind of functionalities. You can have light emitters, light detectors, light modulators, filters, all this, you can have. However, the waveguides are going to be very lossy. Your waveguide losses are going to be high because it is a direct band gap material. Whatever light you generate, you will be absorbing it as well.

So, that means you need to put amplifiers in the circuit in order to compensate for the loss that you have. And the other problem that you might have in III-V platform is a size of the circuit itself.

The size becomes larger because of your index contrast. In III-V semiconductors, primarily, you grow, epitaxially one on top of each other. So that means these materials are lattice matched, that means your refractive index difference is also very small.

However, in silicon-on-insulator platform, refractive index contrast is very large. It is the Δn is 2. So, this will allow you to make the circuits rather compact. But the problem associated with this is the absence of light source and also, the modulation techniques that we are trying to exploit, may not be as fast as you get out of non-linear processes like Pockels effect.

So, Pockels effect is absent in silicon because of the centro-symmetry that we saw in our active discussion. So, you need to have [non]centro-symmetric crystal. But still, we can realize light modulation in silicon. So, we will see those in this lecture series.

So, to sum it up, choosing the right application, right wavelength, right material platform is essential to build a successful photonic circuit. So, with that preamble, let us go into, again, a demonstrator here. So, we are trying to see how we could take different components that we have and then realize the functionalities that we can use particularly for communication applications. So here, our focus is on communication. How we can use photonic circuits to communicate data? So let us look at that.

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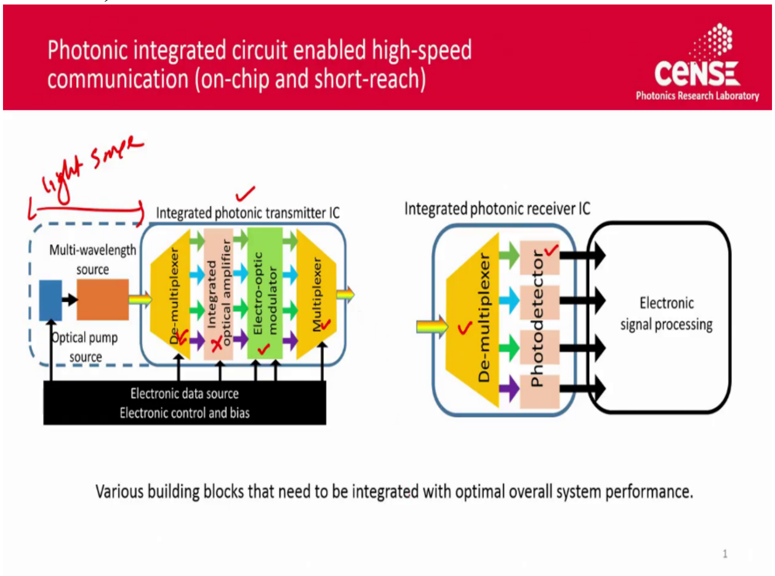

So, this is a very simple block diagram of photonic integrated circuit enabled high speed communication. So, what we mean by that is there is a photonic IC transmitter that has these various components.

So, we have wavelength source, so this is our light source. So, this may or may not be on chip. But then, we have de-multiplexer. So, we may or may not need amplifier because if you are using silicon-based circuit, so this is not present.

The electro-optic modulator, how do we modulate light? And then how do you combine all this? So, this is something that we saw earlier. And then, de-multiplex it and put it all through the detector.

So, we are going to look at this individual components, multiplexer, de-multiplexer and then electro-optic modulator that you could realize in a photonic IC. And we are also going to look at some of the interesting functionalities that you can do with these waveguides.

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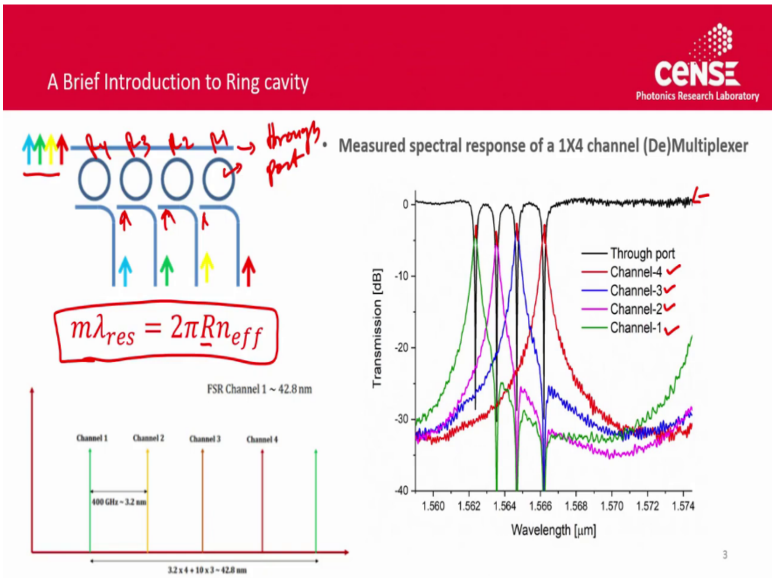

Let us first look at wavelength filtering. So multiplexing and de-multiplexing. So here, de-multiplexing is basically, you have multiple wavelengths coming in and you want to take individual wavelengths out by using this very simple ring resonators. You can also do the other way around. You could actually add, you can add our wavelengths here and then it can be combined into a single channel.

So, you can do both, multiplexing and de-multiplexing using this particular device configuration. So, this is how a simple ring resonator could be used. And how do you choose the wavelength? So how do you use the right wavelengths to pick up? And this is the formula that we use. So, this is something that we have seen earlier. This is just a recap of that.

So, $2\pi R n_{effective}$. And R is the radius of the ring and $n_{effective}$ is the effective refractive index of the waveguide that you have here. By using this, you can calculate the resonance wavelength. And based on this design, you can have different radiuses. R1, R2, R3 and R4. So different radius will give you different resonances.

And you can see here, four different channels that are designed to resonate at four different wavelengths here. So nicely they are capturing the channels that we have here. So, this is the through-port. So through-port is this. And what you see is all the drop-port responses from different channels here. So, by using this, you can realize a filter. multiplexer, de-multiplexer, you can do by simply using this ring configuration.

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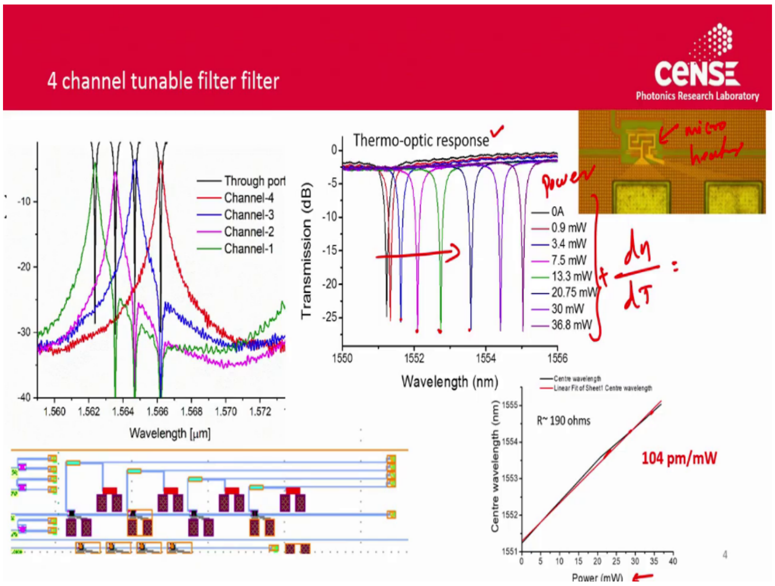

So, is it possible to tune this response? The answer to this is of course, yes. The way to do that is by using thermo-optic effect. So, silicon has a positive thermo-optic coefficient. So, this factor is positive.

That means when you heat it up, so this is the power, heater power that you apply. When you apply a heater power, and this is the, the heater here, micro heater. You can change the resonant wavelength here.

So, what you see here at the bottom is nothing but a change in the electric power gives you change in the central wavelength. Very linearly, you can move. So, this gives you a tuning option. So, you can choose whichever channel you want to take up or you can also correct for any fabrication imperfections that you may have when you are using these wavelength filters.

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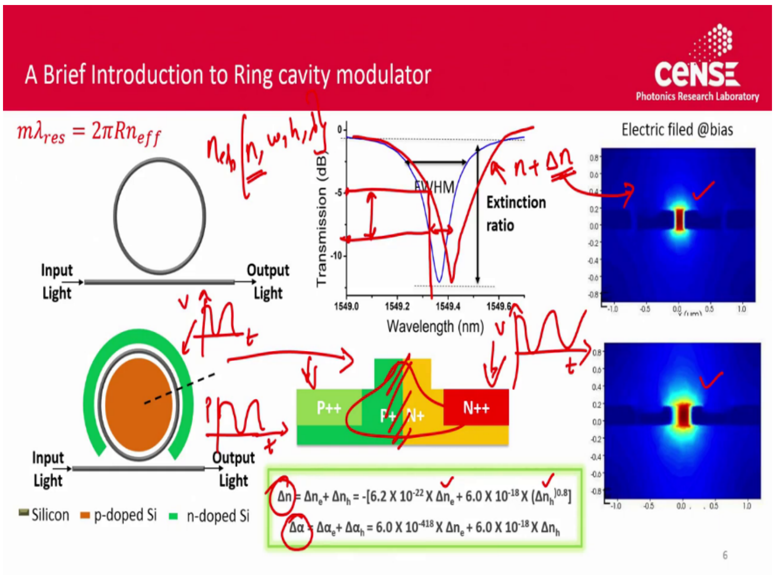

So, the same wavelength filters could also be used to realize a modulator. Let us look at how we can do that. So, I have a ring here and it will have a certain response. So, this is our spectral response of a throughput. So, this is our resonant wavelength. So now, instead of having a passive resonance, I am going to make a diode in this waveguide.

So, the cross-section of this particular structure here is a simple p-n junction diode. So now, the light is sitting here. So, the light is sitting here in the depletion region. So, by applying voltage across this junction, I can change the depletion width.

By changing the depletion width, I can change the carrier concentration. So, what you see here is change in the carrier concentration that I can do, that would result in a refractive index change. So, what you see here is a refractive index change.

So, I can change the electron and the whole concentration here in this particular region by applying a bias. I can apply an electric field, that would result in change in the refractive index. And this change in the refractive index will affect our resonance condition. Your $n_{effective}$ depends on the refractive index of silicon, the width, the height and the wavelength.

So now, I am going to change the refractive index of silicon by putting in more charges. So, this putting in more charges is going to result in change in the refractive index. So, at the same time, I am also going to have absorption as well. So, it comes with its side effects. So, you can change the refractive index and because of these charges, you are also going to increase your absorption. So let us look at how this is going to affect our resonance.

So, when you have resonance here, for $n_{effective}$, but then when I add more charges, this is going to move to the next location. So, there will be a change in the resonance frequency when you have $n + \Delta n$.

And when I have my laser, my laser light is pointing here. So, I see a difference in the transmission now because of this refractive index change. Initially, I had higher insertion loss. But now, I have low insertion loss. So, by changing the refractive index, I can move my transmission itself. And this change in the refractive index is coming from the charge change.

So, this is coming from bias that I apply. So, this is coming exactly from the bias that I apply here. So, I can move this back and forth, faster now. So, I can push and pull the charge carriers, like a sinusoidal signal there. So, I can move my voltage up and down. So, I can move my voltage as a function of time and if I do that then this particular position is going to move up and down. That would result in light modulation.

So, instead of a continuous wave, I will have the optical power which will follow the electrical voltage that I apply. So this is how we create optical modulation using a ring resonator.

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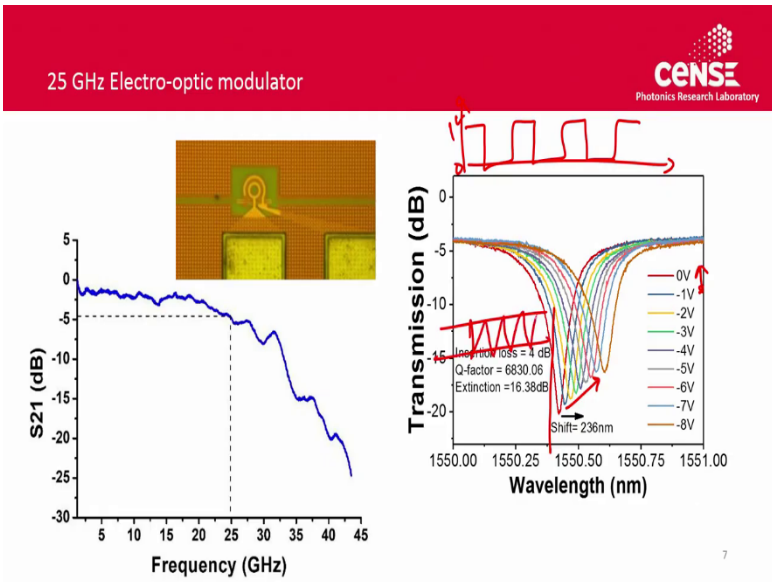

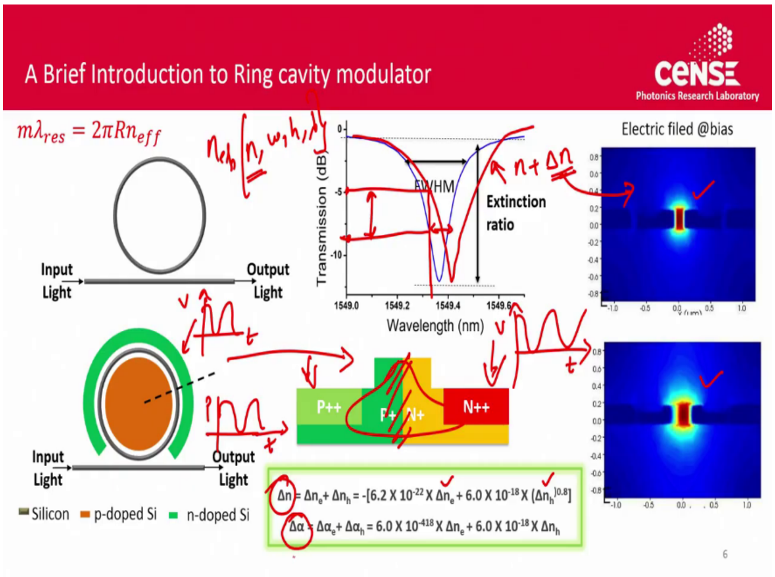

So, let us look at the example, here. So, what you see on your right side is what we just discussed. So, when you change the bias voltage, you are going to move your resonance. So that is obvious. But we also said that you are also going to increase your absorption, the alpha is also going to increase.

And that alpha increase would result in reduction in the extension. See, you are going this way, but you are also going this way. So, you are getting broadened and so on but there is an effect of extension here and the slight on the quality factor as well.

But nonetheless, what we are interested in is shift in the wavelength. So, we can do it really fast, back and forth, going from 0 volt to 1 volt, up and down. So, we can make this sort of changes. You are going from 0 to 1. 1 volt and 0 volt. So, when you are going back and forth, the transmission is going to also swing between these two.

And that is what we measure as the electro-optic bandwidth here. So, what you see here is the electro optic response of this particular modulator that you see here. This is 25 gigahertz electro-optic modulator, where you see a very nice response, 3 dB of about 25 gigahertz. So, what can we do with this?

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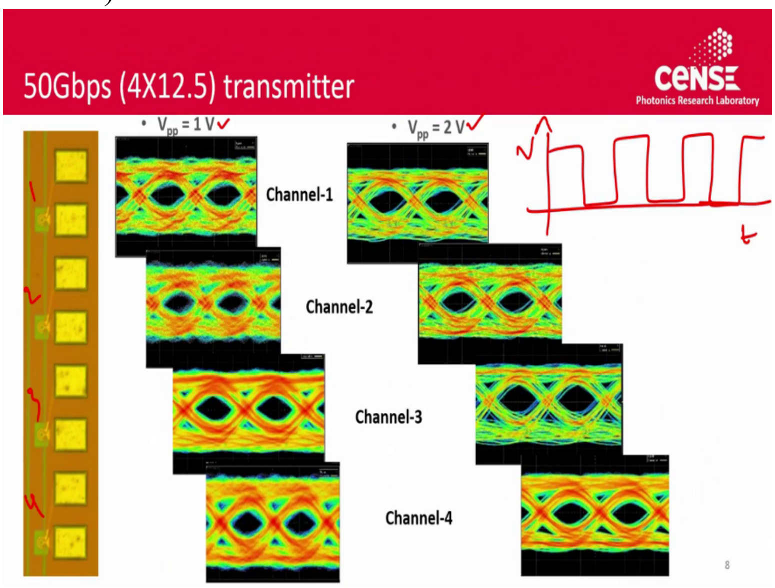

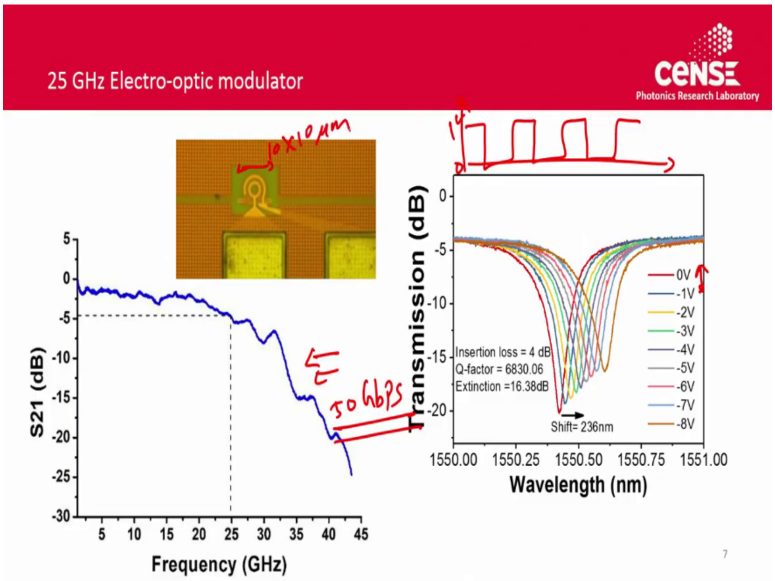

So, we can do data transmission with this. So, this is what one can do with this. It can be done in parallel. That is the power of integration here. So, you have 1, 2, 3, 4, there are four transmitters or four modulators that are sitting here from different channels and you can see, you can swing off 1 volt peak to peak and you could have peak of 2 volts as well.

When you increase the voltage, you get better 'eye'. So, the eye diagram tells you the quality of the signals that you have. The quality of signal extension that you have as a function of voltage here. So, the higher the swing, the better the eye diagram is.

So, overall, in this case, four channels, each channel is pushing out 12 and a half gigabits per second. Now, these four channels can push 50 gigabits per second. So, when you have a 25 gigahertz elector-optic bandwidth, in principle, you can push this to 50 gigabits per second when you do on-off key.

In this case, we are only doing 12 and a half because this is good enough to show that these transmitters can be used for high data rate transmission. This is single device. Look at this device. This device is only about 10 by 10 micrometers. So, such a small device, you are getting very high data throughput. So, the data density could be very high when it comes to this sort of ring-based modulators.

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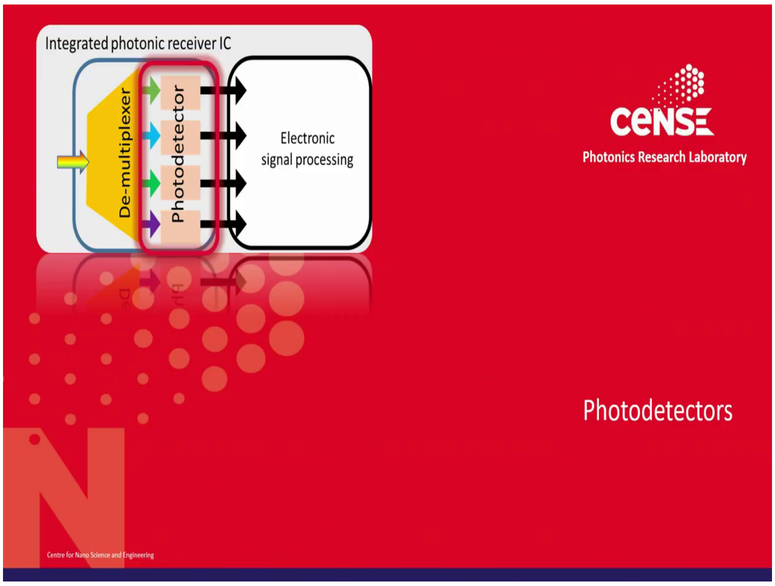

So, we have modulators done, so we have de-multiplexers also available to us, that we just saw. How about the detectors? Can we realize detectors in silicon? In fact, we can realize detectors in silicon but then the only issue is, they will not work at 1550. The silicon detectors are really sensitive till about 900 or 1100 nanometers. Less than 1 micron, I would say.

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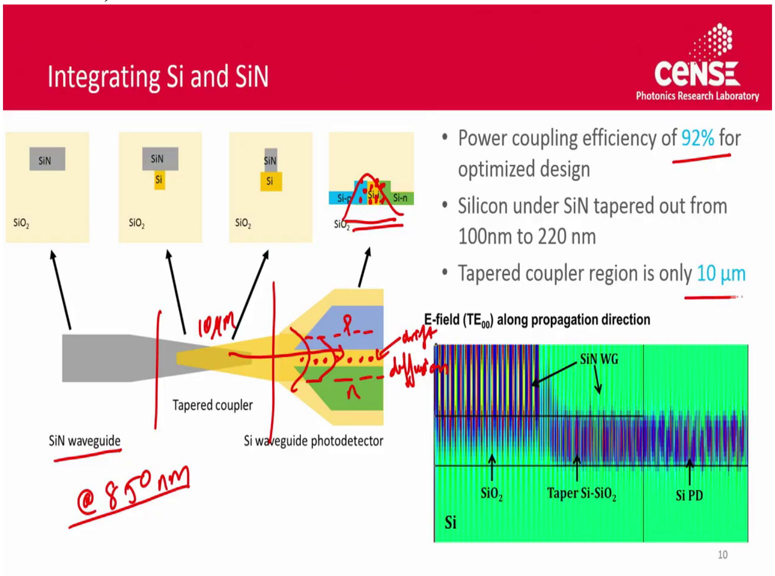

So, that is done by using again, a very simple diode structure. This time by using silicon nitride waveguide. So here, the wavelength of interest is 850 nanometers because silicon is absorbing at 850. So, you want to have silicon nitride waveguide which is transparent at 850 and then use some intelligent way of tapering.

So, this is a directional coupler again. So, this part is a directional coupler, that we use in order to couple light from silicon nitride to silicon waveguide here. So, this silicon nitride is sitting on top, and silicon is sitting at the bottom. So, what you see here is the light that is propagating in silicon nitride is now coupled into silicon.

And this is again our simple couple mode theory understanding here. So, what is the length required for this to couple onto the other and here this is 10 micrometers. So, you can use our phase matching condition between these two waveguide systems.

So, if you remember, in our couple mode theory, we talked about coupling between the super modes. So, these two waveguides could be very different. They will have two different normal modes. And if you want to couple them, it is indeed possible as long as you get the phase matching right.

So, that is an important aspect of directional coupler here. This is again a similar kind of strategy where you couple the light from silicon nitride into your silicon structure. So, when the light goes through this, you have the p and n type doping here and the light is going to generate carriers here.

So now, we are talking about our p-n junction. In this particular case, p-i-n junction here that we studied earlier, that this p-i-n junction, the light is going to be absorbed in this intrinsic region and also, in the p and n type region.

But this p and n type region where it is getting absorbed are within the diffusion region. So, we have diffusion region, and we have the drift where we have the large depletion region. So, with, since it is within the diffusion region where we generate the carriers because the optical mode is like this. So, the optical mode is only sitting here.

By doing this, we can efficiently collect all the carriers. So, simulation wise, the coupling efficiency is about 92% between silicon nitride and silicon here, and the coupling taper length is only 10 micron.

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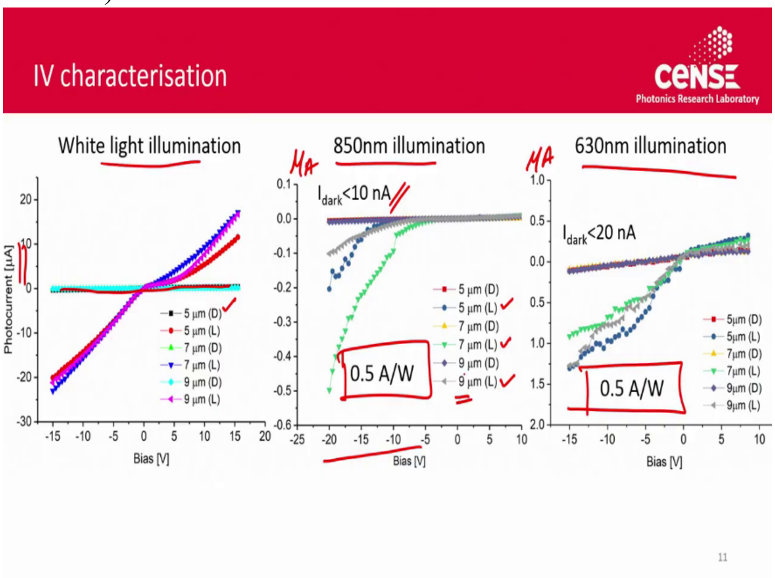

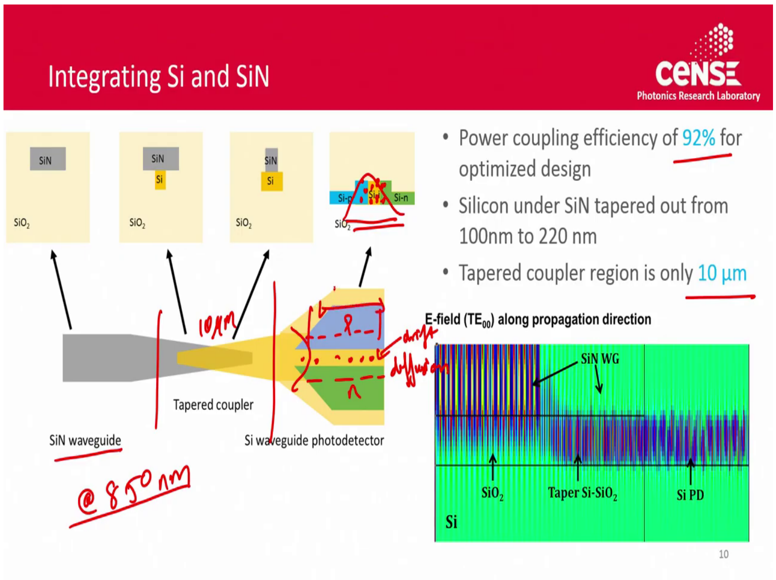

So, what you see here is a device that is characterized for 850 nanometer illumination and 630 nanometer illumination. So, when you have of course, white light illumination, you will see a typical diode response here.

So, you can see the dark current is almost 0. This is very, very small. So, the dark current is less than 10 nano amps in both these cases and in this, in the another device it is 20 nano amps. It is very, very small.

While our photo current that you measure is in micro amps. So, the photo current that you have is all in micro amps, that you see. So, in the, this is, this happens only in reverse condition. So that is what you see here as you increase the voltage. Your reverse current increases. So, this is what we call transit time limited. When you increase the voltage, your collection efficiency increases.

So again, from your basic understanding of transit time and the diffusion time, so when you increase the bias, your field is going to pull all the carriers and that would increase your collection efficiency and your responsivity as well.

So, you can have different length scales. So here, the length meaning this particular length of the detector. So, what is the length of that detector? So, when you increase the length, you will also get much better coupling and much better light collection.

So, that is about our coupling or rather I-V characteristics based on static illumination. An important thing to notice is your responsivity. 0.5 amp per watt. So, this is a very good responsivity that you get out of a very simple, very small, very, very small, you have 9 micron and 10 micron type devices with very low dark current and so on.

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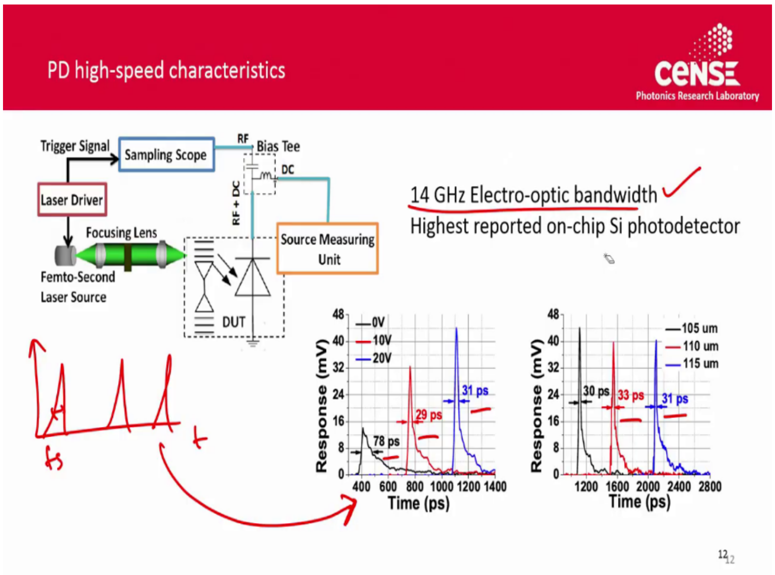

So, now the idea is whether this particular diode will be high speed. That is again, another requirement. So, we want these detectors to work at high speed. So, what is the requirement for us to have high speed? We want to make sure that the diffusion lifetime is 0. There is no diffusion current at all.

So, that is the reason why I was emphasizing that your optical mode is within that diffusion length region, that there is very less current that is contributed from this diffusion. You want to make sure most of this is coming from your drift only.

So, when you have this diffusion limited system, your speed is going to be low. But since the design is in such a way that you are primarily dictated by your drift, now, we can have photo detectors that are high speed. This particular photo detector, you can see here, the decay time here, the line widths are in pico second. So, the responsivity is reasonably good with pico second time resolution here.

So, based on this one could calculate our lifetime here, speed here, electro-optic speed here, is about 14 gigahertz. And this is done by illuminating a femto second laser pulses. So, you illuminate femto second laser pulses as a function of time. So, you have femto second pulses and you measure the, you measure what is the time response of the detectors here.

So, by using this simple load attached to your photo detector. By doing this, the same detector that we developed was high speed as well. So, this is a very interesting demonstration of using a very simple compact silicon diode for doing light detection at 850.

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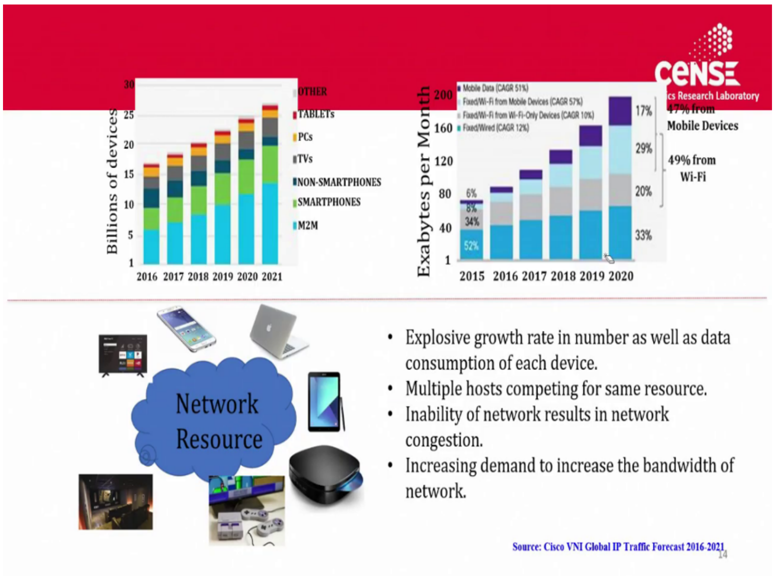

So, that is all for the communication purpose but how about doing some RF signal processing. So, you want to do communication, but you want to do some signal processing.

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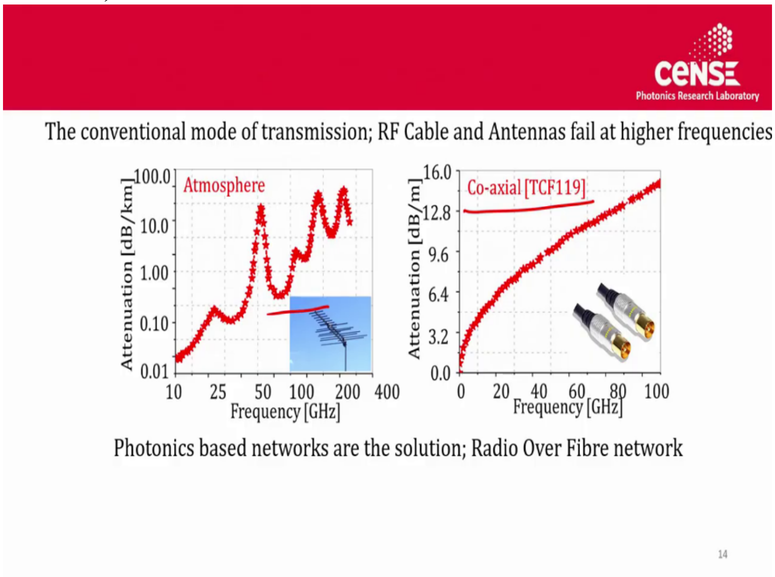

So, one of the important things here is looking at the difference between the low frequency and high frequency, overhead or the limitation that we have. So, currently everything works with RF cables. When you go for high frequency, particularly next generation 5G technology and other higher technologies that are going to come, you are looking at high frequency. Looking at more than 20 gigahertz, even in millimeter range. So, in those ranges, your cable losses are huge which is not sustainable. At the same time, your transmission through atmosphere is also very poor. So, we need to find an alternative.

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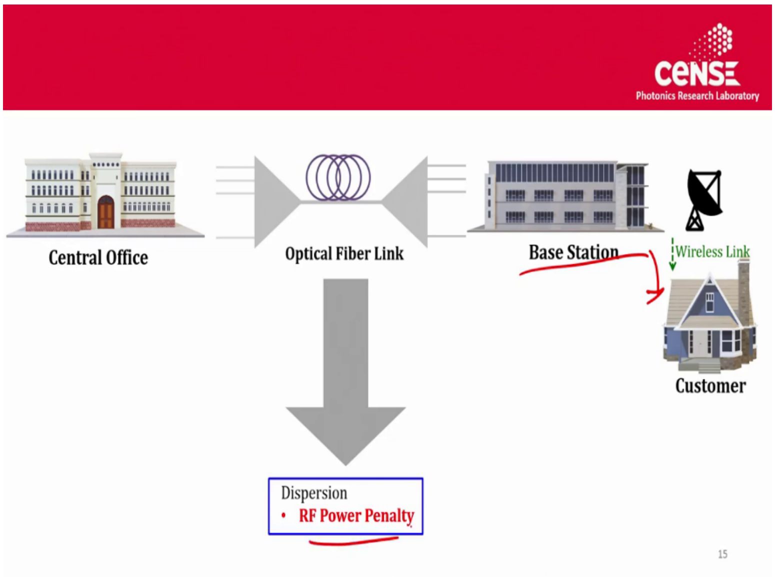

So, photonic based network solutions or what we call radio over fiber networks are the solutions to this kind of problem that we have. The way that we solve this is by sending this high frequency or high frequency RF signals through the optical link and from the base station, we can put it through your wireless locally. So, we avoid all the losses that you have. But the problem here is what we call RF power penalty.

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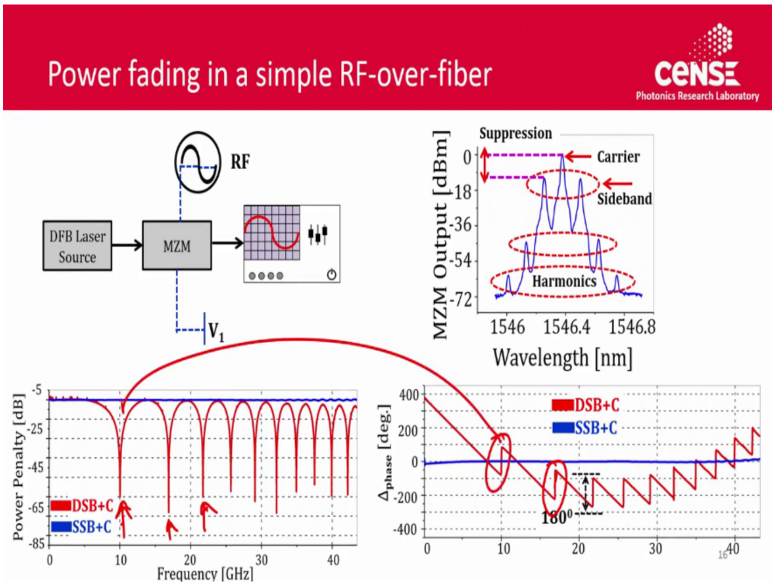

So, when you are sending an RF signal through an optical fiber, you will have what is called power fading. At particular frequencies you will have very high insertion loss. And this insertion loss is coming from our modulated harmonic side bands. And there is a phase shift associated with this transmission as well. So, wherever you have 180^0 phase shift, you see that the loss is very high. So how do we solve this problem?

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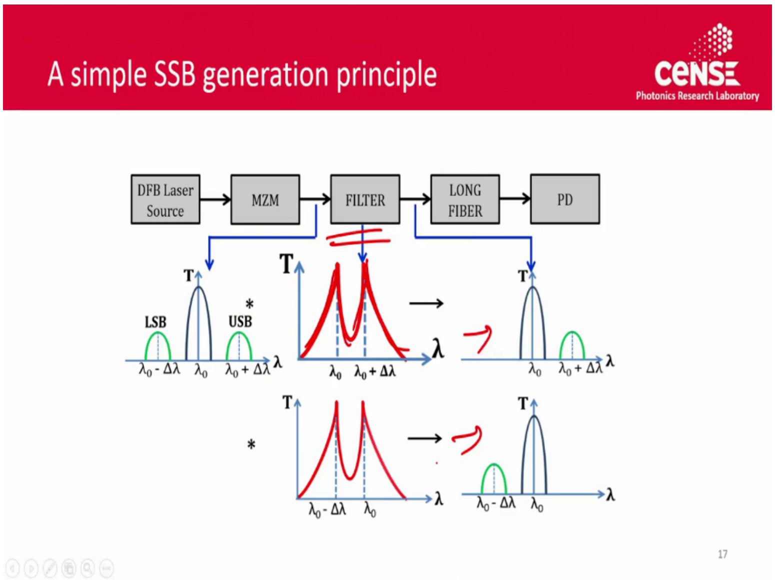

This problem could be solved by using a single side band transmitters. So instead of sending a signal with two side bands, you can do single side band but retrieve the data. So, all the data is still there but you do not need the other side band. So, the other side band is the one that is causing all the dispersion. So, we are trying to reduce that dispersion.

And in order to do that, you need a filter of such a transfer function. And when you have this kind of transfer function, we can align it on top of this and remove this. Or we can align on this and then remove this. So, these are all the two ways that you can get this. How do we achieve this sort of transfer function?

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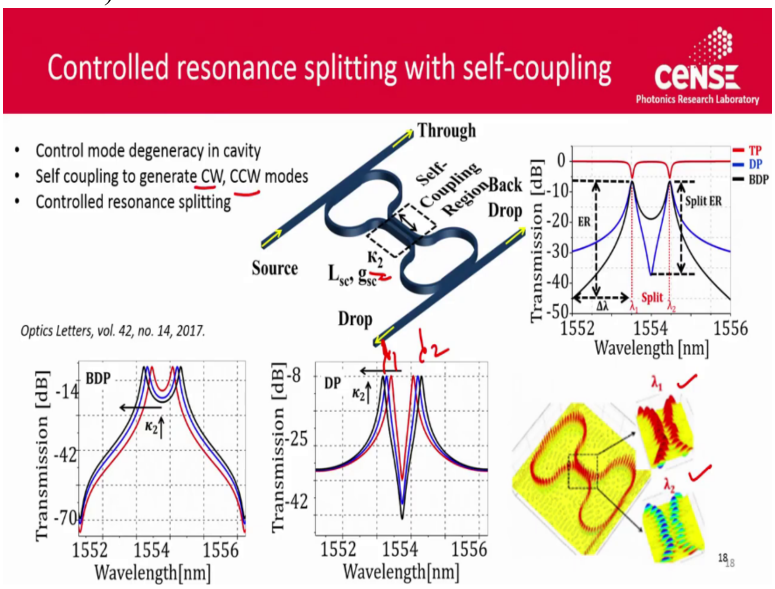

You need to be little bit creative here. We talked about ring resonators. So, this is again a form of resonator, but it is a self-coupled ring resonator. So where, based on the coupling, your transmission response is now split. You see, there is a split based on the coupling that you have.

So, what you have here is the two different resonances, λ_1 and λ_2 that gives you the split response here. So, we have clockwise and counter clockwise propagating degenerate mode through which we can generate this particular function. So, there is a reference here, if you want more details, you can have a look at that.

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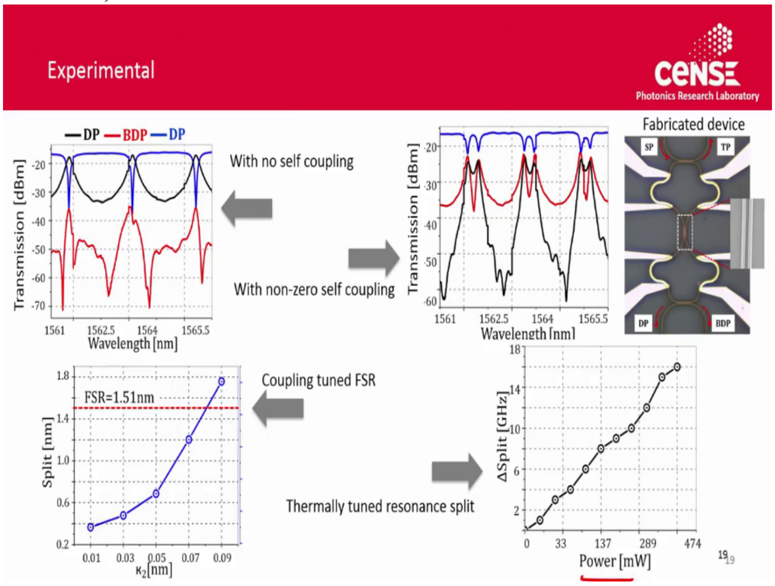

And this is the experimental demonstration of such a proposal. So here you see the split response where you can have these two resonances of this device, and this is tuneable as well. So, you can tune these resonances based on your thermo-optic tuning that we saw earlier, and the split can also change based on your coupling here.

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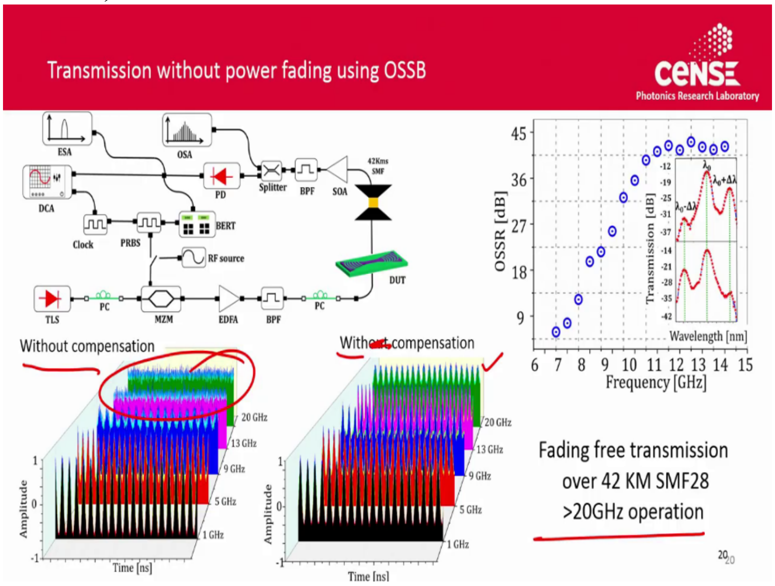

So, based on this filter, you can put it into your network. Without compensation, you can see beyond 9 gigahertz you do not see anything. So, these signals, greater than 9 gigahertz, there is no signal out. But then with, this is with compensation. What you see is, all the signals was able to recover completely without any problem. So, this can happen over a very long-distance cable as well. So, this demonstration is for 42-kilometer-long cable where one could demonstrate this transmission.

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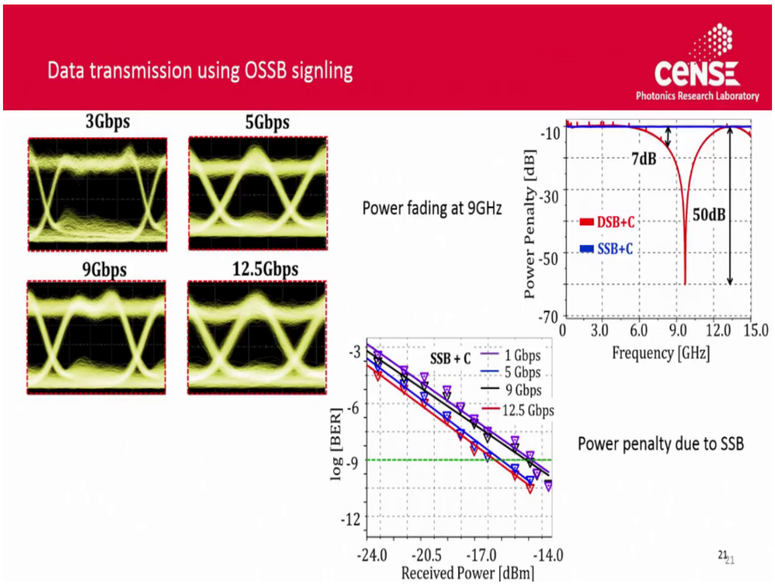

And this is just a data rate example. So how much data one could transfer this without having any power loss, in this case 12.5 gigahertz just for demonstration purpose. As you can see here, you have very clean 'eye', so you have still lot of power budget in order to go to higher speeds as well.

So, with that, we have demonstrated using photonic devices, very simple photonic devices, to go from coupling to demonstrating transmission. Not just transmission, but we also demonstrated detectors on chip as well.

So, the wavelength that you select and the material platform that you select as I mentioned are very specific to your application and you can even do RF signal processing, just we saw now.

So, it is all up to us to exploit this platform. As an example, I have presented you with these options. One can take this and then develop on top of this. So, it is only your creativity, imagination that is stopping you from coming up with some new device configuration.

So, with that, we can summarize that you can effectively use photonic circuits for communication application but in the next lecture we will see how we can exploit this for sensing applications. Thank you very much for listening, see you in the next lecture.