Photon Integrated Circuit
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Lecture 48
PIC Technology Building a Simple Circuit

Hello, everyone. Let us look at the circuit technology itself. So now, we have all the basic ingredients that is required to build a very simple photonic circuit. So, I would like to take this as an opportunity to build a very simple circuit, a passive circuit let us say, let us also keep it reasonably simple.

So, that we start from the material platform, let us say we select silicon on insulator as a platform and then we have the coupling device, we will have some passive device design and how do you go about in that and then finally on the characterization, so how it looks like, when you characterize such a device. So let us look at a very simple passive device platform.

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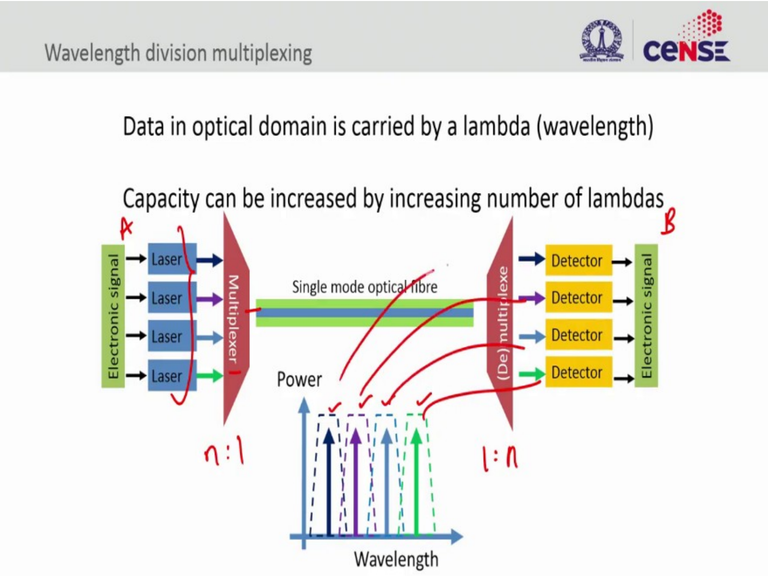

So, we would like to see whether we can develop a WDM chip. So, your wavelength division multiplexing chip. So, what is the requirement for this particular chip? So, when the data that you want to send from point A to point B is given to a laser so there is a direct modulation that happens and then you can put it into a fiber and then you receive it at the detector end. So, this is relatively straightforward. We all know how to do this.

But then how do you increase the capacity? So, if you want to increase the capacity, we have more number of lasers. So, though we know that the different laser wavelengths do not interact with each other, we have to physically put this together, so all these things together and at the same time, on the receiver side, we have to discriminate different wavelengths because the detectors are broadband detectors.

That means they sense photons that are present in wide range of frequencies or wavelengths. So, we cannot, we have to make them wavelength selective through some means. So, that means you have to make a wavelength selection or wavelength filter.

So, on the transmitter side, we need to have a multiplexer that takes n number of inputs and then creates one output. So that will be n to 1. So now, on the receiver side, you want to demultiplex from one physical input to n outputs. So, this is our challenge. So, we want to understand how we could realize this wavelength division multiplexing.

And this multiplexing could be achieved through multiple ways. So, in this one, we will select reasonably easy way of doing it. So, all we are looking at is, there are four different wavelengths, and we want to filter out each of these wavelengths and give it to the detectors here. So that is our target.

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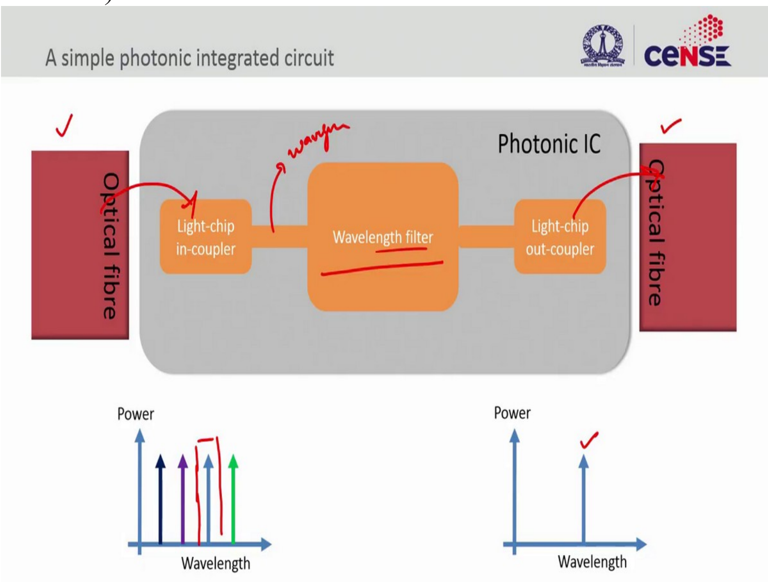

So, let us start with a very simple block diagram of how one can go about in building a simple photonic integrated circuit. So, we have an input optical fiber and we also have an output optical fiber. So, the input has four different wavelengths. But on the output side I just want to take only one. How do I achieve this? So, this is the question that we have.

Obviously, we need a wavelength filter. So, we want to filter out only this particular wavelength. And in order to get the light in, we need optical couplers so light-chip in-coupler and then the light-chip out-coupler to take the light out.

So, the coupler should be connected through waveguides and then you need some waveguide-based wavelength filter in order to do this spectral filtering. So, this is how you build a very simple block diagram. So, what you need to create this functionality.

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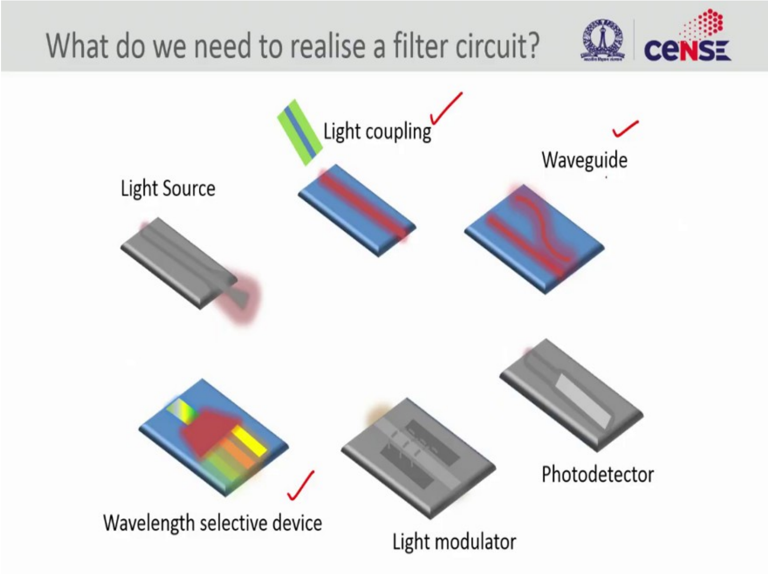

So let us look at what are all the components that we need in order to develop this filter circuit. So, I hope you remember this particular slide in a different form, earlier in the course where we discussed about different functionalities that you have on chip. Starting from waveguide to detector, wavelength selective device, sources, light modulators and couplers.

So, the problem in hand right now, is relatively simple compared to some of the complex functionalities you can realize using a photonic integrated circuit. So, in order to realize a filter circuit, we need light couplers, waveguides and wavelength selective device. So, this is all we need. We do not need active devices here. No need for photo detectors, modulators or light sources. So, they are going to be outside. So, let us, let us go ahead and then see how to build this circuit by developing these three components.

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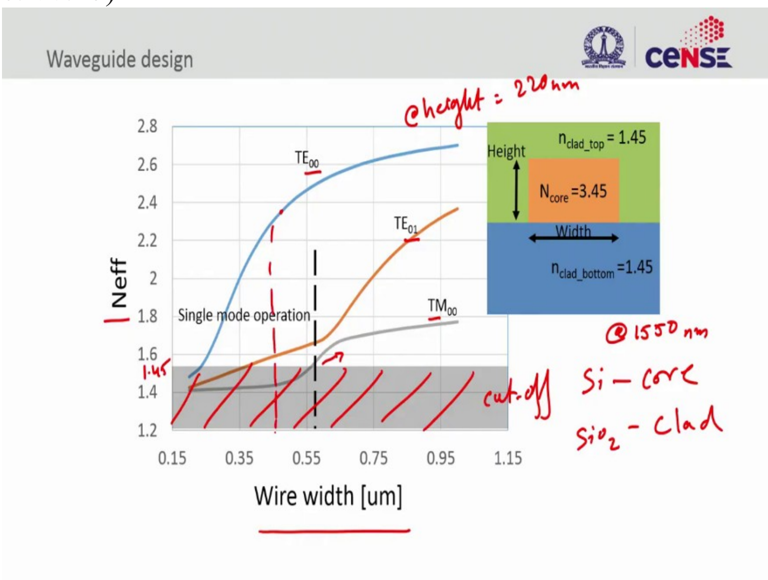

So, let us start with waveguide design. So, we have identified silicon as the core material and silicon dioxide as clad material. So bottom clad and top clad are identical. So now, we have a core refractive index of 3.45. Let us say, we are having this as telecom wavelength of 1550 nanometers.

So, the first thing we have to do is to find the waveguide dispersion. So that is $n_{effective}$. So effective refractive index. So, we find these modes. So, we have transverse electric mode, this is the fundamental mode, the first order mode and we have transverse magnetic mode. So, these are all the different solutions that you have for various wire widths. So, wire width is here, this particular width, that we have here.

And the height, we can choose whatever height we want, in this case, perhaps it is about 220 nanometer, let us say. So here, height is let us say 220 nanometers. So, you get all of this $n_{effective}$ calculated either through numerical methods or you can also do analytically.

So, once you have this, you can see a certain region is marked grey here. So, this is what we call cut-off region. So, this is cut-off region. We already studied about cut-off in our waveguide design.

So, the cut-off region is where the modes are not, or the solutions are not confined in the waveguide. So instead of this, you might have solutions that are outside. So, these outside solutions are cut-off. That means they are leaky modes, they are radiative, radiating modes. So, are radiating solutions.

So, anything above this, $n_{effective}$ above this is called propagating modes. And this is given by the cladding index that you have. So k_0n_2. So, this is what we had, in this case, k_0 1.45. So, this is cut-off point. So, all these are propagating modes.

And you can see here, we call this as a single mode operation if you have only one mode present in it. So, in this case TE polarized light is getting transported, which has much higher β or $n_{effective}$ compared to TE_{01} where TM is not present at all. The TM is only starting from here. So, this region is called the single mode region. So, we can operate in this particular wavelength, or sorry, waveguide width. So, you can choose a waveguide width here that is single mode.

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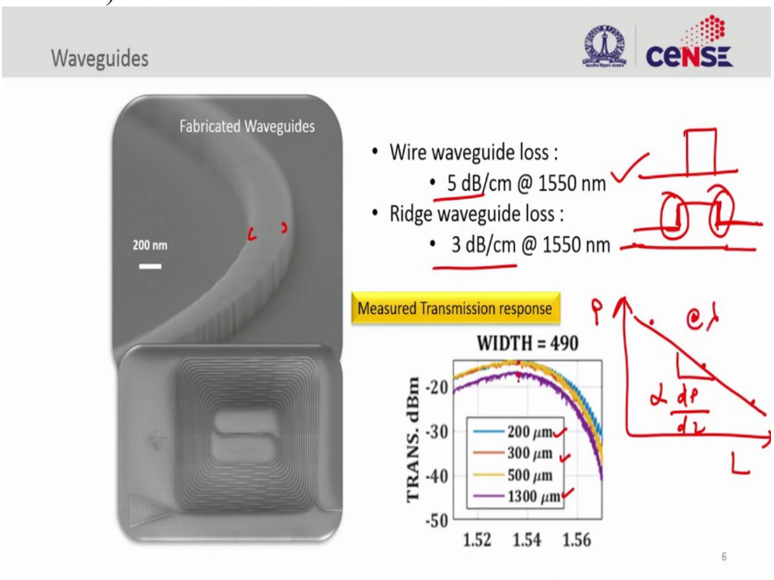

So, once you have this waveguide design, this is the width that I want, you can go ahead and make these waveguides. So, what you see here is a single mode waveguide, but you can see here, what I talked about in our earlier discussion, about the roughness that you would have. So, this is a fabricated waveguide where we see the roughness here. So, light would get scattered because of this roughness.

And because of this scattering your propagation loss is about 5 dB per centimeter. So instead of having the wire waveguide, you could have a shallow etched waveguide. When you have a shallow etched waveguide, the loss is reduced. Why the loss is reduced? Because you have lower overlap, or lower thickness to etch so your roughness is also lower here.

So, by using a ridge waveguide, you can reduce your propagation loss. And how do you measure the propagation loss? We measure it like we measure resistance. So, we have length and then you have power going through. So, for shorter length, you have more power as it, power increases, sorry, as the length increases, your power decreases. And this slope gives you your loss. So, how your power is decreasing as a function of loss. So, you have different lengths and then you can measure the loss out of this. So, you take these points and then measure for, at certain lambda of course.

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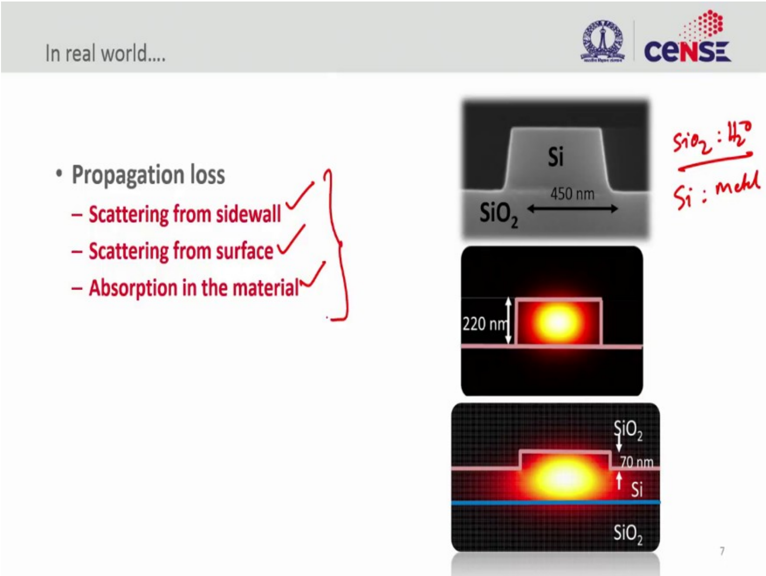

So, as I mentioned, you can play with your waveguide structure in order to reduce loss. So, this is a fabricated structure that you see. It is a silicon wire waveguide and when you look at the intensity, so most of the light is sitting inside. So instead of having this, you could have a shallow etched structure, where only 70 nanometer, only 70 nanometer is your etch depth. That means the roughness that you have is only important for the 70 nanometer.

But in this case, you have the roughness across this thickness. So, your scattering loss is going to be much higher. So going to a ridge waveguide is beneficial if you want to have low propagation loss. So that loss is coming from scattering from the sidewall. You could have surface scattering as well. You could have scattering from the, from this surface as well. And finally, absorption in the material as well.

So, you could have absorption in the propagating medium itself. For example, crystalline silicon is supposed to be pristine, but you could have some contaminants and these containments could result in absorption. Similarly, if you have silicon nitrite or silicon dioxide waveguides, silica waveguides, if there are some contaminants or the material itself is absorbing, for example, we saw in the last lecture about water content in silicon dioxide.

So, this can result in absorption loss. Or you could have some metal contaminants inside silicon. So, this can result in absorption loss. So, in practice, you will have these losses coming from your waveguide.

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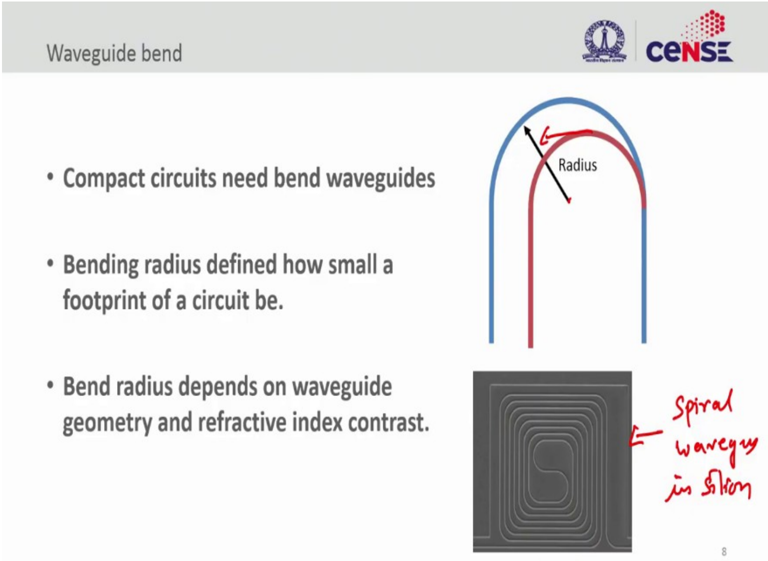

And the next important type of structure is bend. Bend waveguides. So straight waveguides are relatively easy to understand because we have done the solutions there but when, bend waveguides are interesting structures on its own.

The reason for having bend waveguides is to make the circuit really compact. So that is what we would like to do. By bending it with very sharp bending radius. So, what is the implication of this bend? So, when you have a bend, the refractive index of this bend wave guides are also going to be different. So, you are going to change the bending radii.

That means you are going to change the propagation constant or the β in these bend waveguides. So, this is something that you might have come across in any of your fiber optics bends that you might have learned. The same concept applies here as well. So, when there is a bend, your light is going to see a leakage. That is why we say do not bend the optical fiber.

When you have a fiber, there is a minimum bending radius, beyond that do not bend it. So, what you see here is a spiral waveguide in silicon. So, this is something that we have done. And you can see here the light is going to propagate through this spiral and then it goes in and then it will come out. So, you can make this light, guiding waveguides very compact and bent as well. So, this is the implication of having a bend.

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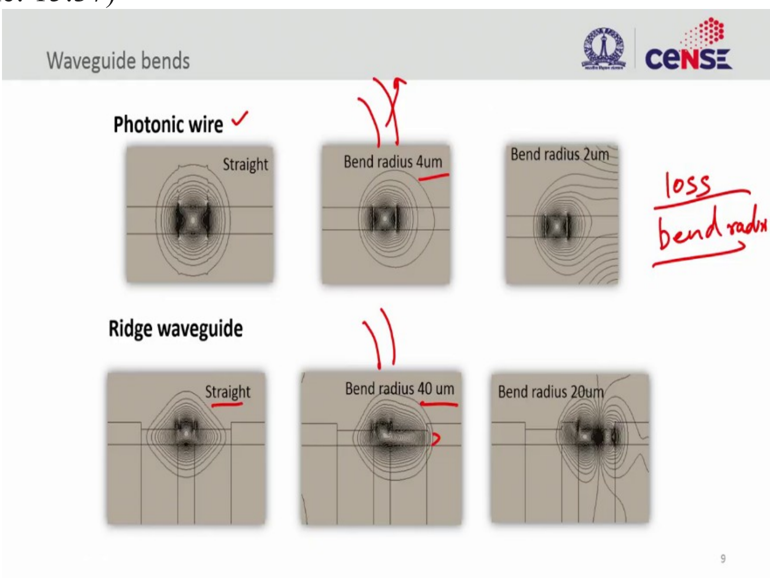

So let us look at wire waveguide to start with. So, when you have a straight waveguide, you can see how the electric field is distributed. It is highly concentrated. This center. But then let us look at bend. So, you start from 4 micron bend. So, you can already see that the light is leaking out. This is similar to driving a vehicle around the bend.

When you are going through the bend, there will be always a centrifugal force that is pulling you out. The same thing applies here as well. As the optical energy flows through the waveguide, when it sees a bend, so this is a bend here and light is going to leak out. And that leak starts here. You can see here; this is for 4 micron.

And when you have 2 micron bend, you can see already, most of the light is leaking out. So when you have a bend waveguide, light would leak out. So that is the reason why we have to be careful about the bending radius.

So, this is for wire waveguide. So let us look at the ridge waveguide. The straight waveguide for a ridge looks something like this. So, where you have nicely confined electric field. So now, if you look at the bend waveguide which has 40 micron bending radius. It is 40 micron. One order higher.

Even with that 40 micron, you can already see the mode is asymmetric and then it is moving towards right. So, the bend is towards left. And now, you can see, the wave is moving out, the propagating wave. But then when you reduce it to 20 micrometer, it has already moved out. It is completely lost. The waveguide is here.

So now, you can see the mode is sitting outside. So, this is completely lost. So, when you are looking at waveguide geometries, you look at loss and you look at also bend radii. So, we need to look at these two factors, selecting the waveguide configuration.

If you want a very compact circuit, then you go with photonic wire waveguide. And when you want very low loss and you do not care about very compactness, it can be reasonably large circuit, then you go with a ridge waveguide. So, it is up to the user to choose the waveguide platform based on the requirement. And there is a trade-off here as I mentioned whether loss or compactness. So that is all about waveguide.

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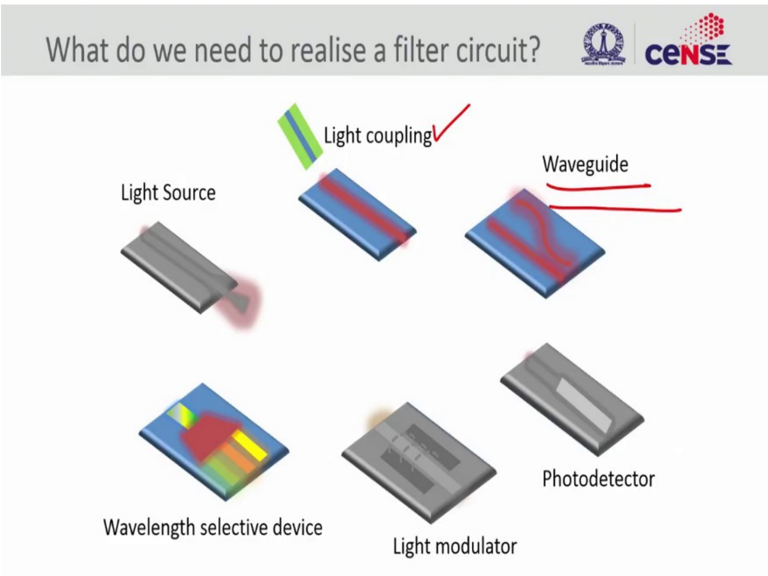

So now, we have designed or understood what kind of waveguide structure we want and what are all the implication of having wire or a ridge wave guide. So, let us move on to the next important factor or next important device. The coupling of light between an optical fiber and the waveguide.

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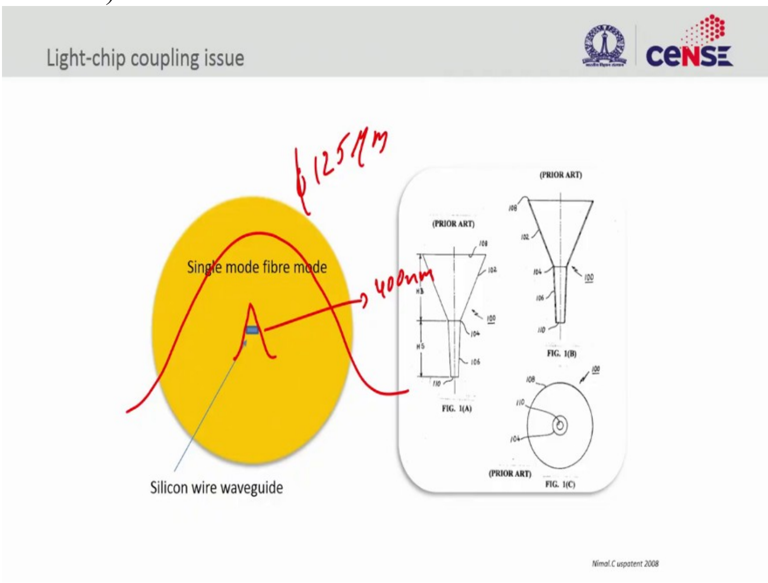

So, the coupling is a serious problem. The reason for that is optical fibers are very large. So, we talk about diameter of 125 micrometers. But our waveguides are very small. About 400 nanometers. So how are we going to move the light from this very large cross section mode into very small?

So, if you look at the mode profile, you are going to have a mode like this and couple it to a mode like this. So, the same coupling problem applies here as well. If you remember, we discussed about coupling in detail. If you do the overlap integral, it is going to be very, very poor. So, it is going to be 0.01 percentage is what you are going to couple-in.

So, one way of addressing this problem is by using funnel like technique. The funnel, the whole idea of using funnel is to take the light or take a large aperture and then put it into a small aperture.

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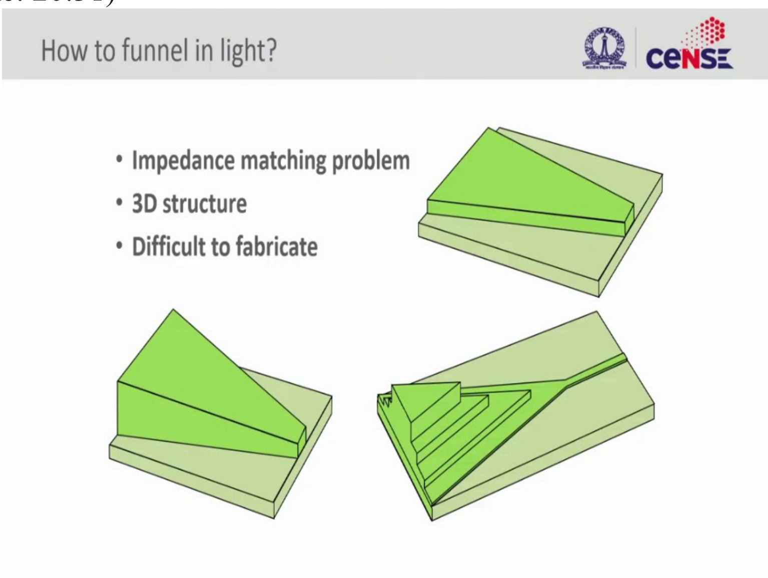

So, we can do funnelling of light by using different strategies. So, one such way is to use a tapered waveguide. So, this is similar to impedance matching problem, in other fields. You can use this kind of very neat funnel like structure on a thin film. You can also make it three dimensional.

But this is very hard to fabricate. It is nearly impossible in a CMOS based process to get this kind of three-dimensional structures. So, what is feasible is like this step like function. So, you can have step like structure that you can realize. But all these processes are very hard to use, or to fabricate as well.

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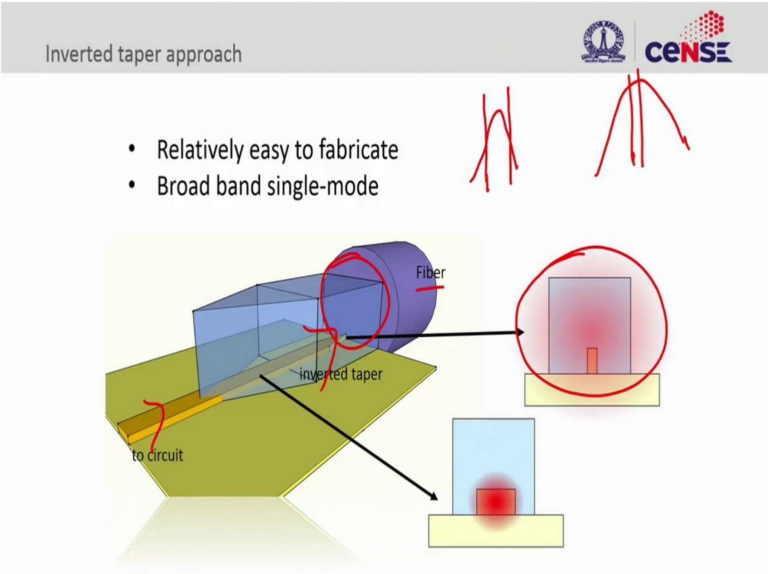

So, people have used what is called inverse taper and this is again coming from our waveguide understanding. When you have a symmetric waveguide, you will always have a mode. Even when you are very narrow mode, you will have a mode propagating, and this is exactly what we do. We have a waveguide mode here and then we stretch the waveguide mode for that, so that it occupies a large area.

And this area can be overlapped with the fiber so that you have coupling in this region. So, this is by using inverse taper-based coupling. These couplers are broadband so there are lot of wavelengths that you could couple in so that you can realize this sort of structure.

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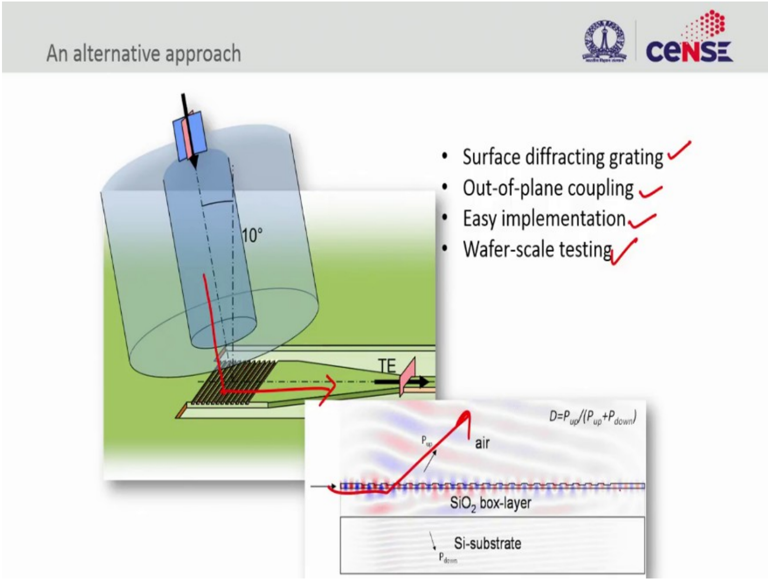

An alternate approach is to use grating. This is again something that we have discussed in our coupling discussion. We are now putting it to use. So, the grating couplers use a simple perturbation that you see where the light is illuminated from the top and then you are exciting the propagation, propagating wave.

So, this is out of plane coupling, which is very, very neat without doing any edge preparation. So, you don't have to chop the chips, you can do it on top like a probing. Just like electrical probing, you can do optical probing.

You can, this is achieved by using simple surface grating. There is nothing very special about this so you can just use surface grating and it is rather easy to implement as well. And you can do wafer scale testing. So, what you see here is just a simulation of how light would get out of such a propagating wave through this grating structure.

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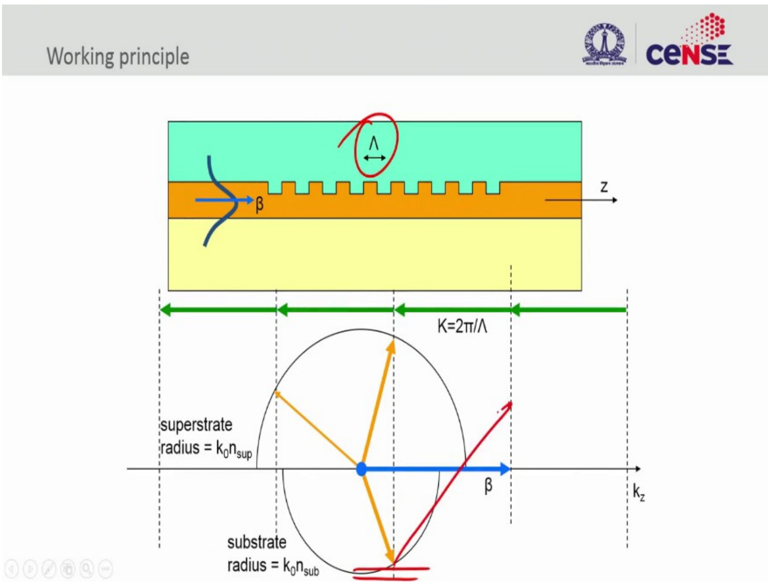

So, this is the working principle of this particular grating. You have in coming wave β and then the light is getting scattered in its different orders here and based on the light, the grating period, you can get the necessary grating diffractions.

And the question here is, you are going to have multiple orders here. So, you will have forward scattering here, upwards, you will have downwards, and you will also have one small backward component.

But this is inevitable in this particular geometry. But then you are having β matching with this particular, or phase matching with this propagating mode.

So, one way to address this substrate problem is by putting a substrate reflector and then we can reflect it back. So, this reflected back light would also be in phase with whatever light you have there.

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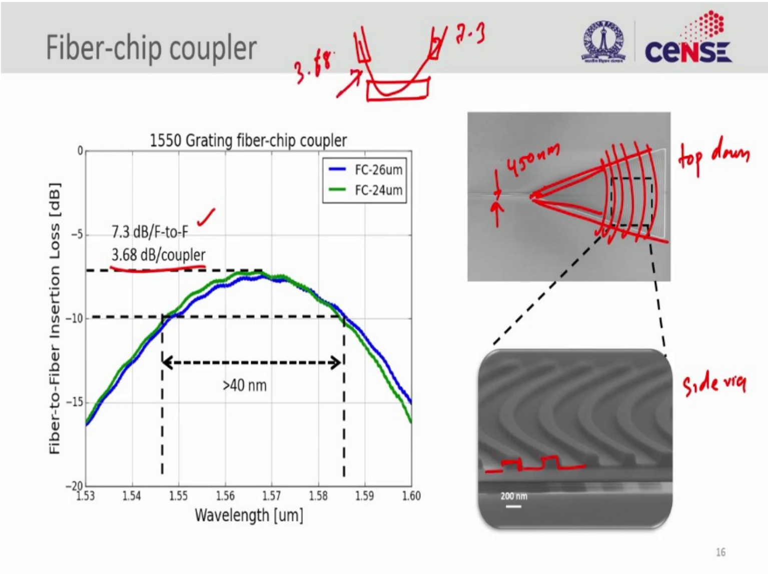

So, this is one such device. It is fabricated. It is a very simple fiber chip coupler where you can see the top down and this is the side view. You can see these nice corrugations, and these are all nothing but the gratings that we just discussed. The conical shape allows you to focus the grating, the light and this curved grating also allows you to focus it to this waveguide which is 450 nanometers.

So, by using this a per coupler efficiency of about 3.7 dB is achieved, but fiber to fiber is about 7.3 dB. So, when you take a chip, so you put in fiber-in and fiber-out. So, this total path loss is about 7.3. Individually, it is 3.68. So, this is how you couple light.

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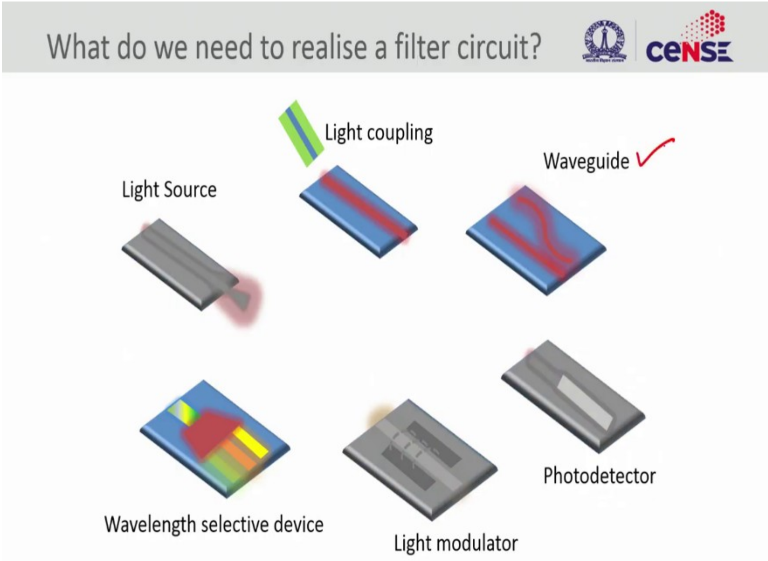

So now, we have gotten the waveguide design done and we know how to couple the light. And finally, we need to prepare our wavelength selective device.

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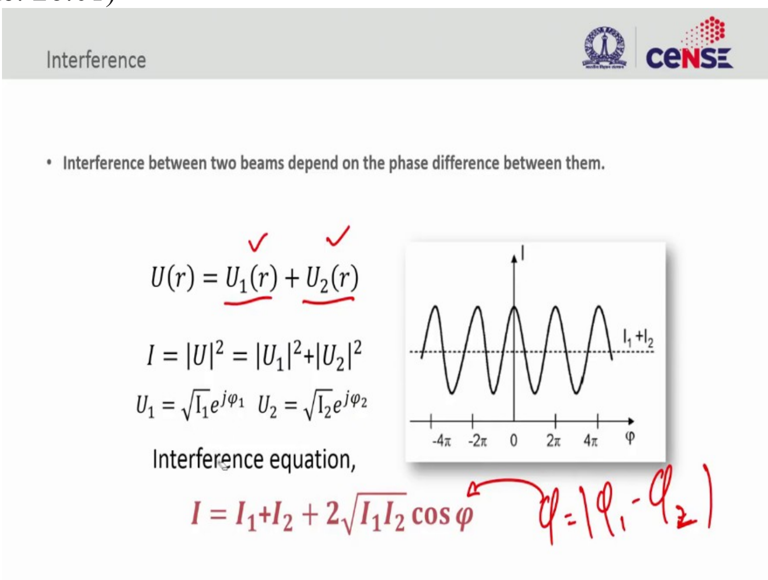

So, wavelength selective device purpose is to create wavelength selectivity. How do we create this wavelength selectivity? So, you could use interference principle in order to create wavelength selectivity. So, this is a very basic understanding of interference. So, you take two waves and then you interfere these two waves.

So, if these two waves got any phase difference. If it is as φ_1 and φ_2 as phase, if there is any phase difference between these two and that phase difference is φ here, any phase difference would result in a sinusoidal or interference pattern. And we are going to take advantage of this interference.

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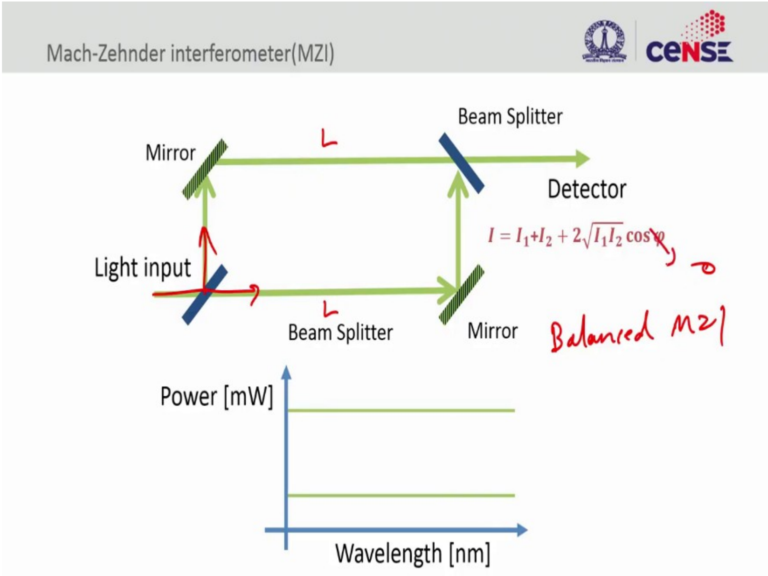

And the way to create this interference is by using Mach-Zehnder interferometer. So, when you have equal path, so the length of the two beams that we split, we take the beam in, and we split it into two and then we are combining it. The path taken by these two beams are identical. If they are identical, you will have either high or low based on the wavelength or based on the phase difference that you have.

So, this is what we call balanced Mach-Zehnder, balanced Mach-Zehnder interferometer. So now, if you add, so, by the way, this φ here is 0. So, this term goes to 0. There is no phase difference at all.

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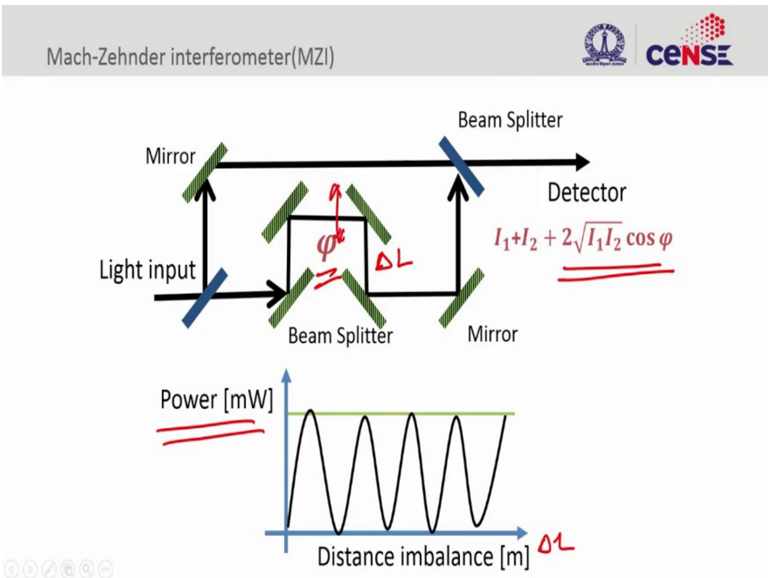

So now, if you are going to put a delay here. So that means you put an additional path difference that creates a certain φ here. So that means this factor becomes sinusoidal in nature as a function of this imbalance. So, this Δ is a function of ΔL. So the power is going to change as you move these mirrors or create this path difference.

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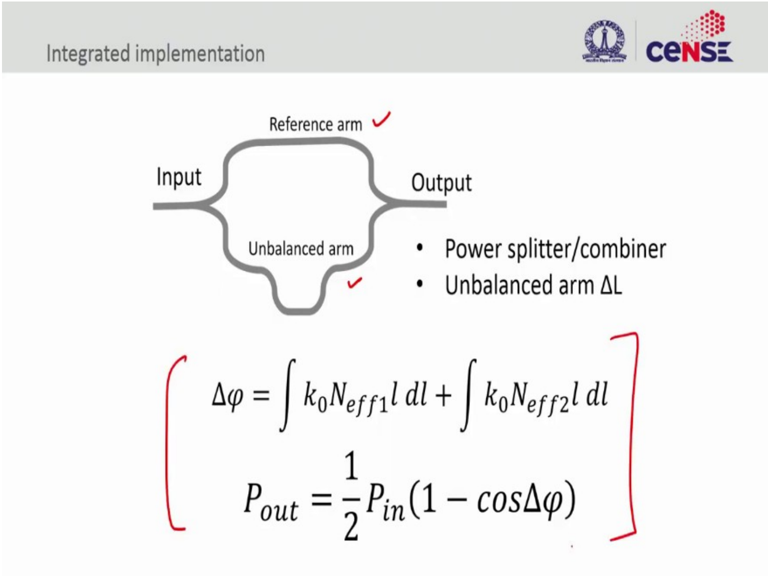

So, in an integrated fashion, this is how we implement a Mach-Zehnder. This is again something that we have seen in y-splitters and combiners. So, we have two y-splitter and a combiner here. And then we have a reference arm and when we had a unbalanced arm. By using this configuration, we can create a phase difference.

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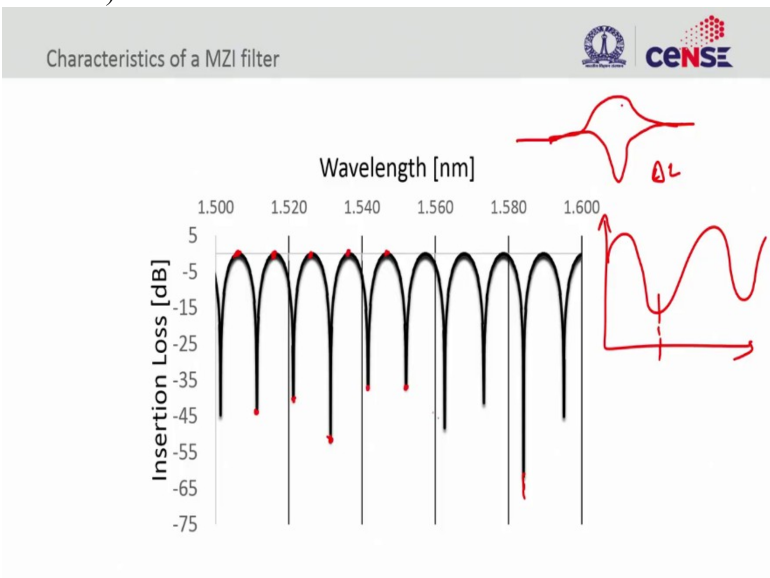

And this phase difference would result in a spectral response like this. So, what you see here is a spectral response from a Mach-Zehnder interferometer, an unbalanced Mach-Zehnder interferometer. So, you had a Mach-Zehnder like this. So, there is a ΔL that we had. Based on this, we have this.

Why you have such a spectrum, this is dB scale, this is in non-linear scale so when you have a linear scale, you would see something like this. All these points are nothing but here. So, you have created now, the insertion loss or transmission based on the wavelength. So, these wavelengths enjoy very low insertion loss while these wavelengths suffer from high insertion loss.

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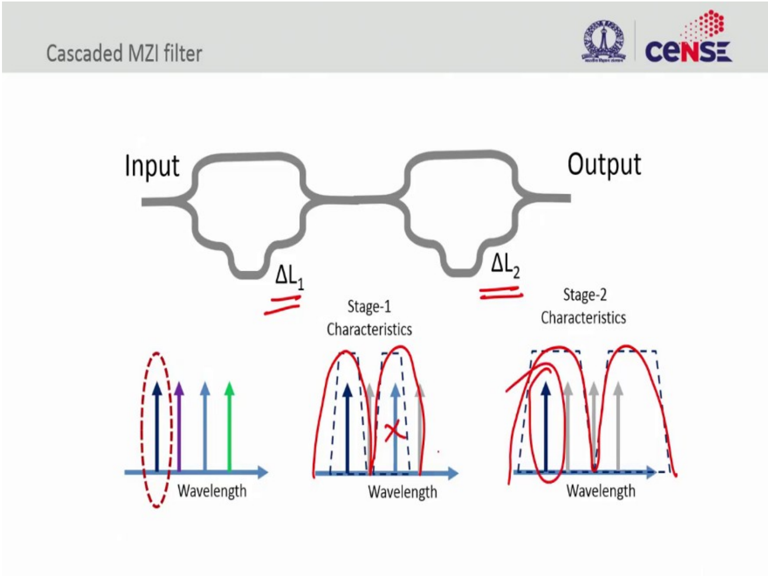

So now, based on this, we can build a cascade of this Mach-Zehnder filters in order to realize the single frequency or single wavelength filter here. So, we have four wavelengths coming in here and we want to take out this particular frequency, let us say.

In stage one, you are going to, your spectrum would look something like this. And we are going to kill this particular spectrum here. We are not going to transmit this particular spectrum in the first stage.

And in the second stage, we will get a Mach-Zehnder that does this. So, this one will be removed. So, for that we need two different types of ΔL. So, when you take a Mach-Zehnder, we can take this kind of configuration to create what is called cascaded Mach-Zehnder filter in order to get only one wavelength out of this particular system.

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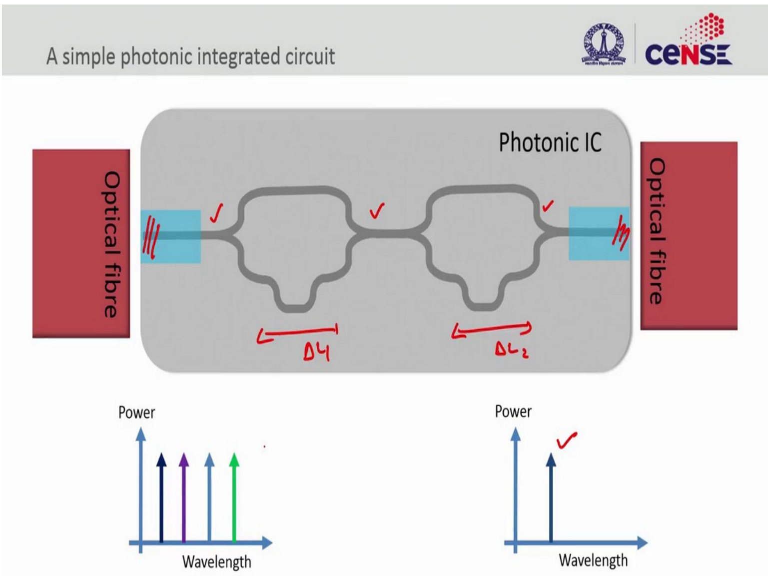

So, by using this, we can create a Mach-Zehnder filter, Mach-Zehnder based filter than can create one single filter out from four different channels. So, what we can conclude here is, we have gone from block diagram, when you started with a coupler design, or these sides and we also looked at what kind of waveguide we want and also, what kind of strategy we can use in order to create this wavelength selective filtering of one single channel out of four different channels.

So, this is how you go about in realizing any application. You can start from simple block diagrams because you know the toolbox. So, what are all the components that we have. So, we have waveguides, we have directional couplers, we have couplers, light-chip couplers, we have filters, there are various types of filters for that matter. So first, we need to conceptualize what are all the blocks I need. And based on the requirement you can choose the right kind of device.

So, we have chosen here Mach-Zehnder based device. You could also choose for example, ring-based device. So, ring resonated based device. So later on, we will look at other examples where we will use rings, but I wanted to be much more widespread in device knowledge so here we just took Mach-Zehnder which will eventually give us what we want.

It is all about choosing the right device and then combining it in a fashion that would result in desired functionality. So, this is again going back to our definition of photonic integrated circuit or in principle integrated circuit in itself. It is not just having discrete components. So, these discrete components should be put together in a desired fashion. We cannot randomly connect it.

These devices should do their own job but then when they are combined, they should also collaboratively work together in order to realize a global functionality. So again, I am going to repeat that photonic integrated circuits are nothing but collection of or connection of discrete components connected in a desired fashion to realize a desired functionality.

So, if you do that, you can do any kind of functionality that you want because that is the power of the circuit that we have and widespread toolbox that we have. Later on, we will see how we are going to apply this, but this should have already given you a good amount of insight into what we are capable of establishing using photonic integrated circuits. Thank you very much for listening.