Integrated Photonic Devices and Circuits
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Lecture - 35
Electro-Optic Modulators for Integrated Photonics: Basic Design and Working Principle

Hello everyone, today's lecture we are starting electro optic modulators for integrated photonics. So, this is an important component for photonic integrated circuits. So, we thought of discussing starting from the basic design and what is the working principle. So, step by step we will be discussing on modulators for high speed data encoding where it is being used today particularly when you talk in terms of photonic integrated circuits. And then there are 2 types of modulators popular, one is phase modulator that is eventually a frequency modulation and then finally amplitude modulation or intensity modulation.

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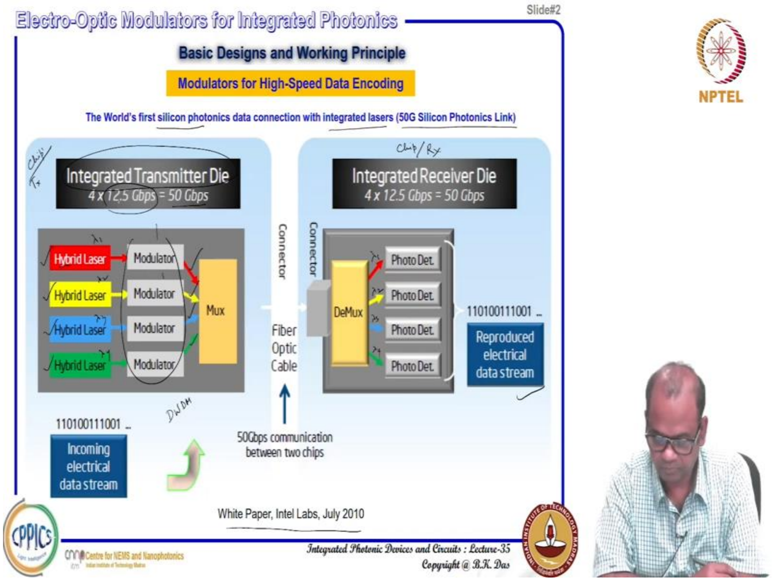

So, let us see how modulators play a major role in high speed data encoding. So, here I have tried to given an example borrowing a photograph the scheme from Intel Labs white paper this was depicted in 2010. So, when they actually demonstrated the world's first silicon photonics data connection with integrated lasers, 50 gigabit per second silicon photonics link. So, before that actually high speed modulators being used for long haul fiber optic communication.

But the modulator mostly dominated by lithium niobate modulator. So, this is the first time silicon photonics modulator fabricated using CMOS technology and tested the performance of those silicon photonics modulator using fiber optic communication link. So, here for example it was shown that they communication is taking place between 2 chips. So, chip 1 that is actually nothing but your transmitter and then chip 2 that is actually your receiver basically.

So that is what it is said that integrated transmitter die so it is fabricated for example using CMOS technology. So, they are 4 different colours shown here they are basically laser they are emitting different colour different wavelength why it is hybrid? Because as you know silicon platform is not at all good particularly silicon material is not at all good to demonstrate laser diode and because of its indirect band gap.

So, mostly the even though if you give a forward bias to a silicon diode with maintaining all the conditions required for a laser but you do not get really photo lumen sensor photon emission because the population inverted electrons in the conduction band that actually relaxed to hallon’s band through different ways with the assistance is required for that and that actually eventually blocks the laser emission possibility photon emission possibilities.

So that is why hybrid, hybrid laser means it is laser normally it is fabricated using 3 pipe compound semiconductors so those lasers were fabricated separately using 3 pipe semiconductor for example indium phosphide platform and they were actually mounted on silicon chip 4 different types of laser as I mentioned this can be considered lambda 1, lambda 2, lambda 3, lambda 4.

And each of these lambda or laser emission it is fed into a modulator so called electro optic modulator where your data can come and the data can be encoded with this laser light having wavelength lambda 1 and similarly lambda 2 another data stream can come and that can be modulated again with another modulator and lambda 3, lambda 4 so on. So, each of them actually can encode data up to 12.5 Gbps so 12.5 Gbps times 4 it is actually 50 Gbps transmitter.

So, in the background you can have your electronic circuit driver circuit where actually you can make all the data stream parallel to this modulators you can divide them into 4 modulators. And since they are actually encoded into 4 wavelengths you can use a wavelength multiplexer. So, normally you know they are very popular it is used in fiber optic communication.

Dense wavelength division multiplex system DWDM where actually for high speed data connection it is more than 160 the number of channels could be multiplexed together. But in this case for silicon photonics transceiver here it is multiplex 4 channels. So that is why these wavelengths separation can be wide enough 8 to 10 nanometer and so on. So, 8 to 10 nanometers separation lambda 1 to lambda 2 and lambda 2 to lambda 3, lambda 3 to lambda 4 and you can multiplex them.

And you can fed into a fiber optic cable that can be single mode and multimode depending on the requirement how much distance you are actually transmitting and then at the receiver end when it is received you can again demultiplexed depending on its color. So, this lambda 1 will appear here and lambda 2 will appear here lambda 3 will appear here along with its data encoded. And then you can use your photo detector there.

Photo detector basically actually demodulate or decode the data that means it converts the optical data into electrical data same way lambda 2, lambda 3, lambda 4, 4 different photo detectors can be used and all these photo detectors actually should be made suitable. So that it can detect efficiently in those wavelengths and then you can reproduce your electrical data stream. So that is how actually modulator plays an important role for fiber optic communication.

And earlier days these modulators were fabricated as I mentioned it is a bulk it is an integrated optical modulator though but it is a standalone modulator high speed modulator that is in lithium niobate. So, these are the first time demonstration high speed modulator at least 12.5 Gbps using silicon photonics technology.

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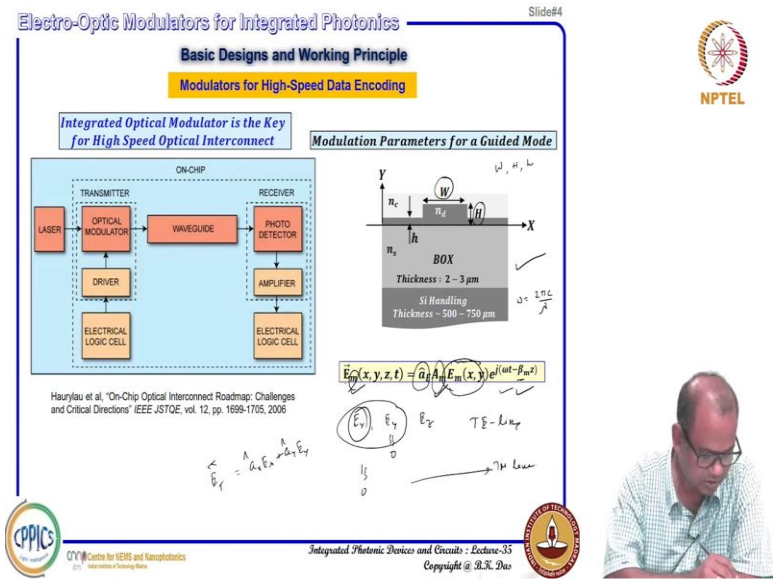

And so not only that actually this because of this advancement of silicon photonics technology as I mentioned in the beginning of this course that people were trying to replace the electrical interconnects with optical interconnects just to get rid of bandwidth limitations. So, here is one depiction that how an optical modulator or silicon photonics technology can be utilized for on chip communication. For example you can use a laser that can be off chip or can be hybrid integrated on silicon photonics platform.

And then you have a silicon modulator where you can co integrate electronics driver and that actually feed into your electrical logic cell whatever data is coming the driver can be conditioned driver can condition the levels 1, 0 levels and then you can actually feed that data stream to optical modulator and then you can just instead of fiber you can just directly launch into a waveguide.

And the waveguide can carry the optical signal encoded with all the data stream that can be guided low loss waveguide can be fabricated on silicon photonics technology platform. And you can take them guide them wherever necessary and you can detect demodulate the optical signal and you get the electrical signal back and you can amplify and again you can feed into another electrical logic cells.

So, in this way you can actually integrate together the optical modulator along with a waveguide or all other devices and then you can try to replace electrical interconnect wherever necessary wherever bandwidth limitation with the optical interconnect. If you want to know a little more than I request you to go through this paper by Haurylau et al the title of the paper is on chip optical interconnect roadmap challenges and critical directions.

So that was the first time it was demonstrated in 2006 that is a long background 15 years ago today we see that a lot of photonic integrated chip available commercially so based on this concept now. So, now let us try to see that what are the modulation parameters for a guided mode? What you can modulate? One thing you can modulate your amplitude and phase as I mentioned before but how that is mathematically you can actually model that let us take an example of a wave get cross section of silicon.

Silicon waveguide cross section that is normally we know that the waveguide cross section. And the design parameters are W that is waveguide width and device layer thickness and you can have your slab about small h according to the requirement and this can be designed W capital H and small h you can suitably choose for single mode guidance if necessary. And it will see even if it is a multimode or single mode whatever mth mode distribution.

We have shown earlier that it can be described by this type of formula as long as orthogonality condition maintained. So the mode profile of the mth mode that is actually the Eigen solution and beta m is the propagation constant is the eigenvalue solutions also for that mode and if the waveguide is propagating along z direction 1 dimension we can express like that and amplitude E m depends on how much energy how much encoded power associated with the mth guided mode.

And one more parameter we have that is actually the polarization of the electric field. Because you know electric field electromagnetic wave or light wave when it is guided through a rewave guide structure then it can have all 3 components E x, E y, E z. So, considering this thing if E x is dominating and E y close to 0 then it is called TE like mode and if E y dominates and this is close to 0 then it is called TM like mode.

So, but many times you will be seeing that your solutions giving both E x and E y significant amount both content E x component as well as E y component. So that time it will be called a hybrid mode. But nevertheless if you see the transverse component that is E x and E y if they are having different component you can actually define which direction their combination may be electric field you can transverse component of the electric field you can write something like this a x, a y.

So direction can be neither along the x direction along y direction you should have components. So, other direction will be so that can be consideration polarization so 3 parameters very important that is a polarization which field which directs an electric field is oscillating amplitude that actually decides how much power associated with the guided mode and E m x, y that is actually your profile distribution that hardly matters as long as it is normalized to that profile is known and then propagation constant and frequency of course.

Frequency means actually operating wavelength it is decided by omega = 2pi C / lambda. So, these are the parameters in your hand when you have a waveguide with some guided mode if it is a single mode you do not need to actually assign E m or something like that just a fundamental mode we will be guiding.

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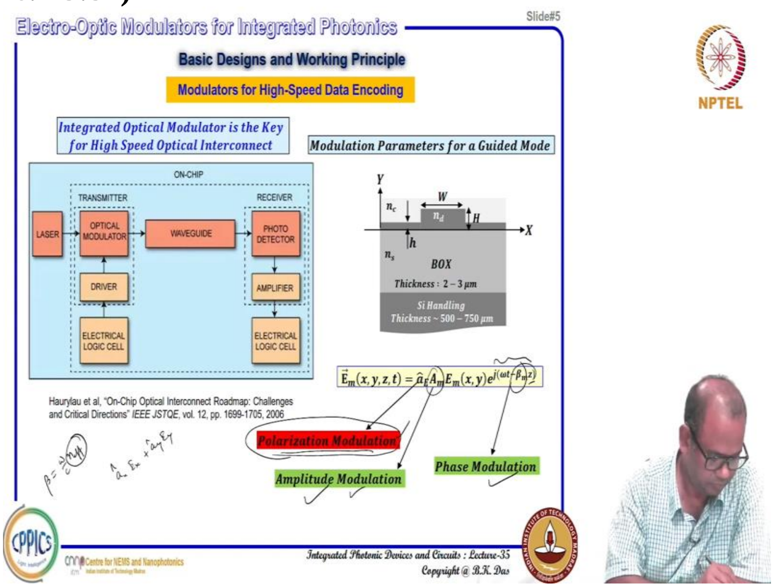

Now you see you can actually modulate the polarization, polarization you can have suppose you have a x component and a y component. So, what you could do? You can actually somehow you can change the polarization components that means E x fraction if you can just modify to higher level and E y fraction can be reduced to the lower level for a given power or amplitude of the electromagnetic wave.

And then you can make it on, off that means you can rotate the polarization and you can sense the polarization at the receiver by rotating the polarization on and off if it is digital communication then you can actually encode the data and at your receiver you can actually sense what polarization is receiving if it is just rotated polarization coming you can say that 0 and if it is not then it is a 1 if it is a digital communication so polarization modulation is 1 option for you.

And then another thing is that amplitude modulation you can have a modulator where as it propagates somehow you can create certain kind of mechanism where amplitude can be reduced to give you a 0 data or according to your requirement it can be higher value you can get 1 or of course you can get anywhere between 0 to 1 level if you can actually have some kind of mechanism that you can continuously any level you can get your amplitude that is how you can get amplitude modulation.

And finally this is the phase as long as your omega is fixed. So, phase modulation means basically you can say that beta m modulation if you can modulate the beta value beta value is nothing but beta = omega / C n effective somehow if you can just modulate the effective index of the guided mode for a certain length of propagation z it is given here. So, you can have certain phase modulation.

And that phase modulation you can effectively detect that can be through a circuit or something else we will be discussing a little while later that how this phase modulation can also eventually help to give you amplitude modulation also. So, these 3 modulation mechanism one can choose but for photonic integrated circuit purpose basically polarization modulation is not preferred because that is very difficult in case of particularly silicon which is basically isotropic material.

So, polarization modulation is discarded not at all popular not at all used for photonic integrated circuit purpose. However with this amplitude modulation and phase modulations are very popular for photonic integrated circuit applications.

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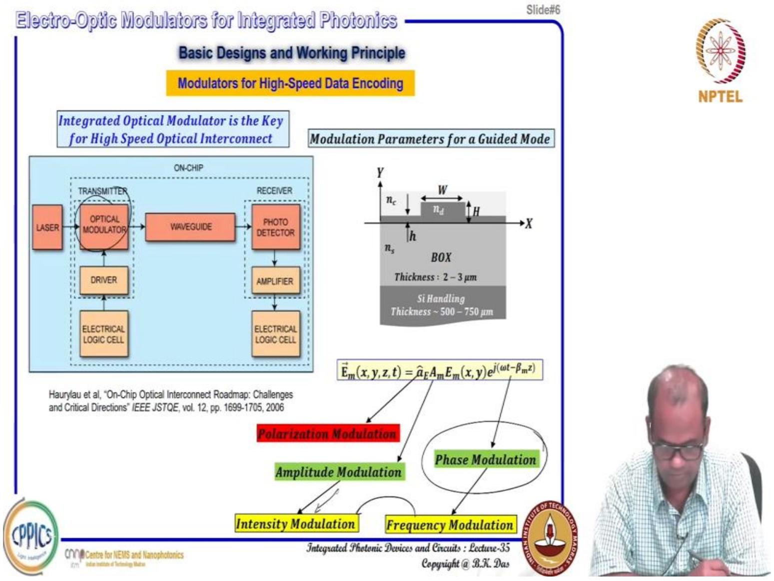

So, now as I mentioned that amplitude modulation eventually gives you intensity modulation and phase modulation eventually gives you frequency modulation also if you just design your circuit interference you can design some certain kind of interfering circuits then you can convert phase modulation into intensity modulations. So, ultimate key is the phase modulation if you can do phase modulation at a very high modulation speed then that can be actually utilized as an encoding element or modulation data encoding or data modulator optical modulator so called optical modulator.

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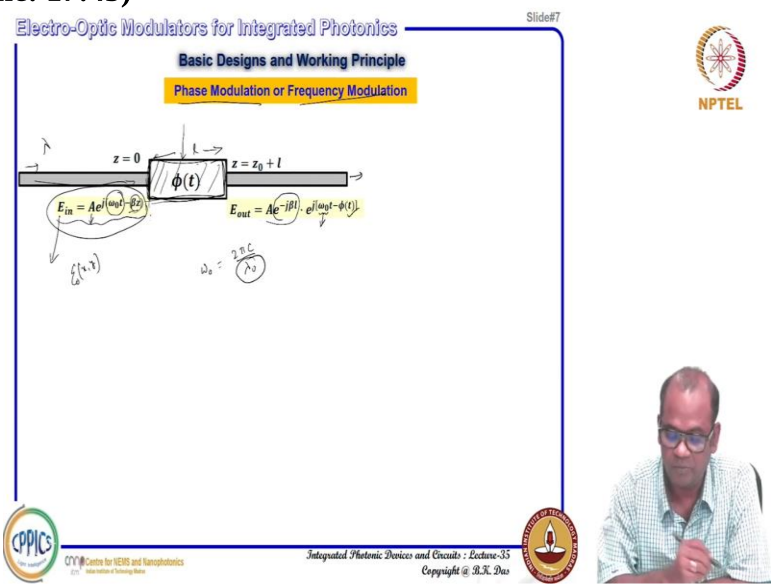

Now next thing how that is done? For example this is your waveguide this is your input and this is your output and as the mode coming and you can consider the electric field you can consider dominant electrical field component if that is E x that means the polarized or is dominant by E y then E y you can consider and then you can consider the amplitude profile you are not considering that thing actually fixed as it propagates we assume that it is fixed.

And amplitude that actually associated with the power of the guided mode and then this one this is your input and you know as it propagates the phase initial phase will be there beta z as you consider z = 0 here at this point z = 0 that means we can consider we start counting phase from here itself before that there will be certain phase initial phase will be there but as I consider this is my phase where I want to encode my phase for this l length.

For example l length somehow I want to do some certain kind of phase modulation I am just discussing about phase modulation or frequency modulation why phase modulation is called a frequency modulation that also I am going to discuss. So, now then after traveling this l length it is supposed to have a phase of e to the power minus j beta l because z = 0 here that means beta l amount travels.

Because of the propagation you get this phase factor. In addition to that if you have a time dependent this is a kind of phase modulator you have integrated here that time dependent phase modulation can give here. So, in that case I can have omega 0 t - phi t where omega 0 it consider as a carrier frequency or you can consider that 2pi C / lambda 0 where lambda 0 is the operating wavelength that is the lambda coming out of certain laser.

It can be hybrid laser it can be external laser and so on so this is the thing. So, if you have a phase modulation, phase modulation means you are changing your phase as a function of time. For example according to your requirement you can actually design what type of phase modulation you want for the moment I am considering that your phase is changing as a function of time. So that means you instead of normally any guided mode when it is Eigen mode so the time dependent part is omega 0 t and beta z we consider this phase dependent part but now phi t is coming so additional phase change is coming that is also time dependent part is here.

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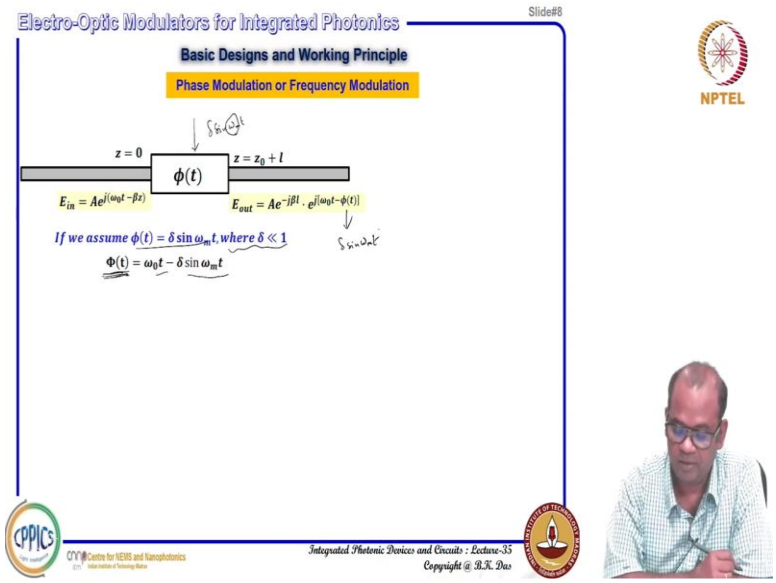

So, now let us consider a simple example let us consider this phi t is a sinusoidal you are just giving your data or some modulating signal so that phase is being modulated based on this one we consider this omega m is that modulation frequency here in this case simple sinusoidal delta sin omega m t here and you can consider this delta is equal to less than 1 because normally it is a fraction then basically it can little bit it can modulate the phase. Whatever phase is coming you can modulate the phase.

So, now you can consider maybe it is this is phi t, phi t is equal to this one now capital phi t is defined as total time dependent phase omega 0 t - delta sin omega t. So, here I am just inserting a delta sin omega m t.

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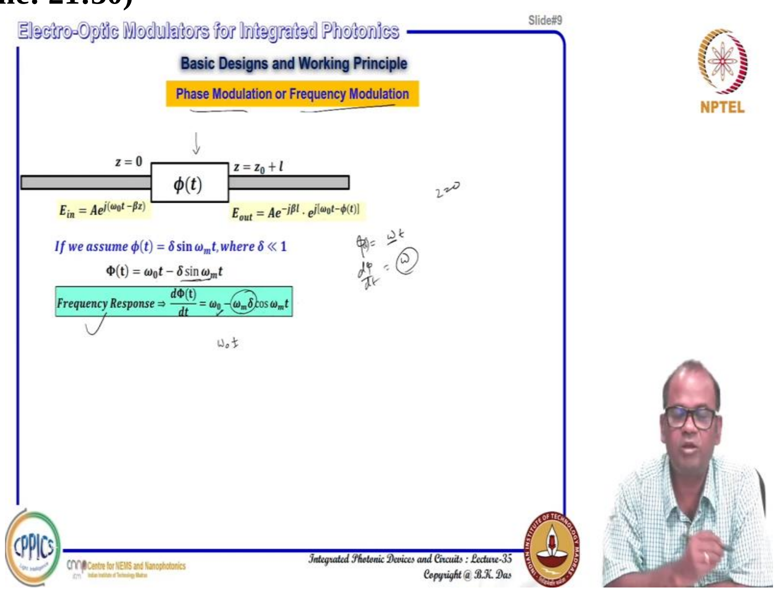

So, now if we do that little bit analysis what we get? Normally we know that suppose you have a phase time dependent phase omega t we write phi t what to get that omega basically frequency that means you can say that per second how much phase it can acquire at a particular point z = 0 for example. So, if I do d phi t / dt then ultimately you get omega that means rate of change of phase gives your frequency of the guided electromagnetic wave.

Now your phase is now has additional part. So if I tried to find out frequency response d phi / dt then you get you see omega 0 t goes and delta sin omega t omega m delta cos omega m t that means just pi / 2 phase shift is there and you have this is your frequency swing you can get instead of omega 0 earlier it was omega 0 now you get because cos omega m t can go plus and minus so you can see that this frequency goes plus minus a certain range.

So that means if you modulate with a certain frequency then you can get your frequency actually you can get modulated also that is why it is called frequency modulation phase modulation is equivalent to frequency modulation.

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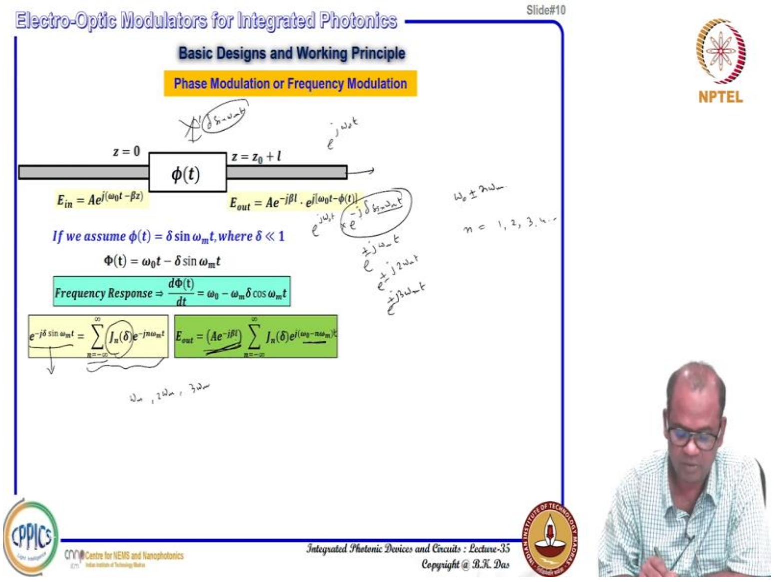

So, now if you just see now try to look into it if you just analyze this one it will be e j omega 0 t multiplied by e to the power - j delta sin omega m t let us look what is this that will exponential and then you have a sinusoidal m t function that is actually again you are just representing with exponential term minus j is there complex problem. Mathematically if you look into it, it can be expressed in this form.

You can have omega m t e to the power - j n omega t where n is the integer starting from minus infinity plus infinity whatever the integer values are there you can consider minus infinity plus infinity and you have a special function so called Bessel’s function this is called

Bessel's function and that Bessel's function is a special function I will just going to give you that expression but that value depends on delta and n suppose n = 0.

And delta a certain value you can find out what is the value of that from this special function you can get and e to the power - j n omega m t that means you are getting this thing can be decomposed into a combination of different frequencies that omega m then 2 omega m, 3 omega m all this frequency component is there and that frequency component is coming here. So that means e to the power j omega m t you can have e to the power plus minus j omega m t.

And then you can have a plus minus e to the power j 2 omega m t then it can have e to the power plus minus 3 j 2 omega m t 3 omega m t and so on all this frequency component you can expect. So, that means ultimately you can get your frequency components omega 0 plus minus n omega m. So, these are the frequency components you will be getting at the optical output.

So, without this modulation of delta sin omega m t if you do not have if you block that you certainly would get only e to the power j omega 0 t only one frequency you would be getting but once you modulate with your some kind of sin omega t with a modulation frequency omega m then at the optical output if you see you can have multiple frequencies omega 0 plus minus n omega n can be considered 1, 2, 3, 4 and so on.

So, so many frequency components you can expect so if you just do this one this is what I have just tried to say that omega 0 - n omega m this is n omega 0 of course you have to write here t and normally propagation constant because of the propagation whatever the phase comes e to the power - j beta l we have written here good.

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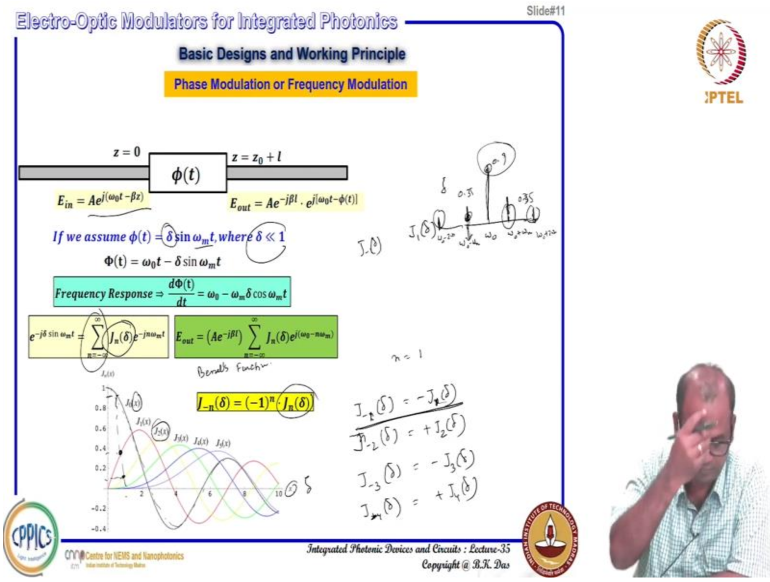

Now you check what is this special function? So called Bessel's function so, Bessel's function you know it can go from, minus range to plus range that is what it is defined here. So, but they have one relationship they are somehow anti symmetric with J - n delta equal to whatever J n delta you will be getting minus 1 to the power n. So n = 1 if you just put J - n delta meaning minus J n delta and if n = - 2 delta that will be equal to plus J 2 delta no, no this is 1 I am writing, this is 2 then you will be writing J 2 delta.

Again J - 3 delta j minus delta should be equal to minus J 3 delta again J - 4 delta should be equal to plus 4 delta. So that means minus plus that mean only odd number if you have just contain odd frequencies you are just considering in that case it will be minus and otherwise plus that means what I meant to say that suppose certain delta and for that you have J 1 coefficient is there and J - 1 delta is there both are there.

But both frequencies will be present but they will be differing by minus 1 that means they will be pi phase shifted. So, if you have a frequency this is omega 0 then you can get this is omega 0 + omega m and this will be your omega 0 - omega m but whatever the amplitude this is your central amplitude of the electric field you are giving here in. So that is there and here you will be getting this one some components you may get.

But you will be seeing that whatever phase it is here omega 0 omega m and this phase for the carrier frequency phase they are same but the other one it phase will be just opposite this will be inverted at any instant of time if you see then this omega 0 omega m component that will have in phase with the carrier but this component generated that will be pi phase shifted and here it is shown if you just instead of delta if you are just repeating thing x I have just copied from some internet most probably from Wikipedia.

You can plot also there are function is there Bessel’s function expression is there based on that you can just plot as a function of x if you see that means delta this value if you keep on increasing here this is suppose delta you consider. So, J 0 delta you see it is n delta = 0 that is maximum and then it will keep on coming down and goes negative as you delta increase and pi but when delta is very small then you can consider somewhere here for example.

So, J 0 will be some this much value so it will not go to 1 rather it will be going literally later maybe 0.9 whatever the values are there. Now for same delta if you see J 1 x that will be these values this will be above 0.5. So, if it is 0.9 it will go up to maybe 0.5 or 0.5 here now I think it is less than 4. So, this can be 0.35 this can be here also amplitude if I just writing 0.35 it will be there because J 1x = - J 1x only amplitude will be different.

So, both sides will get frequency components but their amplitude will be almost 30% less than the main carrier coefficient. So, you get extra actually whenever you are doing some kind of phase modulation with a sinusoidal function with the frequency omega m then you can see all this side frequencies will be there and then you can get also another frequency that is omega 0 + 2 omega m that will be here and omega 0 - 2 omega m that will be in phase.

That means this one and this one that will be in phase but unfortunately when delta is very small if you just try to see what is the value of J 2 x you are getting that will be somewhere here. So, it will be very less so that amplitude will be reduced so that means your frequency components will present but the amplitudes will be reducing in fashion when delta is very smaller than 1 hopefully this is clear now.

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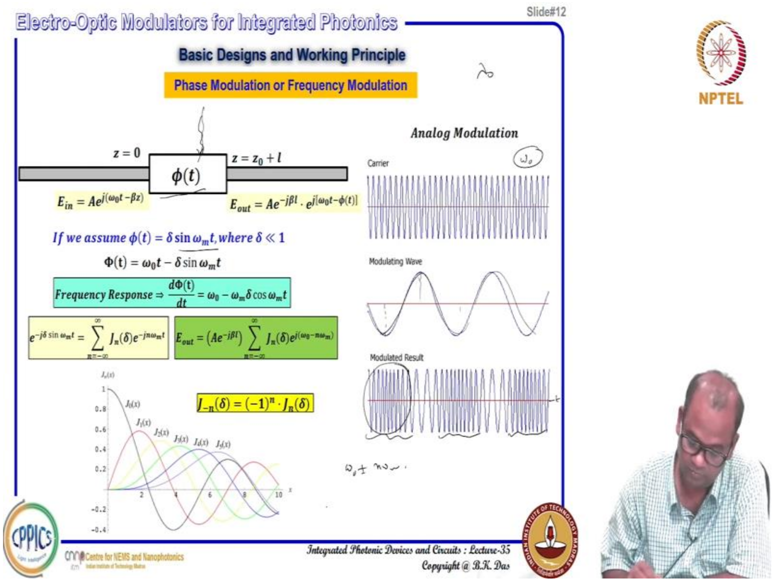

Now you see if you try to see analog modulation that means this phi t can be a function of time with sudden modulation like this, this type of analog modulation not like that phi t is a step function just a 0 or some values instead of that as a function of time it is changing your data can be your incoming data whatever data is coming that can be also certain kinds of any value it can take.

For example based on that that phi t you also it will be proportional to that data strength signal whatever data you want to encode depending on the strength this phase will be also decided. So, suppose this is your carrier that is actually omega 0 that is a electromagnetic wave corresponding wavelength lambda 0 for example now this is your modulating wave which is actually relatively lower frequency that is your data you can consider an analog data this is there.

This type of modulation if you are doing now as you keep on changing your phase so that means your this is your maximum this is your delta value and then plus delta this way it will be oscillating like this. So, modulated results what you will see that at this point your signal if you see that it will be their frequency will be actually such that the lambda will be a function of t for example.

So, lambda will be the quenched and then relaxed where depending on the value here it will be just this type of modulation you can see this time dependent the amplitude so the time period here reduced and relaxed time period reduced relaxed time period reduce relax. So that is how depending on the and it is not like step type it is actually depending on the strength of this one you will be getting the frequency will be modulated.

So that is what it is called analog modulation your frequency change is happening and that frequency change actually corresponding proportional to the strength of the sinusoidal power. So, frequency component engine but if you just do Fourier transform you will see what is the frequency that whatever I mentioned omega 0 plus minus n omega m you will be getting.

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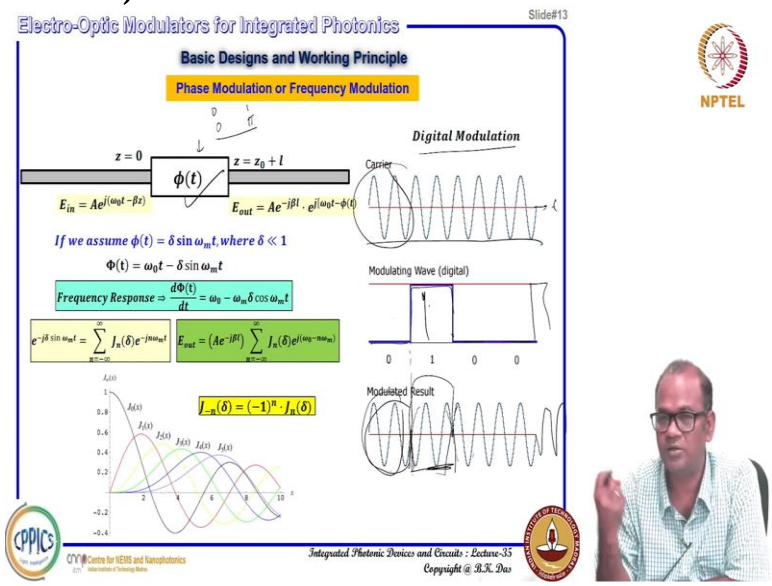

So, now digital modulation so digital modulation means what you can consider this phi t can be either say certain value 0 or some value pi for example. So, this 0 and pi that actually depends on your digital 0 or digital 1 suppose 0 coming certain phase is there and then beta when 1 coming phase will be different for example here consider your carrier as a function of time you see this one.

Now this is your modulated wave say digital data for example your 0 beat 1 beat and then 0 and then 0 all these beats streams are coming for example so when 0 is there you do not see anything change that means no phase change is happening here. So that is why this portion is fantastic up to here up to this portion this is the portion up to here it is okay. Now when 1 is there you see this thing actually somehow phase is sifted.

Because the presence of this 1, 1 means certain voltage you are applying for example. So depending on the voltage refractive index is changing and refractive index changing means you have changed the phase. So, phase shift is happening so that is why it is instead of going from this to this instead of that some delay it will be as if it is starting from here at this point of time so, it is just shifted here.

Similarly when this is withdrawn that 1 beat is gone then again it will be again relaxed instead of starting from here it is actually starting from here. So, this region if you see phase revert some phase shift is happening. So that is how we can say that this digital data whenever it is coming 1 that means you are getting a phase shifted signal depending on the height of the signal you can have a driver you can control the voltage.

And controlling the voltage you can change the refractive index and that phase shift can be added here during this period and once this phase shift again withdrawn then again it will be like as usual wave guide structure. So, it will be again propagating like this again another one comes that time again phase shift will be there like this so on. So that means you can have analog modulation you can have a digital modulation. But challenges that if it is digital modulation or analog modulation your receiver photo detectors should be able to actually detect the frequency change or should be able to detect this phase shift basically so called.

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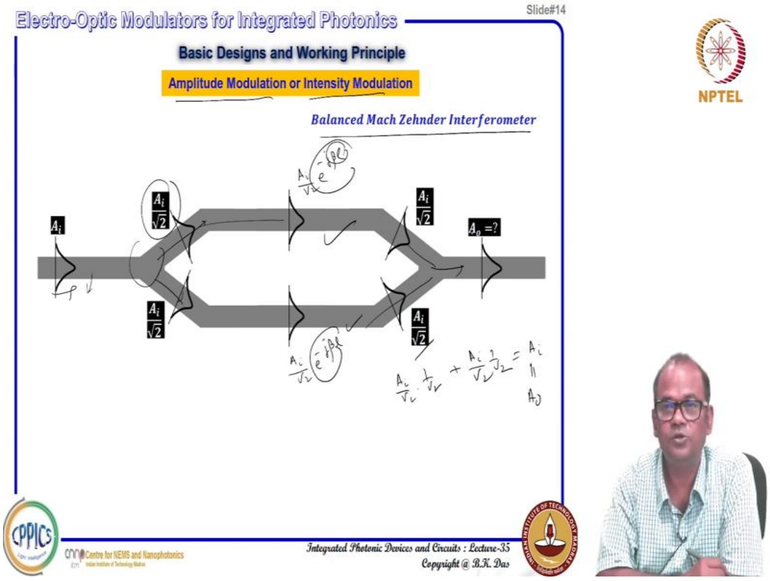

So, now I will be discussing amplitude modulation or intensity modulation so that is so far it is very, very popular for photonic integrated circuit for optical interconnects. So, phase modulations are also popular but phase modulation is used to get amplitude modulation or intensity modulation. So that you detection particularly when you are detecting with a photo detector photo detector is a square intensity detector basically square law detector.

So, it can actually easily it can see change in power so if it is digital communication 0 and 1 means you can think of that power is completely switch up to 0 nothing is coming to the portrait detector that time photo detector will detect as a 0 bit and when some current is there in the photo detector certain value then it will see that bit is 1 this is a simple example. So, how that is done let us consider a balanced Mach-Zehnder interferometer.

We have discussed so many times before I reproduced it again here for the understanding of modulator particularly amplitude modulation or intensity modulation let us consider a balanced Mach-Zehnder interferometer constructed by y junction single mode waveguide here y junction it splits into 2 amplitudes amplitude splitting just preserving the energy conservation also. So, A i / root 2, A i / root 2, so A i is amplitude coming in here.

This we have discussed earlier I am not going into the detail why root 2 comes and then as it propagates you know it will be A i / root 2 e to the power - j beta l the as the propagation that beta length that phase will be there. Similarly A i / root 2 e to the power - j beta l as long as it stays balanced that means this arm and this arm same they are balanced Mach-Zehnder interferometer this part will be same for both the things.

And when it comes here combines here then again A i / root 2 will come here with additional 1 / root 2 and then + A i / root 2 this one that will again additional 1 / root 2. So what we will be getting you will be getting A i so that will be actually equal to A 0 that is what we discussed earlier.

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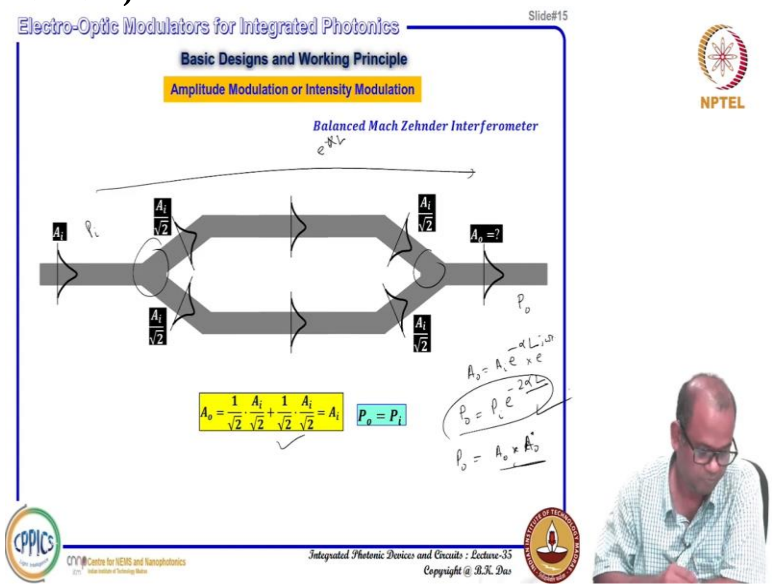

So, here reproduce that thing so we have to will be this one so that means if it is a balanced Mach-Zehnder interferometer whatever input power you are giving here same output power you are getting here as long as you consider that the waveguides are lossless junctions are lossless but if waveguide losses are there and if this length is suppose say length is l that means e to the power - alpha l amplitude loss will be there.

That means A 0 will be equal to A i e to the power - alpha l that means amplitude and power loss will be p 0 p output will be p i e to the power - 2 alpha l because power is nothing but we according to our convention that is A 0 and A 0 star complex conjugate you have to take along with that you have e to the j omega t so on that is complex conjugate will cancel. So that is why 2 times multiplication that is why minus 2 alpha l.

So, alpha is the amplitude loss coefficient 2 alpha is the power loss coefficient intensity loss coefficient and but for the moment we are considering it is a lossless case anything loss is there you have to calculate accordingly.

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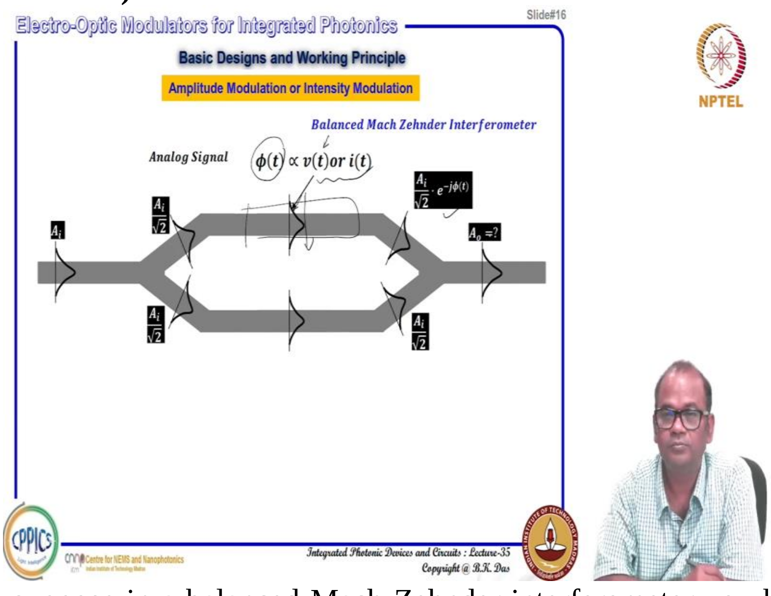

So, now you see suppose in a balanced Mach-Zehnder interferometer you have a phase you are adding here to this mode in the upper arm which is time dependent and this phase can be changed in terms of voltage time dependent voltage or time dependent current that is eventually your can be your analog signal or digital signal as a function of time voltage can be fluctuating depending on the data current can be fluctuating.

So, depending on the mechanism of this waveguide structure and to design of your phase modulator that phase can be either modulated because of the applied voltage or because of the current flowing through it across the waveguide structure so phase can be changed. So, if that type of phase is changed then what you can say that upper arm whatever coming out function of time phase has to be included then what would be A 0. If you have some time dependent phase is there let us see what it is.

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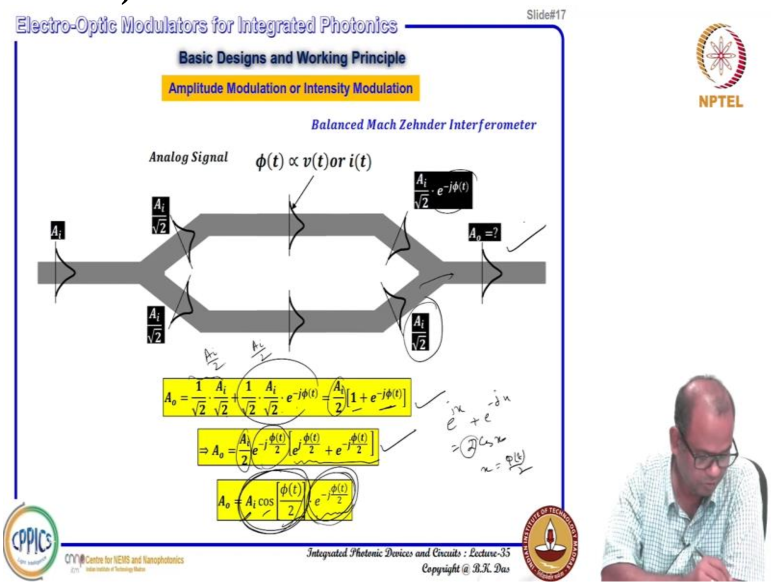

You see A 0 equal to the first thing is that this one I am writing A i / root 2, 1 / root 2 when it is coming here and then second term this one A i / 2, 1 / root 2 times and then your phase factor it is there now it is simplify so that this term will give you A i / 2 and this one will be giving A i / 2 so A i / 2 common the first time will be 1 second time will be this one e to the power - j phi t. Now what do you do simplify it you take A i / root 2 this one I am just writing directly here.

And then I take common factor e to the - j phi t / 2 then within a box I can write this one e to the power - j phi by 2 because this one if we multiply then you will get 1 this one you multiply then you will get this one this is just a simple simplification purpose then you see this is like e to the power j x - e to the j x that is nothing but 2 times cosine x x is equal to here phi t / 2. So, now what we do here I am writing here A i / 2 because A i / 2 is there.

And these 2 will come that gives you A i and cosine x and times this phase factor. So, this will be phase factor and this will be your amplitude. So, amplitude will be now time dependent it is a cosine function cosine phi t / 2 along with that you get additional time dependent phase so amplitude modulation as well as time dependent phase modulation you are getting here.

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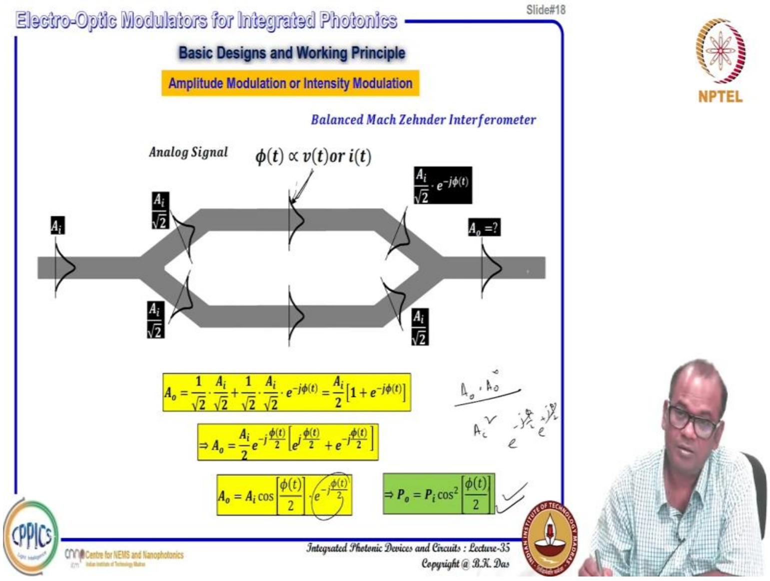

But if you try to see what is a power that means you have to take A 0 and A 0 star if you take A 0 and A 0 star multiplication that is to give power that should be proportional to A i square or square phi t / 2 that is nothing and this one will be complex conjugated to be e to the power - j phi / 2 it will be a j phi / 2 that will be cancelled. So, ultimately we are getting intensity modulation.

So, what you get if you have a phase modulation here then at the output you get amplitude modulation as well as phase modulation but once you try to detect with the modulator then a photo detector sorry then you get only power modulation amplitude modulation or intensity modulation. This is a very popular structure that you use your balance Mach-Zehnder interferometer you whatever phase required you just introduce in one of the arm and depending on the phase you can get your output intensity modulated accordingly. So that can be analog that can be digital.

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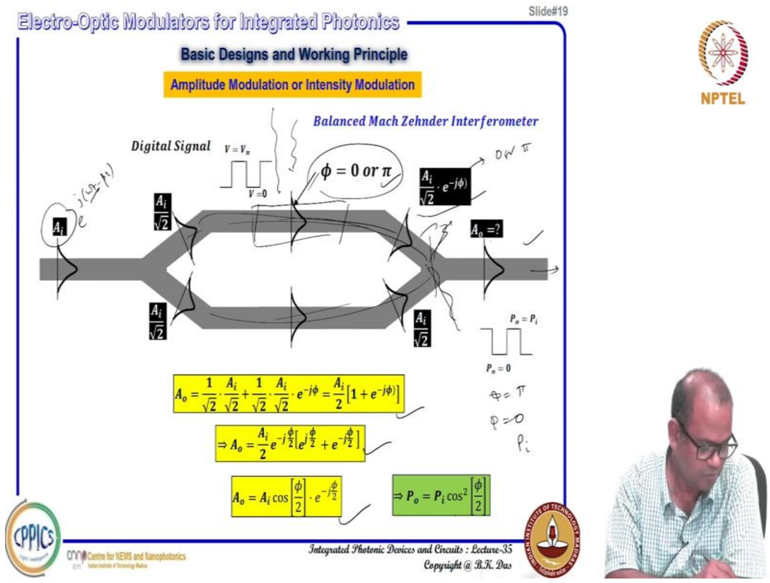

So, if you have a digital signal like this so you have 0 here v = 0 if you are giving here or you are giving some voltage v that is actually corresponding to phase difference of phi if you are giving 2 phase either 0 or phi you are choosing as a data 0, 1 coming here to modulate this section of your waveguide then what you get let us try to see that upper arm you get e to the power - j phi, phi can be again 0 or phi.

And this one nothing is happening while the propagation length that is common to both the arm so I am not considering there and what would be the A 0? Let us see same formula same formula same formula we are using instead of time dependent we are using phi to 2 digital value either j or 1. So, 0 or phi so if it is 0 then your power will be phi = 0 that means your power will be just exactly p i. If phi = pi then your power will be just p i phi / 2 = cos phi/ 2 = 0.

So that means your this power actually here can reproduce 0 or phi whatever 0 your electrical signal comes that will appear as a 0 and high power and low power as a light output power but when you are getting 0 here no light is coming out here that means the optical 0 that time light is actually basically getting lost in the section I have discussed that how that is actually lost there because it is a single model wave guide.

Here you can assume that it is like excitation or higher order mode and that can be dissipated here. So that means your digital electrical signal can be converted into optical digital signal and then since it is optical. So, you can use your optical waveguide or optical fiber for data transmission.

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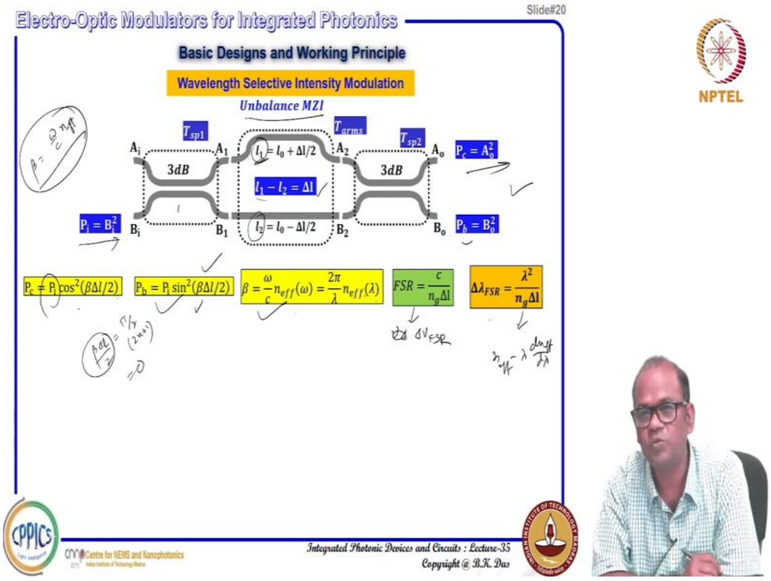

Now another type of modulator we normally use that is actually for example when we discuss this thing here this A i can be multiplied by e to the j omega t - beta z so on. So, here omega or lambda can be anything any lambda you can choose because identical arm is going ultimately your desire is that you get either 0 phase shift or pi phase shift. So that is how you can get your output lambda can be independent.

Now we can there are some issues are there to have a very good high speed amplitude or intensity modulator using balanced Mach-Zehnder interferometer. So that is the reason people modified this Mach-Zehnder interferometer a little bit differently. So that your design issue will be particularly intensity or amplitude modulation will be easier but your device will be operating only at one wavelength or is just kind of a certain set of wavelengths.

This type of structure also I discussed earlier. So, it is basically unbalanced Mach-Zehnder interferometer 3 dB power splitter and then you have unbalanced means the upper arm having a length l 1 which is certain l 0 + delta l / 2 and lower arm l 2 = l 0 - delta l / 2 such that l 1 - l 2 this is a lower arm length this upper arm length l 1 - l 2 = delta l and know that if you are have.

If you just see what is the transfer function for this one that we have derived earlier also that the cross board if you are launching here in across board means here P c, P c whatever you will be getting P i cos square beta delta l / 2 where beta again you know beta is nothing but omega c n effective beta delta l / 2 and bar port what you supposed to get here that will be sin squared and your beta whatever ever written here it is written down here.

Again 2 pi / lambda n effective lambda and you know then please spectral range that means you know if you are just changing that because this is beta is actually wavelength dependent that means this type of phase condition for example beta delta l / 2 if it is actually pi / 2 then you supposed to get cross port 0 if that is 0 then cross port you will be getting just exactly the P i.

So, this pi / 2 again depends on beta which is actually nothing but 2 pi / lambda n effective. So that means you can have a basically you can consider 2 pi times 2 n + 1 integer. So that means a series of lambda successive lambda with certain separation they will be actually giving you a 0 output or maximum output at the cross port or bar port because cross port and bar port they are cosine function and sin function.

And those wavelengths which are giving maxima here or minima at the cross port or bar port their separation in frequency FSR delta new FSR just consider delta new FSR frequency domain free spectral bands C / n g delta l that also we have derived earlier just reproduce here for the completeness. Similarly delta lambda FSR if you just consider instead of delta new FSR just delta lambda FSR then lambda square / n g l n g is the group index nothing but n effective - lambda d n effective / d lambda all these we have discussed earlier just reproduced here to understand how this type of structure can be useful for modulation intensity modulator.

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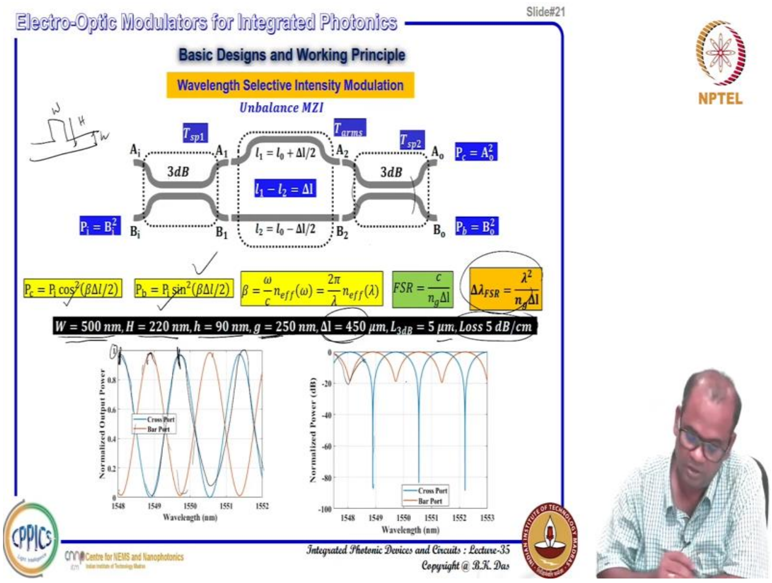

So, we have just simulated for a certain waveguide structure where waveguide with you know this type of waveguide to consider in silicon this is the W and this is H and this is a small h. So if you are considering W = 500 nanometer device layer thickness equal to 220 nanometer h = 90 nanometer and gap g this g means when you are designing a directional coupler that gap is we are considering wave guide to wave guide separation is 250 nanometer.

And this delta l = 450 micrometer is considered in this example and l 3 dB if you are considering this gap that 3 dB length of the directional coupler is above 5 micrometer that is calculated. And if we assume that overall loss of the waveguide is about 5 dB per centimeter then transfer function cross port and bar port you know that cosine function and sin function so cross port beta delta l lambda = 0.

Then you are just getting this one this maxima then periodically it is going like a cosine function and this will be going like a sin function it is going like in the bar port and you see this is plotted as a function of lambda. So, when I say that this delta lambda if FSR that I mean this to this separation this is actually the wave length separation that is called pre spectral range. And if you just consider in the dB scale you see normally it is not going up to the 1 level.

That means input power is a consider so for example it is a 1 but at the output of neither in the cross port nor in the bar port it is going to the level of 1 because there is a loss I have considered in the waveguide structure in your simulation that standard Mach-Zehnder interferometer transfer function you can use and you can just plot this one using your simple

MATLAB program then you get and dB scale if you see cross port this is a blue curve and bar port this is the red curve.

You see in the dB scale if you see that there is a extension when this certain wavelength supposed to be minimum that is not going up to the level whatever about more than 80 dB is going for the cross port when it is minima coming this is because this is unbalanced in nature you can get this one but nevertheless you get extension about minus 20 dB even in the bar port and cross port you can go very high that is fine. But you can design such that both cross port and bar port you can adjust the wavelength waveguide losses etcetera so that you can get both the arm similar type of extinction that is possible.

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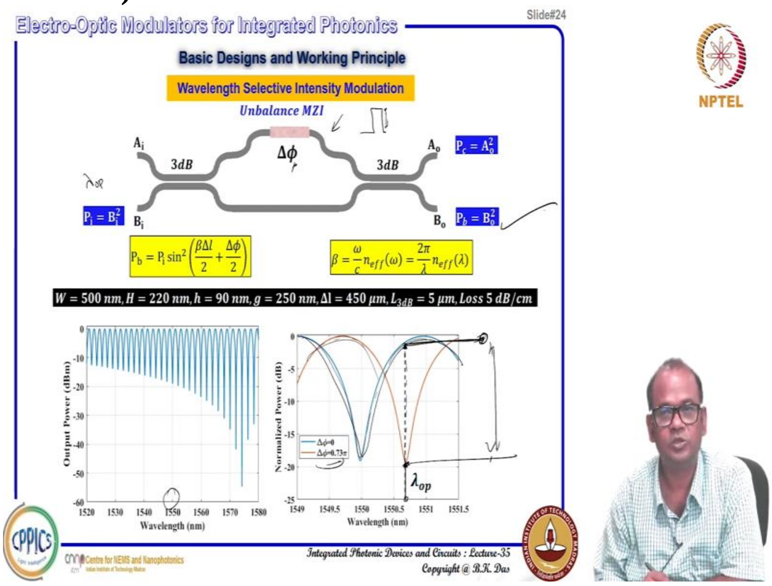

But for the moment let us concentrate only on one output. So, if you just take from 1520 to 1580 nanometer was 16 nanometer periodically you get see in the one of the output but you are considering for example in the cross port or bar port we are considered. So, you see this one that this is the thing 1520 to 1580 nanometer are considering you little bit zoom in around 1549 at this region you zoom in then you get this is the output 20 dB.

So, this is considered as a bar port for example. So this is about 20 dB considered means it is actually in the bar port. So we are just following in the bar port output if you are launching here that means this is your bar port this is your cross port. So bar port transfer function that will follow here this function and because you are using some kind of phase delta phi here because that will be this delta phi you have to control for your data purpose.

So, if delta phi = 0 then you get this type of transfer function according to the all the other parameters given here. Now you zoon in you get this one and when you get this one you see this is the delta phi 0 curve. Now if you give a little bit of phase shift here delta phi 0.73 pi then this transfer function will move to this one. Now suppose your lambda operating wavelength is set here around 1550.5, something here lambda.

So, when no phase is there you supposed to get laser power up to here this is your output transmission but when this delta phi comes here then transfer function moves your transmission drops to here that means you can have your output this level to this level. So, when there is no phase you supposed to get a power level here transmission is close to 0 dB that means normalized 1 if it is 1 milliwatt close to 1 milliwatt input is 1 milliwatt close to 1 milliwatt you are getting.

But whenever you are just tuning phase here in 1 of the arm then your power transfer function is moving then you are getting drop. So, if you can tune delta phi between 0 to this much phase 0.73 pi then your power can go on off like this. So, it can get an intensity modulation but you can find out what is the phase for if delta pi is corresponding to 0 bit and delta pi corresponding to 1 bit this 1 bit the voltage height.

If you are just considering this as 1 bit this voltage height should be some voltage or current flow or whatever should be such that it should give at least 0.73 pi phase shift then you can get this type of intensity output or the bar port here so that will be digital modulation.

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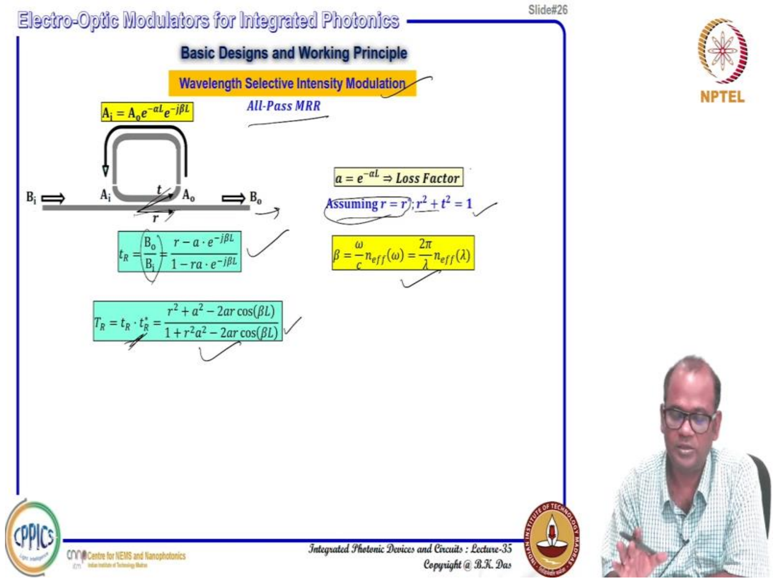

So, similarly similar type of design one can get you know this kind of wavelength selective intensity modulator for all pass micro ring resonator you know we have discussed also the amplitude transfer function beta l or l is the parameter length and this is the round trip things and this is the intensity transmission here that is actually nothing but B 0 / B i B 0 by B i. And then take their complex conjugate then you get a power transmission or intensity transmission beta again redefined.

And here we consider this is the throughput coupling and this is a cross coupling t. So, that we assume that it is a real that coupling coefficient is real and r square + t square = 1 and loss factor a we defined already when we discussed about micro ring resonator to minus alpha l file just reproduced here to show that how micro ring resonator also can be used useful as you photonic integrated modulator.

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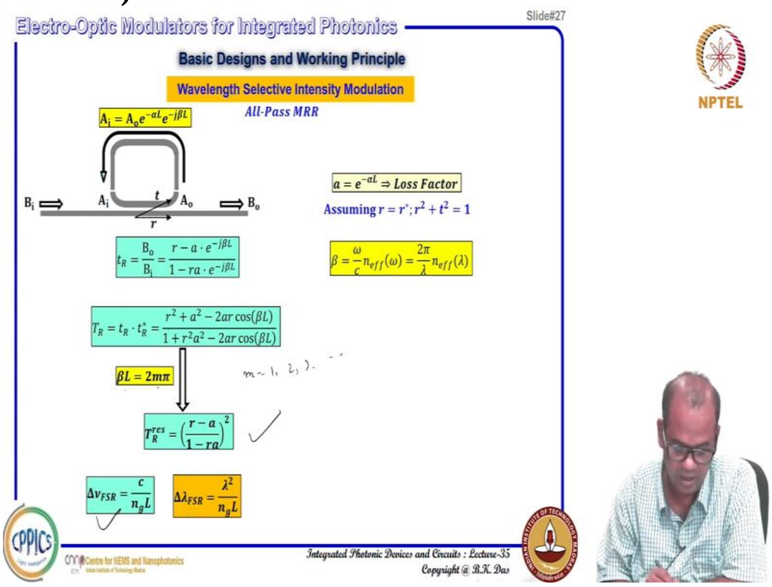

So, now you see we know that at the resonance condition transmission will be this one where beta l = 2 pi times integer m = 1, 2, 3, 4 so on and we know that also for a ring resonator this delta FSR frequent pre spectral range for the ring resonator c / n g L and in terms of lambda, lambda square by n g L that we know that earlier.

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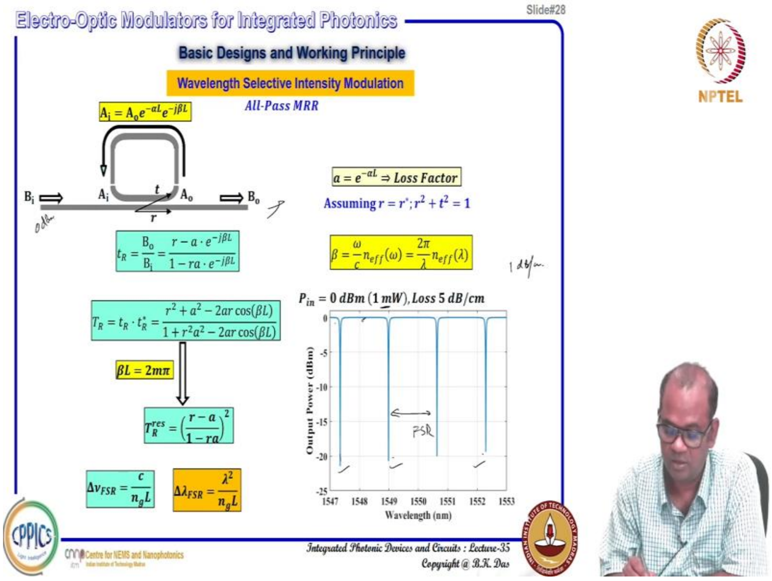

Now see as you if I consider the input here you are just considering 0 dBm or 1 milliwatt power - 0 dBm is equivalent to 1 milliwatt just 1 milliwatt you take the log scale so then you get 0 so because milliwatt we consider this 0 dBm I think all of you know that how to do that and loss again we consider the waveguide loss is about 5 dB per centimeter nowadays waveguide loss can be reduced to 1 dB per centimeter as well.

So, transmission characteristic if you see this is extinction is coming down to less than minus 20 dB everything and at resonant and wavelengths this is the so called a FSR as long as lambda dependencies you are considering this is the transmission operation and almost everything is coming out here at 0 level coming out here dBm scale we are showing here.

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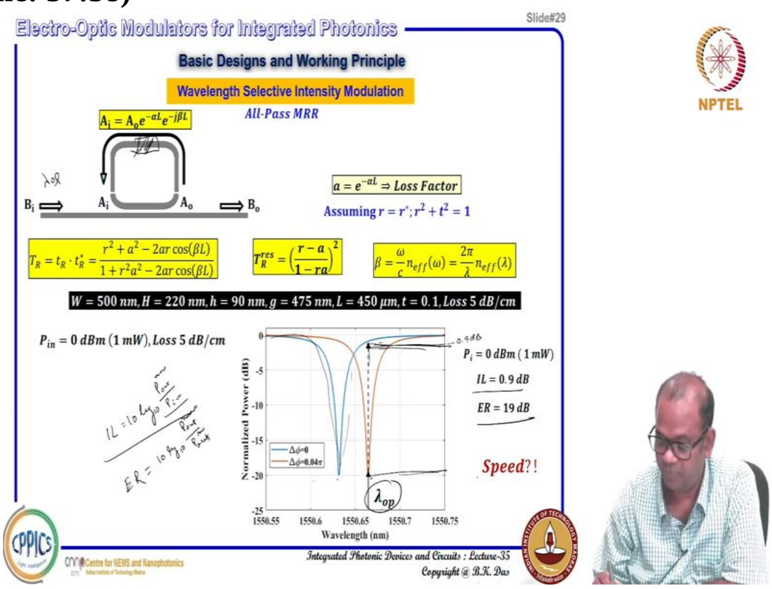

So, now if you see you have a phase shifter here for example you just consider a phase shifter. So, this phase shifter if you add only 0.04 pi then your transfer function actually tuned from this wavelength to wavelength again if you just choose if you are choosing your lambda operating here at this wavelength laser. Now for 0 phase here at this point your output level is this one and if you are giving this much pi output level will be coming down this.

So, that means; on off will be this to this level so minus 20 dB to almost 0 level we are getting. So that is actually almost 90% of 0.9 dB less from 0 to insertion loss we are considering this much. So from 0 to hear maybe minus 0.9 dB level you are getting depends on your choice of in your lambda. So that is actually insertion loss, insertion loss is nothing but actually log of 10 p output maximum by p input.

So, when you are maximum getting here and whatever you just normalize to input that is called the insertion loss and extinction loss is actually your extinction ratio not loss extinction ratio is actually log of 10 so p out max by p out minimum that is actually called extinction ratio that is 19 dB.

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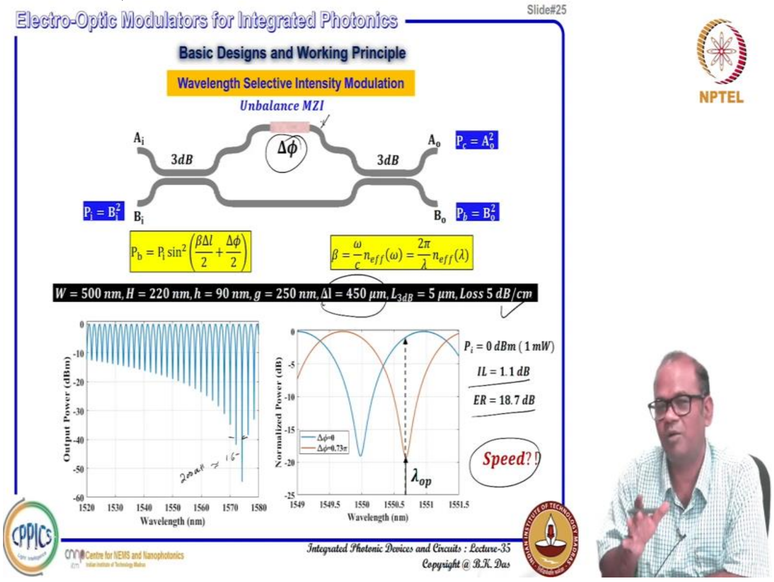

So, I see that same thing we discussed about your in case of here so it is almost similar type of thing insertion losses about 1.2. Similar type of waveguide structure will consider same type of delta l we consider in the unbalanced arm difference in arm length and micro ring resonator also we consider the ring resonator length 450 micrometer so FSR is almost similar. So this FSR we consider about 1.6 nanometer or about 200 gigahertz in frequency domain.

That is the ITU channel normally we use that any ITU channel if you use and at this around disabling that will be intensity modulated with extinction ratio of 18.7 dB. But one thing is considered speed how fast you can switch this on off that actually depends on your how fast you can encode your data that means this delta phi change you need to do how fast you can do faster you can do your data encoding will be very fast.

So, you need to find out what is the technology problem what is the material related problem? What limits the speed that is most important part of the modulator design especially for photonic integrated circuit when you are talking about CMOS compatible silicon photonics. So, l will be discussing later on what are those mechanisms in future classes. What are the modulation mechanisms?

How this delta phi get changed from 0 to certain value? That depends on your applied voltage into the waveguide or certain amount of current flow into the waveguides carrier change or whatever what all those mechanisms are there we have to discuss first and then how the speed is limited how much maximum speed you can achieve by a certain design of modulator structure.

So, here today we have discussed that waveguide design what type of architecture device architecture we can use for your amplitude modulation or phase modulation. And later on I will just come back to discuss about what are those mechanisms and what are the speed limit and how you can achieve a maximum possible efficiency merits compactness and also require voltage lower voltage or higher voltage as small as voltage required. It is good and all those types of things we will be discussing in the future classes. Thank you very much.