Integrated Photonics Devices and Circuits

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Lecture - 37
Electro-Optic Modulators for Integrated Photonics: FCCE Based Silicon Photonics Modulator

Hello everyone, so in the last lecture we have discussed about various physical mechanisms for realizing integrated photonic modulators. And we have also explained that this free carrier concentration effect actually is the most important one and using that specially various types of silicon photonics modulators have been demonstrated and very much popular these days for photonic integrated circuits particularly for optical interconnect applications.

So today we will continue to some of the demonstrated devices silicon photonic devices means silicon photonics modulators. What is their design principle that means design parameters? And of course, how they work what sort of principles what type of design architectures, people are using and various type of performance metrics also for silicon photonics modulators will be discussed today.

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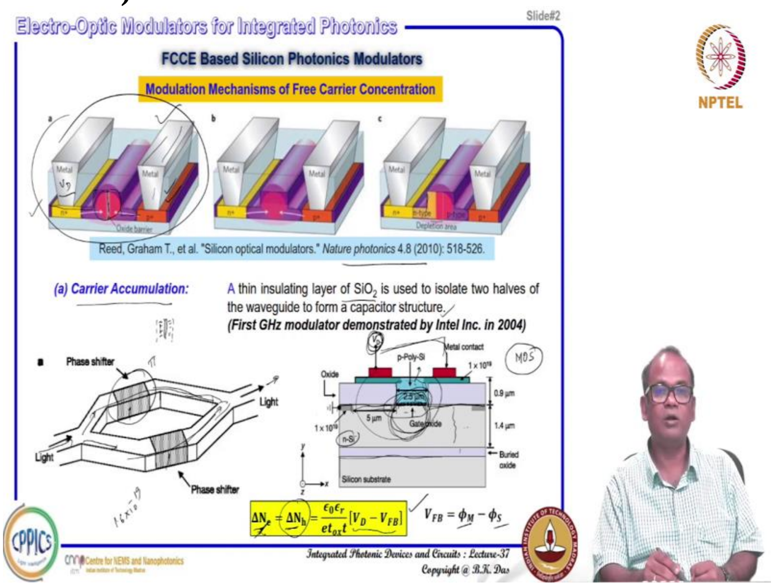

So let us try to see that, what are the main mechanisms used for free carrier concentration for exploiting free carrier concentration? So first thing is that I have taken 3 representative cartoon figures from this paper it was actually published in nature photonics in 2010 by GT Reed who is actually one of the pioneer figure for silicon photonics devices and circuits the first one is this one. So if you just carefully look into it this is your actually Reed waveguide structure if you see here this is your Reed waveguide structure shown here.

And in the slab region, you see this side is actually p type doping p plus means it is moderately doped and top of that you can have a metal structure. So that you can access you can make a contact with the p plus and you can also have n plus and you inside this is actually can be your low doped regions and in between you can have the oxide barrier very thin layer of oxide barrier.

This is one type of the structure and then another type of the structure it is actually simply similar basically but this thin layer of oxide is not there. This is your guided mode it is shown with some red spot here and here also it will be also guided mode will be there. So in this case, the only thing is that only difference same thing only difference is that thin layer of oxide is not there and another type of structure which is actually a pn type waveguide structure.

So this is your waveguide of course and one side is p type this is a diode basically pn diode so, p type p plus doping for contact and then p type doped and then another one half it can be n type doped and then n plus you can make a contact also there. So these 3 different types of device architectures today used for demonstrating high speed modulators, I will discuss one of the render.

First let us concentrate on this one that is called carrier accumulation. So this thing is called this type of waveguide structure or modulator structure it is actually works in the principle of controlling carrier accumulation in the waveguide region. A thin insulating layer of silicon dioxide is used to isolate 2 hops of the waveguide to permit capacitor structure. Now if you see this cross section a little bit more elaborately then you can see that one of the demonstrated devices using this structure it is shown here.

Actually you have the silicon substrate here up to here this is the silicon substrate and then this is your box layer of course this box layer not shown up to the scale and this is your what you call that small layer of box here it will be there, but here this region is n type doped silicon substrate. So this is a silicon substrate and then a thin layer of oxide gate oxide very thin layer and then you can deposit poly silicon.

Poly silicon you know poly silicon can be used as a gate material gate metal and then you can actually make a contact with the metal here. And you can apply voltage here and this metal contacts both sides you can actually apply voltage. So if you apply a voltage what happens depending on the voltage positive or negative you can see both sides of the gate oxide you can have charge accumulation.

So one side will be positive charge and other side will be negative charge accumulation. This is something like a similar type of structure like metal, oxide, semiconductor structure. So if you give a bias you can actually accumulate free carrier around this gate oxide both side and if you withdraw the voltage then your carrier will be removed. So as you know the in the previous lecture we have discussed depending on the carrier concentration refractive index can be changed both real part and imaginary part.

So in this case these people they exploit it basically real part of the refractive index. So if you analyze the metal oxide semiconductor structure, you know that the carrier accumulation either electron in one side and holes will be other side positive other side their carrier density will be identical and that can be expressed by this equation. What is that? Epsilon 0 r this derivation I am not giving you because the any of the solid state device books this type of formula always will be there.

If you are interested you can just learn from there and here I have just taken the expression directly. So epsilon 0 r epsilon 0 is the permittivity of the free space epsilon r is the relative permittivity or dielectric constant and e is the electronic charge which is nothing but 1.6 into 10 to the - 19 coulomb and t oxide is the oxide thickness here using this layer oxide thickness and this t is nothing but your thickness of the what you call that.

So gate oxide layer thickness and this t is the thickness of the r. Now I remember so, t oxide thickness and this t is the thickness of the layer where this charge is being accumulated. So if you have a thin oxide layer then both sides this side will be positive holes will be accumulated this side will be negative accumulated but you will get an effective thickness both side if that thickness is basically t small t then your carrier concentration is inversely proportional to that thickness.

And also inversely proportional to gate oxide thickness inversely proportional to your electronic charge and directly proportional to the dielectric constant and you have this is the voltage. Where V D is the applied voltage you are given here either from this side this is your V D you can say with respect to the other side you can have V D and V FB is the so called flat band voltage is nothing but basically work function difference between metal and semiconductor.

So metal here it is this poly silicon been used as a metal it is a conductive layer and semiconductor basically this is the n type silicon you are considering and they are work function difference is called flat band voltage. So if you can apply the bias voltage over the flat band then you can see your carrier concentration is going to be changed can be accumulated carrier can be accumulated here in this thing and you know waveguide how it is designed? How waveguide is happening?

It is like a Reed structure you see this is your silicon layer and the top of it is a poly silicon that means including poly silicon you can have your waveguide structure. So Reed region is a poly silicon and bottom region is your silicon substrate. So your waveguide mode will be just like this here it will be confined the waveguide mode and it has been shown that about 9% of the field distribution is penetrated into the poly silicon because, you know, poly silicon is like a metal if it is more field is penetrated into the metal you can experience a lot of losses.

So that is why it is designed such that majority of the guided mode will lie in the silicon and type weakly doped silicon surface is there and here a small portion you have heavily doped so, that body can be grounded. So that whatever the voltage you are applying here with respect to the ground and body is grounded and this one this 2 things can be actually connected sorted here.

So that both side you can apply voltage and depending on the voltage charge carrier will be accumulated here. So that amount of carrier concentration you can just find out this one of course, here if you see this carrier is not carrier concentration has been changed but not entire field profile of the guided mode. So that is why this effect is relatively small though but it was the first time actually demonstrated giga hertz modulator that means, this carrier modulation that means accumulation and non-accumulation that speed can be very fast.

You can just attract carrier and then refractive index change and you can remove the voltage the carrier again will be relaxed and then your refractive index will be changed and you can see the phase modulation. So you can use this type of structure in arms of the Mach-Zehnder interferometer. For example, 3 dimensional view your light is guided here and it will be splitted into 50% here 50% here and it can have both side phase shifter but you can utilize one of them.

So that because you know there will be certain kind of losses even in the absence of voltage and one of the arm you can see that the light wave propagates directly they will be equally attenuated. So that equal amplitude comes here and they will be constructively interfering it will reproduce very constructive interference light will be there. So when you go for on a condition that means, if you are just introducing phase shift by changing your V D changing your carrier concentration that means you can get destructive interference.

So your extinction will be very large on off extinction will be very large because the on off extinction to be large it is mandatory that both the interfering wave this would be of equal amplitude. So that is the reason the phase shifter you are integrating here and also phase shifter are equal same phase shifter integrated here, but you need to give voltage only in one of the arm. So that you can actually change certain kinds of phase in one arm you can get a phase difference and phase difference you can modulate and you can get like modulation output here that is what we have discussed earlier how Mach-Zehnder interferometer works.

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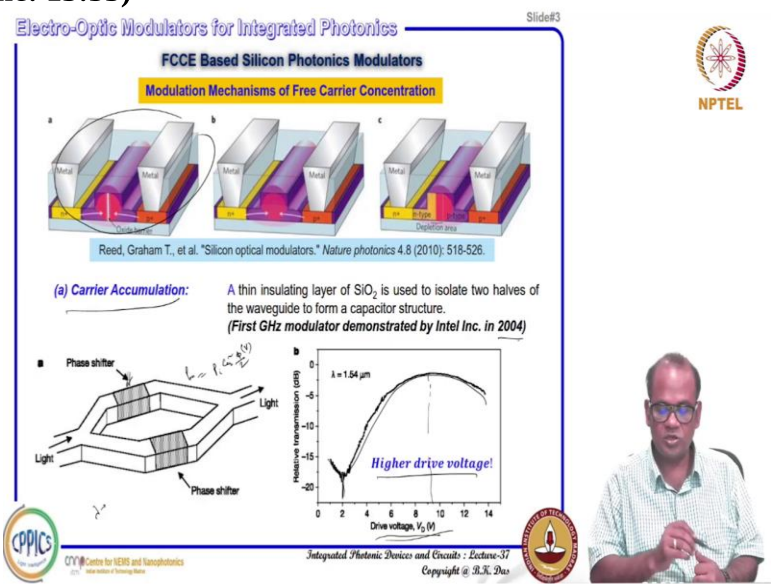

So if you see that as a function of drive voltage here drive voltage in one of the arm I am just discussing only this part here carrier accumulation you can get a carrier accumulation of this type of thing but the structure I have shown here this device I have shown here that is actually first demonstrated modulator silicon photonics modulator using this MOS capacitor type architecture. So here if you see as you increase the drive voltage so, because of some kind of imbalance it is you expect that depending on the voltage.

Normally the function of voltage it is almost proportional refractive index is carrier concentration variation is proportional and we have seen from the router model so, Bennett model, empirical model that refractive index is more or less proportional to the carrier concentration. So I can say that the refractive index change is proportional to the voltage and voltage refractive index when it is proportional to the voltage that is fine and also phase change also will be proportional to the voltage when lambda is fixed lambda h constant.

So in that case you are here output will be pi cos square pi whatever the phase difference is there pi / 2 so that means it as a function of phi. Phi is a voltage and it is almost linear to the voltage. So that means pi increasing means your output here that will be pairing as a cosine function cos square function. So it is seen that it is almost like a cosine function is increasing so as a function of voltage you can see this one but if you see that from maxima to minima this is maxima minima.

You will see the voltage difference is more than 8 volts 7, 8 volts or so, that is a higher drive voltage though but since it is a carrier accumulation and carrier deaccumulation you are happy we are creating and in this way they could demonstrate a first gigahertz modulator in 2004 that is by Intel of course. Intel with its advanced technology they have demonstrated this type of modulator so carrier accumulation that is gone.

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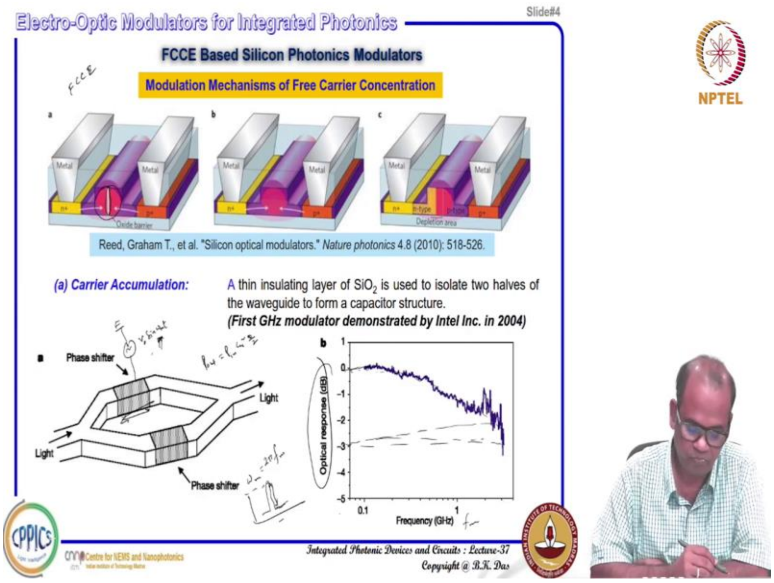

And then this try to see that if I say normally this is as I mentioned that p output will be equal to p input cosine square pi / 2. Normally if you see your modulation frequency, suppose you are giving a modulation frequency here. So and this one it is grounded and this may be dB or sin omega t or giving sine omega m t modulation frequency and depending on that your phase will be modulated and as the phase modulated your light intensity will be modulated so maxima minima.

So that means high you can go constructive interference and destructive interference how fast you are modulating them that is decided by the modulation frequency omega m. So as you increase the frequency modulation frequency of course omega is nothing but 2 pi times fm. So this is fm for example linear frequency and you see that optical response, optical response means you have to see that this is a minima and then if you are going maxima and minima.

Because this is your destructive interference and this is high intensity if you are giving that it is a high intensity and this is low intensity this variation is actually extra modulation response optical response I would say modulation depth. So this modulation depth you can that is actually called as your optical response. So this optical response actually can vary as a function of frequency. Because, you can think of that as frequency is more and more the carrier movement may not be that fast that cannot follow that frequency.

That is the reason the modulation depth or optical response is going to be changed. So that is how you say that the modulation response is slowly reducing this is the experimental results. So at least you see that this is the normalized value that means highest extension and slowly,

slowly as you keep on increasing frequency the extinction will be reducing and this if this is the 3dB this is your 3dB up to 3dB because of the limitation of whatever the modulation signal of that frequency and photo detector response etcetera.

So they have shown up to 1 gigahertz and up to 2 gigahertz 3, 4 gigahertz but if you see it could show the bandwidth in order of gigahertz 3dB bandwidth is more than 1 gigahertz. So that was the first demonstration of gigahertz modulator using FCC that means free carrier concentration effect by modulating carrier concentration in that guiding region they could demonstrate gigahertz speed modulator for the first time in 2004 by Intel.

So but the problem is that in this type of device that your voltage requirement is very high and also the length is also very important because refractive index is changing because you know that if you are even if you are considering this thin layer the carrier concentration is changing only very small region but waveguide mode is spreaded over large distances that is why your effective change of refractive index or overlap of the carrier concentration with the mode is very little.

That is why you need a very long length of the in the millimeter length of the waveguide for the required phase shift that is actually drawback for these things. But nevertheless it showed a path that if you can control the carrier effectively then you can go for a very high speed modulator.

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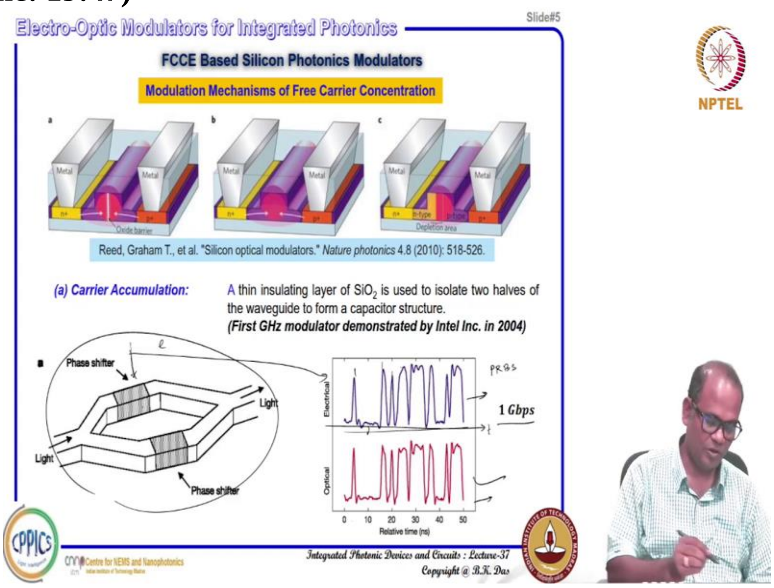

So next there shown also how they for example they have used a PRBS Pseudo Random Bit Stream they have used and they try to see if you are electrical here you are giving this signal. That means your phase shifter is responding like that because this may be 1 than 0, 1, 1, 1 than 0, 1 and so on if your data streams are like this this is as a function of time then according to your data stream your phase will be modulated.

And according to your phase modulation your light intensity will be changed they have shown that they are actually almost one to one replica you are getting this is your electrical signal and this is your optical signal and that is how you can say that electrical signal is converted into optical signal. So that is how you can transmit with the optical frequency that is the role of the modulator basically.

So they could reproduce up to 1 Gbps the bandwidth is more than 1 gigahertz and then pi the optical response optical on off output that is your digital data you can encode very nicely up to 1 Gbps. So first gigabit per second transmitter optical transmitter they could demonstrate for the first time.

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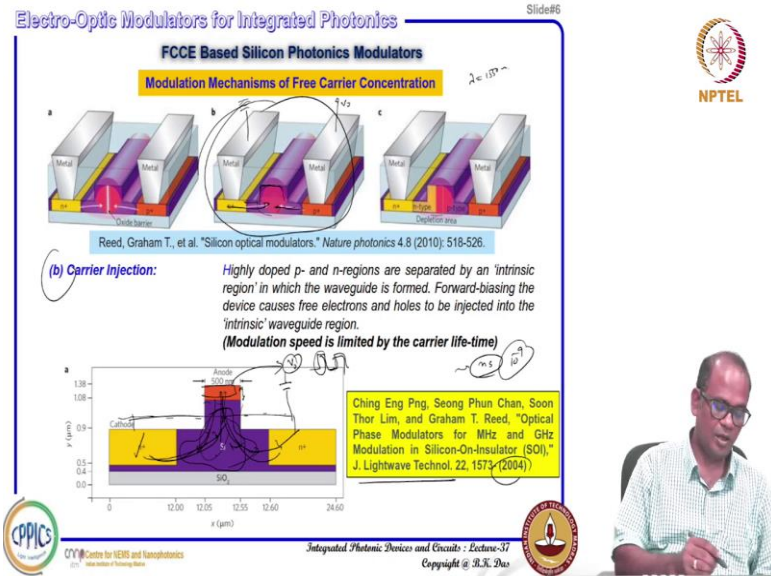

Now, next type of things that is called carrier injection so this is a model I am talking this is the device architecture. So this is same p type doping, n type doping that is fine but no oxide layer this region is completely intrinsic. So intrinsic means when you are not controlling carrier you are not injecting any carrier the light will be documents around say lambda = 1550 nanometer wavelength. So that wavelength actually it will see like intrinsic silicon it will be guided like a dielectric material medium.

So no attenuation nothing will happen no refractive index nothing will change now if you give you a forward bias suppose you are giving a positive to this one this you are giving positive V 0 and this may be you are grounding or negative terminal you can connect here then what happened because of the forward bias hole will be injected this side and electron will be injected this side.

So you can by giving a forward bias you can inject a carrier you can enhance carrier both the sides you can increase your electron and from this side you can increase your hole and you know electron and hole both can change your refractive index. So that actually demonstrated with this type of structure for example actual real device when they demonstrate it you see this is the Reed waveguide structure here that is intrinsic region when light will be guided here confined guided mode will be here.

Once it is the p type doping in the top is a slightly very small thickness you have doped with a p type material and both side n type doping. So this 2 things you can ground it you can have one terminal confine it and here you can put your positive bias here you can connect your positive bias. So you can give a positive and then you can connect here and this one can be connected with an oxide layer it is not shown here.

So in that case what happens hole will be injected this side and this side it will come this side it will come and electrons will be going from this side to this side because of the bias condition. So in this process they could demonstrate megahertz to gigahertz range modulation but it could not be increased. The modulation frequency could not be increased the reason being you know it is like a you are injecting carrier you are injecting carrier from this side to this side.

Now, when you are withdrawing your voltage where those carriers should go the carrier you are not again pulling back what happens these injected holes and electrons they recombine that recombination lifetime takes a time it has its own lifetime for a given semiconductor if you have certain kinds of carrier density per electron and hole excess carrier you can create that excess carrier once it is generated they will actually try to recombine and it will take its own speed time.

And that time is in the order of say nanosecond 10 to the bar - 9 or something. So maximum if you want to give suppose you want to give a digital data for example, this one. So if this data coming and you have injected carrier now, this next data you can say 0 you have to wait until those carrier have injected this would actually recombine then all the your next beat can come that is how your modulator speed is limited by the carrier lifetime.

Nevertheless that was a very nice demonstration. It is also demonstrated in 2004 up to gigahertz modulator but so far I remember in this paper if you read and that is Ching Eng Png et al they have actually demonstrated this device with some kind of theoretical model and they showed that theoretically by simulation laser they showed that this type of modulator can go up to gigahertz range but again it cannot be not beyond that.

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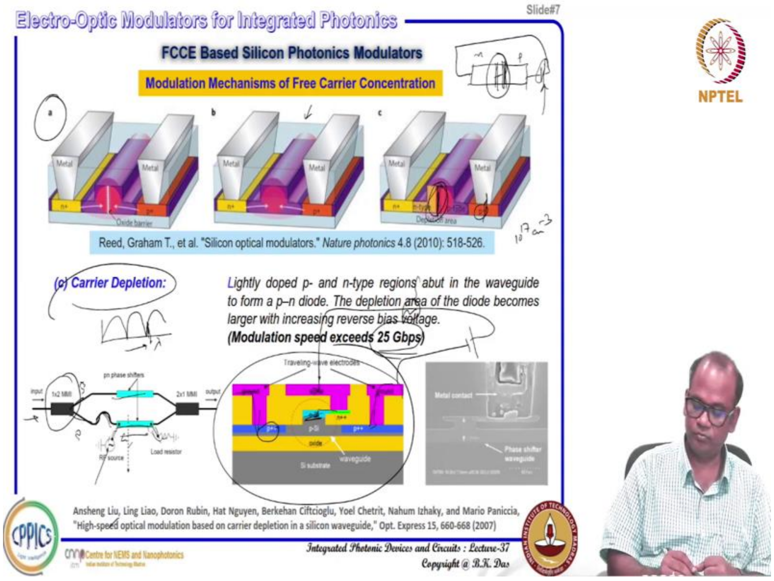

Then another type of modulator that is actually carrier depletion. So A is actually what I said that carrier accumulation and this one is the carrier injection you are injecting by forward bias and then depending on the forward bias on off you can actually control the carrier you can modulate your signal real part of the refractive index and you can use a Mach-Zehnder interferometer, the another type of structure if you just directly make a pn junction.

This is a heavily doped for contact purpose p plus and they likely doped p in the order of 10 to the power 17 centimeter cube and another half n type. So you have a junction in the semiconductor diode junction is there just particle to the waveguide cross section. This junction region you know any diode whenever you make a p type and n type, so, one side is suppose this side is p type doping and this side is n type doping then in the junction region in the metallurgical junction region.

You can see that hole will be diffused to this side and electron will be diffused this side and you can get a depletion width and in the depletion width normally there is no free carrier only ions will be there. So because there is no free carrier but ions will be there so, free carrier's absence means there is no refractive index change. Now, if you can just control the bar you can just depletion region always you know that you can have a diode and if you give a reverse bias suppose you are giving something this is negative and then positive.

You are giving here then what happens if you are giving a reverse bias this depletion region also will be increased. That is also you can find any semiconductor device book that because of the reverse bias your depletion would actually enhanced now, you can increase the depletion width and you can decrease the depletion width by controlling the reverse bias voltage.

So this can be your data. So depending on your electrical signal that how much reverse bias you are giving high or low depending on that you can modulate the depletion width. Module or the depletion width means actually you can modulate the carrier overlap with the guided mode. So free carrier overlap with a guided mode. So that way actually you can control the refractive index carrier concentration is changing and the overlap also concentration is in the waveguide mode region it is changing then you can see some kind of phase change.

So these guys this Liu et al they demonstrated in 2007 that Mach-Zehnder interferometer they have used a multimode interference 1 is to 2 1 input 2 outputs instead of directional coupler they have used multimode interference coupler where 50% goes here and 50% goes here. And they again put a phase shift on both side if there is any losses because of the imaginary part of the refractive index change identical phase shifter they fabricate.

But one of the phase shifter they are giving a RF source and they are using a load register because this length is sufficiently large. So it is like a transmission line signal goes your travels here and comes back here to a load distance so, that any RF signal that should not be reflected back from it is a kind of transmission line you are just terminating with impedance matching.

So that way they have done and they have used additional arm length that means they are unbalanced Mach-Zehnder interferometer you know in the unbalanced Mach-Zehnder interferometer we have discussed earlier we are actually we have shown that your transport function can be also like a cosine function. So as a function of wavelength you will see that the transfer function will be like this as a function of lambda.

So if you operate at a particular lambda and then if you just change a phase then you can see that the transfer function that means the output will be changing high to low high to low that we have discussed earlier how it can be done but that high too low that phase change mechanism is here is the depletion carrier depletion you are depleting the carrier then you are changing because you are reducing the carrier that means the refractive index is increasing. That means phase is increasing in one of the other arm is not.

So in that case you could actually demonstrate a very do high speed modulation and data transmission they have shown up to 25 Gbps. So this is the waveguide cross section here for this phase shifter you see p plus plus and they have taken a wire for grounding and this side also they have taken grounding and central region in the top layer n type doping and bottom layer is p type doping.

So even though it is shown like that but here the junction is in the horizontal direction so that means you are giving n plus plus you are giving a bias here and these 2 you are giving a another bias this p type so, you are connecting this one to negative terminal and positive terminal you are connecting here. So that means reverse bias case is happening now, you just give your signal somewhere here that is your data and this depending on the data high low high low voltage actually you can control your reverse bias here. And you can control your carrier concentration in this region which is overlapping with the guided mode you can see your phase change and you can see your modulation output they could send the 25 Gbps data.

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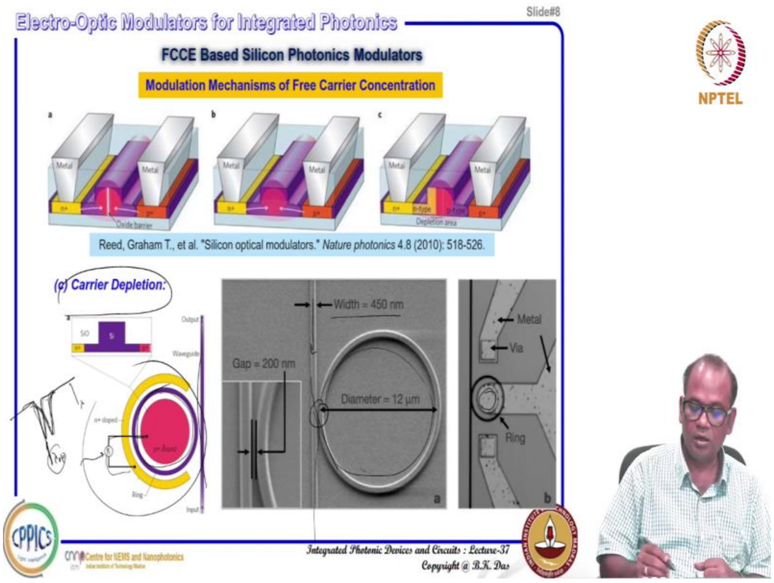

So this is another type of structure they have demonstrated with carrier depletion that is actually ring resonator. So you know earlier we have shown that this unbalanced Mach-Zehnder interferometer you have used wavelength selective modulator or a ring resonator type structure also you can use as a modulator wavelength selectable laser. So you have to if your ring resonator has having a resonance not like this you can use a wavelength here an operating wavelength lambda op.

And then if you tune you can change the refractive index it can change the phase of the ring this is your ring waveguide, this is your box waveguide and this is p type doping and this is n type doping and you are giving a signal here you can give a reverse bias then your data here. After the reverse bias and data then you can actually modulate this thing you can modulate here you when you are applying voltage transfer function goes here and you are not applying voltage transfer function goes here.

So if you are laser operating here that means when transfer function is here, that means you can get a high transmission and when transport function comes back low transmission so, you can get an intensity modulator only thing is that your modulation depth. It is actually you can control you can actually modulate a wavelength which is actually close to your resonance wavelength.

So that is how you call it as a wavelength selective modulator so that means you cannot use your wavelength somewhere here which can be modulated with this ring resonator you need to have a wavelength which is close to the resonance which must be closer to the resonance so that you can tune a little bit of phase shift that means you can go for intensity modulation. So here also they have demonstrated using same carrier depletion earlier example we have shown Mach-Zehnder interferometer unbalanced Mach-Zehnder interferometer.

And here are just microring resonator, some of the structure if you see 12 micrometre diode ring very nicely fabricated this is the mass waveguide and waveguide width is about 450 nanometer and in this region how ring and this mass guide is connected. So if you are launching here then the light will come here and little bit it will recouple and it will be circulated and circulated comes back here.

And then you can see that modulator output and some of the electrode structure etcetera it is shown here contact pads that the central region how it is dope and to the outer region how you get back in contact. Of course there are all the process in the top there will be oxide you have bias and metals everything will be there. And you can understand if you want to learn a little more.

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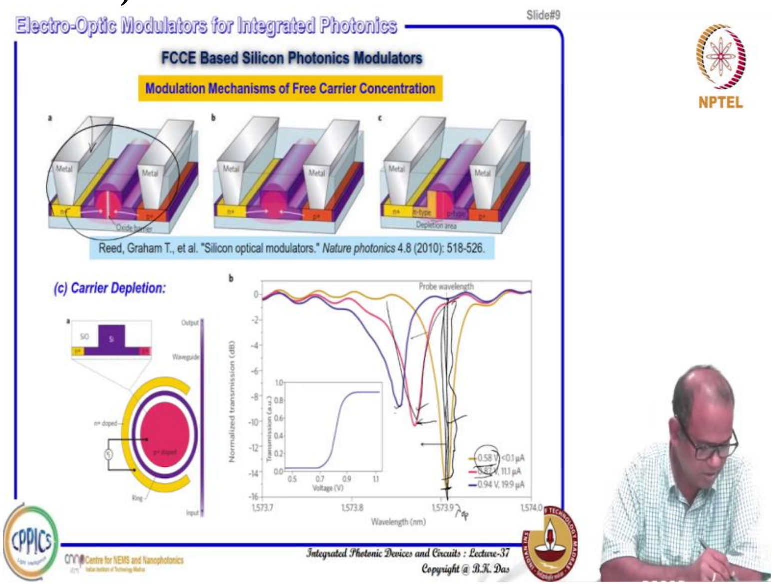

Then you can actually take a paper that is actually published by Lipson et al I think it is published in 2007 from a Cornell group. Professor Michal Lipson, her group actually demonstrated this kind of modulator the beauty of this modulator is that it is very compact. It is very compact because it is 12 micron radius if you go for this type of modulator for example this type of modulator this length is in the order of some millimeter or something like that.

So if you use your ring resonator the first time they say that a very small footprint micro ring resonator they have used for modulation purpose. So it was very promising and today I must say that most of the optical interconnect transmitters and also the receiver end for demodulator purpose demultiplexing purpose people are using a fairly micro ring resonator because of the footprint alone.

And you can although it is actually wavelength dependent; but you can use a series of micro ring regenerator each of them can modulate each of the different colors and you can multiplex them. So it is kind of WDM interconnect can use for data communication chip to chip within chip and also even rack to rack extra those type of transmitters are nowadays available actually commercially also available.

So here the actual device when the fabricated and you see that transmission characteristics whenever you are giving different type of bias voltage here different bias voltage how the transfer function is changing and they are extinction is also changing. Because, you know as you give a bias internally the waveguide inside the waveguide losses are actually modulated because as I mentioned that imaginary part of the refractive index also changed and glossy also modulated.

And because of the loss modulation your Q value also changed and extinction also is going to be changed of the microring resonator. That is why you see that whenever you have this much voltage you have transfer function here now, if you are just increasing the voltage transfer function is moving in this direction because refractive index is reducing. Because you are giving a positive bias voltage reducing this side this side and as you go for reducing the voltage.

Then instead increasing the voltage and the forward bias then you are actually injecting the carrier that transmits transfer function is changing. So that is just to see that how it can be tuned just by biasing and you see the bias voltage is very small. So that is actually the advantage when I explained the first demonstrated gigahertz speed modulator that is the accumulation type this type of structure.

There actually we have shown that then required voltage this V D here whatever voltage you are giving that is in the order of 10 volts or so, but in this case you can actually detune you can modulate the very small voltage which is actually smaller the voltage you can use your CMOS driver circuit with advanced technology and high profile driver control circuit you can design your and that will be very much useful and indeed it is being used for on chip transmitter applications.

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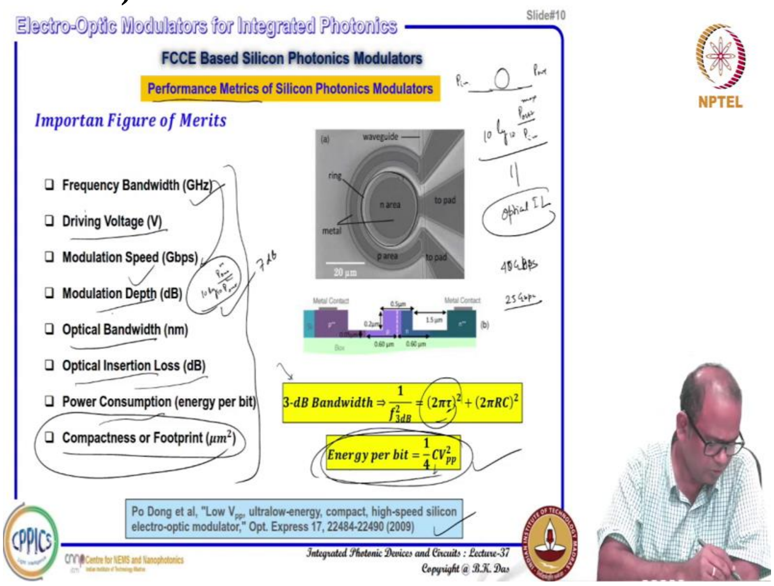

Now, I will be discussing the last thing that is most important of course ultimately you know different types of architecture different types of mechanisms, different type of wavelength selective or Mach-Zehnder ring resonator or Mach-Zehnder type different types of device architectures all those types of things you are considering so, far but ultimately at the end of the day you have to see the performance metrics.

Ultimately you have to see that the device you are designing that is useful that is energy efficient, that is high speed and all these parameters you have to think of I have listed a few parameters here that you must whenever you are designing a modulator whether it is micro ring resonator based or it is Mach-Zehnder interferometer whether it is the phase modulator based on accumulation type carrier concentration with that the phase modulator is based on injection type carrier modulation or it is in the depletion type.

But you have to keep in mind all these things that your frequency bandwidth should be as high as possible. So that I have shown one characteristics here you remember that thing. So this bandwidth that should also operate at very high frequency you should see that it should be planned coming like this. So it should not happen that at higher frequency your carrier is not possible to move as fast as your electrical signal because it is after all it is a free carrier concentration you are changing modulating.

So that modulation carrier movement that should be actually fast enough so that you can get a high bandwidth modulator when bandwidth is high you can actually send your data at a faster rate. Whether it is a different type of modulation format you can use a different type of modulation format but after all your ultimate speed depends on what is the bandwidth of your modulator so now one thing one thing is that.

Then driving voltage as I mentioned, driving voltage should not be very high and modulation speed of course that actually related to the band modulation depth. So this modulation depth as I mentioned that if you are just using here suppose your laser is somewhere here this is your lambda operating and then when you are modulating here the transfer function moves here. So then these 2 these it will come earlier it was output will be at this level now it will be going up to this level.

So this difference actually called modulation depth is defined by actually if I just say that modulation depth that is actual tan log of p max p output max divided by p output minimum to the base 10. So that is your modulation depth this modulation depth it should be reasonable amount. So benchmark is about 7 dB but many of the device we are showing that it can be done much more particularly the ring resonator these modulation depth can be very high.

But, another thing is that important that the optical bandwidth for example, if you are using ring resonator in case of ring resonator your wavelengths should be around a resonant wavelength but if you want to use the same ring resonator for modulating another optical wavelength that will not work. So, you have to choose another resonance; probably but if you are using balanced Mach-Zehnder modulator and if you are changing the phase by means up all these reasons accumulation, depletion and as well as injection everything.

S, in that case it can operate for the broad bandwidth. So whatever things you are designing we have to look into that figure of merit as well and optical insertion loss optical insertion loss is suppose if you are modulator here and then you just see that whatever the maximum you are getting suppose this is your ring resonator modulator and this is your output this is p output this is your p input.

And lambda you are making with a resonance to the ring resonator that is fine but whenever you are getting p output max divided by p input log 10. That is actually called as a what do you call that optical insertion loss is p output max by p input and you take tan log and modulation depth is tan log in p output max by p output both our output but maximum to minimum that is actually modulation depth.

And that is actually optical insertion loss power consumption that means energy per beat suppose you are sending 45 Gbps data or 40 Gbps data. That is the standard sometimes 40 Gbps data you are sending and particularly silicon photonics most of the time people are just targeting 25 Gbps for one channel 25 Gbps for that you are actually you have a driving current driving voltage all those types of things are there.

But you have to calculate that per bit how much energy is being consumed per bit transmission how much energy was spearing electrically, that is actual energy per bit that should be as small as possible people are making benchmarks up something like that femto joule per bit. So a couple of femto joule per bit it should not be more than that so, otherwise people think that why to go for optical interconnect if it is not actually meeting electrically interconnect whatever energy required there.

Because here it involves a lot of other things not only your electrical power your laser power you need to you have to pump a lot of power also, but the benchmark for the electrical power loss power per bit of transmission, it is basically calculated by this formula support you know if you are using a for example. Depletion type or most type capacitor if the capacitor value is certain value and then your modulation peak to peak voltage is V PP then energy per bit can be soon to be 1 / 4 CV PP square.

I have taken this thing this expression from this paper also if you are interested you can just learn so, that means if you want to reduce the energy consumption per bit of transmission then you need the driving voltage to be as small as possible and capacitance that means device capacitance. It is whether it is a mass capacitance or it can be a depletion diode capacitance that should be as small as possible so, that energy consumption can be low per bit things.

Of course the 3dB bandwidth I have mentioned that 3dB bandwidth actually it has a 2 component one is that how much is the reason whenever you are driving in the driving circuit you have a series resistance in the modulator and then capacitor both things are there and you know that RC constant actually that controls the bandwidth. And another thing is that if it is a ring resonator you know so, you are giving off resonance and on resonance, on resonance means light will be stored inside the cavity.

Now, whenever you are withdrawing 2 things you need to take care how first your carrier is changing carrier concentration is changing, and how fast your light stored inside the ring resonator that is being depleted that is being drained out so, 2 factor actually controls the optical bandwidth in the output. So this tau basically actually measures the time relaxation time basically depends on the Q value quality factor of the ring resonator.

So that means smaller the tau you can actually operate first that means when they store some energy whenever you were withdrawing the voltage or signal high to low or low to high whatever then the energy stored inside that would be released very fast. So you cannot get also very high Q value micro ring resonator for modulation purpose at least if it is very high Q value that means your tau will be at as high as possible that means it will try to store the energy longer time because loss is less.

So for high speed modulation you need low Q value at the same time you need extinction the resonance extinction should be as high as possible so, that your modulation depth is also high. So all these parameters are very important and after all, the last but not the least for large scale integration your devices should be as compact as possible footprints would be smaller.

So the present generation actually they are going for micro ring resonator where footprint is more though there it is basically wavelength selective. So but that is actually very future you can multiplex more number of modulator more number of ring resonators, instead of millimeter of Mach-Zehnder interferometer length, you can have 10 microns of micro ring resonators, and you can actually integrate 100s of them. So in this way one can get more benefit using micro ring resonator.

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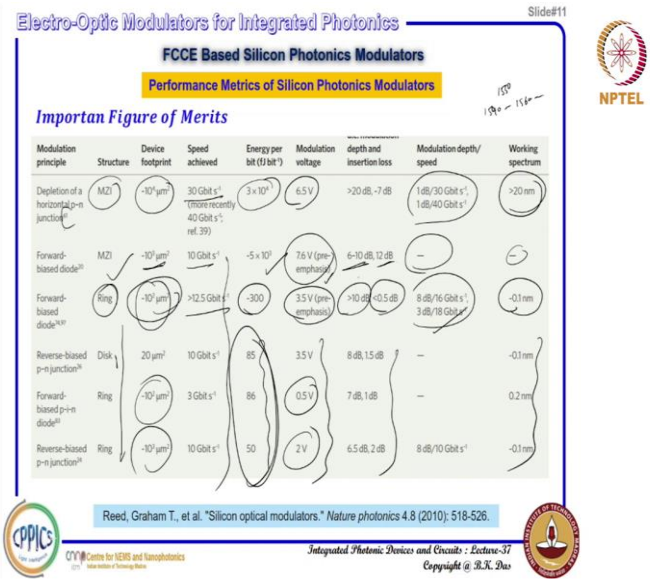

Modulation principle	Structure	Device footprint	Speed achieved	Energy per bit (fJ bit^{-1})	Modulation voltage	depth and insertion loss	Modulation depth/ speed	Working spectrum
Depletion of a horizontal p–n junction[61]	MZI	~10^4 μm^2	30 Gbit s^{-1} (more recently 40 Gbit s^{-1}; ref. 39)	3 × 10^4	6.5 V	>20 dB, ~7 dB	1 dB/30 Gbit s^{-1}, 1 dB/40 Gbit s^{-1}	>20 nm
Forward-biased diode[20]	MZI	~10^3 μm^2	10 Gbit s^{-1}	~5 × 10^3	7.6 V (pre-emphasis)	6–10 dB, 12 dB	–	–
Forward-biased diode[24,97]	Ring	~10^2 μm^2	>12.5 Gbit s^{-1}	~300	3.5 V (pre-emphasis)	>10 dB, <0.5 dB	8 dB/16 Gbit s^{-1}, 3 dB/18 Gbit s^{-1}	~0.1 nm
Reverse-biased p–n junction[26]	Disk	20 μm^2	10 Gbit s^{-1}	85	3.5 V	8 dB, 1.5 dB	–	~0.1 nm
Forward-biased p-i-n diode[83]	Ring	~10^2 μm^2	3 Gbit s^{-1}	86	0.5 V	7 dB, 1 dB	–	0.2 nm
Reverse-biased p–n junction[24]	Ring	~10^3 μm^2	10 Gbit s^{-1}	50	2 V	6.5 dB, 2 dB	8 dB/10 Gbit s^{-1}	~0.1 nm

So I want to just give some kind of overview here I have taken from this paper that is published in nature in the year 2010 long back though but this list is complete I thought of giving you an idea. Now, during last 10, 11 years it has progressed a lot a lot of advance papers are there you can find out some of the figure of merits demonstrated by different group they have shown here.

So for example depletion type some references are given in this paper 61 that is depletion or horizontal pn junction Mach-Zehnder interferometer structure footprint 10 to the power 4 micrometer square speed achieved 30 gigabit per second energy per bit you see 3 into 10 to the power 4 femto joule per second that is a large amount of power this Mach-Zehnder interferometer modulation voltage is 6.5 volt large.

And then the extents and that is very good greater than 10 dB and insertion loss is 7 dB that means input output in such a loss I have seen and modulation depth speed that means how it is rolling out the modulation that things is given here 1 dB per 30 Gbps. And working spectrum that means optical bandwidth, optical bandwidth is very large as I said that Mach-Zehnder interferometer.

If it is a balanced Mach-Zehnder interferometer then bandwidth can be very wide long wider bandwidth that means you can support it is designed for 1550 nanometer that means you can actually operate from 1540 to 1560 nanometers up to this level you can use and then another data is another device demonstrated that is 10 to the power 4 that is actually reduced that is footprint is reduced to 10 to the power 3 but at the same time speed is also reduced in 10 Gbps and energy consumption is reduced.

That is 10 to the power 4, 10 to the power 3 so as it progress you will see this is a competition going on who can actually design a better modulator. And here you see the 7.6 volt along with that some additional pulse width modulation pre-emphasis is required. And that also they have used and again the modulation depth is 6 to 10 dB that is good enough and 12 dB is the insertion loss that is a very large amount but not available I think modulation depth. It is not actually given here per speed actually not given here.

And ring resonator micro ring resonator forward bias you see the dimension reduced just 100 micrometer square and Gbps is very large energy per bit just reduced to 300 Femto joules per beat voltage requirement 3.5 volt and modulation depth 10 dB and insertion loss is very low 0.5 dB and some this modulation depth pass speed this is another figure of merit given and bandwidth is very low 0.1 nanometer as I said that if you are using ring resonator you have to be restricted very small around resonator range.

So now, keep on progressing ring resonator disk resonator people used also you see now the basically micro ring resonator that is in the order of 10 to the power 2 that means micrometers 100s of micrometers squared this is a little bit larger and you see at least 10 Gbps region and energy per bit now reduced to really femto joule per second that is the benchmark people are targeting that.

I think recently people demonstrated in the order of a couple of femto joules per bit actually these are the important figure of merit otherwise it is no way that you can actually compete with the electrical interconnect. I mean to say that how you can say that, if I use so much technology just I want to replace electrical interconnect with optical interconnect because you have so, many advantages ultimately practical device should give not just theory.

So these are the practical devices they are showing and the driving voltage is again down to 2 volt 0.5 volt that is fantastic for CMOS driver you can co-integrate the driver electronics as well with advanced technology node and all these parameters are coming within the range and quite helpful and this is the thing we can use. So with this I just closed the module later chapters. I think in the next couple of lectures I will be just discussing about how hybrid integration of laser possible in silicon photonics platform for really complete.

So that complete both light source modulator, photo detector everything can be co-integrated including driver circuits and these are the trend how it is silicon photonics technology or photonic integrated circuit technology is progressing. Let us wait for the next lecture, till then, thank you vey much.