Integrated Photonics Devices and Circuits
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Lecture – 03
Progress in Optical Interconnect Technology and Beyond

In the last lecture, we have discussed about moods law and electrical interconnect bottleneck and today, we are going to discuss about the progress in optical interconnect technology and beyond. So, we have also seen that optical interconnect for long haul communication was very successful, but we will be discussing that how it is also getting successful or short haul communication and also on chip communication just to replace bandwidth limited electrical interconnect.

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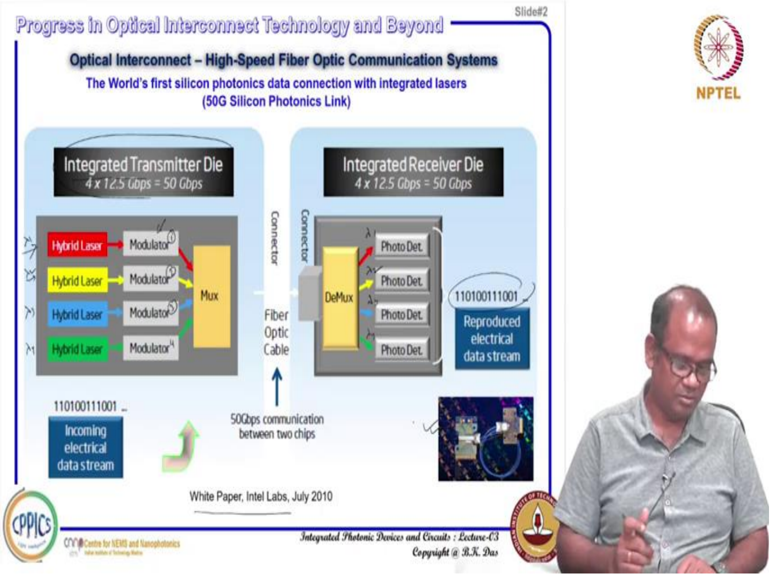

So, what are the components required for any optical interconnect? So, if you see the optical interconnect, particularly here I have taken one example of the first silicon photonics data connection which was demonstrated by Intel 50 Gbps optical link in 2010 just this picture I borrowed from the white paper from Intel labs and because this view this particular artistic picture actually gives the individual components important components is normally used for any optical interconnect.

So, here it is shown that integrated transmitter die which is nothing but 4 different lambdas lambda 1, lambda 2 this colour if you see that is basically wavelength optical wavelength lambda 3 lambda 4 red to green to red. So, higher wavelength you can say that they can be particularly sufficiently spaced and then your data comes to modulator 1 this modulator 1 modulator 2 modulator 3 modulator 4.

So, you can have parallel data stream can come to 4 different modulator where you have 4 different colors different lambda coming in and you are modulating and you are muxing them and you can use a high bandwidth fibre optic cable and you can have take the output and you can wherever you need that one you can have a integrated receiver die where you can demux this. This is the photo detector detecting lambda 1 wavelength, but what data coming in and this photo detector that this would be detecting lambda 2.

You can just separate them lambda 3 lambda 4, so, you can recover the data stream again back and this can be a digital data it soon here. So, this was the nothing new here, this type of transceivers basically people use for long haul communications, but this particular thing you need to demonstrate such that you can use short-haul communication because short-haul communication you know because of the data centres, boom etcetera you need many more such transceivers circuitry, where your cost cannot be that high it should be integrated one.

It shows should be scalable. So, you need high bandwidth, high data rate, but lower cost. So, that you can also use, you can overcome the limitation over budget etc. What is normally used by copper cabling, etc? So, that type of technology was needed and Intel developed that demonstrated that and some of the miniature modules shown here for short-haul 50 meter 100 meters also it is possible.

So ultimately, you need to know that any optical link these are the basic building blocks basically. You need laser source, you need modulator, you need mux, demux and you need photo detector and then you need electronics also. Electrons as usual you will need that. So, all these things are the components they have achieved good remarkable success in 2010.

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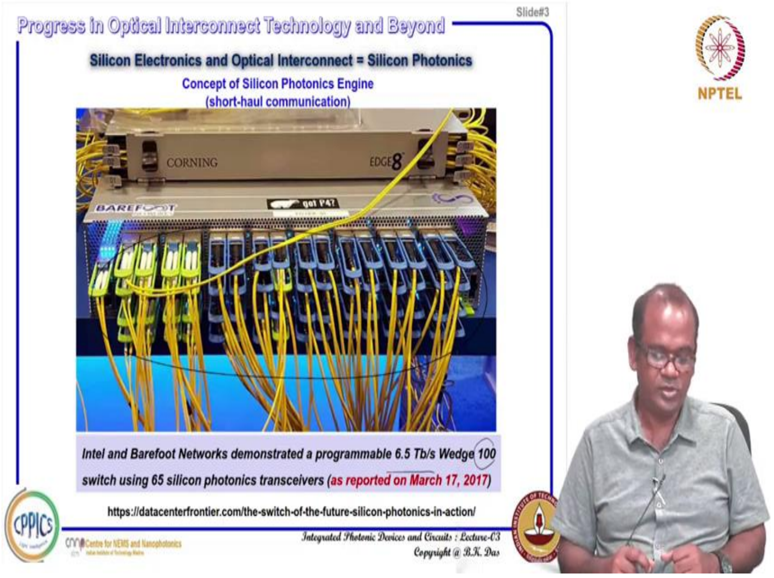

And, they have started Intel actually started the research on this transceiver development using so called silicon photonics technology. I will also discussed that in course of time what is how that silicon photonics technology also evolved separately in another lecture, but here I would like to show you that, that this transceiver actually Intel's contribution, Intel's huge investment on silicon photonics technology gave them an edge.

So, that they could demonstrate this picture I have shown you earlier just repeating again here, so, how just to give you a feeling that that how this technology is being used for a data speed of 6.5 terabyte per second different colour different switch transfer there are 65 transceivers switch made out of silicon photonics technology used and 100 switching 100 switch, optical switch also you need because you need to communicate one particular destination to another destination.

Data can be switched from one particular destination to another destination. So, that switch matrix also switch fabric also require. So, that thing already got a huge industrial success that is what this is just kind of communication within the data centre rack to rack communication short-haul communication and few 100 meters not long-haul communication. So, that has been possible because of the silicon photonics technology because you need millions of such switches across the world to be installed in data centres. So, for that your cost everything needed to be reduced and that has been successful.

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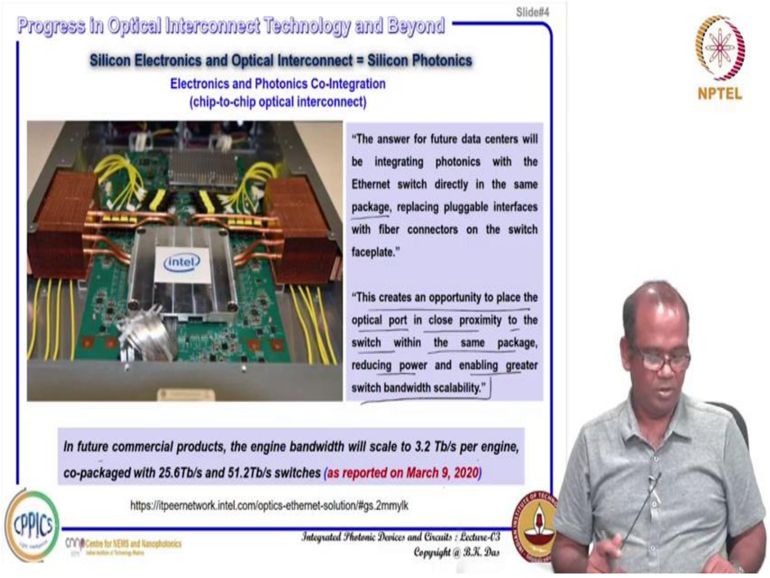

Now, well, so, just progressed going on and this is their latest thing. So, earlier they have shown that 6.5 Tbps and that is that is the lab level demonstration etc. And data centre applications for in Gbps level. But here this is their project that is already R and D successful is there. So, chip to chip communication, this type of transceiver module they have used for chip to chip communication one chip to another chip not rack to rack chip to chip.

So, they say that the answer for future data centres will be integrating photonics with the Ethernet switch directly in the same package not that you take out fibre and then take few 100 meters or a few meters and then another transceiver will be there and they are giving feedback giving input. So, instead of that, if you want to have everything within the box, you have different chip will be there at chip to chip communication.

Just you can have maybe you need only less than a meter communication, just few centimetre communication that can be also useful for fibre to fibre and you need for that actually very high data rate. So, those types of things also they have demonstrated by improving the transceiver technology. So, this creates an opportunity to place the optical port in close proximity to the switch within the same package reducing power enabling greater switch bandwidth scalability that is the future coming up.

In future commercial products the engine bandwidth will scale to 3.2 terabyte per second per engine and co-packaged with 25.6 terabyte per second and 51.2 terabyte per second switches as reported on March 9, 2020, just 1 year back report. So, here one thing you can imagine that

that you need a rack to rack communication, huge number of transceiver modules you need that is being that is being already in use.

Now people are going into the box level communication. So chip to chip communication, that is also you are just scaling up in terms of how fast you can communicate, switch and terabyte 51.2 terabyte per second. That much high speed communication so that you can process you can mine the data very fast and in no time. So, those types of things are the coming technology.

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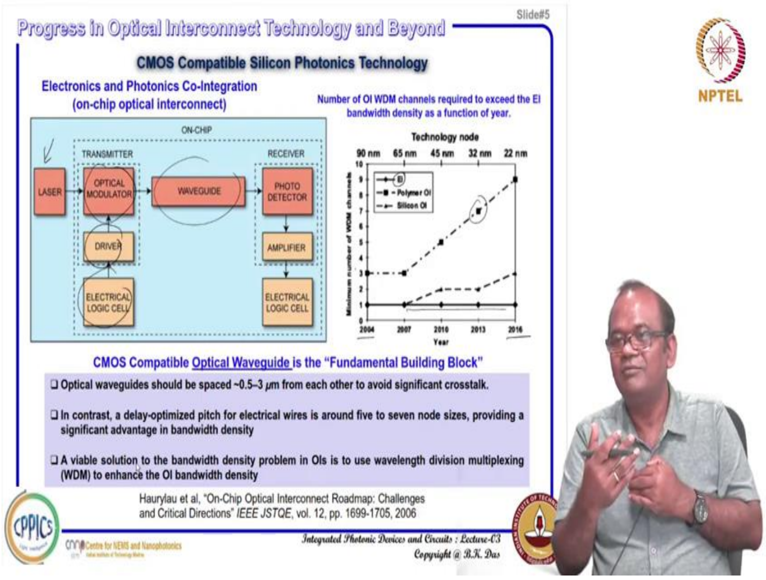

So, chip to chip. Now, the next level is that so, as I tried to give you a picture that in 1980s long-haul success of long-haul communication then in the beginning of this Millennium people try to go for short-haul communication rack to rack communications few meters to several 100 meter communication just replacing electrical copper cables and then people are thinking that within the chip for example, I was talking about wafer scale engine.

Wafer scale engine means you have entire system on chip system on wafer I would say 300 millimetre wafer. So, within that way for your interconnect bottleneck is there whether it is possible to integrate optical interconnect on chip. So, you do not need transceiver module, receiver module separately. For that communication you need to communicate one particular block of electronics to another particular block of electronics within the chip within the wafer. So, wafer scale engine can be demonstrated that is what we have demonstrated earlier.

So, here one scheme is shown how that can be possible you can have on chip you have electrical logic cell and you can have a driver electronics and on chip you can have a modulator in silicon. Silicon cannot support laser. So, laser can be optic and then within chip you can fabricate waveguide optical waveguide in silicon, low loss optical waveguide instead of fibre now, you are thinking about waveguide on chip waveguide once you convert electrical signal into optical signal that optical signal you can handle within the chip.

So, that waveguide can carry the information in optical domain and then it can send to deliver to a photo detector remotely placed within the chip within the wafer convert back into electrical signal amplify that electrical signal and feed into another electrical logic cell. So, in this way, you can actually solve the interconnect bottleneck within the chip within the wafer. So, but ultimately at the end of the day you have to see whether you are really gaining in terms of energy in terms of cost or not.

If you are not getting that advantage then even though technology available you can demonstrate no one who is going to use them unless and until it is economic. So, here it is actually one estimation year wise starting from 2004 to 2016 it is shown that y axis is minimum number of WDM channels required x axis is the year if you are using elliptical interconnect that means this curve.

We are following this solid black curve how much number of channels you need for electrical interconnect suppose 1 channel needed to get some kind of bandwidth density advantage. If you are using a polymer optical interconnect this waveguide if it is fabricated out of polymer 2004 you are using polymer waveguide you need 3 WDM channel 3 lambda 2007 also 3 to consider and then as it goes that if you are using polymer optical interconnect number of channels 5 and then 7 and so, on-going for 9 or so on.

Just to gain the bandwidth advantage by using optical interconnect or optical waveguide fabricated out of polymer but you know polymer in silicon chip in electronics chip within that it is very difficult things polymer is temperature sensitive and also it is not CMOS compatible all those types of things are there. So, it is always good if you can use your silicon waveguide silicon as you will get material. But that technology, up to your; in that case you need number of channels, much less required.

You need only 2 here 2 up to hear up to 2013 2 and then you are getting as do advanced you need more and more data communication rate then your channel can be improved to say 3 or so on. So, if you can use a silicon waveguide. So, from fibre long-haul communication to short-haul communication and then on chip when we are talking you can have 2 options one is polymer waveguide right and you can have CMOS compatible CMOS fabrication process compatible silicon waveguide in that case number of channels superior.

So, CMOS compatible optical waveguide is the fundamental building block. So, CMOS compatible that means CMOS complementary metal oxide semiconductor for example, CMOS circuit type, so, for inverter CMOS inverter circuit for logic operations or different type of logic operation when you demonstrate and IC is fabricated that they are fabricated in wafer scale by developing certain kinds of different fabrication processes.

So, same fabrication process if you can use to demonstrate this optical modulator waveguide, photo detector etc. Then your fabrication costs will be reduced. However, there are some subtle mismatches there CMOS actual CMOS electronics technology and if you want to integrate optical waveguide, optical waveguide you may not need many optical waveguides because at one particular optical waveguide can carry him he was amount of data. However, the optical waveguides should be spaced whatever optical waveguide you fabricate in silicon.

I will discuss how the waveguide can be fabricated in silicon their space need to be 0.5 to 3 micron from each other to avoid significant crosstalk if waveguides are coming closer, they will be interacting each other so, crosstalk will enhance. So, that is a problem. So, those types of drawbacks are there. In contrast, a delay optimized speech for electrical wires is around 5 to 7 node sides support if you are talking about 10 nanometer technology node in CMOS fabrication process, your interconnect separation can be just 5 to 7 node.

Say 100 nanometres 70 to 100 nanometer 50 to 100 nanometer spacing is sufficient but whenever you are introducing waveguide your spacing is needed more. So, you have to calculate that whatever gain you are getting by reduced number waveguide and bandwidth that should be more than whatever you are getting chipped by electrical interconnect. So, these are the things whenever any technology in its subject grown and getting successful, you need to go through all this process.

So, these are the things I am trying to give you all these information. So, that you can understand why this topic this subject integrated photonics devices and circuits. So, important to learn, so, they have a viable solution of the bandwidth density problem in optical interconnect is to use wavelength division multiplexing. WDM to enhance optical interconnect bandwidth you can use 1 waveguide but different lambda.

For example, here it is shown only one lambda on chip also you can think of multiplexing different lambda integrating different lasers that is the challenge in laser you cannot integrate but there are solutions also coming out.

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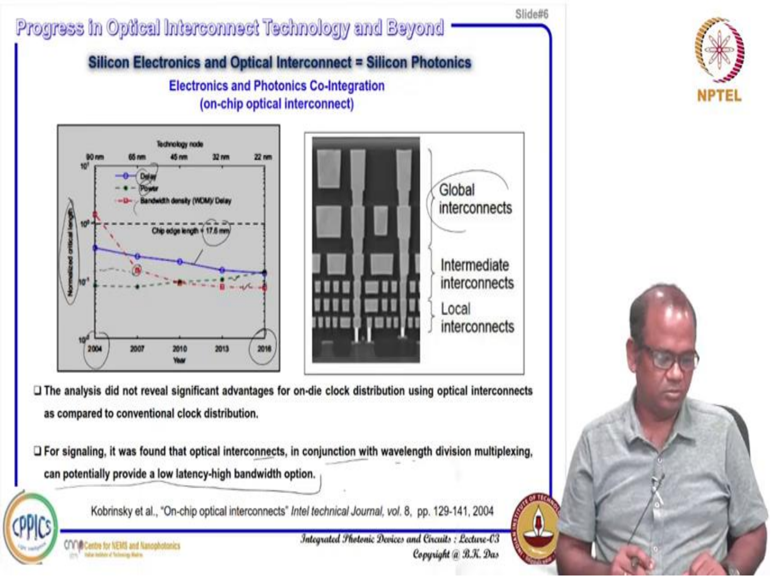

So, now, it is another estimation also from Intel in 2004 they have shown that whatever components available at that time and till 2016 whatever is going to improve in terms of laser technology, modulator technology, waveguide technology, electronics technology etcetera. Then what is the minimum length limit is possible for electrical interconnect beyond that if you use if you replace electrical interconnect with optical integrity it will be advantages.

For example, here it is shown 2004 to 2016 it is shown here 2016 this one 2004 and y axis it is shown normalized critical length of the chip silicon cheap per integrated circuit, typical chip size consider 17.6 millimetre you can consider this is the 10 to the power 0 means that 17.6 millimetre is considered 10 to the power 0 means 1 normalized to 1 here 1. So, this is you can consider this length is corresponding to your chip length of 17.6 millimetre.

Now if you have a delay power bandwidth year wise if you just see depending on the performance everything, so, delay you are considering this curve power you are considering this curve power consumption and bandwidth the density per delay bandwidth the density per delay, you were just dividing then you are getting this red one. So, if you see that, this up to in 2004 within chip you are not getting much advantage in bandwidth density WDM per delay.

Within that link, if you are going beyond 17.6 millimetres that is actually some kind of possible optical interconnect would be helpful, but as the time passes this optical interconnect will give you that anything for example, you take this data that means this is 10 to the power -1 that means, it is 0.1, 0.1 means 1.76 millimetres 17.6 divided by 10. So, 1.76 millimetre length may be 2 millimetre.

So, if you are using any interconnect beyond 2 millimetre length within the chip it is better to replace electrical interconnect with optical interconnect. So, that is how the estimation comes in. So, it is all this thing this is actually how within the chip even if it is 17.6 millimetre area the length of the chip within that also if you can use all these optical interconnect components to replace certain electrical interconnects you will get some benefit.

So, this is the thing even if you are using global interconnects bigger cross section they are not so, useful it is better to replace them with optical interconnect. So, but nevertheless the analysis did not reveal significant advantages for on the clock distribution clock particularly longer length communication needed just for clock distribution, because you need to send the clock signal for a longer distance to recover the data clock data recovery you will needed that.

For signalling it was found that optical interconnects in conjunction with wavelength division multiplexing can potentially provide a low latency. So, only one channel is not sufficient again it is re-emphasizing that multiple wavelength is essential to overcome to actual get benefit out of the optical interconnect that is a take home message and that was actually demonstrated in just 1 paper article written by Kobrinsky et al is a Intel employee basically and he has written an article on chip optical interconnects.

So, you know Intel like industry when they want to invest something they want to see the profit first. So, they estimate it and they find that this is very good and this can be think up so, they invested.

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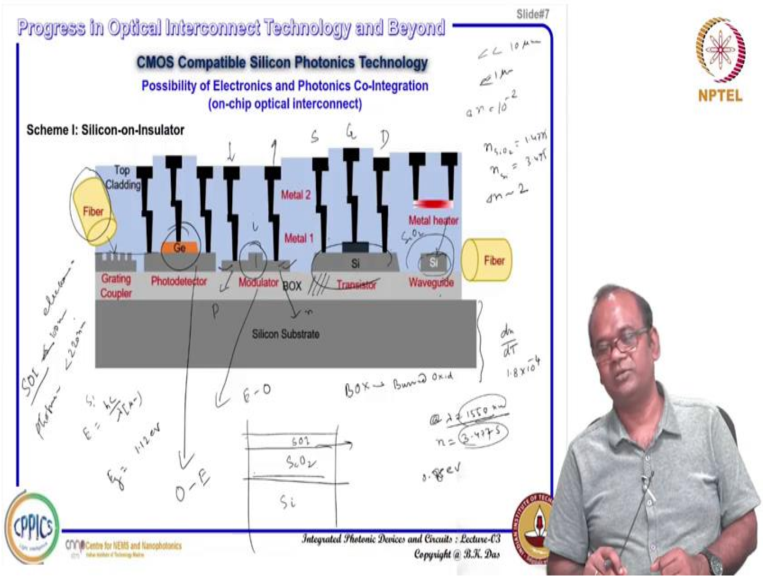

So, for on chip communications you need basically whatever the previous model says that you have to co-integrate electronics and photonics using same technology how that is possible this was the such kind of artistic view artistic sketch so that you can actually it is possible to integrate both photonics and electronics together. For example, here it is shown, silicon platform silicon laser cannot be fabricated on chip you can use your optical fiber and get certain kind of grating coupler.

And you can also use the fibre also in light you can actually say light from the top or you can sign light from the edge you can couple light into the waveguide. What is that waveguide? Waveguide basically, you know this layer in pack this is your so called silicon layer and this is your so called box layer this layer, this layer is box. So, called box means buried oxide and this is your substrate and commercially you can get such wafer as an oxide and then substrate.

So, this is your substrate silicon and silicon dioxide that is box and this is called SOI silicon on insulator. So, this type of 3 layer system wafers are commercially nowadays produced for CMOS electronics, because CMOS electronics needed this type of silicon on insulator for instead of bulk silicon so, that you can actually easily using your CMOS technology you can actually easily insulate one transistor to another Start wherever necessary.

So, this SOI wafers are used since 1990s purse CMOS industry. Same SOI wafers are you can use for co-integrating electronics and photonics as I mentioned that for photonics your optical waveguide is the basic building block what you do you have a silicon you make like this type of rectangular cross section and surrounding it is oxide. Is 2 a lower refractive index material silicon is a very high refractive index material at lambda equal to 1550 nanometer wavelength silicon actually have a refractive index of 3.477 pi.

Remember that this 1550 nanometer wavelength corresponding energy is about 0.75 to around 0.8 electron volt, if you just convert photon energy that 0.8 electron volt 0.75 to 8 you can calculate that because, the energy you can calculate photon energy you can calculate AC by lambda you can put h Planck constant C is the velocity of light lambda is the wavelength if you are using that in micrometre and then SI unit all those types of things if you put them it can be electron volt.

Any standard fundamental book if you see you can find out. So, this wavelength the photon energy this wavelength electromagnetic wave the quantum of photon energy, if you see that actually that energy is lower than the band gap of silicon-silicon band gap is equal to 1.12 electron volt. So, any photon having energy lower than the band gap that is actually transparent in silicon. So, electron will not be able to capture the photon energy and to be ejected into conduction band.

So, for 1550 nanometers silicon is a dielectric material. So refractive index is 3.477 pipe and you can have a native oxide buried oxide and top oxide or silicon nitride any other material lower refractive index you can use that can be used as a cladding the silicon can be a core you can structure a rectangular cross section silicon surrounding silicon dioxide and that can be used as a waveguide you remember that in when integrated optics proposal came in.

That time it was mentioned that if the core refractive index is just 10 to the power -2 to 10 to the power -3, then you can confine a light you can make a guide you can make a laser beam circuitry that 10 to the power -2 core refractive index delta and you need there but here you see n SIO 2 is about 1.4775 and in SI refractive index for silicon is 3.4775. So, if you see Delta n it is in the order of 2 very large refractive index contrasts.

So, larger refractive index contrast to how it is advantages you can make very small core in which lighter can be confined you can make a waveguide wave guide dimension can be much much less than 10 micrometre earlier proposed it can be just in the order of 1 less than 1 micrometre that cross section. So, that means, you can confine the light within very small cross section and you can make that structure as long as possible and you can guide the light around 1550 nanometre wavelength is transparent in silicon.

And you have a native oxide can be acting as a cladding. So, that you get total internal reflection etcetera. So, waveguide can be fabricated and same layer you can fabricate it you can use for your transistor silicon, you can p type doping n type doping, this is your gate, this is your gate this is source, this is drain, you can use your bio metals. So, waveguide you can fabricate and you can fabricate this type of structure also. So, if you just clean up this thing, it will be clearer I can explain this one.

Here, if you just see that this type of reed structure, this is a silicon this is silicon and here silicon height is more the higher silicon height this region you can actually confined light also it can be a waveguide also we will show that that can be acting as a waveguide also and you will need this type of slaps, you can consider both side so that you can dope maybe one side p type doping another side n type doping.

By controlling the bias this kind of then if you are doping this side is p and this side is n and this is intrinsic region where your optical mode is sitting guided mode, then if you are giving a signal here signal in a signal out then depending on the signal inside carrier p carrier you can control inside the waveguide depending on the carrier. You can change the refractive index you can control the phase of the guided light that is how manipulator works in silicon and you can have a poor detector you know that 1550 nanometre is transparent in silicon.

So, you cannot make any diode pn junction diode it can act like a detector for 1550 nanometer because 1550 nanometer the photon energy is not sufficient to create electron hole pair and current for example, in photovoltaic cells you are fabricating out of silicon that you need visible light sunlight visible light should be coming here. So, that that visible light photon energy is high. So, that you can electron hole pair you can generate you can put like.

You can put a voltage you can generate in silicon sources, but we want to use 1550 nanometer because of the fact that 1550 nanometer is transparent in silicon. But this silicon diode you cannot use for detecting the signal at 1550 nanometer because it cannot have job to create electron hole pair. So, that is the reason another material that is another semiconducting material germanium, which is also CMOS compatible silicon germanium is very much well known and semiconductor foundry they use.

So, if you can make silicon germanium alloy or germanium alone then 1550 nanometer can and germanium diode for example, silicon germanium diode then band gap will be reduced and when band gap is reduced to absorbed 1550 nanometer in that diode if it is reversed bias silicon photon pair will be generated and you can get clear current. So, that means, this modulator can be useful for electrical to optical conversion photo detector you can fabricate so, that you can convert optical to electrical waveguide you can just use for routing, multiplexing, demultiplexing components.

And if there is a fabrication error is there or you want to reconfigure any component waveguide component You can also vertically up you can use a metal heater resistive heater you can pass current some jubilation will be there and then because of the temperature heat energy temperature of the silicon can be increased as the temperature increases you can change the refractive index also.

Because silicon is also very good thermal coefficient is there dn / dt that means, refractive index change per unit temperature rise is about 1.8 into 10 to the -4. So, that is good enough to reconfigure any waveguide devices also. So, that means, the strategy is clear that if you have a silicon on insulator where you normally use your electronic devices if the device layer silicon on insulator so called SOI silicon on insulator.

SOI means silicon on insulator this layer is the top layer is called silicon on insulator and that thickness is in the order of for electronics purpose it is in the order of 100 nanometer and for photonics electronics less than 100 nanometer and for photonics. This is for electro electronics and this for photonics it can be less than normally typically people are usually less than 220 nanometer thickness. So, you can have some kind of compromising device layer thickness so, that you can integrate both electronics and photonics together in silicon on insulator substrate.

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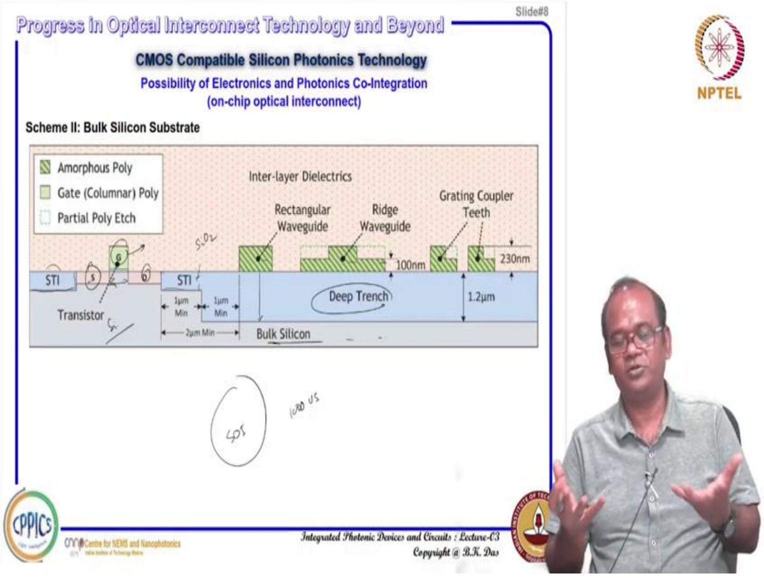

So, now, so, you know the silicon on insulator 3layer system that wafer products and manufacturing is very expensive. So, researchers also in search to have certain kind of co-integration of electronics and photonics in bulk silicon if you use just simple bulk silicon then the bulk silicon you know your transistor is fabricated gate, source, drain and this is your channel link as I mentioned earlier.

And this is you are using some kind of shallow trench isolation shallow, you just edge a bit silicon and then you just filling with oxide that is the technology for bulk silicon CMOS technology. But same technology you can use for co-integrating photonic components also. How that is possible? So, instead of STI that means shallow trench isolation and filling oxide these are oxide basically SIO 2.

This is silicon substrate these are this is bulk silicon is shown here this thing. So, you need to a little more so called deep trench to create and then fill with oxide. So, you can grow or you can fill there are different techniques already available. So, you can grow that and you can make some kind of planarization. So, whenever you are just using your gate material that is typically a polysilicon you use that polysilicon for waveguide components also.

Polysilicon that means polycrystalline Silicon. Allurin silicon on insulator, the waveguide all the devices they were fabricated in crystalline silicon, but here you can have source drain channel everything is in crystalline silicon, but get normally that is a little bit of conducting unit polysilicon people use same polysilicon you can use for a waveguide but since it is conducting it can be lossy.

So, you need certain kinds of treatment to reduce the waveguide loss also and they have demonstrated getting coupler waveguide modulator etcetera. And of course, that is a polysilicon made out of waveguide made out of polysilicon some conductivity p carriers are their loss will be a little bit higher. But in spite of that, you gain a lot of things in the cost because of the wafer because silicon on insulator wafer if you why 300 millimeter wafer if you are buying today's silicon on insulator the cost is about more than 1,000 US dollar.

But in bulk silicon if you just 300 millimeters cost is very very less dollar of 10, 15 dollar you can get 100 dollar maximum you can get. So, raw material cost is much lower if you use this technology. So people are trying also demonstrating we will discuss that also.

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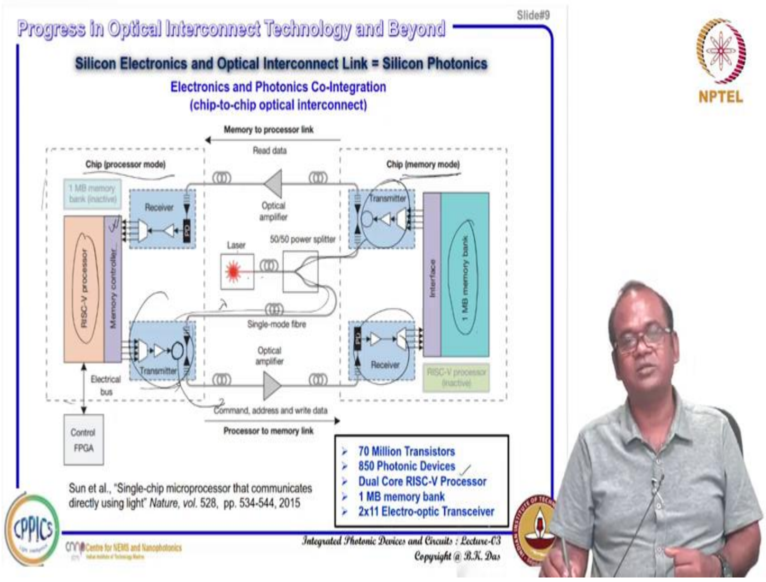

So using that technology first time, you know this co-integration still is a challenge people are demonstrating but before that per chip to chip communication first demonstration in 2005 we are actually co-integration they did but not for on chip interconnect. So, you see here this for example, if you just consider one chip here this is a silicon chip where actually certain kinds of electronics and photonics integrated.

So, this is called the RISC 5 processor and this is also another chip, you can consider this as a memory mode and this is a processor mode where you are doing computation etcetera. So, RISC V processor here and here 1 megabyte memory bank and memory controller is their controller electronics is there where you can actually use some kind of serial laser DC laser for data, you can read out data and this is your transmitter.

What is the in the transmitter? You have a laser source you will power and you are launching light here into this waveguide and here you are using a ring resonator. So, if it is a particular lambda is coming here and that lambda you are launching into the silicon waveguide here and because of the ring waveguide here and it is very close to the this bus waveguide that lambda light comes and coupled into the ring and that lambda if it is region into that ring that will be actually stored in this ring.

That particular lambda will be stored in this ring. But depending on the data you can control the voltage you can take in the face of the ring then you can control the light out. So, any digital data coming into this driver and feeding into the ring with some electrical this is kind of some kind of modulator ring modulator I would say that means electrical to optical conversion happening then modulators light will be coming.

So data would be encoded here that is actually called transmitter. So laser light coming and then you will use a fibre optical amplifier and then you have a receiver photo detector de serializing again interface here and from here again you have a transmitter. So, within the chip memory chip also you have a transmitter and you have a receiver and you have you are splitting your laser source one is going to the memory side and other coming to the processor side.

And then you can take here transmitting you can get to processor and here transmitting you will get given to memory. So, in this way you do have photonics and electronics communication as your integration within the chip and here also photonics and electrons co-integration within the chip, but chip to chip communication you were doing with a fibre and external laser amplified because they cannot be fabricated Using CMOS technology in silicon.

So that has been demonstrated in 2015 co-integration I mean to say whatever the things co-integration that is the vision that is the future right now, normally whatever transceiver blocks everything is being developed or commercialized where photonics chip is separate the electronics chip is separate and you are just interfacing them optically and electrically and in this case you could actually demonstrate.

Actually it was published in nature 70 million transistors 850 photonic devices co-integrated in each of these RISC V processor. Dual core processor 1 megabyte memory bank and 22 electronic transceivers modulator ring modulator type things they have demonstrated.

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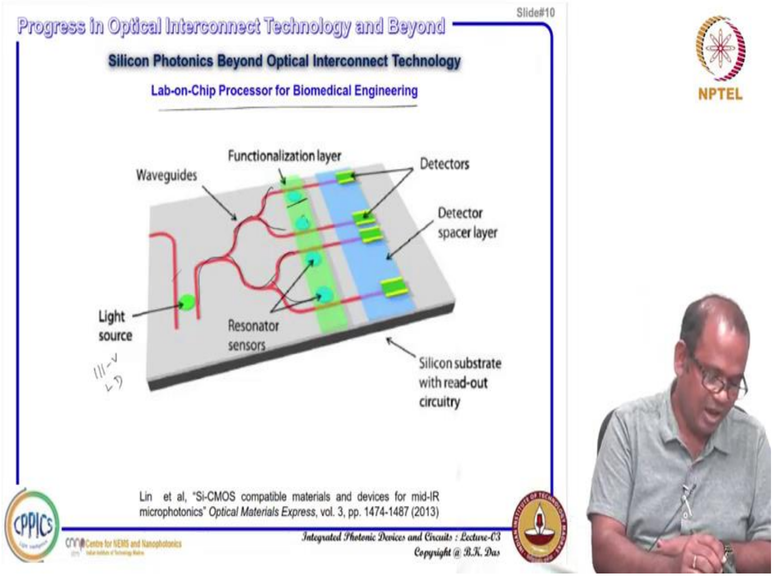

So, now, we have discussed that this integrated photonics actually revived because of the electrical interconnect a bottleneck and making a dramatic advancement in the transceiver technology optical interconnect technology. But since technology is available, people try to explore other areas also. So, for example, here One example is that the beyond optical interconnect technology you can have silicon photonics technology or integrated photonics technology.

For lab on chip application for biomedical engineering lab on chip application processor for biomedical engineering what is that you can have a some light source it can be some coming out of 3 5 gallium arsenide type or any other indium phosphide layer 3 5 laser diode you can just bond here on the chip and you can have a waveguide the output of the laser you can couple here you can split the power into 2 halves and then further you can split here.

Here also you can split you can probably get your own guide and here in this region, you have you see it is very painful to hear some device it can be ring resonator type things and this is ring resonator, ring resonator, ring resonator 4 different ring resonators are there and this ring resonator is a ring waveguide basically, any laser comes in if that is resonant to the ring that will be stored here it is like a modulator.

Here will be stored it will be stored it will be stored here, but what you could do suppose you want to taste some sample biomedical sample, some protein sample for some virus you want to detect for example, so you can have that sample and particular you want to identify a particular protein sample or particular viral infection is there or not that type of thing, if you can somehow erased the top of the ring resonator.

You have to functionalize and then that functionalization purpose is done so that to arrest the particular specific things which you want to detect whether it is there or not, after functionalization, if you pass that fluid and then because it functionalization that will be arrested and once it is arrested surface layer dielectric constant of the ring will be changed refractive index change and path length refractive index phase everything will be changed.

Then it can be optimum that can be once it was the resonant and light was stored there. Now it will see because of the change of the refractive index, the resonance will be shifted by looking into the shift in the resonance you have a detector here you can detect intensity or whatever you can actually read out that way that particular specific item is there or not. So you can use that as a so called sensor purpose biomedical sensor purpose that is one application.

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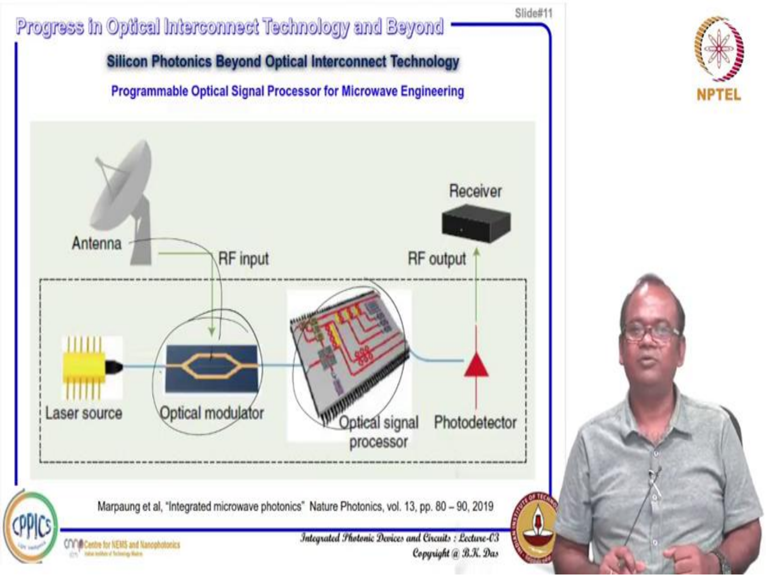

And another application is microwave engineering. So, programmable optical signal processor for microwave engineering you know microwave engineering people are trying for higher and higher frequency carrier frequency to go for 5G communication 6G communication people are going beyond 25 gigahertz and so on. But for higher carrier frequency in electrical domain the electronic processors is more and more becoming complex and expensive.

So, same optical interconnect technology you can translate into microwave photonic engineering technique so that you can reduce the electronics budget. How is that possible? For example, you have a laser source and you can have a just kind of modulator optical modulator one type one or you can just feed into your RF signal coming out of radar and then you can encode the data and then the electrical data RF data is now in optical domain you can use your optical processor.

That optical processor can be silicon photonics devices can be fabricated using CMOS technology and you can process it optically to reduce the electronics budget glowed and higher performance superior performance in optical domain you can get it and you can again detect in the photo detector finally, to get back your RF signal. So, this is a huge subject and the very latest trend hot topic microwave photonic engineering that is also coming in with the progress of silicon photon CMOS compatible silicon photonics technology.

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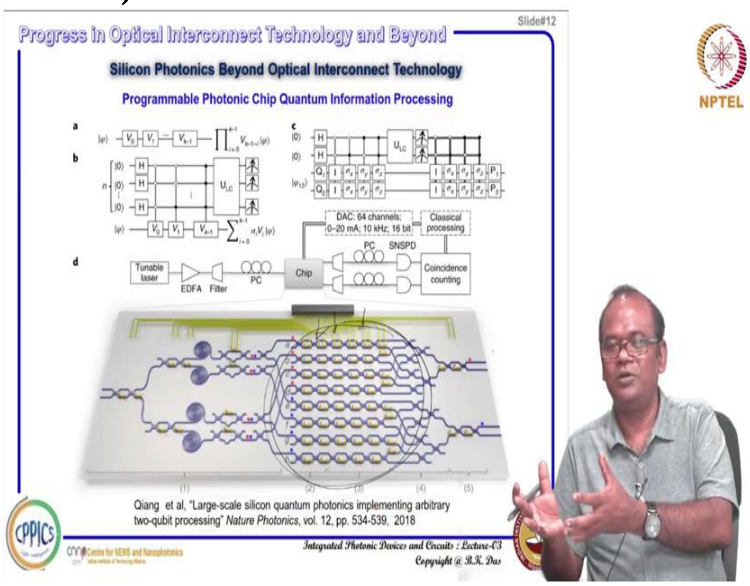

And at last I would like to present that the quantum things I hinted earlier actually people demonstrated quantum photonic processor also here if you see in 2018 large scale silicon quantum photonics implementing arbitrary 2 cubit processing cubit means quantum bit you know quantum photon electromagnetic wave light if you treat them, they are actually they can be treated as a stream of photons.

Now, if you have some kind of device, where a photon can be isolated and it can be treated as a quantum object, that quantum object quantum 1 particular photon can be considered a cubit and that cubit actually you can use for quantum signal processing quantum photonic operations and so called photon interference everything you can utilize for advanced quantum processing like quantum key distribution, quantum computation, quantum metrology all those types of things can be done.

And all that can be done simply using all the classical optics only thing is that you have to generate quantum nature of the you have to generate deterministically quantum nature of photon and then use classical devices like waveguide, power splitter, interferometer everything you use, you can manipulate this photon quantum nature and then you can detect and then that manipulation can happen using your electronic signal.

You can have all the electronic signal you can control all the optical things by means of some kind of FPGA field programmable gate array electronics things and you can using that FPGA you can actually program your photonic circuit also. So, by programming you can actually do a lot of quantum photon processing and whenever you are programming you are programming classical device, classical merger, classical waveguides all those types of things.

So, that is a huge things are coming due once it is out process the quantum nature of the photon you need to detect with a various high performance photo detector. So, far single quantum level single photon level sensing on chip sensing is very difficult people are using. So, called superconducting nanowire photo detector SNSPD and that is in cryogenic temperature that has to be done.

So, detection normally is being done nowadays optics sometimes people have done some progress for on chip integration, but performance is lower in this example, they have used photo detector outside and that thing also coming in. So, that means, the technology is mature becoming mature and mature and using that technology you can use in biomedical applications you can use in microphones photonic engineering microwave engineering, you can use in quantum photonic engineering.

So, the subject silicon photonics integrated photonics is really a subject for the century as well as next century I would say also. So, I close this today's lecture here and we will come to the next lecture to discuss about the evolution of this is all things are in a superficial way. Now we will be just going into the technology front how the silicon photonics technology slowly slowly evolved in course of time that will help us to understand the all the components everything.

At the moment you are getting high level understanding. And so macro level understanding now onwards will be going slowly, the micro level understanding individual device, how their technology work, how they are functioning, their working principle everything will be discussed slowly and then some mathematical operations all this type of thing coming in course of time.