Integrated Photonics Devices and Circuits

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Lecture - 34
Tunable Devices and Reconfigurable Circuits Programmable Silicon Photonics

Hello everyone in today's lecture we are going to discuss about programmable silicon photonics. So, far we have discussed important passive components and also we have discussed how phase shifters can be integrated particularly thermo optic phase shifters to reconfigure certain components circuits. And next level is we can have some photonic circuit defined in silicon photonics technology platform that can be programmed for multipurpose for various different functions same circuit can be reconfigured for other type of applications.

So, towards that first what we are going to discuss universal 2 by 2 optical gate sometimes it is called tunable basic unit. So, this is actually a we can it is just similar to any electronic gate will be trying to present one component device specific device which can be programmed for gate operation optical gate ah. So, keep in mind that when we say optical gate basically it is not like for digital operation 0 or 1.

It can be analog optical gate it can it is normally called as a analog optical gate. So, between 0 and 1 any other values also we can get. So, now using that optical gate universal optical gate I will try to show some outline how one can demonstrate integrated photonic switch fabrics using building blocks major building blocks will be given. And how this universal 2 by 2 optical gate can be arranged in a certain fashion to get a photonic switch fabric on chip integrated photonic switch fabrics.

And finally the most interesting thing that is called field programmable photonic gate array note that this is FPPGA not APGA, APGA is a field programmable gate array that is for used for electronics digital electronics for digital logic operation that is also that is programmable also but here also we will be just demonstrating this is recently materialized visualized and demonstrated also some certain circuits which can be called as a programmable photonic gate array field programmable photonic gate array that can be programmed for various types of functionalities.

Of course that is optical functionalities which can be digital as well as analog also. FPPGA in electronics is necessarily it has to be digital logic but in this case this FPPGA field programmable photonic gate array that is mostly used for analog function analog operations photonic analog photonic signal processing purpose.

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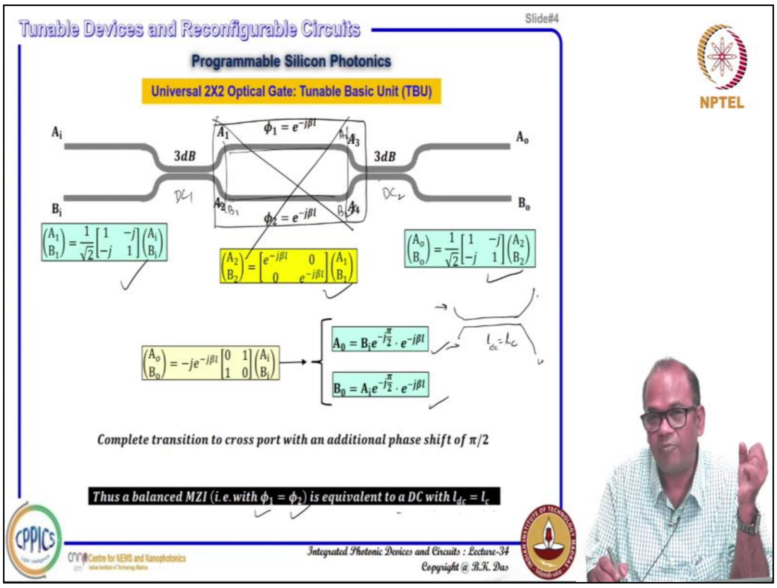

So, now let us try this universal by 2 by 2 optical gate how it is consider concept this is nothing but if you just see the passive structure first that this is a waveguide structure it is like A 2 by 2 max gender interferometer first you consider. And you see in this structure that is a 2, 3dB power splitter may be directional coupler here DC 2, DC 1 they are just cascaded and it is you know it is normally called as Mach–Zehnder interferometer 2 by 2 Mach–Zehnder interferometer.

And you know the transfer function for this Mach–Zehnder interferometer we have derived earlier I just reproduce here for completeness you know this 3dB power splitter if I anode that input coming here in the port 1 A i and another input can be fed at another input port that is B i that is that means this is the field amplitude as you know it is represented by A e to the power j omega t - beta z, beta is the propagation constant of the guided mode and then also you should have field distribution also for the guided mode.

So, this A whatever amplitude is depicted here it is launched here field profile for a single mode waveguide you can think and that mode can have a phase propagation that is omega t minus beta z like that. Similarly another field another signal you can think of B i is here. So, in that case if A i, B i and here any field is coming out that can be related using this transfer matrix this is for a 3dB power splitter.

3dB power splitter when directional coupler used as a 3dB power splitter the transfer matrix we have derived earlier this is directly reproduced instead of that I think it is better to represent A 1 B 1 this is B 1 and this should be A 2 B 2 that way it is better to explain. So, this is A 1 B 1 A 2 B 2 anything you can give but in this expression what you see that that is related to A i 2 A 1 B 1 this is A 1 and this is B 1 whatever field is coming here that is related here.

And if this is a balanced Mach–Zehnder interferometer that means the length l 1 equal to l 2 equal to l then when propagating through this length for this field it will acquire certain phase that e to the power minus j beta l we just put down here and phi 2 also it is basically phi 1 equal to beta l and phi 2 equal to beta l here that means normally the phase factor it should mention as a phase factor then I can relate this A 2 B 2 in terms of A 1 B 1 that is like this.

And then if you have a second directional coupler that is related to output field here output amplitude A naught and B naught that can be related to A 2 and B 2 like this. So, using all these expression if I just consider that is actually A 1 B 1 let us consider like this correct it and this is A 2 and B 2 like that then what we can get using this for example A 1 B 1 can be written from here this is one matrix you can write here and then whenever you are getting A 1 B 1 A i B i you are getting and A 2 B 2 you can just write like this.

So, A 2 B 2 equal to A 1 B 1 here. So, what you could do instead of A 1 B 1 instead of A 1 B 1 you can write this one then ultimately using these all these matrix you just multiply then you can relate A naught B naught to A i B i. So, A naught B naught and A i B i you can relate. So, this is your transfer matrix fine. Now if you just find the amplitude what is A naught? A naught will be this one and what is B naught? B naught from this you get this one.

So, you are just launching A i here this A i and here B i this A i appear as a B naught with some additional phase the propagation phase factor and then additional phase factor is just pi by 2. Similarly whatever you are launching bi that will appear in the cross port as A naught bi with additional things. So, this is both of them will be in phase basically if you launch here whatever you get here whatever phase you will be getting you will launch here.

Here also you will be getting same phase basically propagation this arm length propagation constant that is the phase e to the power minus j you can say that beta l plus pi by 2 that is the phase you will be getting but it will appear in the cross port that we have discussed earlier. So, we conclude that complete transition to cross port with an additional phase shift of pi by 2. So, propagation constant whatever propagation length dependent phase you are getting that is there.

But in addition to that because of the directional coupler it will be having another pi by 2 phase shift that we know this is we have discussed already before. So, you can think of instead of this balanced Mach–Zehnder balanced arm if you could think this 3dB and this 3dB DC, DC 1 and DC 2 if it is directly connected that means you are doubling the directional coupler length obviously this will be your B 1 this will be your A 2 this is B 2 according to the annotation all these expression we have given.

So, using this again what we can get if this is missing for example then whatever you supposed to get here that is exactly like a cross directional coupler with cross coupling length that is what does a balanced Mach–Zehnder interferometer that is with phi 1 and phi 2 that phi 1 equal to phi 2 is equivalent to a DC with l DC equal to lc. So, if you have a directional coupler length of l DC equal to lc that means cross coupling length then if you launch here it will directly appear in the cross port and if you launch here it will directly appear in the bar port.

So, this type of Mach–Zehnder interferometer balanced Mach–Zehnder interferometer if you operate passively it is actually nothing but a simple directional coupler instead of 2 directional coupler cascaded with a gap with a distance with a certain wave guide in between as if you can think that that is missing if that is missing also your functionality point of view no difference.

But we can use that this 2 arm in addition to this 2 3dB power splitter to get advantage of some kind of integration integrating a phase shifter in this arm. So, you can integrate the phase shifter here that can be actually isolated from the lower arm and if you integrate a phase shifter here this preceptor can be isolated from the other arm it will not affect the other arm. So, to get that advantage we use this type of thing.

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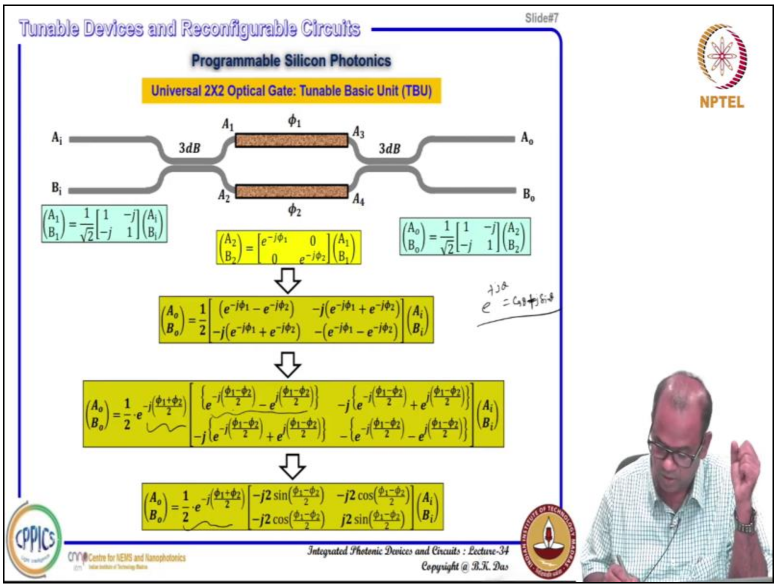

Suppose you have a phase shifter here phase shifter here phase shifter and this is also phase shifter that can be a thermo optic heater micro heater then if this is phi 1 this is phi 2 phase additional phase is there. So, phase factor will add to the amplitude minus j phi 1 here and here it will be adding minus j phi 2. So, in that case if you use this one A 2 B 2 and A 1 B 1 relationship here.

So, this in this case A 2 B 2 this expression can insert here and this A 1 B 1 can again insert here then ultimately you can relate A naught B naught to A i B i that means input to output you can relate with A 2 by 2 matrix here transfer matrix this is the transfer matrix of the so, called Mach–Zehnder interferometer with additional phi 1 and phi 2 phase shifter in upper arms and lower arms respectively this can be actively controlled it can be tuned phi 2 can be tuned depending on the pi one and phi 2 you supposed to get this type of matrix.

So, this matrix little bit can be simplified how that is let me try. So, what you do this one you just multiply this factor and every element you multiply with e to the power j phi 1 + phi 2 by 2. So, minus and then every element if you multiply this one then you have to multiply minus j here. So, that is same. So, if you multiply this one this term becomes like this. So, it was e to the power minus j phi 1 and if you multiply this term then it will be becoming like this phi 1 minus j phi 1 minus phi 2 by 2.

And if you multiply this one with this one this will be coming also phi 1 - phi 2 by 2 but instead minus here plus same way if you multiply this one with this term then you get this one. So, minus plus and additional minus j will be there and this term also identical if because this one and this one same. So, in that case you will get another term similar to diagonal terms are same these 2 term are same and then this term if you multiply this one with this one you get another one exactly like this with additional term minus.

So, this is a now little bit modification this modification is such that instead of pi 1 and phi 2 variable we have now 2 variables that is that is the trick that mathematical trick we have used to get a particular type of mathematical simplification. So, we have instead of phi one phi 2 we have 2 variables phi one phi 2 and phi 1 phi 1 + phi 2 phi 1 - phi 2. So, this is the expression for the transfer matrix.

Now you see this is the thing we have written. So, this one if you just expand that means e to the power minus j theta you can write cos theta plus minus j minus it should be minus j theta e to the j theta can be e to the power cos theta plus j sin theta D' Morgan's theorem. So, if you use that then what you get this factor I leave it as it is and this one it will be you will be getting minus j 2 sin phi one minus phi 2 by 2 and this one would be minus j 2 cos phi one minus phi 2 by 2. So, sign cos function we have just established.

So, we just introduced 2 different variables instead of phi 1, phi 2 they are sum of the phase and subtraction of the difference of the phase that 2 variable we have introduced and of course divided by 2 that is it.

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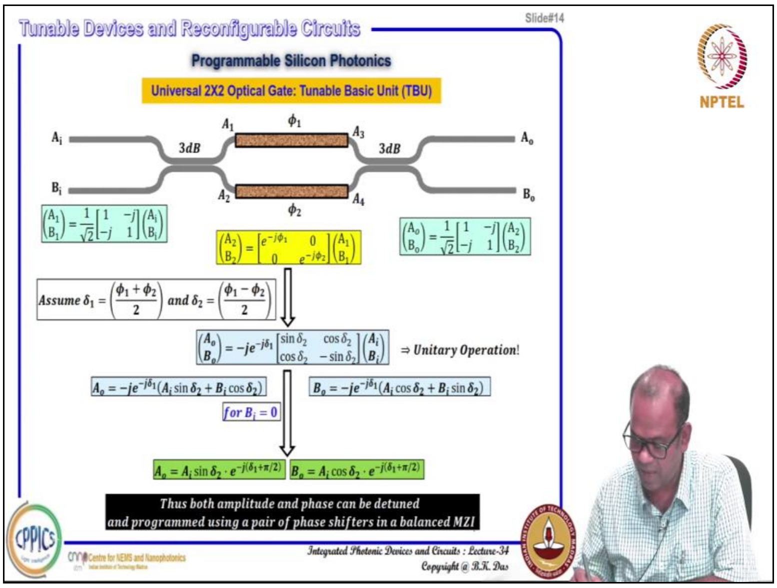

Now let us see we just reproduced here now what we do we can take you see minus j 2 we can factor outside. So, if you do that. So, what you get and also you assume phi 1 + phi 2 by 2 as a delta 1 phi 1 - phi 2 as a delta 2. So, in that case I can have minus j 2 sin delta 2 minus j 2 cos delta 2 that zoom. So, phi 1 phi 2 you are just substituting this simple straight forward then what you get minus 2 j if you take out then sin delta 2 cos delta 2 all the elements cos delta 2 minus sin delta 2.

This is actually unitary operation that means if you have phi 1 and phi 2 whatever you get but this matrix actually if you see determinant of that matrix if you are calling that matrix as a x. So, determinant of x actually if you see sin square delta 2, so, this is actually minus one that means it is giving some minus pi phase shift and as well as the amplitude is one. So, such type of operation is called if determinant is one that type of operation you are operating on this vector and then operating this matrix then you are getting this matrix is actually unitary operation that means unitary, unitary matrix this matrix called unitary matrix.

That unitary matrix actually of course this is unitary when you are considering there is no loss in the structure. So, we are assuming that loss is negligibly small and in that case you can get this unitary operation and where all the power energy you are launching here that will appear here without any loss. And this thing you see additional phase will be there that is common to both the arm A i A naught and B naught that we can actually define like this.

So we have reproduced same thing like previous slide and then you see what is A naught A naught is this one and B naught is this one after unitary operation. So, that is why it is called universal 2 by 2 optical gate and why it is optical gate that will be revealed quickly. So, if you understood up to this point it is easy for you. Next forward let us see why it is called universal 2 by 2 optical gate because this type of 2 by 2 this is a gate first of all why this should be called as a gate?

For B i equal to just think about that bi equal to zero for example assume you have without B i equal to zero you have this A naught will be this one B naught will be this one whatever you supposed to get. So, now once you disable this one then this one will go this one will go that means A naught will be A i sine delta 2 times e to the power minus j delta 1 and then minus j will give you minus j pi by 2 this is the phase factor.

And this is your amplitude and this is your phase and here also in V naught this is your amplitude and this is your phase factor. So now you imagine this device very interesting device why if you just change delta 2 then you can change amplitude at the suppose this is input here this will be called as a bar port. In the bar port amplitude varied varies as delta 2 what is delta 2 this one.

So, amplitude can be varied by the factor of phase difference between the 2 arm. So, if you maintain certain kind of phase difference then you can actually control the amplitude whatever you are getting here. Now phase, how much phase you want that that is actually decided by delta 1. So, if you can tune this one then you can actually control tune if you are if you can program phi 1 phi 2 can be tuned.

So, that you can tune the phase without disturbing, so, phi 1 phi 2 phi 1 + phi 2 you tune such that phi 1 minus phi 2 is constant when phi 1 minus phi 2 is constant amplitude remain constant and in that case your phase will be changed. So by controlling delta 1 and delta 2 you can control here both amplitude and phase independently. Similar cases for B naught. So, delta 2 actually can control your amplitude and delta 1 can control your phase.

For example if you are considering suppose phi 1 equal to phi 2 for example. So, that means if I am whatever phase I am giving here same phase I am giving here. So, in that case what happens this one will be delta 2 will be equal to 0. So, delta 2 equal to zero means this one will be equal to zero B i is not there. So, at the bar port you get 0 amplitude but in the cross port you can get maximum cos delta 2 equal to 0 equal to if you call putting 0, 1.

So, that will be like a simple thing that is actually whatever established before and if you are just changing phi 1 and phi 2 equally. So, equally you are changing this is 0 but this value is not going to be zero that will be something phi 1 equal to phi 2 may be equal to phi. So, delta 1 will be equal to phi. So, that means whatever phase you are giving that phase will appear here. So, it will be coming here this whenever you are launching here that will be coming here as a output but both phase if you are equally changing phi 1 equal to phi 2 then that phase will be introduced here.

So, it will be just phase can be modulated phase can be tuned. So, now what we have established that by integrating 2 phase shifter thermo optic phase shifter we can program that by programming that at the output I can control both amplitude as well as phase. So, this is a very nice device and it you can use that as a building block for large integrated circuits that is why it is called tunable basic unit how that is that can be used as a basic building block for large scale integrated circuit.

We will be discussing in later slides but here you just consider why it is called tunable because both amplitude and phase can be tuned nothing to do with the wavelength we are considering same lambda operation. So, any lambda you operate here all these derivations that will stand. So, that is why it is called a optical gate and this in this optical gate you are not expecting only digital data 0 or 1 any amplitude you can get any phase you can get.

So, that is why it is called analog optical gate. So, it is not just to distinguish the electronic gate. Electronic gate normally when we define that is actually digital gate but here we will call whenever optical gate is there that is basically analog optical gate. So, you can completely disable power here if you launch here you can bring here just by controlling phi 1 and phi 2 and fraction of power here and fraction and rest of the power here that is also controlling by phi 1 by phi 2 and their phase can be also detuned.

So, now what? So, this is the conclusion both amplitude phase can be detuned and programmed using a pair of receptors in the balanced MZI that is just a take home message. But after getting this how you can utilize you this is a nice device this is a this is giving you a unitary operation for these inputs 2 inputs and 2 output you are getting a unitary operation fantastic and also any of the output ports you can control your amplitude and phase at your wheel by adjusting phi 1 and phi 2.

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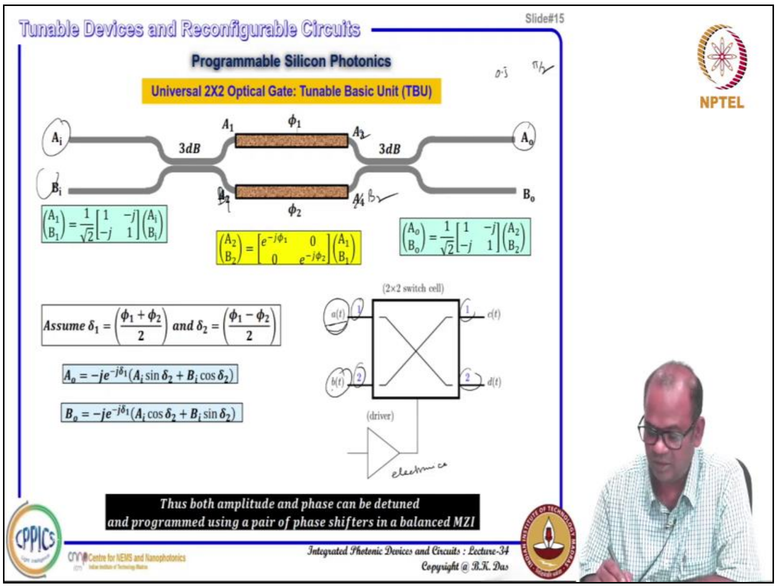

How that can be done? You need to have a design you have to design a driver electronic device because you need a program. Suppose you want here suppose you need amplitude may be 0.5 and phase may be pi by 2 for that you have to compute what phi 1 and phi 2 combination you need and that combination can be supplied by a electronic driver electronic driver. So, if electronic driver can actually control the signal from port 1, port 2 input ports to port one and port 2 output ports here we are considering.

But thing is that you can have optical signal which is modulated some data can be encoded analog that can be analog data that can be digital data. So, that data we represent as a signal time signal time dependent amplitude variation is there irrespective of the time variations here A 2 B 2 whatever the data you are getting you can actually sync your electronic driver accordingly. You can change your path from this to this you can have this A signal partly in ct and partly in dt.

B signal also partly in ct partly in dt also. So, you can mix any combination of these 2 signal for at any instant of time by programming this electronic driver circuit.

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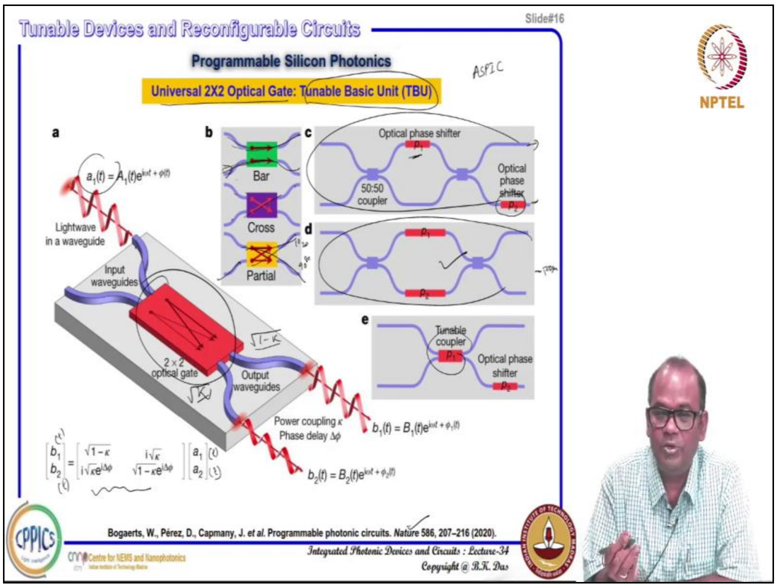

Here is a good example a very recently published paper by Bogaerts and that was published in nature journal that is called programmable photonic circuits that is the latest trend. So, far all the photonic integrated circuits used they are actually application specific that means a particular circuit you can use for a particular function. Now if you can somehow program your optical gate then you can actually route your signal to different path and you can actually feed output of one signal to multiple device at the multiple device.

So, that you can get different functions using this; whatever so, called tunable basic unit. So, here it is nicely a perspective pictures given suppose you have a signal coming here and this is 2 input waveguide and this can be a magenta interferometer or maybe simply we can consider this whatever signal comes here copper fraction can of the power copper fraction of the power can be coupled to the cross port and one minus kappa power can go to the bar port right one.

So, square root whenever kappa is there that can be considered as an intensity coupling coefficient one minus kappa is the intensity or power coupling coefficient square root of you use that will be amplitude coupling coefficient amplitude coupling coefficient to this path and this path. And correspondingly as we have established our earlier the matrix whatever the transfer matrix which is unitary transfer matrix it is written in a different form but it is same basically.

So, you can get this B 1 and B 2, A 1, A 2 and it is missing that it can be time dependent it can be time dependent signal it can be time dependent signal it can be time dependent signal.

So, this is actually can be represented and pictorial it is shown here that signal coming here coming here it can go directly this path and this path if you are putting like this you can program such that this will only go to bar port and whenever you are putting here that also will only go to bar port.

And you can program again you can actually change your phi 1, phi 2 as discussed before such that this power completely goes to cross port and this can completely goes to cross port they change their path route but you can also program partial. So, something goes here and something comes here similarly whatever you are giving here something. So, that is why it is this type of situation you can say that it is actually like a digital type on off situation is happening.

So, whenever you are going there that signal is missing here but something coming here that will be coming here that will be missing here. But here you can get any amplitude you can split you maybe 10% here 90% here maybe 20% here 80% here. So, any amount of fraction a power splitting ratio you can control program using whatever we have discussed super tunable basic unit or universal 2 2 by 2 optical gate.

So, this is the different way of phase shifter integration it is shown here actually you can use a simple max gender only one phase shifter here and another phase shifter instead of both arms you can have phase shifter at the other arm. So, you can actually control phase as well as amplitude at the both the output by controlling this P 1 and P 2 this one I have explained in the previous slides and this one sometimes instead of going for.

So, go back to the previous slide it will be clear instead of just controlling amplitude here you can think of just simple one directional coupler you know directional coupler you can design like L c this is L c. So, if you launch here normally everything should be coming here and if you launch here everything should be coming here but what you could do you can have a phase shifter here. This phase shifter it can be thermo optic phase shifter which can actually affect more to the closest waveguide compared to the furthest waveguide.

So, if you just control this control the phase of one of the coupled waveguide then you can actually control amplitude as well as phase at the output. So, if but normally it is very challenging task if you just 2 parallel waveguide and if you put a heater the parallel waveguide there separation is hardly 100 nanometer to 200 nanometer. So, if you heat one of the waveguide automatically it will be hitting the other waveguide.

So, it is very, very expensive and the design cost is very high and complicated design of course. So, that you can insulate one object to another gate when you are hitting one of the waveguide coupled waveguide other waveguide remain insulated that is very difficult. So, most of the time people use this type of tunable basic unit so that you can avoid this type of complicated design however if you are using this type of building block or this type of building block relatively your footprint will be large.

So, far the compact design of any tunable basic building block or tunable basic unit so, far demonstrated for unitary operation or universal 2 by 2 optical gate in the order of more than something like that in the order of 500 micrometer. So, that it can be really considered close to unitary operation losses etcetera can be negligibly small fine. So, this is what recently published in 2020.

So, that now people already you can imagine that people started using this type of basic unit tunable basic unit or T-Bus or universal 2 corss 2 optical gate for large scale integrated circuit for field programmable gate array.

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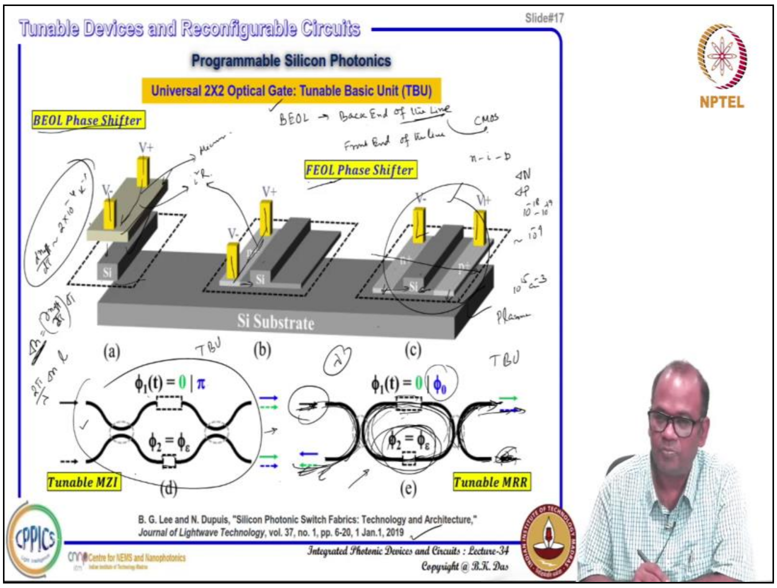

Before going into the fatal programmable gate array we just want to discuss the technology. What type of technology and what type of building block is that the Mach–Zehnder infometer is can be considered as your only choice of tunable basic unit. For example directional coupler if it is designed that is that can be also possible there are many different ways of design people are considering so, that compactness can be succeeded.

So, that footprint can be lower because you want to use this type of optical gate for large scale programmable circuits integrated programmable circuits. So, compactness is very much important that is the reason people also but that design should be such that it should be compatible to CMOS fabrication technology, CMOS compatible fabrication technology. So, normally to this type of programmable circuits or tunable basic unit or 2 by 2 optical gate they are materialized by integrating a thermo optic phase shifter as I mentioned.

Thermo optic phase shifter we have discussed earlier. So, that type of thermo optic phase shifter one can have this is your substrate silicon substrate you can define your silicon and you can have electron in this layer in the device layer but you can have in between you can have a oxide and top of the oxide you can have a heater this is your heater this is your micro heater, micro heater and then you can have a bias where you are actually v plus b minus.

So, that current can flow in this direction and then you can have A i square R and then joule heating effect that will actually transfer the energy to the silicon and then because of the thermo optic effect dn effective by dt that is actually in the order of 2 into ten to the power minus four per Kelvin. So, that type of refractive index change and then this refractive index change can be if delta T temperature then the delta n effective by dT delta T and time delta T and then this delta n in eventually it can change the phase shift that is nothing but 2 pi by lambda delta n times L path length.

But this type of phase shifter it is called BEOL phase shifter BEOL stands for Back End of the Line. So, Back End of the Line process means this line process means it is a CMOS process and back end normally after fabrication whenever you are fabricating defining your waveguide structure different type of active elements electronics etcetera that is actually called front end process.

So, front and after front end process line everything completed in the back ear back of the process line that's why it is called back end of the line you can integrate the phase shifter that's why it is called BEOL phase shifter but sometimes you can have also in the phase shifter can be integrated in the front end of the line FEL Front End of the Line means you can have a rib type of structure and some region you can dope a bit.

So, that your conductivity can be increased normally silicon waveguide when you fabricate typically they are intrinsic concentration is in the less than 10 to the 15 per centimeter cube or so, but whenever you would that means conductivity is very poor but if you little bit dope here. So, that conductivity high and then you can make a contact pad and you can send a current. So, here you can have i square R and then this heat can be transferred directly to the silicon waveguide because you have a conducting path also thermal conducting path also there.

So, you can get a phase shifter. So, this type of phase shift are also very popular sometimes we have found that this type of phase shifter is having power consumption power ratings that means figure merits is much better than this type of phase shifter. So, one can also define front end of the line phase shifters. Only thing is that you have additional process which is very costly process that is actually n plus implantation but that is a part of CMOS technology that should not be a problem.

And another type of phase shifter also people realize you know instead of that is also fronted phase shifter how that is you have silicon waveguide in the center one side it is n doping another site is p doping. Now if you bias in between this is something like that this is kind of n i p device diode in this cross section if you see n doping intrinsic and p. So, it is basically a diode pin diode type thing if you read from this side it is a pin diode.

If you are giving forward bias what happens then the carrier this hole will be injected to this side and here electron will be injected to this side. And whenever withdraw the bias forward bias then carrier will be again return back again it will be depleted from the waveguide region. Now we will be showing that by controlling this carrier concentration in delta n or delta p if you can control if you can just increase or decrease by controlling the free carrier you can also change the refractive index.

That actually is possible for phase shifter reasonable amount of phase shifter that you can if you can just carrier concentration if you can vary in the order of something 10 to the power 18 to 10 to the power 19 carrier concentration you can get the refractive in exchange in the order of 10 to the power -4 which is actually equivalent to your thermal refractive index change. So, that refractive index change also you can get and you can get a phase shifter and that also you can integrate in the front end of the line.

So, this type of receptor you can do and it is shown here basic building block in this paper actually this is recently published also in 2019 in journal of lightweight technology by B. G. Lee and Dupuis silicon photonic switch fabrics. And they have used all the they have compared all these three types of phase shifters and their figure of mirrors etcetera controlled and they have shown that using this phase shifter you can realize a Mach–Zehnder interferometer where this time dependent phase it can be zero or pi for digital application.

You can have phi zero and you can have another arm where you can actually give certain kind of bias to compensate if they if there is any type of phase difference is there after fabrication post fabrication etcetera you can do that. And at the same time this is actually T view you can consider this is a tunable basic unit or 2 by 2 optical gate. Another 2 by 2 optical gate can be demonstrated here it is explained nicely that is with a ring regenerator.

You see this is a ring regenerator and one waveguide you can consider this is input and another waveguide bus waveguide here connected here and that is another input you can consider one input here another input here and you can access here and here. So, 2 input ports and 2 output ports the problem is that in this type of structure 2 input ports are in one side and 2 output ports in the right side but in this case both side input ports are there one side input port and another side input port.

So, whenever you are launching something launching something here if it is a resonant wavelength it will be coupled here and it will keep on circulating here and then part of it while circulating it can go here output here, part of it, it will go here as it circulate here. So part of it will go here and when it is circulated it is coupled and coming back then part of it will go here also.

Now whenever you are launching here that same situation it will go here if it is resonant it will be coupled here it will be stored here and it will be coming here and part of it, it goes here and again goes here. So, it is actually a representation of 2 by 2 only thing is that your operating wavelength you are using here that should be resonant to the ring. If it is off resonant then you can control the phase here bias here.

So, that particular wavelength can be also resonant to the micro ring regenerator. So, by controlling phase in one of the arm here you can actually adjust the operating wavelength and by controlling another phase shift you can actually make the device for digital operation phi i Tcan be 0 or pi 0 anything any phase you can consider and you can control the power coming out here and coming out here.

Same kind of passion you can show that both output amplitude can be detuned by amplitude and beta tune as well as phase can be also detuned. So, it can be also considered as a TBU however because it is a resonant device very much sensitive to lambda etcetera. So, relatively difficult to implement however footprint, footprint for a ring regenerator based TBU will be smaller relatively smaller compared to footprint of the Mach–Zehnder interference based.

Because this ring resonator can be as small as 10 micrometer things and however the phase shifter if you use if you want to introduce a reasonable amount of phase that if it is thermal phase shifter that means your temperature rise will be very high which is actually not so desirable that is the reason to control the temperature instead of thermo optic phase shifter one can go for this type of phase shifter.

It is called plasma dispersion effect that means carrier concentration you are controlling free carrier concentration and by that means you can control the refractive index and forward bias you can use so, that you can have your phase control plasma dispersion based phase control. I will be discussing little more detail this one when we will be discussing high speed modulator. Because in high speed modulator also same configuration it is used but instead of forward bias they are we have to give reverse bias.

So, that high speed switching can be done for modulated high speed modulation purpose you need high speed carrier drifting away from the core of the waveguide. So, that I will be discussing in the next class in detail how this refractive index change happens, how it is dependent on pre carrier and wavelength dependencies etcetera. Will be discussing and how that can be translated into demonstrating different type of photonic integrated module integrated photonic modulator in silicon photonics platform right.

So, this is the TBU as I mentioned that this TBU can be used Mach–Zehnder interferometer 2 by 2 Mach–Zehnder interferometer that is a perfect thing but one can also try for compactness purpose a micro ring resonator based TBU also but which is very much lambda sensitive, good.

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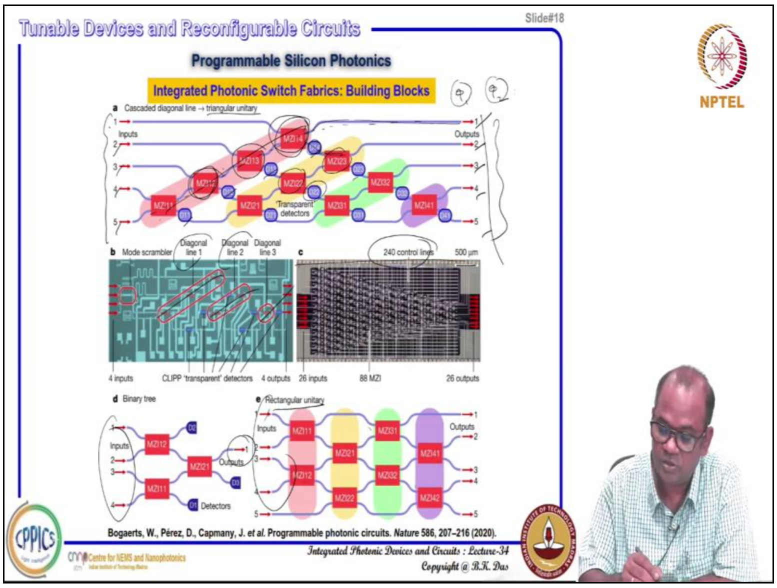

Now here one example again this taken from this paper nature they have actually shown that how a integrated photonic switch fabrics can be demonstrated for example you have instead of 2 by 2 ports you can have multiple input ports 1, 2, 3, 4, 5, and you have multiple output ports 1, 2, 3, 4, 5 and they are cascaded with Mach–Zehnder interferometer you see this is called Mach–Zehnder interferometer one four.

Why it is one four? Will be explaining little while later, this Mach–Zehnder interferometer 1 3 that means first number representing the input port and second number it is routing to port 4 this is actually that is how they have indexed in the paper. And you see one of the port it is going like this and another output port it is coming through that but in between you have a d14 one device is there that device normally it is very difficult to implement though.

But they have demonstrated that is called actually transparent photo detector you can detect how much power in this arm but it will not lose any power, power will go most of the power will come to the next Mach–Zehnder interferometer. So, all these Mach–Zehnder interferometer are streamable you can control phase and amplitude everywhere and how much power because of the programming purpose you are controlling your phi 1 and phi 2 in each of these Mach–Zehnder interferometer.

So, that amplitude and phase can be there that can be detected by transparent detector d 14, d 13, d 12 actually tactfully placed so, that you can find how much power is transmitting. So, that you can train the entire circuit that if I have to I have to set phi 1 equal to this one and phi 2 equal to this one for a set of amplitude this one and phase this one. So, the pertaining purpose these types of integrated photonic photo detectors also require.

And this is actually triangular separate unitary operation cascaded diagonal line that is actually triangular unitary operation. You see this is actually you are launching here and light will this will be activated like that. So, that it can pipe to one it can go. So, you can just activate that to operate certain set of magazine interferometer with certain set of biasing. So, that certain set of output port even if you are launching here you can get any of the output ports 1, 2, 3, 4 or 5 anywhere you can choose.

So, some other micro photograph shown for different type of switch fabrics where you can have for example here you can see that you can have a more scramble scrambler and diagonal line word diagonal line 2 that means this thing this thing it is shown here these three things this operation it is shown here. And with some lines shown here for control electronics control lines that kind of metal lines will be there.

So, that all the bias can be controlled to different phase shifters and this is another one where you it is shown that there are 240 control lines because multiple TBU tunable basic equivalent or magenta interferometer is cascaded to get a switch fabric. So, that you can get you can route your signal in different direction and you can mix your signal for different applications also.

So, you can you can see this type of chip they have demonstrated that is an 2020 paper this scale is 500 micrometer. So, entire chip may be in the order of maybe 2, 3 millimeter or so, length. So, it is a millimeter size chip, so, some other type of operation it is shown here you have four input ports but only one output puts you need here 4 by 4 again but with a different set of activation Mach–Zehnder interferometer actually rectangular unitary.

This is called triangular unitary operation and this is rectangular unitary operation you see all the things actually the path actually it is showing like a rectangular path it is means all these things you are arranged in a this way for example pipe it is going here. So, you have to activate all these things like this to going there. But here in this case you do not need that all these diagonal things or triangular path needed you can just activate depending on the colour code etcetera you can get that is actually a programming part.

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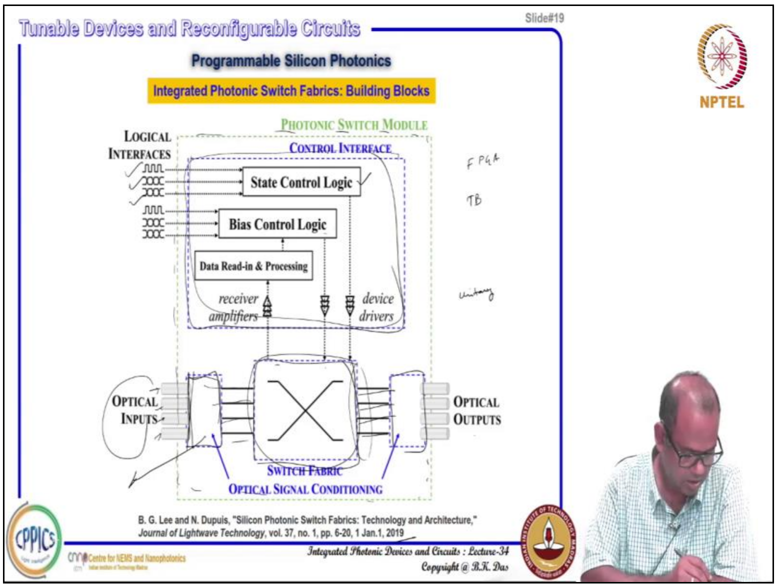

So, that programming how one can do? Here it is a nice example again I have taken from this 2019 paper where actually you see this is your. So, called this green colour dashed line within this is called photonic switch module and in the switch modules what all things are there first thing is that you have a switch fabric that is what discussed previously you can n number of input and number of output.

And in the input side you can have optical input that can be fibers these are fibers optical fibers single mode fibers and then you can have a input side certain kind of block called optican signal conditioning. Because you know whenever optical signal coming through a fiber it can be coming from long haul communication right long haul fiber bringing signals and those signals can have certain polarization and certain dispersion things are there.

But your switch fabrics they are fabricated for example using CMOS technology in silicon photonics it cannot handle arbitrary polarization it is a kind of polarization dependent circuit and certain dispersion it may be it may give you some adverse effect in switching. So, that is why you can all these things whatever the dispersion polarization etcetera that can be adjusted here in this block with different type of application specific photonic integrated circuit.

And that is why it is called optical signal conditioning and then the all these input ports again you are coming here and you operate with unitary operation. So, called unitary operation, so, that can be switching fabric that can be interferometric operation so, on and then whatever output here coming again you can give it to any of the output ports. And before feeding into another channel another fiber you can have another optical signal conditioning block.

You can anything distorted here signal etcetera you can just process it treat it and you can send it to another ports. But in this switch fabric what you need you need a state control logic you need a bias control logic sometimes you need a bias and sometimes logic control this can be digital control circuit digital data is coming here and you can feed into different control line different TBU's you can give bias also can go to different TBU's.

And sometimes data read in processing receiver amplifier sometimes in the before you send it to you have to check for example you need in this case you have a some kind of transparent detector that detector signal it will see it can read the signal whether power is right or not in that branch that power you can read and based on that you can give it to the feedback control here.

So, that control logic will automatically adjust your bias all those type of thing bias can be also changed suppose power is fluctuated a bit. So, this detection unit it will give some feedback to the bias control unit. So, that it can readjust your bias such that power level can be adjusted. So, this is for control loop. So, all these electronics so called driver circuit that actually will have logic digital logic digital signal that can be time dependent signal can come here.

And some signal you can give that signal bias controlling purpose for different things and something for receiver and giving some feedback control. So, all these electronics they are actually well known they are normally used in electronic circuit for decades and you can use that type of the self APGA for example pit fail programmable get array or you can design your driver circuit according to the standard PDK's and you can integrate co integrate with the photonics switch circuit and silicon and then you can have enter control.

So, optical input to output you can just optical signal processing purpose you can use. So, this is the whole architecture for operating photonics chip in the name of photonic switch fabrics here but you need it need not be just a switching fabric it can be some other functionalities for example some kind of computed computation chip optic photonic computation chip silicon photonics computation chip quantum photonic chip I would say.

So, those types of thing I will be just giving some example may be later if time permits. So, that also can be designed that can be controlled with a different type of TBU's and tunable basic unit and unitary operations and that can be that driver circuit also can be co integrated.

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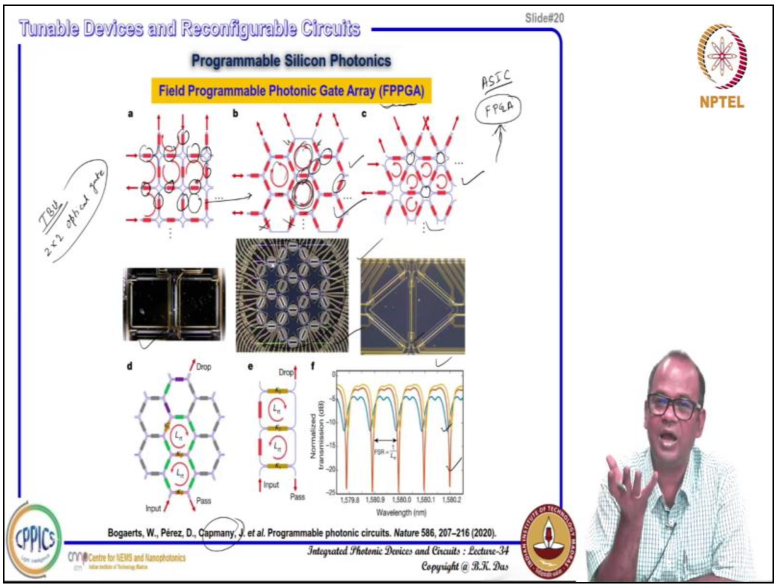

Now the final thing field programmable photonic gate array. So, you have the TBU tunable basic unit for 2 by 2 optical gate operation as MZI and can be ring resonator optical gate 2 by 2 optical gate that is basically MZI type or microwaving regenerator as discussed. And this TBU's we have shown that how that can be used for a switch fabric people demonstrated already.

And you can have you can control program that TBU individual TBU can program to get a certain type of output. Now we know that APGA field in electronics domain a PGA field programmable gate array. So, you have some ASIC circuit application specific circuit in electronics and that ASIC circuit actually it is sometimes you may need a different type of application different type of circuit instead of that people thought that if some circuit you can design you can actually program that for different application.

Then your cost and put print everything and lot of functionality additional things you can get also advantage. So that thing is that they are actually APGA you have logic gates individual logic gates you just arrange in a certain fashion you can make certain circuits. So, that you can actually configure them using very lock program and different other type of programs are there and then you can reconfigure that one for different functions.

So, people thought that if it is possible for electronic domain for electronic functionality maybe you can also have similar type of approach for photonics functionality for photonic signal processing but remember that photonic signal processing people want analog processing but APGA it is like a digital processing. So, people thought that a structure for example like this you can think of TBU's it can be arranged like in a square mesh or you can arrange like a hexagonal mesh or you can arrange like a triangular mesh.

So, if you see it is A 2 input 2 output that 2 input output goes here and it can be connected one goes to one MZI and another input comes from another MZI. So, in this way it is connected. So, this is a MZI unit these are all MZI unit. So, you can arrange in a square mesh. So, these individual Mach–Zehnder is called it's a individual gate 2 by 2 optical gate and they are actually arranged in a square mesh.

And that can be also arranged in a this TBU's can be arranged a hexagonal mass like you see six MZI is required to complete a hexagon. You know the hexagon is a very compact design but thing is that for making A 1 round ring type of resonator type of architecture you have to pass through 6 different TBU's but in this case if you want to get a round trip circulation resonance type of things.

Then you need to pass through a only 4 TBU's and you can have also triangular shape also in the triangular shape one disadvantage is that this area this footprint is unnecessarily wasting and here in this case you do not have wasting when you are connecting to different TBU's here also whenever you are connecting some kind of wasting is there but in case of hexagonal design architecture you are not wasting at all.

So, this type of 2 by 2 unitary optical gate optical gate you can arrange and then you can program each of these TBU's. So, that you can route your signal in a certain path such that if you are circulating the signal only in this path then you can get certain kind of ring resonator operation and you can also think of that this ring and this ring can be activated. So, that you can have a coupled ring this type of ring resonator coupled with this type of wing resonator also this resonator can be coupled also.

So, coupled ring resonator you can get also you can have cascaded for example you want to cascade certain Mach–Zehnder interval cascade this one this one and this one and then you can go this one you do not need to activate this one you can cascade this one and then you can keep you can have also delay line also delay path you can as much as you want you can actually route the signal according to your requirement.

So, you can have a delay line you can have a cascaded interference parameter MZI type based interferometer you can have a coupled ring resonators all this thing you can use coupling resonators or cascaded interferometers you can use for various type of interference experiment performance as well as different type of what do you call that delay lines filter characteristics all those type of operations you can have.

Here are some of the fabricated device shown here and they have demonstrated basically Bogaerts and Perez particularly this Capmany group in University of Valencia they designed and they fabricated and they their results shown here for example by controlling by programming this type of hexagonal mesh structure they could actually demonstrate different type of filter characteristics ring resonator filter characteristics.

Either this one or this one different order first order filter second order third order filter they can demonstrate by coupling one basic filter unit to another filter unit cascading those type of things they have demonstrated. So, this is actually this is why it is called field programming photonic gate array you can every field you can independently you can program to get a certain type of functionalities.

It is like a each of them like a logic gate but optical logic gate which are which can be used as an analog function purpose but FPGA in electronics domain that can be used for a digital electronics operation purpose. But remember that this APPGA it is just for photonic signal processing and FPGA for electronic signal processing. So, the purpose for FPGA is different and purpose for APPGA is completely different.

It is not that this APPGA is going to replace APGA. FPGA has a different function rather it is interesting to see that this FPPGA field programmable photonic gate array this type of architectures for different type of operation different type of functions you to control them to program them people use FPGA control electronics is normally is designed using APGA circuit. So, APGA is a component for APPGA operations.

So, APPGA is not to replace FPGA normally people always think that photonic circuit it can replace electronic circuit as I always mentioned that it is not true photonics is actually complementing electronics where electronics failed or cannot be improved the performance, performance cannot be improved there some of the functionalities you can replace by photonic counterpart.

So, this is one of the area recently being opened and it is going to go very long way because you can design a particular circuit you can fabricate a circuit and that can be reconfigured for various functionalities including microwave signal processing to microwave photonic signal processing to quantum photonic processing quantum information processing all those type of thing can be done.

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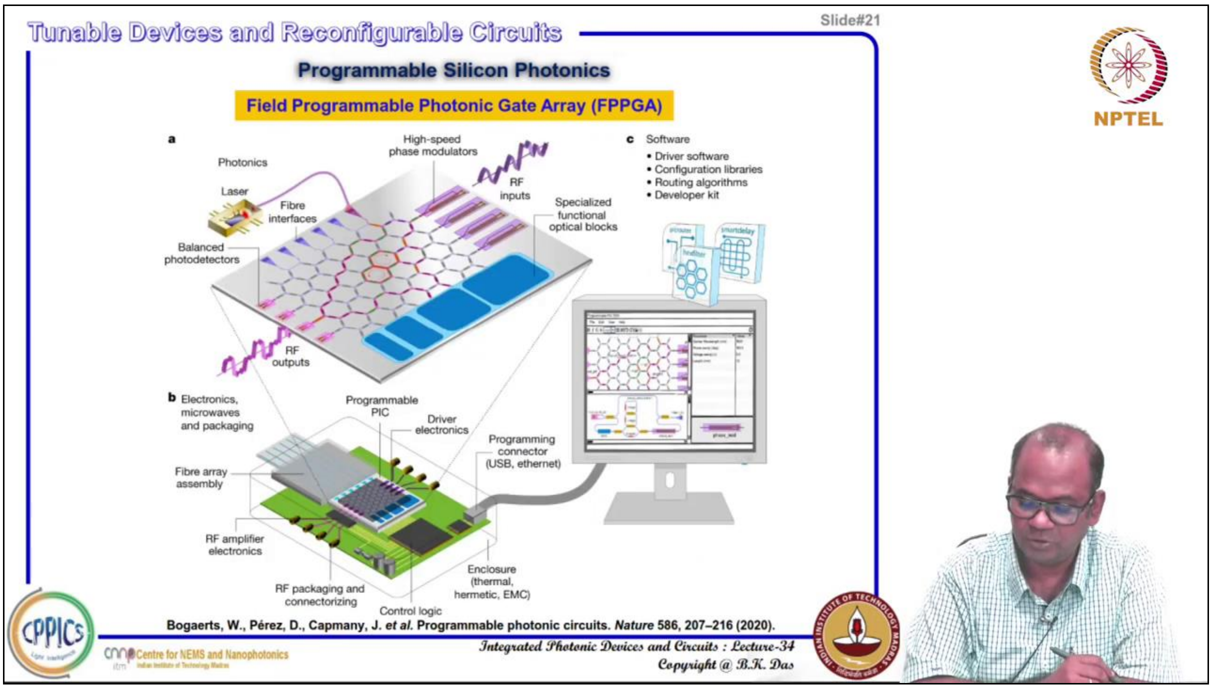

And so, here is a particular how you can do it and there is a pictorial it is shown here in the same paper. So, you have a APPGA unit and this is actually programmable part that means

FPPGA part and you can have some of some devices like high speed phase modulators. I will be discussing that they are application specific device you can have and some of the block you can assign those are specialized functional optical blocks.

You can have which you cannot actually realize using your field programmable gate array you can just whenever necessary you can access them and laser of course silicon you cannot integrate laser can be off chip. So, your RF input for example in this case you have the for example RF signal coming or if a signal is modulated with the optical signal and then this thing can be coming as a input and then this input you can process with optical signals.

And all these TBU's optical gates they can be controlled by a electronics right that electronic circuit can be object this is for example here electronics is here this is your FPGA and all the RF signal can come here RF signal can be output here. So, both side input output RF signal and optical signals can come here these are the optical lines and you can interface that with a computer.

So, your electronics can be programmed and according to that program that is driver electrons can be programmed and according to the program signal will go to individual TBU's and you can route your signals amplitude phase you can just change according to your requirement and then you get a particular functionalities for different applications. So, I close this for this lecture today.

So, this is an import I mean to say that this particular area is just recent and you may not find anything in the textbook. So, you have to rely on all the material you have to collect from literature recently published. For example this nature paper this paper and also I recommend to recommend you to read also this paper also by this a very nice paper switch fabrics technology and architecture.

And that other paper for field programmable greater or programmable photonics nature paper that will give you lot of insights whatever I discussed and much more you can learn from that paper, thank you very much.