Integrated Photonics Devices and Circuits
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Lecture - 33
Tunable Devices and Reconfigurable Circuits Thermo-Optic Switching and Tuning

Hello everybody in this lecture today we continue that how to design tunable devices and in turn reconfigurable circuits and we discussed in previous lectures what are the factors important for tuning a devices and the configurable circuits. And today here we are going to discuss thermo optic tuning that is a very important tuning mechanisms and switching mechanism for especially for silicon photonic circuits.

So, first of all I will discuss about the thermo optic phase shifters. So, how to design a thermoptic phase shifters are the figure merits and how to optimize design parameters. Then I will be discussing using the thermo optic phase shifters one can design optical switch on chip or integrated optical switching devices. And finally again using same phase shifters thermo optic phase shifters we can also reconfigurable resonant devices like micro ring resonators to operate different operating wavelengths. So, that is how we call it as a thermo optic wavelength detuning.

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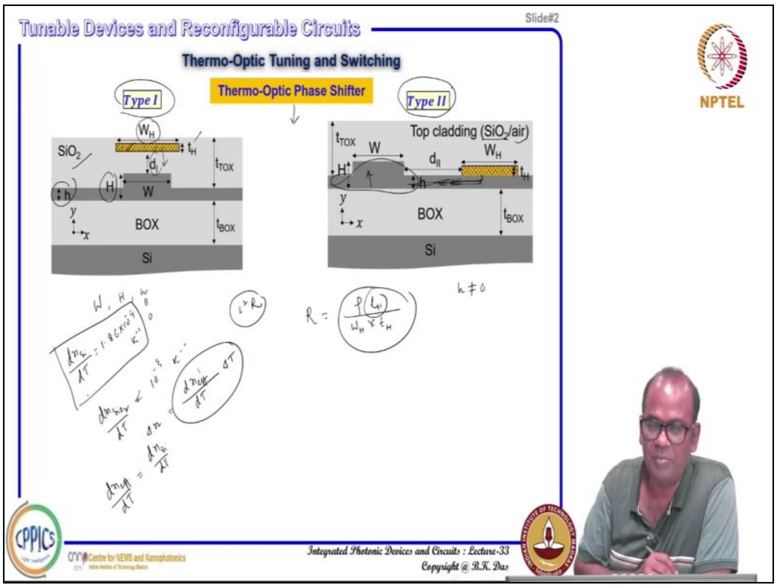

So, first thermoptic phase shifters as usual we have just categorized 2 different type of thermoptic phase shifters type one and type 2. Also it is clear that from the name thermo optic meaning you have to apply some thermal energy. Then some optical property will be changing in this case phase of the guided mode we mean to say page of the guided mode will be changed and because of the thermal power silicon itself is a very good thermo optic material.

So, if you just raise the temperature refractive index will be increased. So, that is the mechanism that is the principle we follow to design thermoptic phase shifters in this design if you see we have given a design of wave guide design cross section re wave gate structure where you have a finite w value with wave guide width and device layer thickness this one. and then of course the slab thickness small h revive gate structure it can be this can be also zero and then type one you can have top cladding you should have in this type 1 design you should have a silicon dioxide top cladding.

Instead of air you use silicon dioxide you grow silicon dioxide up to a certain level and then after a d1 height from the waveguide surface you deposit a heater that is nothing but resistive heater it can be a some metal like tungsten like titanium, nickel so, on. So, here in this case the width of the heater it is defined by W H and thickness t H depending on the thickness and width you can have the resistance of the micro heater.

For example resistance of the micro heater you know that can be rho resistivity what is the resistivity of the deposited material and length proportional to length divided by a W H multiplied by t h. So, that is the resistance. So, this is pursued thickness actually lower the thickness resistance will be increased or width lower resistance will be increased. So, this is cross section I will show you that this L actually as it should be this micro heater should be parallel to the waveguide surface and as long as L runs for the micro heater that is called that will be called as a waveguide phase shifters way.

Why it is preceptor again I will discuss and on the top of it again you can also have some kind of silicon dioxide box light again you deposit to passivate everything and where you want to make a contact you can open the oxide and you can do it easily from bonding where bonding or making some contact out of the device. So, if you pass the current through this one micro heater from one end to another one.

Then because of the joule heating I square r you can imagine that joule heating heat energy that will transfer through the oxide to the waveguide silicon waveguide. And because of the higher thermal capacity and conductivity in the silicon, silicon temperature will be increased compared to more compared to your surrounding oxide. So, as the temperature increases you know that bulk silicon actually have a thermal coefficient thermo optic coefficient equal to 1.86 into 10 to the power -4 per Kelvin.

And also you can think of that cladding dni Sio 2 by d t you can also have that is in the order of 10 to the power -5 or. So, it is actually less than 10 to the power -5 or so, per Kelvin. So, mainly your silicon core will be heated if you are just doing some resistive heating by sending current through the across the heater. Then it will be heated. So, once it is heated. Then refractive index change as you know it will be actually can be expressed for a given wave guide effective index n effective by dT you can see that normally this dn effective in principle more or less will show that dn by dT for silicon case it should be ns i by dT normally.

So, if you are raising temperature of delta T. Then you can find out how much refractive index change you can actually raise in the waveguide structure that is one type. And second type is you should have a waveguide design where the slab not equal to 0 and top of the slab with a safe distance we can call it d II and this is d I vertical distance that is lateral distance d II safe distance you can deposit a metal heater identical metal heater.

Because why I am saying safe distance because whenever your mode is just confined here this mode should not mode evans and field should not penetrate it towards the metal because below the metal if some field exist and that field can be attenuated by this metal because metal has a reasonable reasonably high sigma that sigma contributes at certain laws. So, this type of heater also cross sectional view also people realized.

And we can show that they there are some kind of pro and cons for both type of heater configuration. And in this case you can have top cladding silicon dioxide or you can keep it just bare . So, here also when heat is dissipated because silicon is heat is dissipated because of the joule heating. Then this heat energy can be conducted this is the conducting part silicon is highly conducting thermally conducting compared to silicon dioxide and will conduct and it can raise the temperature of the waveguide.

And by the same effect you can see this temperature will be rise refractive index will be changed and you can have some kind of phase shifter depending on the length. So, these 2 type of this heaters mostly used in CMOS industry and also lot of experiments carried using these 2 type of thermo optic phase shifters. There are many other type of phase shifters are available but they are still in the in an ascent stage.

So, they need to be mature. So, I am not discussing in this course all those type of receptors particularly thermo optic phase shifter with different configurations but with this 2 configurations you get you can get a better idea and overall working principle.

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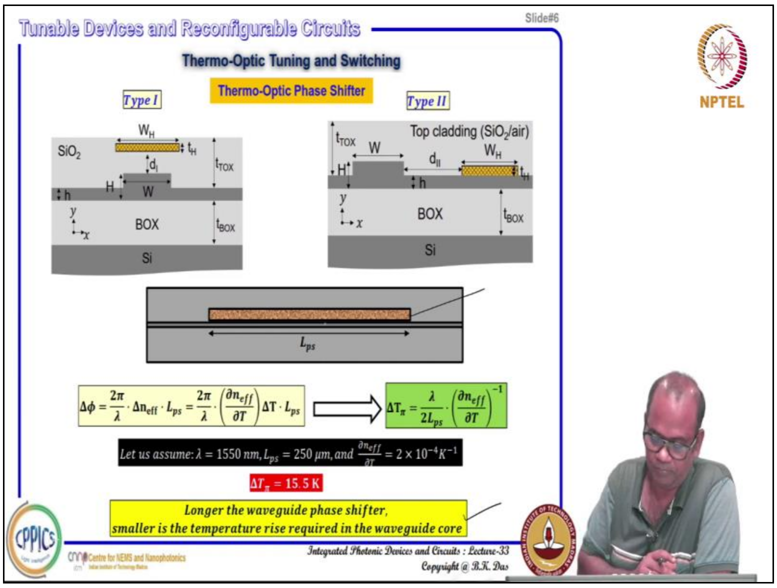

Let us see how it works. So, let let me just show you the top view. So, this is your waveguide where your light can be launched and your mood is excited and it will be propagated through here until it will be going out through that. And in the top you can have this heater or this heater along the length it is shown something like that this is your heater. Length you can say L phase shifter.

Here it is shown length of the phase shifter we can say this can be waveguide and this waveguide can be any form it can be bend structure it can be ring type of waveguide structures but for the simplicity for simple purpose simple discussion purpose we have just considered here a straight waveguide configuration. So, this waveguide can be said this waveguide and micro heater configuration can be type 1 and type 2 just for perspective view I have shown just outside the waveguide top view.

So, this is the waveguide top view and also micro heater top view. This micro heater can be directly on to the top of the waveguide here as shown here. So now let us see what happens. So, suppose L ps that means the length of the phase shifter where you are sending a current you are making a contact here. For example you are just connecting a voltage source here and then this will send the current because it is R some micro heater resistance will be there.

So, you can think of micro heater current is actually V by R H whatever the source you are giving depending on the current will be there and this current in turn will cause some kind of joule heating of this heater and that heat energy will be transferred to the waveguide. So, if it transferred to the waveguide some refractive index will change take place. And we have seen that the phase shift for a precipitate length of L ps delta phi equal to 2 pi by lambda lambda is the operating wavelength operating wavelength.

So, if your device is operating at lambda input laser you are launching here lambda 2 pi by lambda and delta n effective we know that beta equal to 2 pi by lambda n effective and phase normally equal to 2 pi by lambda n effective L. So, if L is fixed lambda is fixed delta phi must be equal to 2 pi by lambda times delta n effective times L that is what it is mentioned here L is the phase shifter.

So, then 2 pi by lambda times delta n effective this delta n effective change how it is happening because of the thermal effect and thermo optic coefficient we have del n effective by del T and delta T is the temperature rise in the waveguide core for example. So, this is your accounting as a delta n effective and multiplied by L ps. Now what you do you are trying to get how much temperature rise required to have a pi phase shift.

So, if you are just putting delta phi equal to pi delta phi equal to pi. Then you can just calculate delta T pi whatever the temperature is required we call it as a delta T pi with a simple simplification with simple algebra you can just find out delta T pi that means that is the temperature rise required in the waveguide section cross section so, that you can get pi phase shift for a waveguide phase shifter of length L ps.

So, that would be lambda by lambda over 2 L ps and this inverse of del n effective by del T this is straightforward. This is the temperature is required for for pi phase shift we are just putting delta phi equal to pi nothing else. So, now let us assume just to see quantitative how much temperature increment required for pi phase shift? Let us assume operating wave length is lambda equal to 1550 nanometer and phase shifter length is 250 micrometer just sufficiently long.

We have considered it can be 10 micrometer it can be 5 micrometer it can be anything depending on that other parameter has to be adjusted. So, lambda equal to 1550 nanometer phase shifter length is about 250 micrometer and del ineffective by del T we have just assumed that 2 times 10 to the power -4 typically it is between 1.7 to 1.9 or so, into 10 to the power -4 per Kelvin typically it is there we just consider T.

So now if we just substitute this lambda value here this L ps value here this delta n effective here. Then we find delta T pi equal to 15.5 Kelvin. So, that means if your precipitate length is considered to be 250 micron and you want to have a thermometric phase shift of pi. Then your waveguide core needs to be heated to a temperature higher than the room temperature of about delta T pi equal to 15.5 Kelvin.

So, you should keep in mind that if this length is more. Then your temperature H can be lower. Let us consider L ps equal to say just 25 micrometer instead of 250 in that case delta T pi will be equal to 155 Kelvin that means your web guide code temperature you needs to increase by 155 Kelvin. So, it is clear that longer the length you do not need to you can actually raise the temperature lower to have a desired phase shipped in the waveguide or for the guided mode.

Now let us see this is what I commented here longer the waveguide phase shifter smaller is the temperature rise requirement in the waveguide code for a given phase shifter. I want pi phase shift that is how we can calculate this is straightforward but challenge is that how you can raise this temperature delta T equal to 15.5 or 155 or even if you want for example even 10 micron or so then it will be even higher temperature requirement may be up to 200 Kelvin people have shown that this temperature can be increased up to more than 600 700 Kelvin or so.

So that you have to raise the temperature such that your register micro heater should not be burnt and also your waveguide should not be destroyed that you have to take care how much temperature you are raising. And also you should keep in mind we will be discussing later that while heating in one waveguide there should not be a thermal crosstalk to another neighbouring waveguide or neighbouring devices.

It should not disturb other neighbouring devices. So, thermal crosstalk should be minimized. So, you should keep in mind that whenever you are designing this device this device thermopic phase shifter and if you want to raise a very high temperature you should be very much careful that this high temperature because of the high temperature there will be some kind of thermal conduction in the surrounding region.

So, surrounding region other devices should not be should not be disturbed. So, that they should be kept at a separate safety safe distance I mean to say.

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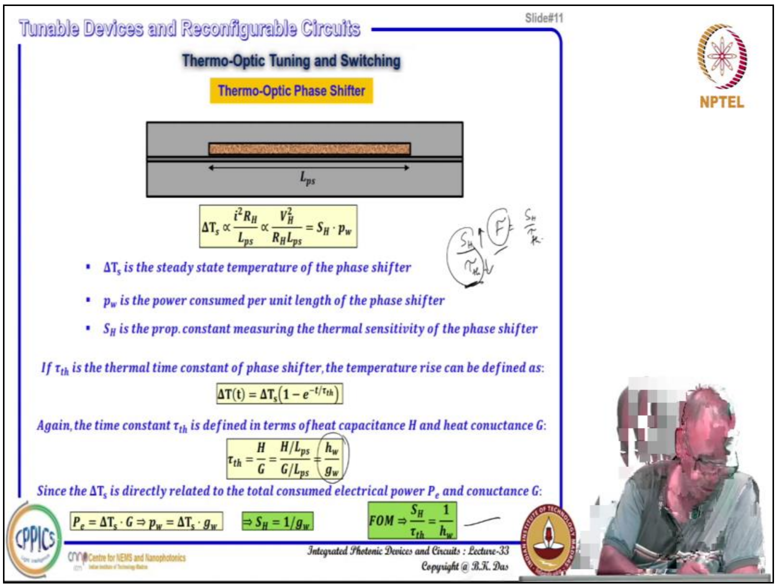

So, now let us see you are not applying voltage here you are applying voltage here in the heater. So, this is for example you are having V and then this one you are just making with respect that potential difference you are making with respect to the ground here you can connect the negative terminal here. So, current will be flowing so in that case temperature rise. So, temperature rise will be how much suppose i current is flowing i amount of current is flowing.

So, total heat energy will be dissipated by this resistor of resistance R H equal to i square R H. Now this temperature rise must be proportional to i square R H divided by L ps that means how much energy we have just normalized with the length of the phase shifter that means how much energy we are dissipating per unit length here. If this per unit length heat dissipation is more temperature rise will be more per unit length heat dissipation is less temperature rise will be less that is why we are writing proportional.

So, i square R H instead of that I can write V H square R H instead of this one if I write v h potential difference V H s square divided by R H L ps i square R H that will be equal to V H square by R H. So, if you have a voltage source you can use this equation if you have a current source you can use this equation. This can be written as you see normally this power this is the total power dissipation and divided by L ps, L ps means phase shifter length.

So, I can write that power dissipation per unit waveguide phase shifter is P W we defined and we just use a different term that is a proportionality constant S H that is we call it as a thermal sensitivity because you see delta T is equal to S H P W how much power you are actually dissipating per unit length actually if S H is higher that means your temperature rise will be higher if certain device architecture giving S H less.

Then delta T S will be less for a given input power. So, here we call it as a delta T S is the steady state temperature of the phase shifter that means you are applying a DC voltage and DC current source. Then whatever temperature has happened starting from the beginning to a certain steady state condition we say that that temperature rising raise delta T S amount of temperature rising is happening.

So, P W as usual I mentioned is the power consumed per unit length of the phase shifter. So, total power it is power you are just how much you are spending for the micro heater it does not mean that all the heat energy is being used up because there will be some kind of heat conduction radiation dissipations depending on the surrounding ambience. So, depending on the surrounding ambience actually this temperature rise will take place.

The surrounding ambience and physical parameters waveguide parameters everything that actually defines that actually decides how good is the sensitivity S H high or low. So, next thing next thing is that this is we call that steady state temperature rise but normally if you want to use that phase shifter for a certain duration of time or you want to make certain kind of switch will be discussing little while later.

So, in that case it is very important how fast you can raise the temperature how fast you can actually cool it down the waveguide. So, that is being decided that is actually decided by a another constant will be calling like S H we can call there another parameter that is another figure of merit called thermal time constant of the phase shifter, phase shifter when I say phase shifter that is actually combined structure waveguide plus micro heater and surrounding region cladding etcetera slab heads everything is included.

So, if this is the case then we know that steady state temperature is delta T S and how it increase. So, if you just see the temperature rise normally it is time and then initially as a function of time if you switch on some step function for example as a voltage source. Then what happens if this is your delta T S. Then you can have that delta T S it will be slowly it will be just reaching to delta T S.

And you know if you are cooling down slowly again it will be cooling down exponentially. So, this rise time and this fall time most of the time actually it is it is almost equivalent but it depends on how close micro heater you are considering you are integrating depending on that how fast it can rise. But whenever cooling down that time this micro heater closeness does not matter it depends on your or everything conductivity surrounding regions everything.

So, that is why sometimes this rise time and fall time can be different but for the discussion purpose here we consider that this tau T H is the rise time because that is actually the ultimate thing you can get you can actually estimate very accurately. Because that is the proximity of micro heater etcetera and the conductivity thermal cap heat capacitance everything controls that one.

So, normally this is actually 1 minus e to the power T H this can be actually following like A T by tau T H thermal constant and this can follow this function. So, it saturates and this is actually called thermal constant. How fast how fast it is cooling maybe how fast the temperature rise or differential temperature is dropped to 1 by e, 1 over e that is actually thermal constant standard way what we discussed normally fine.

Next thing is that how you can define normally this stout is normally you know if you have a RC circuit and anything voltage rise and voltage discharging normally we say that the time constant t by rc r is the resistance is the capacitance for a RC circuit the rise time fall time or the time constant is normally RC that you know from the very basic course of your electrical circuit.

So, similarly here also instead of electrical circuit consisting of resistance and capacitance here also what you can consider resistance 1 by R of course you know that is conductance is responsible current conductance G or whatever things you consider. In this case we can also have whenever there is a thermal source through the material that thermal energy how fast it can conduct how good conductivity is the surrounding material.

So, that conductance or the inverse of resistance thermal resistance inverse of thermal resistance is thermal conductance or inverse of thermal conductances thermal resistance. So, that means like RC circuit whatever conductance is responsible or resistance responsible here also thermal constant is also responsible. How fast it is cooling or how fast it is actually heating up that actually depends on the conductance thermal conductance.

When I say that thermal conductance this is actually we are saying that heat conductance or thermal conductance we are making and another thing is the heat capacitance you know heat capacitance means how for a given for one degree temperature? How much heat energy is required and if it is one gram? Then it is a specific heat otherwise if it is just a bulk material how much energy is required to raise the temperature of the substrate of the material up to one degree that is actually called heat capacitance.

So, that means this can be considered equivalent to capacitance and this can be considered equivalent to one over resistance for an electrical circuit analogous to electrical circuit. So, that is the reason you see I can write that thermal constant tau thermal equal to H is equivalent to capacitance and inverse of G that means inverse of conductor thermal conductance that is actually resistance.

So, it is like a RC thermal constant in normally tau equal to RC in electrical circuit here also it is something like that H is equivalent to C thermal capacitance instead of electrical capacitance and then you have thermal conductance inverse of thermal conductance is thermal resistance. So, you can actually define thermal constant tau h equal to H by G. So, you need to know the entire system what is H value and what is the g value of the systems you know this phase shifter is a part of a large integrated circuits.

So, it is not so, easy to find out it is actually stupid to find out heat capacitance for the entire chip or conductance for the entire region. Rather we can just try to define distributed heat capacitance and distributed conductance. So, how that can be done you can define this H divided by L ps. So, you just consider the length of your phase sector you normalize it. Similarly denominator also you can normalize with phase shifter and that is called say H W and G W H that means H W waveguide phase shifter I mean to say H W equal to capital H by L ps.

Whatever effective heat capacitance you have for the system surrounding the micro heater that you normalize with the L P and that can be considered as a distributed heat capacitance of the micro heater waveguide phase shifter system. So, we can say this is a characteristics heat capacitance distributed heat capacitance similarly you can define distributed conductance that means overall conductance per unit length you can distribute over interface shifter L ps.

So, G W, so, this can be written that means instead of this one I can write the per unit length how much capacitance we are normalizing just nothing else normalizing with the length that will be actually thermal constant. So, if you can quantify H W and G W by experimental means or by very good theoretical model. Then you can predict that whatever the thermal constant is possible and that thermal constant you know that is very important it actually decides how fast you can heat it up and how fast you can cool it down.

So, that is how you can think of how fast what would be the modulation speed thermo optic modulation speed that that entirely depends on tau value thermal constant . So, next thing is that since this delta T S is directly related to the total consumed electrical power Pp that that means total consumed electrical power that is nothing but i square R H or V square V H square by R H. So, this value or this value this is the total value this week define as a total electric pole consumed and conductance G.

Then normally it can be shown that that temperature rise multiplied by conductance temperature rise multiplied by conductance that actually equal to your power consumption electrical power consumption P e we can write like that if we can model like that. So, then what you can do here this P W that means you just divide left hand side by L ps and hand side also L ps that means left hand side will give you P W right hand side delta T S G W that means.

You can remember that this P W now that means power consumed per unit length of the waveguide phase shifter is actually help how much temperature rise in steady state that decides by what how good it is the conductance. So, it is clear that if I am using say one milliwatt per micrometer of waveguide phase shifter. So, the temperature rise will be more for that given power if G W is less conductance is less.

Clearly if thermal conductivity is less surrounding region whatever energy you supply you supply that will be actually helpful to raise the temperature. So, that is how it is justified. So, you would like to have lower conductivity lower conductance thermal conductance to dispense of the lower power to get a desired phase shift. So, that is very important now you see that is why we call it we define say sensitivity here you know delta T S is proportional to P W.

So, if we just compare this one and this one this equation and this equation. Then we can find that sensitivity equal to 1 over G W whatever sensitivity we are getting that means higher the conductivity sensitivity will be lower. Higher the thermal conductance lower is the sensitivity smaller the conductance sensitivity high what sensitivity means this kind of capacitance like how good it is temperature rise is happening.

So, this is a different way of modelling a waveguide phase shifter good next thing is that figure merit. So, figure merit you want S H to be as high as possible and you want tau T H should be as low as possible. So, this is one figure of merit we want good sensitivity should be good for a given power the temperature rise should be as high as possible. So, that you do not need to spare a lot of electrical power to get a desired phase shift.

Similarly you want very fast switching very first temperature rise tau T H should be as small as possible. So, in that case we can define a figure of merit something like that we can call that is actually S H by tau H you have to maximize this figure of merit maximizing that figure made it means you have sensitivity is higher and thermal constant is lower. So, you can do very high temperature rise and in a quicker time interval that is why it is called figure of merit.

So, this figure of merit will be S H by tau H now you know S H is 1 over G omega tau H you know H omega, H omega means W I would say W, H W by G W. So, ultimately the figure of merit if you see that depends on 1 over H W Heat capacitance distributed heat capacitance. So, distributed heat capacitance should be smaller that means your system you should design such that you need to have very low very low heat capacitance that means very low power needed to raise the temperature that is the different way of just explaining modelling your thermotic phase shifter good.

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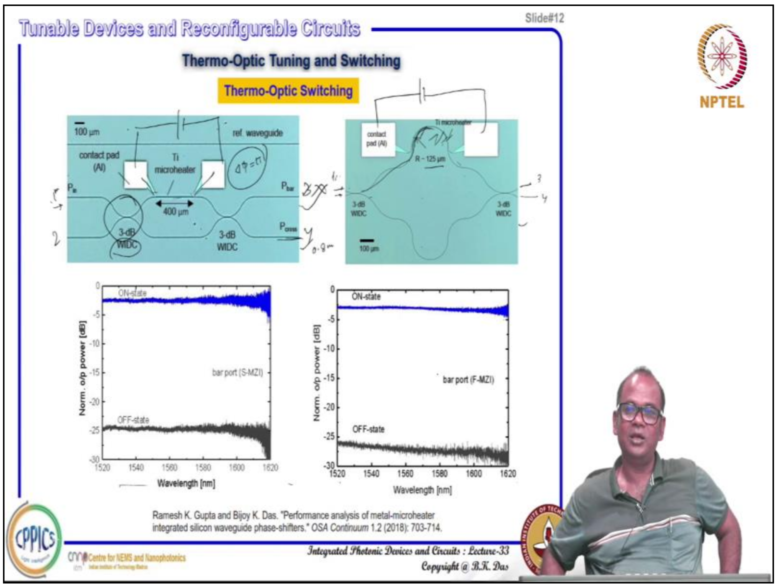

So, now we discuss phase shift are related how fast what is the power requirement what is the design requirement critical things we discussed. Now using that type of thermoptic phase shifter we can actually demonstrated switch. Integrated optical switch integrated optical switch is what suppose you want to switch from one port to another port enter power entire signal from one port to another port.

We know that magenta interferometer working principle of magenta inter parameter it has a 2 port 1, 2, 3, 4 and if you launch this magenta interferometer 2 by 2 match general interferometer it is actually constructed by 2 3db directional coupler 5050 directional coupler WIDC means we just mentioned that it is actually wavelength independent directional coupler that means it is a broadband operating about more than 100 nanometer around 1500 to 1600 nanometer NC communication window.

Similarly another 3db bandwidth then what you call what you have this is a balanced Mach–Zehnder interferometer if you launch any wavelength any power. Then entire power will be coming in the cross port according to the transfer function we know this is a balanced magenta inter parameter transfer function you have learnt earlier also if it is a balanced. Then it is 3db as if this 3db this 3 will be connected together it is a longer directional coupler and it is used for cross coupling purpose.

So, ultimately if you launch here entirely it will be coming in the cross port if you are launching here one milliwatt maybe you will be getting 0.8 milliwatt maybe 0.2 milliwatt will be lost because of the directional coupler etcetera but nothing will be there in the bar port. However you know if you have a phase shifter here where thermo optic phase shifter in this case it is a titanium heater is deposited very close to the waveguide structure.

And that has been connected to an aluminum contact pads through which you can actually supply some voltage and because of the current because of the temperature rise if you can introduce a pi phase shift. Then what happens this power entire power will switch over to bar port. So, you can actually switch power from the cross port to bar port. And since this directional couplers are designed wavelength independent.

So, any wavelength from 1520 to 1620 it has been tested that the entire power can actually for all wavelength you can switch by just giving pi phase shift. This is actually actual device fabricated in our lab and also this is actually optical micro graph it is shown just photograph it is shown Mach–Zehnder interferometer you know this micro heater length is 400 micrometer here.

And if you see in the on state on state means what you get you are getting in the heater is on. If heater is on you supposed to get everything in the bar port you see entire wavelength all the way this is wavelength region and normalized optical power output on state all the power will be in the bar port and off state in the bar port it will be dropped. So, if you withdraw your current heating current. Then power enters all the power will go here and if you just switch on your current on state. Then power will be in the bar stone.

So, this is how one can actually design a switch. Here similar thing already demonstrated instead of straight micro heater that means micro heater deposited along the wave guide parallel to the wave guide you can have a bend structure like this it is also balanced 2 by 2 port one port 2 here it is shown here it is a fabricated device also it is port 3, port 4 you are launching here P input.

And this is the length waveguide length here and this is how you get identical length only we have made a curved structure so, that your micro heater also can be curved along the waveguide. So, now you can again apply voltage here. So, what happens if it is a curved micro heater we have seen that that is relatively efficient because you know in the curved region.

So, some of heat will be consolidated more in this region in the state region it will be just straight portion of the waveguide will be individually per unit length power dissipation and temperature as you be whatever will be there here per unit power consumption temperature rise will be more. We have seen that is why bend structure is more efficient we have just created a band wave gate structure of 125 micrometer bending radius and balance structure.

There also we have seen that it is actually switching off state to on state on state you are getting entirely everything in the bar port off state entire wavelength spectrum whatever tuning whatever you can have experimental results wavelength can be tuned and you can see from 1520 to 1620 nanometer interval length you can switch back and forth. So, using thermo optic phase shifter integrated with a balanced magenta interferometer and if that Mach–Zehnder interferometer designed with a 3db power splitter which is actually wavelength independent.

Then that can be actually used for a very broadband integrated optical switch that has been demonstrated and we have published here. If you are interested more you can just download this paper and you can return its very details it is explained there.

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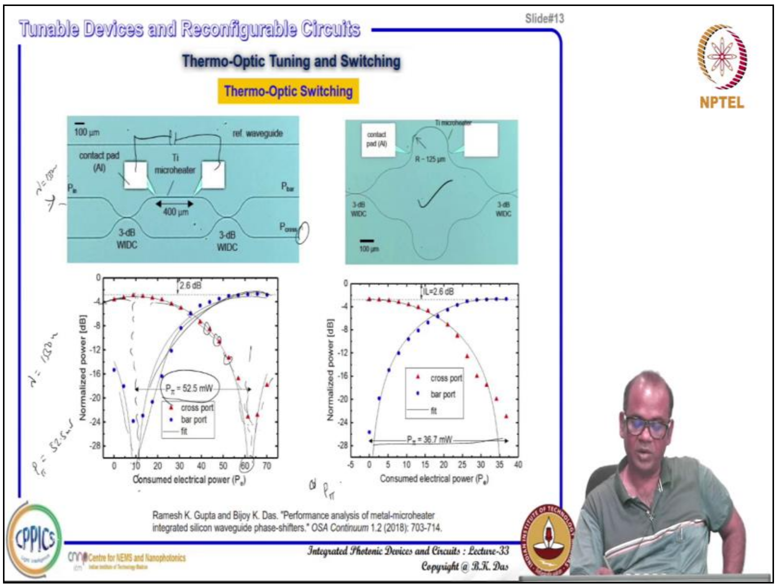

Now you see this is instead of tuning your entire wavelength range you just focus on only one particular wavelength so lambda equal to 1550 nanometer you are launching here. Now if you just calculate the you just send a current here or connect a voltage source and you see depending on the voltage as a function of voltage you can actually control if your current source you can actually control the current and if you know the resistance.

Then you know what about the power consumed by the entire heater. So if you just plot if you launch here say lambda equal to 1550 nanometer certain power you are launching here in this waveguide. Then as a function of consumed electrical power here or power dissipated by the micro heater if you see that that cross port and bar port you see this is the cross port power will be maximum and slowly slowly it will go down and then it will be increasing.

You see this triangle they are actually experimental results and the solid line that is actually theoretical results theoretical results extinction can be it can be extinguished very high but in practice optical devices you see we could measure up to minus 25 db extension. So, that means in the cross port for example cross port whatever power is there you can switch it down to minus 25db.

So, it is about 20 more than 20db extinction is possible at the same time when it is dropped in the cross port here where that energy goes you see that energy goes up in the bar port this is the bar port results we see that. So, that means we can say that it was the maximum here somewhere here it is in the cross port maxima and somewhere is the cross port minimum. So, if I just subtract this power to this power to this power we can find that about 52.5 milliwatt power required.

And that is happening maxima to minima happening because of the pi phase shift that means I can say that P pi equal to 52.5 milliwatt. So, that much power required to switch the power electrical power you need 52.5 milliwatt to switch power from cross port to bar port. If you withdraw that power. Then again it will appear in the cross port and that can happen for any wavelength this is the experimental result evidence.

Similarly for if you just do similar experiment for bent micro heater structure where the efficiency or sensitivity is slightly higher we found that actually the P pi the maxima to minima happens that is only in 36.7 milliwatt. So, it is because the heat is con actually concentrated within a small region and that is why longer length of the waveguide is getting higher temperature and phase shift will be higher that is why you need low power consumption and for a certain temperature rise.

And in turn your V by P pi that means power required to get a pi phase shift is much lower at least you can see that 1.5 times lower about 36.7 milliwatt good.

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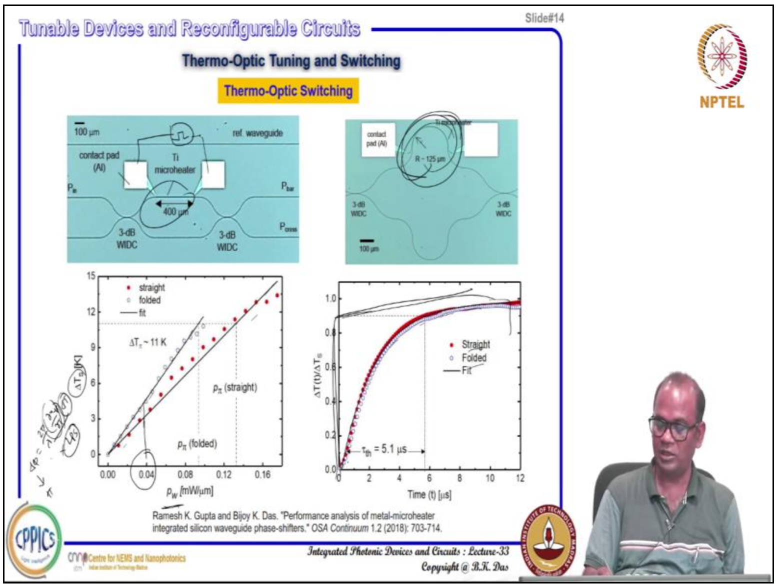

So, now you see some more study we have seen that we calculated back because you know that P pi phase shift you know delta phi equal to 2 pi by lambda times delta n effective by delta T times delta T that is your delta n multiplied by L ps L ps known del n effective by delta T known lambda operation known delta phi if we are having pi phase shift that means I can find out temperature rise.

So, we need to know also as I mentioned earlier that you should be very careful that temperature rise should not be very high. So, that that can result into a thermal crosstalk to another devices we have found that 2 different type of things this micro heater straight micro heater valve integrated in the balanced Mach–Zehnder interferometer and bent micro heater also integrated with a balanced Mach–Zehnder. What do you mean by balanced?

Balanced means both the arms are of equal length. So, if you see that this curve corresponding to folded one that means this one and this one corresponding to straight one. If you are just plotting the delta T a steady state temperature rise as a function of power dissipation per unit length power dissipation power thrown out by the micro heater into the substrate per unit length milliwatt per micrometer.

So, for example if you see if you are using 0.04 milliwatt per micrometer then the temperature rise in the curved waveguide structure straight waveguide structure is actually lower but the folded this one temperature rise will be higher. Same power same length of the micro heater if you compare straight wave guide and bend structure wave guide. Then temperature rise will be higher in the bend structure.

So, that is more efficient more temperature rise means more phase shift will happen this plot is shown for the straight waveguide it is somewhat experimental results is following a straight line that is what shown and we have seen that the temperature rise how fast it happens? If you just give a square pulse suppose somewhere some square pulse you are giving step function square pulse voltage pulse you are giving here.

Suppose here you are giving a voltage pulse. So, and then you monitor in a oscilloscope how fast temperature when just voltage start from 0 to certain voltage may be 5 volt or so then temperature rise will happen you have to see how fast it is happening. You see for straight waveguide and folded waveguide the temperature rise you see it is following same path as a function of time.

So, it does not take much time because per unit length that is the physical parameter of the waveguide structures how what is the slab thickness what is the waveguide width how far the micro heater from the waveguide all those actually depends on your so, called thermal constant actually depends on earlier we have discussed you remember that. So, thermal constant this depends on thermal capacitance and thermal conductance; that nothing to do with the architectural geometry of the device.

But that thing actually if you can actually engineer this thermal capacitance and thermal conductivity of the structure then this can be actually engineer also this rise time can be engineered. We have found that the rise time for both type of structure is about 5.1 microsecond around 5 micro second or so.

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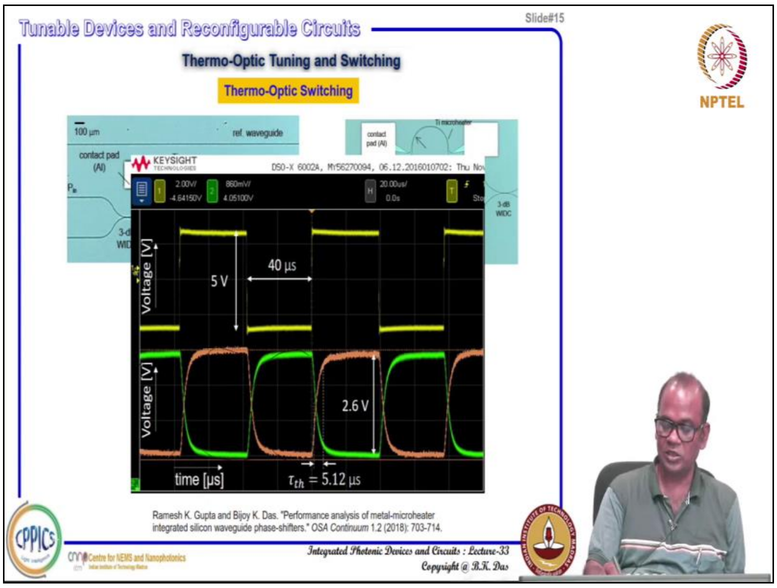

Now so, this is the result here again that you see this is the voltage 5 volt it is given directly from the oscilloscope it is shown here. And then you see one is for the this is the high cross port and bar port it is shown there when cross port is reducing bar port is increasing reducing increasing. So, you can actually switch back and forth between cross port and bar port and it is clearly showing that how fast it is rising 5.12 micro second.

And falling also nearly identical 5.12 micro second again the details are given in this paper if you want you can download and then you can study.

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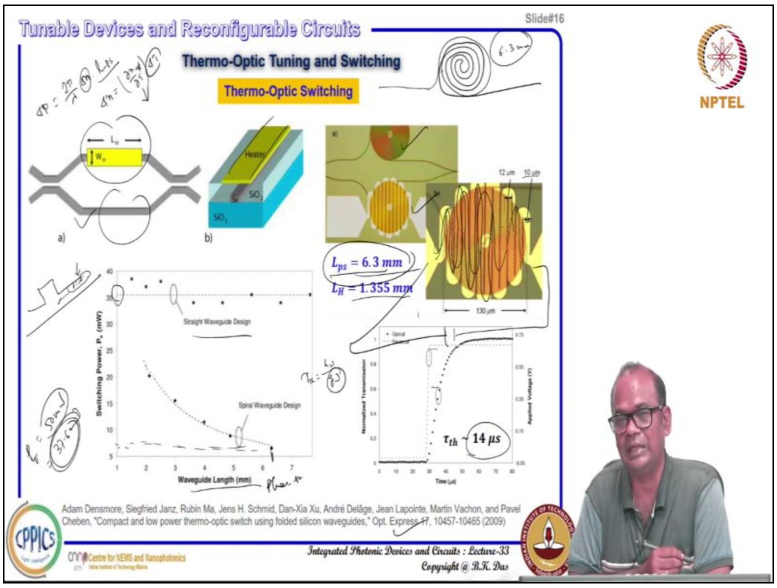

Now next thing is that well we have shown that our micro heaters P pi is the is in the order of say 50 milliwatt for straight waveguide structure and for other type 37.6 milliwatt or something like that for bend waveguide structure that means band structure is really effective. Earlier also it has been shown that the magenta interferometer designed balanced magenta interferometer designed to tactfully.

Then you can get a base better efficiency not only better efficiency you can actually you do not need to go for very high temperature rise as well. Here if you see this is a typical magenta interferometer and it is possible it is like a type 1 type micro heater that means your waveguide and then oxide and directly on the top of the oxide you are just depositing your micro heater this is the micro heater.

And what it is done you have a this upper arm and lower arm you just make a spiral waveguide structure you bring something like that upper arm one stripe and then you bring something like this you bend spiralled away like this and then come back. Another way wave guide you define little bit longer like this and come back like this and this wave guide in this case in this paper they have explained and that is in 2009 they have created a spiral waveguide of length about 6.3 millimeter phase shifter length.

And on the top there will be oxide identical arm length this is also spiral this is also spiralled and then oxide is deposited top of it micro heaters are deposited but micro heater is not like a straight micro heater instead there is a meander type micro heater deposited on the top of the spiral drive gate. This is the micro heater so, you see the separation between 2 lines is 2 micrometer and thick width of the micro heater is about 10 micrometer this is spiral line and of 1.355 micrometer.

And then if you are just applying voltage here, here. Then current will pass through here and here. Then all the heat i square R will be generated in this micro heater that will be actually directly actually will be radiating towards conducting towards the waveguide from the top that means your L ps is now 6.3 millimeter long and your all the power you are concentrating in this area heating power.

So, entire length is being actually affected temperature can happen right. So, in that case since the waveguide length is very long and I know that delta phi phase shift is 2 pi by lambda and then how much delta in refractive in exchange happening and then L ps longer the L ps you need slower delta n and delta n is what delta n is delta n effective by delta T delta T this is fixed. So, delta in lower means delta T can be lower.

So, you can have a very lower temperature for a thermoptic phase shifters and they have shown that the waveguide length and if it is a straight wave guide switching power requirement is about 35 milliwatt exactly whatever we have got for our about wind wave gate structure our statewide gate structure we have demonstrated it was for 50 milliwatt. But here they are getting almost any waveguide length you need the power required for switching is about 35 if you are using straight waveguide.

So, straight wave guide whether you use a shorter heater or longer heater or phase shifter power requirement is same only thing is that how much temperature rise you are doing that actually differs longer the waveguide preceptor length the temperature rise will be lower but total power consumption needed almost equal 35 milliwatt that is what it is shown waveguide length that means I mean to say that is a phase shifter.

But if you are using spiral waveguide design like this then waveguide length if you are just increasing waveguide length up to 6.3 millimeter here. Then power consumption for pi phase shift is exponentially decaying and it is required very less amount of power you see that is about in the order of 5, 6 milliwatt. So, from 37.56 milliwatt you could reduce your power consumption power requirement of about 5 times lower 5, 6 times lower.

But at the cost of longer waveguide length beat up longer footprint and longer waveguide length in turn waveguide loss can be introduced but if you have a low loss waveguide design. So, whether it is a 250 micrometer or whatever the 6.3 micrometer maybe you can lose some power optical power but your electrical power will be reduced dramatically. But one thing is that since this is a type 2 heater is just directly on the top of the oxide not directly direct heating.

Like earlier we have explained here that this device this micro heater here we have just this is in the slab region. So, directly on the slab region heater was integrated but in this example heater is just on the top of your waveguide but above certain thickness of cladding oxide layer. So, that is the reason the thermal constant thermal constant as you know H W tau T H equal to H W by G W.

So, the conductivity will be poor now because oxide is cladded surrounding region. So, oxide if it is poor. Then tau T H thermal constant will be higher and obviously they found that it is 14 microsecond thermal constant. So, that means switching time would be little bit longer in this case. However your power requirement for P by phase shift pi phase shift is much much lower. So that is a nice demonstration there are many other type of phase shifter are available also but within the scope of this courses I just restrict ourselves these 2 types of type 1 and type 2 only metal register heater.

There can be instead of heater deposition one can think of that you have a slab wave guide for example you have a slab wave guide rib wave gate structure and one region instead of metal deposition you can dope. It is a silicon when you fabricate waveguide that is intrinsic now if you doped p type or n type then it will be conductor. So, that there through that if you just send current also. Then heat joule heating energy also will be conducted and temperature of the waveguide will be increased and in turn you can get a higher refractive in exchange. So, that is another type.

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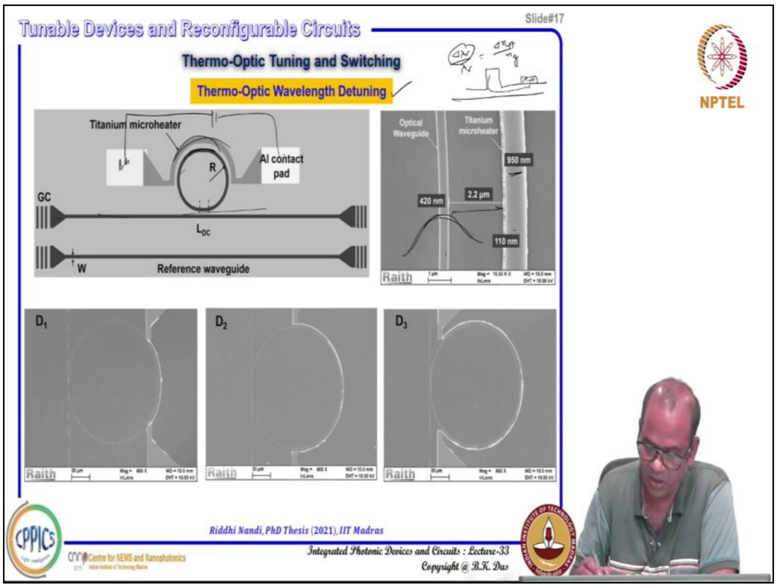

Now we will be discussing thermo optic wavelength detuning. So, we have discussed how phase shift can happen what are the figure merit. And also we discussed using that type of thermo optic phase sector how one can design a magenta interferometric switch. Now we would like to discuss how this thermo optic phase shifter can be useful for wavelength retuning we have already shown earlier that this delta lambda R resonant shaped for a given wavelength resonant wavelength that is actually a delta N G by any sorry delta N effective I am sorry this should be this should be something we have derived earlier delta n effective by delta N G group index of the waveguide.

So, that means this delta n effective actually proportional to the temperature rise and if you just increase the temperature rise a resonant wavelength will be shifted. So we can we have designed a all pass configuration this is the bus waveguide this is the ring and then micro heater bent structure is a titanium micro heater again contact pad aluminum here aluminum here you can pass current through here and then i square R it will heat up.

Then phase shift will be there refractive in exchange will be there and correspond delta lambda R will be there. So, in this case this is the scheme and after fabrication if you see this is the waveguide this region it is shown here zoomed region waveguide region and this is the micro heater region titanium micro heater region it is shown here it is about 2.2 micrometer away it has been kept with a safe distance.

So, that more actually propagating within the waveguide that should not be disturbed by the metal otherwise if it is closure then this field will be attenuated loss will be higher. So, he kept except distance 2.2 micrometer and then since it is a slab integrated micro heater this is the silicon is there that means you have a micro heater here. So, heat energy dissipated here that will be conducted and waveguide will be heated up.

So, 3 different type of device studied D 1 where quarter of the ring waveguide is cover up with the micro heater half and this is almost 3 quarter 3 different type of devices we have tested.

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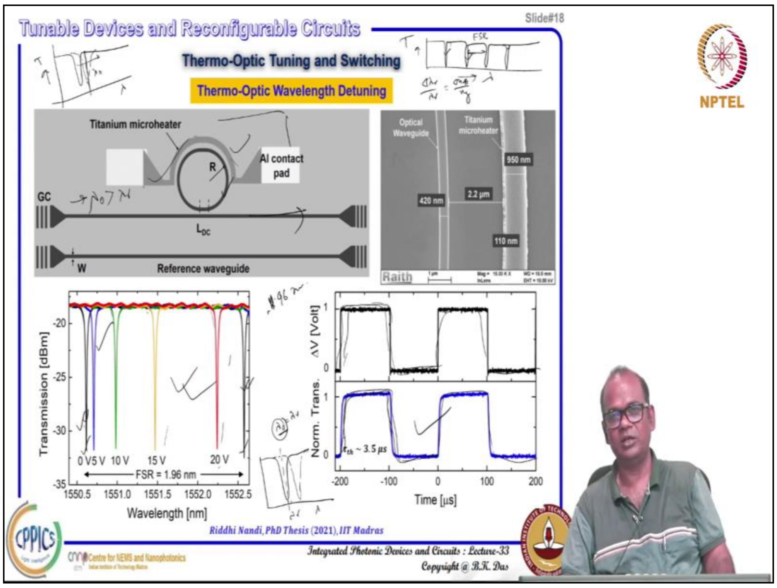

And we have shown here one particular device all this type of you know longer the length you can have a lower the temperature rise. So, that is what we tested and we found it is established and you see that for a ring resonator you know if you see the transmission as a function of lambda this is transmission according to the transfer function you know that will be regularly coming like a phases these are the resonance.

This would be the resonance and this one successive resonance separation is called free spectral range and this particular microwaving resonator is giving a free spectral range of 1 point about 1.96 sorry 1.96 nanometer. So, if nothing is given no current is passed. Then you see this black curve this one resonance it is shown around 55.5 this one this one resonance and next resonance will be this one and this is actually a phasor 1.96 this resonance is there but if you flow current through the micro heater.

Then it will heat up. Then because of the thermoptic effect refractive in exchanges and delta you know that delta lambda R by lambda R that resonant wavelength around 1550 that will be delta ineffective how much change by N G group index and that will be tuned if you are applying zero voltage you get this resonance and this resonance. Now apply 5 volt you see this blue curve the resonance shifted red shifted you could tune.

And then if you give 10 volt. Then again shifted green curve 15 volt it comes here 20 volt it comes here. So, almost entire first FSR it could detune whenever you see the ring resonance you see get resonance here and resonance in between there is no resonance. But if you can program it you can tune to get a resonance anywhere in between to successive resonance all ready for passive waveguide.

So, that is how you can reconfigure and also if you just position a particular suppose you have this transfer function this is your ring transmission it is showing like that and then if you have a laser this is the wavelength dependent transmission. And if you are just putting a laser here laser wavelength here operating wavelength lambda is given operating lambda O is given here.

Now if you what you can do if you can tune your resonance by means of micro heater. Then your transfer function will come like this. So, originally your laser light would see high transmission but whenever your resonance tuning this side. Then it will be seeing the low resonance low transmission. So, that means you can get certain kind of intensity modulation intensity switching.

So, that means you can make on off of that particular laser high low high low you can make. So, that is what it has been shown for a given wavelength you are just operating a particular lambda and this lambda for example lambda operating is actually say greater than lambda R certain resonance. Now you see whenever some voltage is high. Then your transmission is high now voltage is lower that means heating current is lower transmission drops.

So, again that way actually you can tune probably whenever voltage is there that means you are getting high that means it is other way that means your if it is your transmission is like this in this particular example this is your wavelength lambda this is your lambda R and suppose at exactly you match your lambda operating exactly to lambda R. So, that means whenever no voltage is there your transmission is lower because that that region that particular operating wavelength will be stored in the micro ring regenerator.

Now apply some voltage. So, that this can be tuned here up to here your microwaving resonator resonance tuned here. So, that means your this particular operating wavelength now it will see maximum. So, that is why when you are just on. Then it is maximum transmission this is optical and this is the voltage source. So, here voltage source you are giving that signal pulse you are giving pulse like this and then your optical output here that also will go according to your pulse.

So, you can get switching on off on off switching. You can get and thermo optic detune wavelength tuning you can get as well as switching also you can get in a micro ring regenerator just by integrating a micro heater you can make it active cool. So, here I stop that thermoptic related phase shifter and switching and detuning everything discussed today. Next another type of tuning of integrated optical devices particularly silicon photonic devices is very much popular that is called plasma dispersion effect.

That effect how it can be useful and how it can be better or poorer than the thermo optic phase shifting thermo optic switching or thermo optic detuning that will be discussed in the next lecture, thank you.