Microwave Theory and Techniques
Prof. Girish Kumar
Department of Electrical Engineering
Indian Institute of Technology, Bombay

Module - 06
Lecture - 30
Microwave Phase Shifters: Switched and Loaded Line

Hello, in the last lecture we had discussed about Phase Shifters and I had briefly talked about Analog Phase Shifter. Analog phase shifters can be generally realized using varactor diode, and these varactor diodes are then controlled by voltage.

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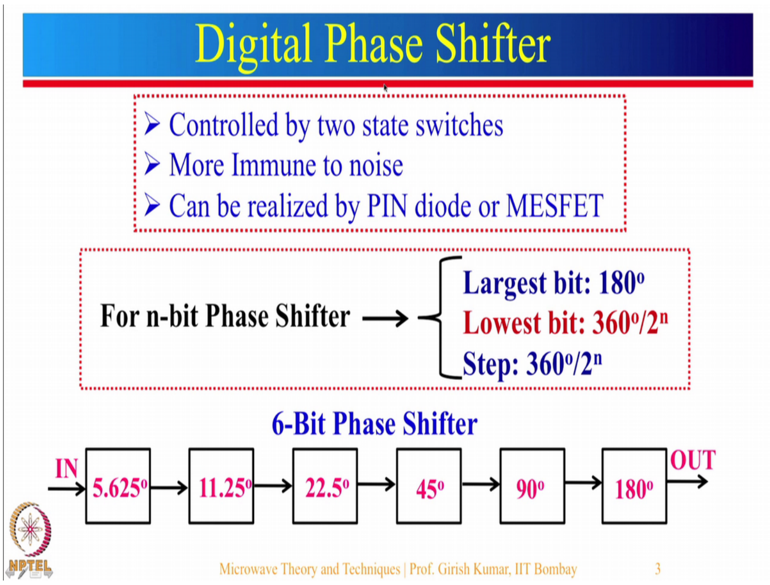

Then we briefly looked at digital phase shifter and for n bit phase shifter largest bit is 180 degree lowest bit is 360 degree divided by 2 to the power n and each step is given by 360 degree divided by 2 to the power n. Then we took an example of 6 bit phase shifter.

So, each bit here is represented; so, 1, 2, 3, 4, 5, 6. So, depending upon which bit is 1 that will be the output phase shift. So, for example, if this is 1 only and rest are all 0, output will have 180 degree phase shift. If this is 1, then output will have only 5.625 degree phase shift. Suppose if this is only 1, then output will have a phase shift of only 45 degree. If these 2 are 1 and 1 each and rest are 0, then output phase shift will be about one 135 degree.

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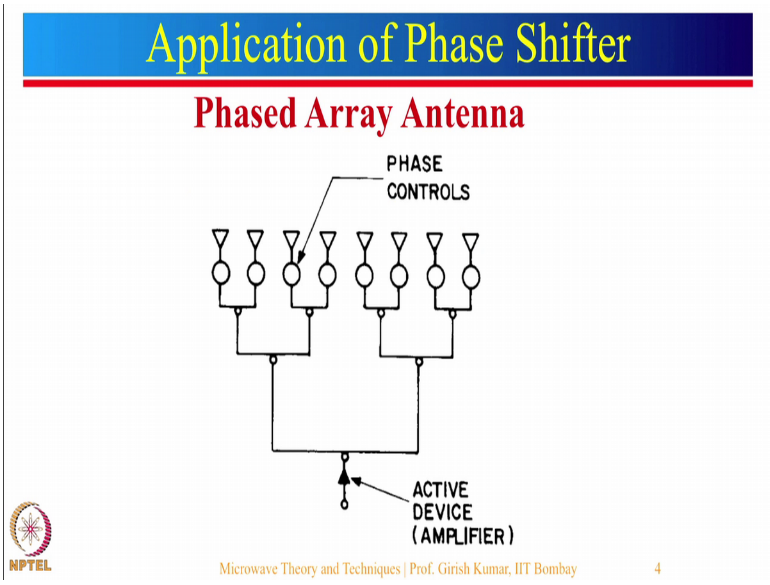

Then we looked at an application of phase shifter and one of the important applications where these phase shifters are used as phased array antenna. So, basically phased array antennas are used to scan viewed from let say minus 30 to plus 30 or maybe minus 60 to plus 60 degree. And these days there is a lot of emphasis on phased array antenna specially, with the advent of 5G technology. So, as you might be knowing that 5G frequencies will be in the frequency range of 20 gigahertz to maybe even 80 gigahertz.

So, that is a very high frequency wavelength will be very small. So, the size of the antenna will be small. So, multiple antennas can be used for example, in today’s mobile phone we can have just one antenna which will be radiating in the Omni direction; however, at 20 gigahertz or beyond one can use even 8 element array instead of just using a single element and these 8 elements will be let say mounted on one side of the mobile phone, another side of the mobile phone and another side of the mobile phone.

So, basic idea is that by using the phase shift between the different elements so, the beam can point in this direction or in this direction or in this direction depending upon from which direction maximum signal is coming. So, this way it can even provide gain in that particular direction.

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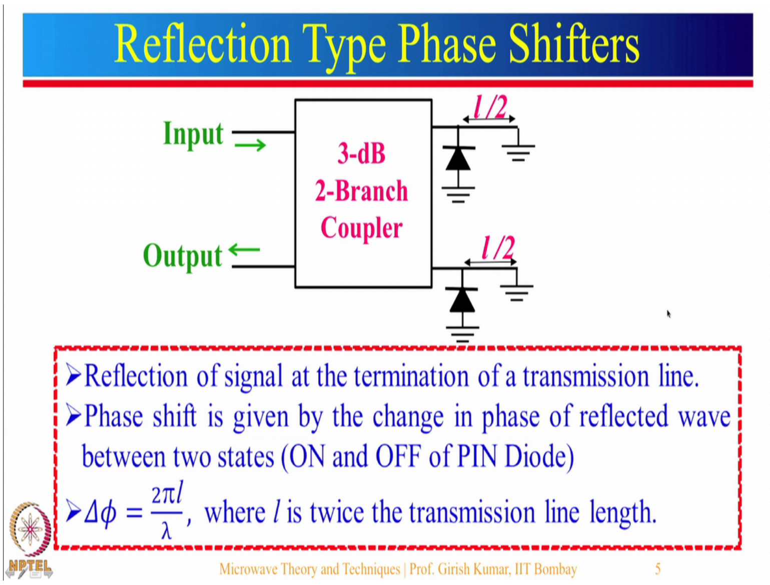

So, now let see, how we can realize these phase shifters. So, let first look at reflection type phase shifter and here we have input coming to one of the port of 3-dB 2-branch coupler, this is the output, the other 2 ports you can see over here that pin diodes are connected over here with the line length l by 2. So, let just look at the concept point of view what really happens here.

So, let say when we give an input at this particular port here. So, half power comes here, half power comes here and nothing goes over here. Now the power over here will have a minus 90 degree phase shift and this will have a minus 180 degree phase shift.

So, let us take a condition when this diode is forward bias; that means, this will be short circuited. If this is short circuited, everything will reflect back. So now, the reflected signal say this was minus 90 degree, let say now this will be another minus 90 degree; so that will be 180.

Signal from here travels 90, 90 180 degree again reflects back so another 90 and 90. So, total path length from here to this particular port and reflected will be about 368 degree. So, this one had 180 degree phase shift, this one will have 360 degree phase shift, these 2 will cancel. Hence, reflected power will be relatively 0 or very small.

Let see what happens at this particular port. So, this experience is a face delay of 90 degree, then from here 90 90 total path will be 270 degree phase delay. And the signal which comes from here goes to here which will be 180 degree phase delay, then another path is 90 degree. So, these 2 reflected signal will add at this particular code. So that means, now input from here will go to output port over here.

So, now let see when the switch is on it will reflect at this particular point, now second state will be obtained when the switch is off. So, when the switch is off, the signal will go to here and then it will reflect back. So, it will experience l by 2 plus another l by 2. So, the total length delay it will experience will be l and that will be equivalent to a phase delay of 2 pi l by lambda. You can actually say it is beta times one or some books write k times l so this will be the phase delay.

So, depending upon whatever the length you have chosen, we can get the phase delay over here. So, you can just take an example for example, if this l I am not talking about l by 2. Let say if this l is equal to lambda by 8. So, if this is lambda by 8 will have a phase delay of pi by 4 which is about 45 degree. So, just by switching on and off the pin diode, we can get a differential phase shift which is given by this particular expression.

Now this is a digital phase shifter. We can realize analog phase shifter here also all we have to do with it is replace this particular portion and this particular portion by a varactor diode over here. So, varactor diode will be connected here, another varactor diode will be connected here and there will be a common biasing to the varactor diode.

So, as we change the biasing voltage, so what will happen? Capacitance will change. So, at this particular point let say we have a reflection coefficient which is represented by gamma. So, what will be gamma equal to Z n minus Z 0 divided b y Z n plus Z 0.

So, now, here Z n is nothing, but given by the capacitive impedance which is nothing, but equal to minus j X or we can say Z is equal to minus j by omega C. So, if you look at the reflected wave from here basically, it will experience a phase delay given by the expression which is tan inverse X by Z 0 and twice of that, this will be shown in more detail in the next slide.

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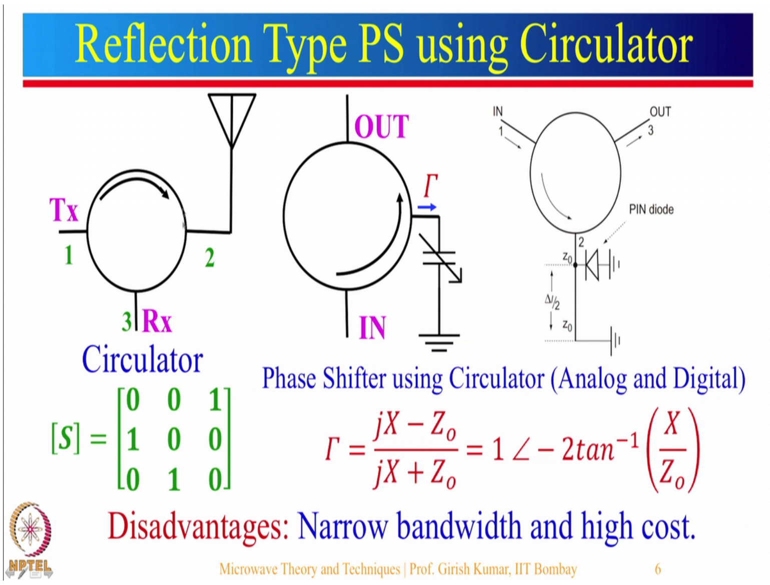

Here reflection type phase shifter is realized using circulator, let us quickly look at what is a circulator? So, circulator is a 3 port device. This arrow direction is very very important. So, this is one of the application not related directly to the phase shifter, but circulators are used for this particular application very commonly.

So, let me just explain you this particular thing over here and these are the S parameters for ideal circulator. So, let me explain you one by one. Let us say we want to transmit a signal from here. So a transmitter is connected here and you can see the arrow over here. So, this signal from here goes to the antenna, antenna transmits that particular signal. The signal received by the antenna comes through here and that goes see again arrow direction; so arrow direction is in this side. So, this signal received at port 2 will go to port 3. So, at port 3 we connect receiver.

So, a single antenna can be used as a transmitter or as a receiver. So, let us just look at the S matrix of this one here; so, as I just mentioned signal will go from port 1 2 port. So, that means, S 2 1 is equal to 1. Then this signal from here it will go to here, that means, S 3 2 is equal to 1. So, that you can see over here; any input given at this particular port will go over here that means, S 1 3 is equal to 0. So, when we give input here, nothing goes over here hence, that term is equal to 0 and when we give a input here nothing reflects back so rest of their terms are 0.

So, lest see now, how this circulator can be designed as a phase shifter. So, here we have a input; at this particular port we are connected a character diode and this is that output port over here. So, when the signal comes from this particular port, it goes over here. At this particular point it sees a capacitive load. For the capacitive load we can say that the impedance will be represented as j X in this case of course, X is negative. So, reflection coefficient can be written as Z in minus Z 0 divided by Z in plus Z 0. So, Z in here is equal to j X as I mentioned X is negative for capacitance.

And this variable capacitance is obtained by using a varactor diode in the reverse bias condition and by changing the biasing voltage of the varactor diode one can vary the capacitance. So, let see what will be the amplitude and phase of this particular thing here. So the amplitude of numerator will be square root of Z 0 square plus X square, amplitude of the denominator will be same which is square root of Z 0 square plus X square; so, net amplitude will be equal to 1, that means, everything will reflect back.

So everything is reflects back. It goes to the output port over here. So, what is the phase difference it will experience? So for this particular term here phase difference will be tan inverse X by Z 0, for this one here also it will be tan inverse X by Z 0; this will have a negative term, this as a positive and this positive goes up here. It will become minus. So, the phase difference experience will be minus 2 tan inverse X by Z 0.

So, we can realize a analogue phase shifter simply by changing the capacitance, which can be realized using a varactor diode with reverse bias voltage. So, here is the realization of that digital phase shifter. So, let us see here what it is input is here, now important thing is please see that what is the arrow direction. So, input is given here, it goes over here.

Now here you can see that there is a pin diode and line length. So, when this is shorted power will reflect from this particular point. When this is open circuited power will reflect from here and then go back. So, it will experience a phase delay corresponding to 2 pi by lambda multiplied by 2 times this particular length. However, this particular configuration is generally not used the reason for that is majority of the circulars have narrow bandwidth and high cost.

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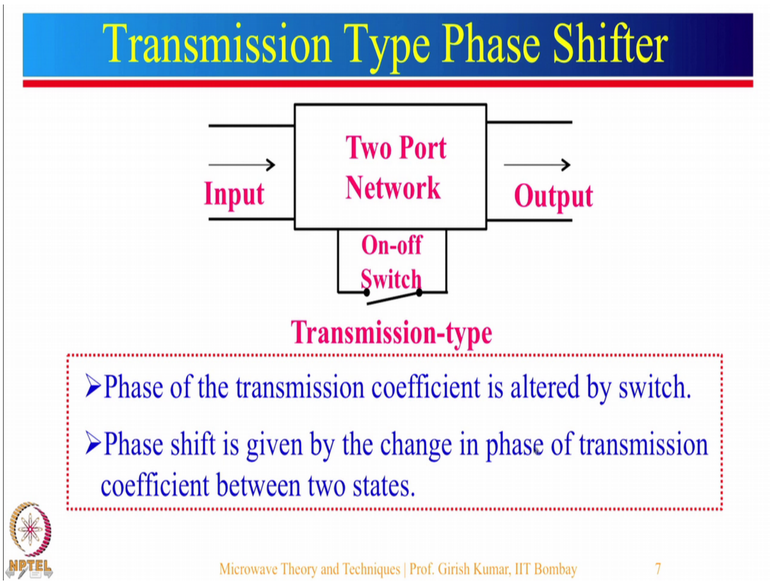

Now, let us talk about transmission type phase shifter. So basically, transmission type phase shifter you can see here there is a 2 port network, we have an input on one side, output on the other side and by controlling the switch position we can change the phase between; the 2 states. So, the phase difference will be realized; when the switch position changes from on to off or off to on.

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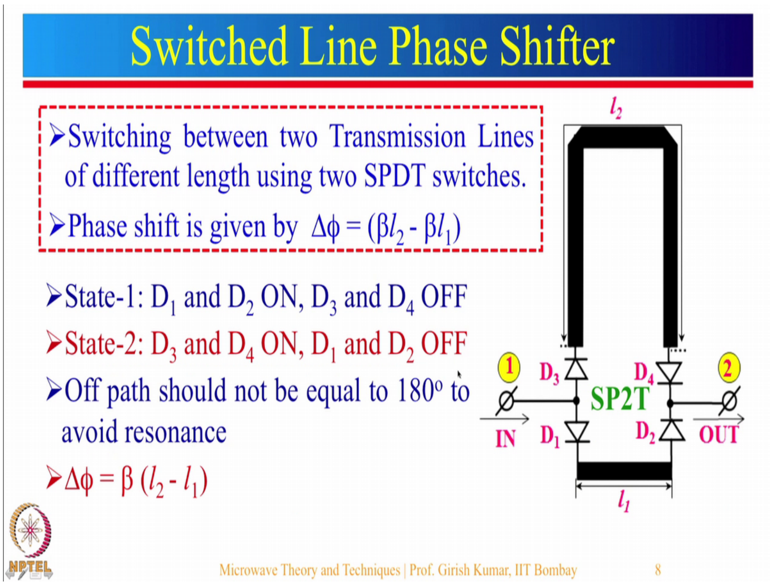

So, let us just take an example of a switched line phase shifter. So, here we have an input at this particular point. This is the output it uses 2 S P 2 T switches. So, this is the 1 S P 2 T switch, this is another S P 2 T switch.

So, let us just imagine a situation where this diode D 1 is on and this diode D 2 is on and these 2 diodes are off. So, when these 2 diodes are off these 2 were on, then the signal will travelled from here; it will go through this and go out from here.

Now when the switch position changes, so now this diode is on and this diode is on. So that means, D 3 and D 4 are on D 1 and D 2 are off. So, in that particular situation input will go through this path and it will go to the output. So, when we change the state of these S P 2 T switches, so what will happen? There will be a phase difference over here.

So, the differential phase shift is given by beta times l 2 minus l 1. So, this total length is l 2 this length is l 1. So, I just want to mention please take 1 precaution and that is do not take this length l 2 to be equal to 180 degree which is equivalent to lambda by 2. Because 4 lambda by 2 length it will act as a resonator, so, performance will degrade [vocalize d-noise]. So, avoid that other than that this particular configuration works very well simply by changing the line length you can realize any value of phase shift.

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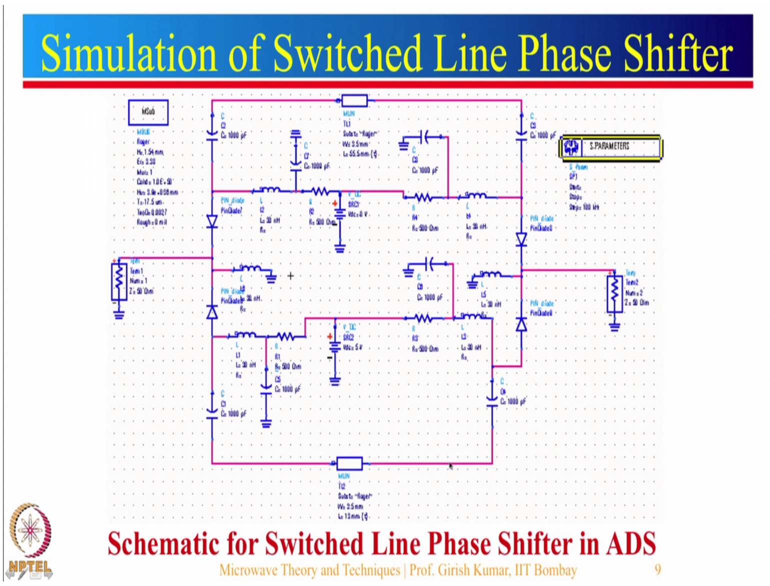

So, we have done the simulation of this particular configuration using ADS software. So, it actually shows a complete biasing circuit also. So, one can see here this is the D C voltage, there is a resistor over here. This capacitance is basically again to stop the ripper. There is a inductor that inductor acts as a short circuit at D C frequency, but it acts as an open circuit at ac frequency. Then D C voltage goes through here travels like this goes through the diode and this provides the path for the D C source, and this inductor again acts as an open circuit at A C frequency.

So, the same thing has been repeated for the other side so you can see here there is a 1 source here, 1 source over here. So, we have to ensure that if this is 5 volt, this should be 0 volt, when this is 5 volt, this should be 0 volt.

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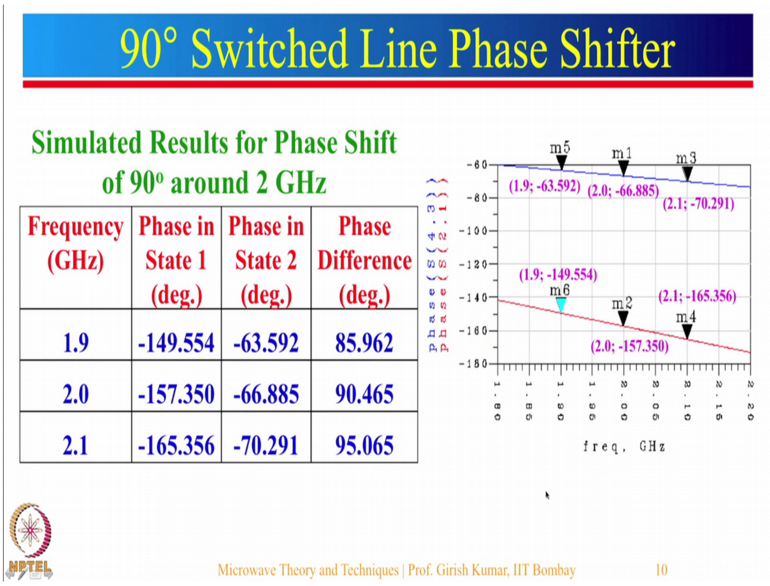

Frequency (GHz)	Phase in State 1 (deg.)	Phase in State 2 (deg.)	Phase Difference (deg.)
1.9	-149.554	-63.592	85.962
2.0	-157.350	-66.885	90.465
2.1	-165.356	-70.291	95.065

So, let see what is the result of this particular simulation. So, here I have shown you the simulated results for phase shift, we had designed this phase shifter at around 2 gigahertz frequency for 90 degree phase shift. So, in the 2 states this is the S 2 1 phase response plot, here are the values. So at 1.9 to 2.1, we have obtained differential phase shift as 85 90 and 95d egree.

So, you can see that around 2 gigahertz phase shift obtained is around 90 degree. Of course, there is a one disadvantage you can see as frequency changes, phase shift also changes. So what is the reason for that? So, just recall I had mentioned that theta is equal to beta times l. Now, l is fixed because the length has been fixed, but beta is changing, what is beta? Beta is equal to 2 pi by lambda so as frequency changes lambda changes and hence phase shift changes.

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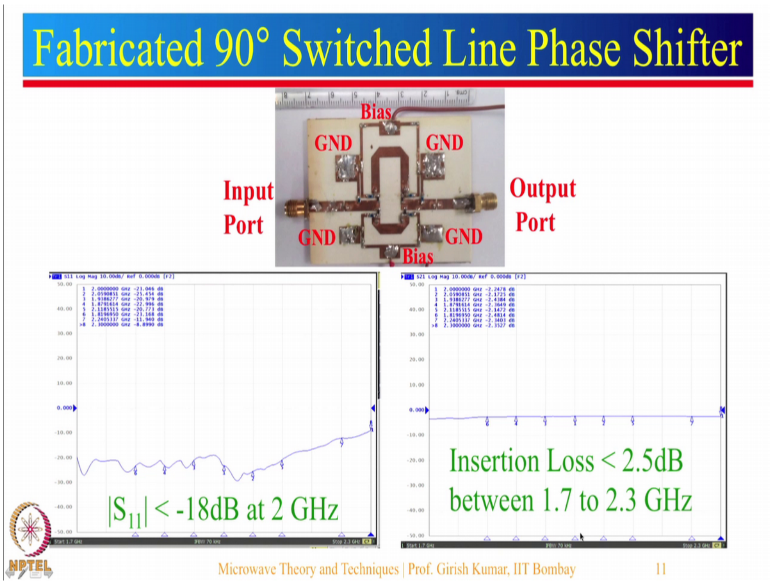

So, letus see the measured results. So we have fabricated a 90 degree switched line phase shifter. So, one can actually see here this is input, that is the output over here, you can see that this is line length l 1, this is the line length l 2 and this is the biasing circuit given to this particular circuit.

So, we have to not only check the phase shift, we should also check; what is the reflected power and what is the insertion loss. You can see the response for S 1 1; this response from 1.7 to 2.3 gigahertz. So, you can see that this is a minus 20 dB line. So, you can see that in most of the range here, it is less than minus 18 dB. Let us look at the insertion loss; insertion loss is less than 2.5 dB in the frequency range of 1.7 to 2.3 gigahertz.

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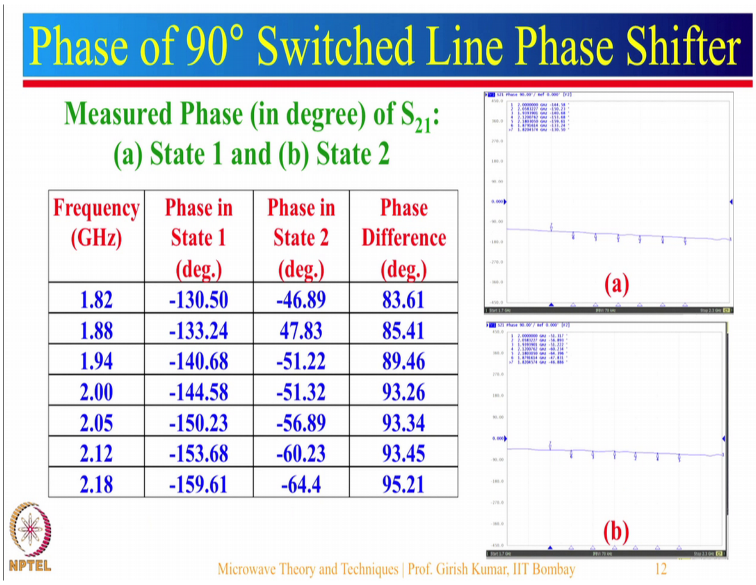

Frequency (GHz)	Phase in State 1 (deg.)	Phase in State 2 (deg.)	Phase Difference (deg.)
1.82	-130.50	-46.89	83.61
1.88	-133.24	47.83	85.41
1.94	-140.68	-51.22	89.46
2.00	-144.58	-51.32	93.26
2.05	-150.23	-56.89	93.34
2.12	-153.68	-60.23	93.45
2.18	-159.61	-64.4	95.21

Now, let us see what are the phase differences in state 1 and state 2? So, these are the plots for the 2 different states state 1 and state 2. So let us see these are the frequency values. So, these are the phase values in state 1, these are the phase values in state 2 let us look at the difference. So, you can see that around 2 gigahertz the phase difference is approximately equal to 90 degree. So, there is a small error, but still you can see that the results are almost similar to what we had simulated.

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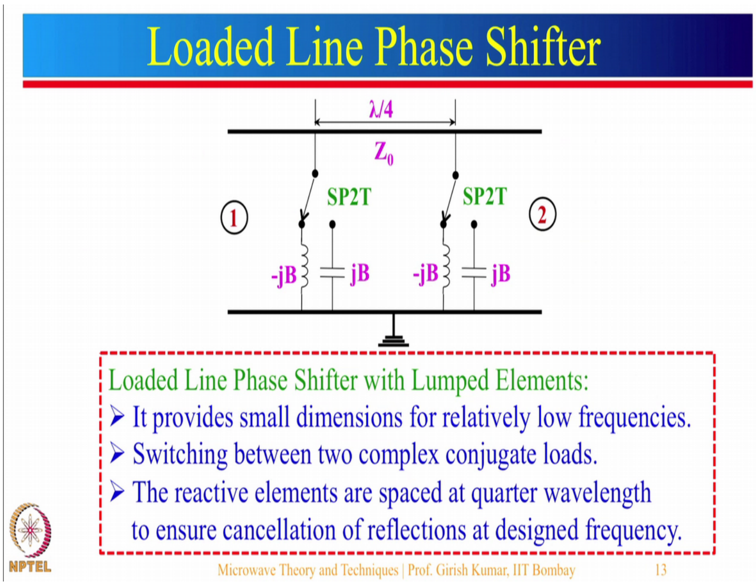

Now, let us look at another type of a phase shifter, this is known as loaded line phase shifter. So, what we have over here? So this is the input port that is the output port. Here we have a 1 S P 2 T switch, another S P 2 T switch and in between we have a line length of lambda by 4. So, let me explain; what is the purpose of this line length over here?

So, generally speaking what is done that when the switch position changes from, let us say this thing to this here this is an inductance. So, admittance of that will be let say minus j B, this is a capacitance; admittance of that is j B. So these two you can say that the amplitude of these two is actually equal. So, when the switch changes from here to here, then what happens at the transmit part you will see that there will be a phase change because, we are changing from plus j B to minus j B.

So, why do we need all these things here? The reason for that is if we do not have all of these things, it was still experience the phase shift as we switch the switch from one position to the other position. But there will be a large reflected wave over here; the reason for that is this impedance will come in parallel with the port 2 impedance. But by providing this particular section we have actually cancelled the reflected signal.

So, let us see how that is achieved so, whatever this signal which reflects back from here. Now the signal is going and again the same thing will reflect back from here, but while going from here to here, it will travel a distance of lambda by 4 plus lambda by 4, which is lambda by 2 and that would provide 180 degree phase shift. So, whatever is reflected from here, this reflected wave will have a 180 degree phase shift. So reflected wave will get cancelled.

So, that is the reason; why we use lambda by four sections. Of course, there is a limitation; whenever we use a lambda by 4 sections, it will have a limited bandwidth.

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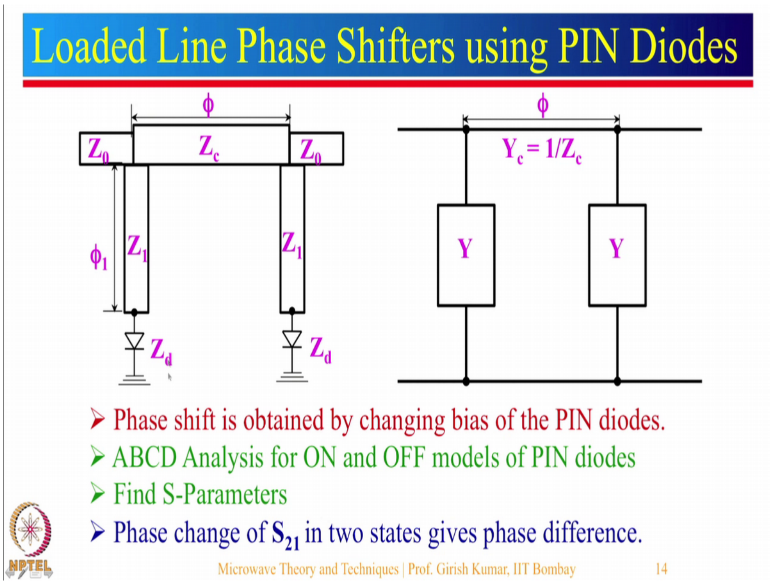

Let us see now, how we can realize lumped elements using a transmission line and pin diode. So, this is just the representation not the actual circuit. So what we have here? This length here will be approximately equal to lambda by 4 after desire frequency, here is a 1 transmission line another transmission line here, which is connected with a pin diode over here.

When the pin diode is forward bias, then this will provide inductance; when this diode is reverse biased, this will provide capacitance so that is the concept. So, when you switch the diode from on to off state so, what will happen inductance will become capacitance? However, as I mentioned this is not the final configuration; in the next slide I will show you what is the final configuration? But how the circuit can be analysed?.

This entire portion here can be realized using shunt admittance here. So, this portion can be realized again as shunt admittance. So, we know how to analyze this particular configuration so, we can find A B C D parameters of shunt. Those A B C D parameters of this transmission line and then A B C D parameters of the shunt multiply these 3 A B C D parameters and then find out S parameter and then we can say that phase change of S 2 1 in 2 states will give phase difference.

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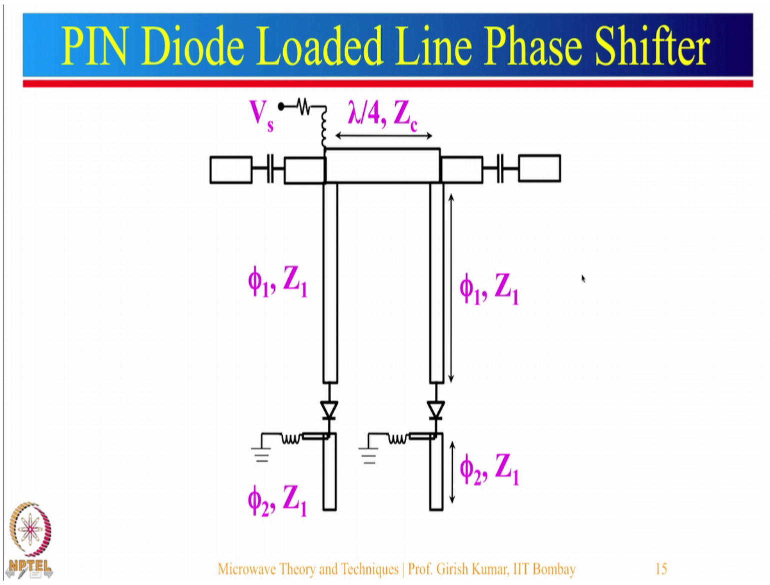

So, this is the circuit realization of a loaded line phase shifter, it also shows the biasing circuits. So we have here input, output and you can see here this voltage is connected through the resistor; which limits the current flowing through these pin diodes. There is a large inductor over here, which acts as a short circuit at dc frequency, but acts as an open circuit at A C frequency.

So, the path for the D C current is provided through this resistor inductor this line through this thing and then through this inductor goes to the ground here. And the same supply is actually used for this thing also as you can see the path will be through this portion over here. So, you can see here there is a additional line length which has been connected over here. The reason for these additional line length is that these diodes will actually be represented as inductance in the on position, capacitance in the off position.

Now the total B value provided by this in the on state as well as off state should be equal.So, that is where this particular additional length is provided so that y equal to plus j B is equal to minus j B, when the diode switches the position from let us say on to off.

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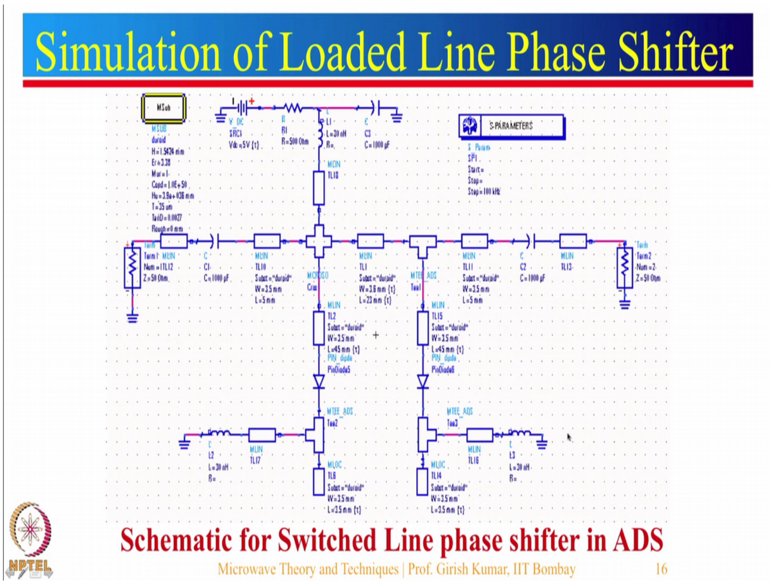

So, let us see the result of this particular configuration. Again it shows the complete biasing circuit over here, one can see that there is a source here, resistor inductor and then there is a diode here the path to the ground is provided through the inductor here, you can see here there is a this additional line length is provided.

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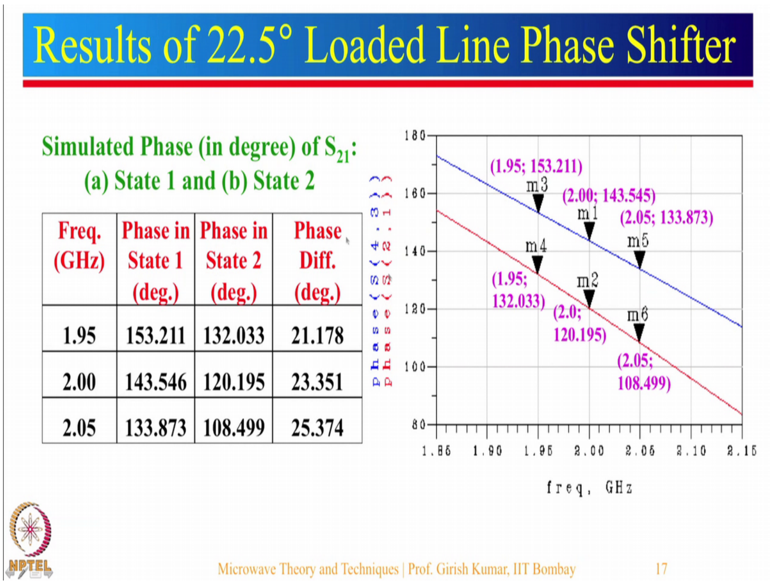

So, we have designed this particular thing for 22.5 degree phase shift so let us see the response here. So, this is the response for one of the state this is the response for the other state. So, let us look at the frequency thing here 1.95 to 2.05. So, we had designed for 22.5 degree, we are getting close to that so this is about 23.3 degree or so. And one can again see that the phase shift changes, if we change the frequency of operation. Now this particular configuration has been fabricated.

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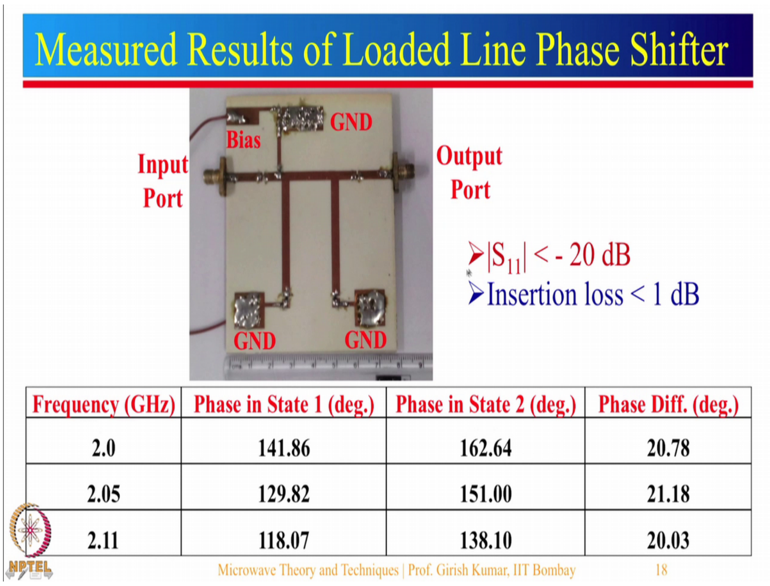

Frequency (GHz)	Phase in State 1 (deg.)	Phase in State 2 (deg.)	Phase Diff. (deg.)
2.0	141.86	162.64	20.78
2.05	129.82	151.00	21.18
2.11	118.07	138.10	20.03

So, let us see the fabricated configuration and what are the results. So, one can see here this is the input port, output port this length is equal to lambda by 4.

You can see here there is a biasing, voltage here, the resistor and inductors are connected over here and you can see that there is a pin diode connected over here, pin diode connected over here and that is grounded through a inductor. So, when we apply a positive voltage over here then these pin diodes will conduct so we will have a 1 state when 0 voltage is applied these diodes will not conduct. So, then we will have another state so let us see what are the face values in state 1 and state 2.

So, here frequencies are given 2.0, 2.05, 2.11. So phase in state 1 is given over here, face in state 2 is given over here. So, one can see that we have got a phase shift of around 20 to 21 degree in this particular frequency region. So, we had designed this particular configuration for 22.5 degree. However, there is a small error in the fabrication. So simulated results and fabricated results are slightly off; however, as you can see that the percentage error is less than 10 percent. Now as I mentioned earlier it is also important to see; what is the reflection coefficient and what is the insertion loss. So, for this particular case as you can see here, S 11 is less than minus 20 dB in that desired frequency region and insertion loss is less than 1 dB in that desired frequency region.

So just to summarize, so, today we have discussed about different type of phase shifters. So, we talked about analog phase shifter and digital phase shifter. So, we saw that analog phase shifter can be realize by using at 2 branch coupler or circulator by simply changing the reverse bias voltage of varactor diode.

Now we did look at a few different configurations for digital phase shifter. So we looked at switched line phase shifter and we also looked at loaded line phase shifter. The basic difference between the switched line phase shifter and loaded line phase shifter is in case of switched line all you do it is you change the path from here to the other path. The difference between the line lengths will give us the phase difference.

In case of loaded line phase shifter we have a one transmission line, it is loaded at 2 different points,. The separation between the 2 loading should be lambda by four. So, that the reflected wave at these two points will cancelled each other and hence, S 1 1 will be relatively small as you can see here S 1 1 was less than minus 20 dB. So, in this particular case we saw that insertion loss is less than 1 dB so with that we conclude phase shifter. In the next lecture one of my T S will talk about different types of transistors and after that I will discuss about different types of amplifiers.

So, thank you very much, bye.