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

Module - 06
Lecture – 27
Microwave Attenuators: Fixed and Variable Attenuators

Hello everyone. Today, we are going to talk about Microwave Attenuators. In the previous lecture, you had heard about various diodes that lecture was given by 1 of my PhD student Rinky Chopra, who was also course ta for this particular course. So, today we are actually going to start with the microwave attenuators using resistors. These are known as fixed attenuators. And, then we will talk about PIN diode based attenuators which are variable attenuators.

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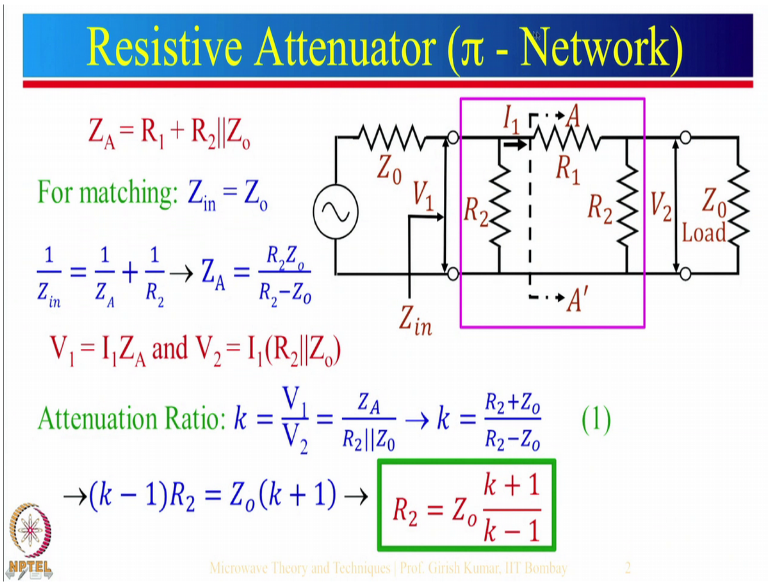

So, let us start todays lecture on Microwave Attenuators. So, we will start with the resistive attenuator and the network shown over here is a pi network. So, we can see that there are 3 resistors are there resistor R 1 R 2 and R 2. And, if you see this network looks like a pi shape that is why it is known as pi network. One of the main property of the attenuator is that the input side, as well as the output side should be matched with 50 ohm or you can say Z 0.

And, the second thing is that it should provide an attenuation from port 1 to port 2 by let us say a factor of k. So, we need to analyze this particular circuit, but before that we can actually get an attenuation even by using a single resistor also. So, think that R 2 is not there, in that case suppose if we have a single resistor R 1. Then, what will be V 2 divided by V 1 it will be Z 0 divided by Z 0 plus R 1. So, suppose Z 0 is 50 ohm and if I say let us say R 1 is 50. So, 50 divided by 50 plus 50 that will be 1 by 2.

So, we can say that the k will be equal to 2, because k will be defined as V 1 by V 2 it is an attenuator and not gain. In the case of gain we always say V 2 divided by V 1. In case of attenuator we generally define V 1 divided by V 2, which is a factor equal to k. So, V 2 divided by V 1 for a single resistor R 1 will be nothing, but Z 0 divided by Z 0 plus R 1. So, for Z 0 equal to 50 ohm and R 1 equal to 50 ohm value will be equal to 50 divided by 50 plus 50 which will be 1 by 2.

So, that is equal to V 2 by V 1, which means k is equal to 2, but if you look at the input impedance at that particular point it will be 50 plus 50, that will be 100 ohm, which is not a matched with this Z 0, which is equal to 50 ohm. Again, we can get a larger attenuation if I take R 1 equal to say 1 kilo ohm. So, then this will be 50 divided by 50 plus 1000 which will be 50 divided by 1 0 5 0 1 can get very large attenuation.

However, again the problem will be that the input impedance now will be very high, it will be 50 plus 1000, which will be equal to 1050. So, lot of power will get reflected back form this particular port here. So, one of the main condition is that the input looking from this side and output looking from this side should be matched to 50 ohm so; that means, input impedance here should be equal to Z 0.

So, for matching Z input should be equal to Z 0 and since the network is symmetrical. So, the output here will be also equal to Z 0. So, that is why we do not use a single resistor R 1, but we use a pi network. In fact, later on I am also going to talk about a T network, which also can be optimized for impedance matching at both input side as well as output side.

So, let us see how we can do the analysis of this particular circuit?. So, first of all let us find out here what is Z input? So, we can say that Z input is nothing, but R 2 in parallel with the impedance seen over here. So, that will be R 2 1 by Z input is equal to 1 by Z A plus 1 by R 2, which is nothing, but parallel combination of R 2 with Z A Z A is the impedance looking at this particular point here. So, from here we can say what is Z A? Z A is nothing, but R 1 plus R 2 in parallel with Z 0. So, that is the expression for Z A.

Now, all we need to do is simplify this particular expression. So, from here we can say Z A is equal to this particular expression over here. Now, we also need to find out what is the voltage ratio? So, we can say what is V 1? V 1 is nothing, but I 1 multiplied by this impedance which is equal to Z of A, which we have written here already which is R 1 plus R 2 in parallel with Z 0. And, what is V 2 V 2 is nothing, but this current I 1, which is coming here and that will be multiplied by the parallel combination of the impedances, which is R 2 in parallel with Z 0. So, that is the expression for V 2.

So, now, if we take the ratio of V 1 by V 2, which we are defining as k and that is attenuation ratio. So, we can just simply see from here I 1 I 1 will get cancel. So, this would be Z A divided by R 2 in parallel with Z 0. So, from here we can do simplification we will get the expression for k ok. And, if we simplify this particular expression further. So, by using a few steps we get the expression for R 2, which is given by Z 0 multiplied by k plus 1 divided by j minus 1.

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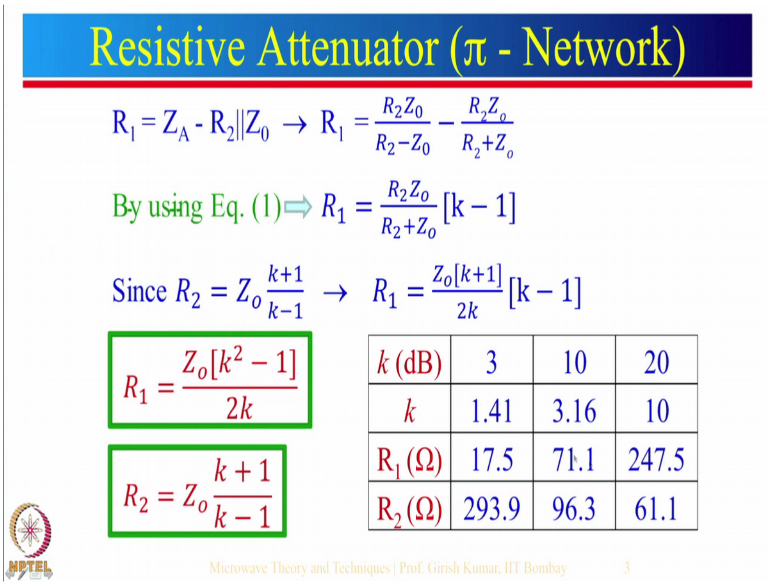

Now, we can do little bit more of a simplification. So, we can expand these things R 1 which is nothing, but Z A minus R 2 in parallel with Z 0 from the previous expression. And using equation 1, we can simplify it and finally, after doing a few of these steps which you can follow through 1 by 1 we get a final expression for R 1, which is given by this particular term over here and we get expression for R 2 which is given over here. So, just quickly we can see over here if k is very large, we can say if k is very large this expression will become approximately 1.

So, we can say R 2 will be approximately equal to Z of 0. And, if k is very large we can say if it is very large, then k square will be much greater than 1. So, we can neglect this term and this one would get cancel here. So, the expression we will get is Z 0 multiplied by k divided by 2. So, let us now see an example for different values of attenuator. So, here we have given the values for 3 Db, 10 dB, 20 dB attenuation ok.

So, from these values we can calculate first the numeric value. Now, here please remember that this is a voltage ratio. So, we have to take 20 log of k. So, 20 log of 10 will be 20 dB ok. And, similarly we find the other values of k and by substituting the value of k in these expressions and taking Z 0 as 50 ohm we get R 1 R 2 values, which are given over here. And, you can actually see that as k is increasing, if we take further instead of 20 Db, if we take 30 dB, this will tend towards which I had mentioned earlier will tend towards 50 ohm. And, if you look at this expression over here you can see that this is Z 0 which is 50 into 10 that will be 500 divided by 2 that is 250 it is tending towards 250 here ok.

So, that way we can do the validation ok. Now, the question comes where do we need attenuator. One can understand that we need amplifiers because amplifier will amplify the signal. Why we want to attenuate the signal? So, there are many applications, where we need attenuators. For example, let us say we want to measure the output of a let us say power amplifier. Even, if we have a just 1 watt output. Now, that 1 watt output cannot be connected to the spectrum analyzer. A spectrum analyzer will actually measure the power and also gives the frequency spectrum; it will also give the harmonics of that particular amplifier.

Now, 1 watt output cannot be directly connected to the spectrum analyzer, majority of the spectrum analyzers which are available in the market. They can take absolute maximum input power as 0.1 watt, but majority of the time they would recommend 0.01 watt power. So, we cannot connect 1 watt output straight to the spectrum analyzer. So, now think about if we have a 20 dB attenuator. So, we gave a 1 watt 20 dB attenuator will give us 0.01 watt power and that can be given to the spectrum analyzer.

So, this is one of the applications. There are many other applications where even variable attenuators are required. So, let me first finish the fixed attenuator, here you can see that the resistor values are fixed. So, hence there will be a fixed attenuation. Of course, we can use variable resistor R 1 and R 2 and that can be then designed to obtain variable attenuator. However, we will show you the applications of what was covered in the previous lecture, which was one of the device covered was PIN diode. So, today we will see how PIN diodes can be used as variable attenuator.

There is an another way where we can analyze the pi network. So, in the previous 2 slides I had shown you how to do the analysis, but recall we have also studied A B C D parameters. So, this particular network can be solved by using A B C D parameter. So, let us see how we can do that. So, here is a one segment here, then second segment and then third segment. So, this can be thought about as a shunt admittance and we know that ABCD parameter for shunt admittance is 1 0 y 1.

So, 1 0 y is equal to 1 by R 2. Now, this is series impedance. So, we know that A B C D parameters for series impedance is given by 1 Z 0 1. So, here Z is equal to R 1. So, this is symmetrical with respect to this port over here. So, this would be same as the first one. So, 1 0 1 by R 2 and a 1, we multiply these 3 matrices and finally, this expression is obtained. Now, we use the conversion from A B C D parameters to S parameters and I had mentioned to you easier way to remember think about this as normalize A B C D.

So, a b normalize will be B divided by Z 0, C normalize will be C into Z 0 plus D. And, the numerator is A plus B minus C minus D. And, S 2 1 is equal to 2 divided by A plus B plus C plus D, which are basically normalized values. So, once we know the expressions for S 1 1 S 2 1, now we have to put the condition. The first condition you can see over here is S 1 1 is equal to 0.

If S 1 1 is equal to 0; that means, reflected power will be equal to 0 and this also implies that Z input is equal to Z 0. So, if we put a condition of S 1 1 equal to 0. So, you can see from here see A and D are equal you can see here so; that means, B divided by Z 0 minus C Z 0 should be equal to 0. So, that will give you one condition. Second condition we have to put is S 2 1 is equal to 1 by k. So, you put over here 1 by k solve these 2 equations, you will get the expressions for R 1 and R 2. These expressions are exactly same as what we had derived earlier.

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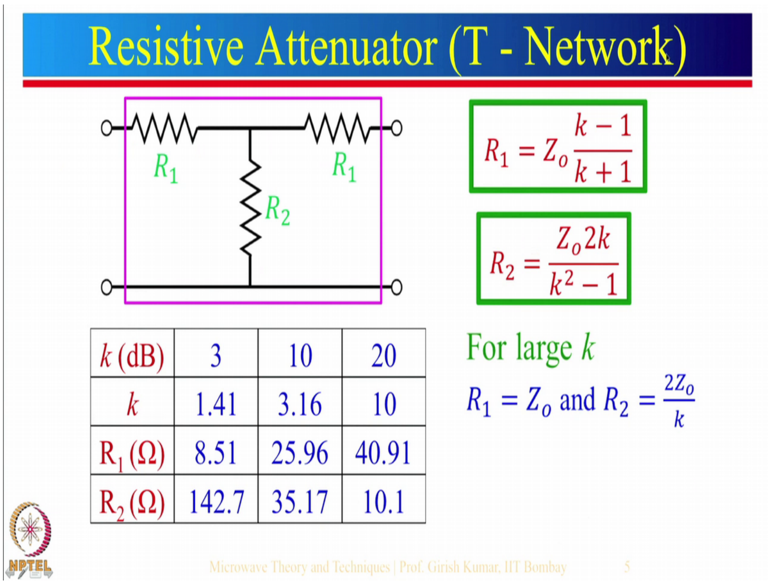

Now, let us see another network, which is a T-Network. So, here the attenuation has been obtained by using T-Network using 3 resistors in a very similar way. So, here again as before series resistance has been taken as R 1 shunt resistance has been taken as R 2. Analysis of this can be done in either of the previous 2 ways. You can actually think about writing a current over here, finding the voltage or you can write a node equation, and then find the expression for V 1 by V 2 or you can use the second approach where you can use A B C D parameters.

So, you again divide the network into one here, then second and then third one. So, multiply the 3 A B C D matrices get the final S parameters. And, again put the same condition that S 1 1 should be equal to 0 and S 2 1 should be equal to 1 by k, by simplifying these equations you will get the expressions for R 1 R 2. So, I have written here what happens for large value of k. So, if k is very large you can say this expression will become approximately 1. So, R 1 will become Z 0 and if k is very large then this term will be negligible. So, we can say this whole thing will be 2 Z 0 divided by k.

So, again let us look at the different examples 3 dB 10 dB 20 dB correspondingly k numerical value is listed over here. And, then by using these 2 expressions I am taking Z 0 as 50 ohm R 1 R 2 values are obtained. So, you can see over here the resistance values are increasing. And, ultimately this will become 50 ohm which you can see from here R

1 is equal to Z 0 for large value of k and R 2 is tending towards this particular expression here.

So, we can actually check the value of R 2 from here also which is 2 into Z 0 2 into 50 100 divided by numeric value of k which is 10. So, 100 divided by 10. So, you can see that it is tending towards 10. So, by using these resistor values you can actually realize of fixed attenuator. Of course, you can actually speaking use variable resistor over here or you can use variable resistors here, and that way you can actually speaking tune the attenuator, by using variable resistors you can realize a variable attenuator.

However, in practice that is not used we use some different method which I am going to show you in the next few slides. So, in the previous lecture PIN diodes were covered. So, we will just have a very quick look into that part.

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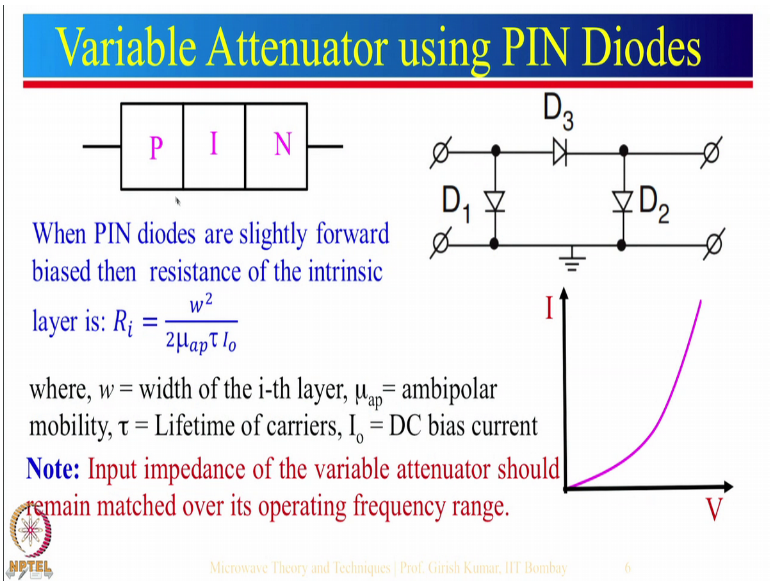

So, there is a P junction, I junction, which is intrinsic junction and N junction ok. So, now, instead of a using resistor we can use 3 PIN Diodes over here, but before we start thinking about using these 3 PIN diodes, let us see where we have to operate and which region we have to operate.

Now, for PIN diode I V characteristics I have shown over here. So, this is typical I V characteristic ok. What we need to do we need to operate only in this particular region. When, we want to use PIN diode as a variable attenuator. So, when this particular diode is slightly forward bias ok? In that particular case, it has a series resistance, which is given by this particular expression this expression depends upon width of the I th layer which is over here. So; that means, if this I th layer is large then width will be large and that would mean R i will be large ok.

It also depends upon the mobility and lifetime of carrier. However, these things are more dependent upon those device characteristics, here we are going to focus more on the circuit performance. So, you can see over here that I 0 which is dc bias current that is in the denominator. So, now, think about these things are actually fixed quantity for a given PIN diode. So, by changing the value of I 0 we can change the value of R i. So, let just see here if it take I 0 for example, 1 microampere we can see that R i will be very large.

Instead of 1 micro ampere if we takes a 10 microampere, then R i will reduce by 10 times, or if we take I 0 as 100 micro ampere, then we can say that R i will reduce further. So, by changing the current I 0 from let us say a 1 micro ampere to about 100 micro amperes, you can see that the resistance value can be changed by almost 100 times. So, we use these PIN diodes over here as variable attenuator; please remember that we are only going to do slightly forward bias.

So, what happens? If the diode is completely forward bias, in that particular case we can see that the current will be relatively constant. And, that will not provide us a variable attenuator or variable resistor value. In fact, I am going to tell you in the next lecture another application of PIN diodes, where PIN diodes will be used as switches, where when the PIN diode is completely forward bias it will be like a switch on, and if the PIN diode is completely reverse bias it will act like a switch off.

However, we will see various variations of switches in the next lecture. So, here there is a only 1 word of caution, which I want to mention. And, that is we can change the value of the resistors of D 1 D 2 D 3, by providing external biasing circuit. So, when I talk about PIN diodes as switches I will show you the biasing circuit. So, the same biasing circuit can be used over here, but here I just want to tell the concept of the variable attenuator and the problems associated with it.

So, the problem associated with this is that these 3 values of resistances of the PIN diode should vary according to the formulas which have been given; you can see here this is similar to a pi network. So, for the pi network we had seen the values of R 1 and R 2 varying. So, we have to change these values according to that and this becomes difficult sometimes ok.

So, there is an alternate solution also. So, let us look at the alternate solution of this particular problem. So, here what we have variable attenuator using coupler?

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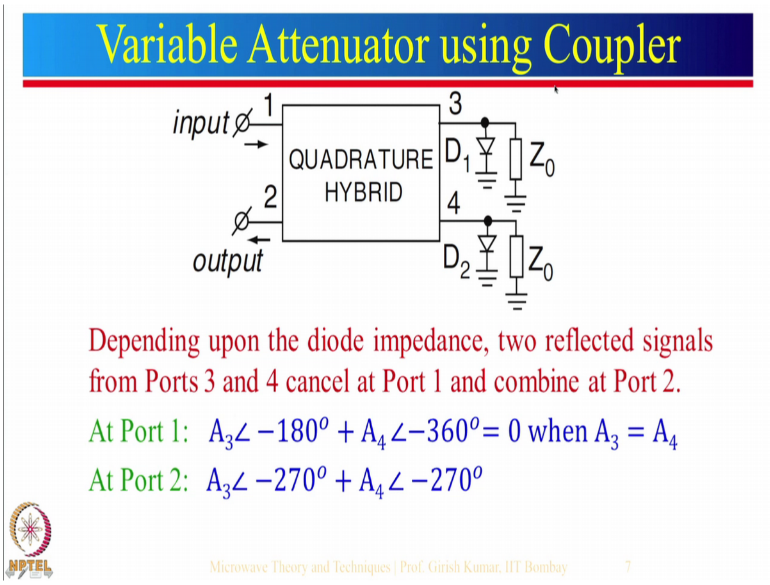

So, let us see what we have here? So, input is given at port 1, output is taken at port 2, port 3 and port 4. You can actually see that there are diodes are there, even though I have written D 1 D 2, but in a reality we generally take these 2 diodes identical and for many practical attenuators you do not even meet Z 0 over here.

So, you do not need to have any transmission line at the end here. So in fact, this can be removed it is not always required. So, only this thing will do the job. So, let us see the working of this particular network. So, quadrature hybrid in fact, you just think about it is a 2 branch coupler. So, please now imagine this is a 2 branch coupler. So, 1 line will be here, another line will be here and there will be 2 branches over here. So, the property of the 2 branch coupler is that when we give a input at port 1.

So, output at port 3 will have a minus 90 degree phase delay and output of port 4 will have a minus 180 degree port delay. Now, depending upon the resistor value, so, just imagine that this is a 0 value here. So, if the resistance is 0 here; that means, everything will get reflected everything will get reflected. So, this reflected way at this particular point will go back to over here. So, there will be another delay of a minus 90. So, minus 90 another minus ninety will be 180 degree.

So, this is what I have written here minus 180 degree and this is the magnitude, which is a reflected back from port 3. Let us see what happens to the reflection from port 4. So, input from 1 goes to port 4 with the phase delay of a 180 degree and then it reflects back to this port 1. So, that will be another 180 degree. So, the total phase from here to here and then back to this particular point will be 360 degree.

And, if we take these 2 diodes identical and they are bias identically; that means, their resistance will be also same in that case a 3 will be equal to a 4. And, if this condition is satisfied the sum of these 2 things will be equal to 0; that means, reflected power will be equal to 0 at port 1. Let us see what happens at port 2. So, now, the reflected power from here let us say from here it goes minus 90 degree and from minus 90 degree, it experiences another 180 degree delay. So, that will be 90 another 90 another 90. So, total 270 degree phase delay.

Let us, see what happens to the reflection from port 4. So, from here 90 90 180 and then another 90, that will be 270. So, if again now if A 3 is equal to A 4 these 2 will add together identically. So, whatever is the input here that will actually go to the output depending upon these resistances value? So, again now let me go through 1 more time if it is short then everything will reflect back; that means, there will be 0 attenuation here except for some losses in the hybrid network.

Now, think about if this is 50 ohm we are assuming that this does not exist here. So, if this is 50 ohm; that means, nothing will reflect back and if nothing reflects back output will be equal to 0. So, by changing the diode impedance from 0 to 50 ohm you can actually get an output which is from 0 to 1 or you can say. So, by changing the diode impedance from 0 to 50 ohm we can get the output, which is going to be from minimum to maximum.

You can do other way round also, we can change the diode impedance from 50 ohm to a very large value even 1 kilo ohm same effect will be notice over here. So, we can provide attenuation simply by changing the resistance values of these 2 diodes, which we should take as identical. So, a single biasing circuit can bias both of these diodes. So, here then you have to change only 1 biasing voltage and by changing that biasing voltage we can change the value of output. There is a only 1 limitation of this particular circuit, that is that the bandwidth of A 2 branch coupler is relatively narrow it may be about 10 to 20 percent

So, this attenuator will work in 10 to 20 percent region. If you want a larger bandwidth instead of using 2 branch we can use 3 branch coupler, or we can use 4 branch couplers, and we have discuss these couplers in the previous lectures. So, you can use those things to realize a relatively broad band variable attenuator. Now, instead of using PIN diodes we can also use MESFET. What is a MESFET? You will learn in detail more about MESFET, after few lectures, but just to mention you might be knowing about MOSFET. What is a MOSFET? Metal oxide semi-conductor field affect transistor.

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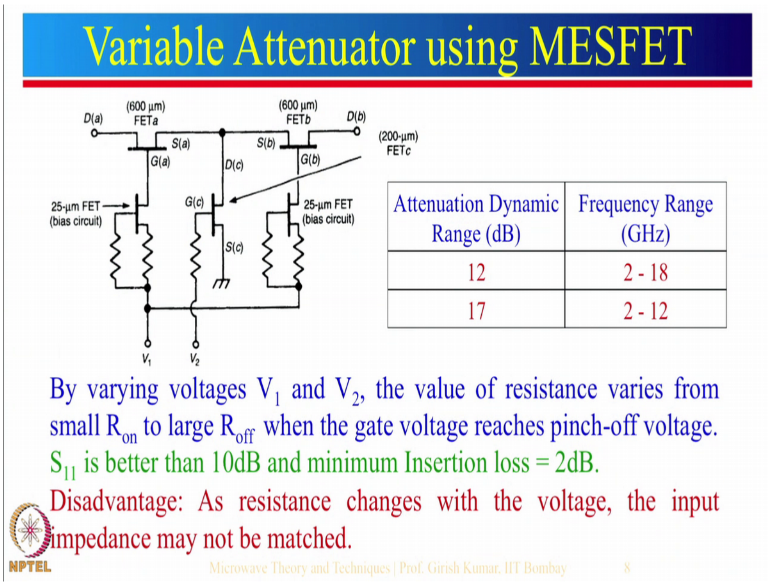

In MESFET basically oxide layer is not there. So, here ME stands for metal ok. So, this is a metal semi-conductor field effect transistor. So, I am just telling the principle of this particular configuration here. So, you can see at this particular point there is a input and there is a output here, these are the 2 control voltages which I shown over here ok. So, what is this particular configuration? You can see that this is the series component, this is the series component and this is the shunt component.

So, by changing the value of the current over here the resistance of this part is changed, resistance of this is changed in the same fashion you can see that this is being controlled by voltage V 1 and if you recall series resistance should be same. And, here is a shunt resistance. So, the value of the shunt resistor is controlled by voltage V 2 ok. So, we have to change these V 1 and V 2 according to the values given for the teen network, which consisted of R 1 R 1 and R 2.

So, here I just want to mention here. So, by changing the value of V 1 and V 2 the value of the resistance varies from small R on to large R off. So, by changing the value of the biasing voltages V 1 and V 2, we can change the attenuation value. In fact, for this particular configuration these are some of the specifications given over here. So, for frequency range 2 to 12 gigahertz, they could obtain a 17 dB dynamic range, but over a larger frequency range 2 to 18 gigahertz the dynamic attenuation range was about 12 dB ok.

And, for this particular configuration S 1 1 obtained was better than 10 dB and minimum insertion loss was about 2 dB. So, from here to here minimum insertion loss is 2 dB and after that there is a dynamic range of 12 dB. So; that means, from here to here you can get 2 dB to 14 dB attenuation. Now, again the only problem in this particular case is that V 1 and V 2 must vary in such a way that the resistance is R 1 and R 2 should follow the teen network values.

So, there may be a small problem as resistance changes with the voltage the input impedance may not be matched. I just want to mention about the software, which I had recommended earlier for designing filters that same R f same 99 software can be used to design attenuator also. So, there is a again an option you can go to that design then go to attenuator. And, there they will asks you want the T type network or pi type network just enter 3 dB or 10 dB or 20 dB or 30 dB whatever attenuation you want and it will straightway give you the values of R 1 and R 2.

Now, I also want to mention many times the values of R 1 and R 2, which you calculate theoretically, may not be available practically in the market. So, what do you do then? So, whatever the nearest practical values of resistors available you put those values in the R f same 99. And, then do the simulation and R f same will give you the plots of S 2 1 and S 1 1. So, please ensure that S 1 1 remains below minus 30 dB. In fact, when you take the ideal values you will actually see S 1 1 is close to minus infinity dB, but S 1 1 less than minus 30 dB is acceptable for most of the application. And then you can see what is the value of S 2 1 and accordingly you can choose the right value of the resistors to obtain desired value of the attenuation.

I am also going to show you one another thing which is a variable attenuator IC available in the market.

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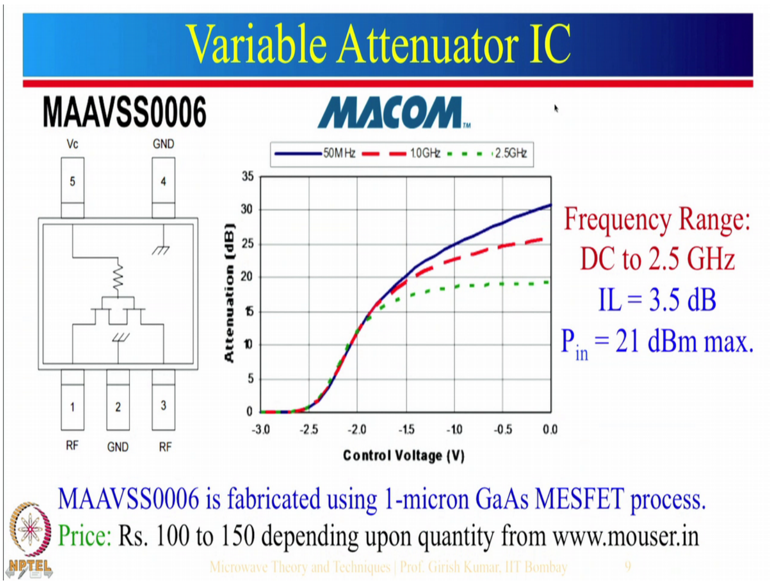

So, I have just given a 1 example ok. So, I am not promoting this particular company ok. I am just telling that this is one of the IC available. So, the number is given over here. So, let us see what we have over here? So, here you can see this is the controlled voltage and this particular thing actually uses gallium arsenide MESFET, again these are the IC manufacturing thing, we as a circuit designer are not really getting deep inside the IC. So, we will look at how to use this particular attenuator ok?

So, you can see over here there is a 1 R f port here one this is a R f port 3, you can use this as a input you can use this as a output or you can use this as input or this can be used as output, it does not matter because it is a symmetrical network and there is a ground connection over here. So, simply by varying a 1 single voltage here so, I want to mention here that here we do not need 2 different voltages; a single voltage has to be varied. Now, this is not the complete circuit the circuit has a many more things this is just a symbolic representation ok.

So, let us see what is the performance we get over here. So, they have actually mention that the frequency range is DC to 2.5 gigahertz in session loss is 3.5 dB so; that means, even for 0 attenuation, which shows over here. I just want to first tell what this is it shows here attenuation versus control voltage? So, we can see here if the control voltage is a minus 3 volt attenuation is 0 and then you can see that attenuation is increasing 3 different curves are for 3 different frequency values.

This curve is for 50 megahertz this curve is for 1 gigahertz, this curve is for 2.5 gigahertz. So, I just want to mention what this in session loss of 3.5 dB means? So, even though it shows 0 dB attenuation, but in a reality it is a 0 dB plus in session loss of 3.5 db. So, when you give control voltage of minus 3 volt, then from input to let us say a output it will be attenuated by 3.5 dB. Let us take a case of 50 megahertz. So, you can see for 50 megahertz for control voltage equal to 0, we get about 30 dB attenuation so, 30 plus 3.5; it will be 33.5 dB attenuation.

Now; however, be careful what is your frequency of operation ok? Suppose you are operating at a 1 gigahertz or you are designing an attenuator around a 1 gigahertz frequency. Please do not use this particular curve. Now, you better use this particular curve here you can see now that the attenuation is about 25 dB. So, as you change the control voltage from minus 3 to 0 volt the attenuation range will be from 0 to about 25 dB.

And, if you are operating around 2.5 gigahertz, which is the frequency of Wi-Fi then in that particular case you can see that the attenuation is of the order of 20 dB only ok. So, control voltage varies from minus 3 to 0 attenuation will vary from 0 to 20 dB please add 3.5 dB in all these case. Now, what is this significance of this here? It actually says p input is equal to 21 dB maximum. So, 20 dB is equal to 0.1 watt ok. So, you cannot pump more than 0.1 watt power over here.

If, you pump more than that power this IC may get burned and this is relatively low cost IC, you can actually see the price varies from 100 to 150, and depending upon the quantity. And, this again I have just given as a reference I am not promoting this particular website in any which way. And, you will see that when you go to the website or you go to any other website, you will actually see that the price changes a lot depending upon the quantity.

So, if you want to buy just 1 or 10 pieces, it will cause much more if you buy 1000 or 10 000 or 1 million pieces, then the costs will be much smaller ok. So, just to summarize today's lecture. So, we started with fixed attenuator. So, we discussed about 2 different configurations, we started with a pi network, and then we talked about T network. And, these were fixed resistive attenuators, then we talked about PIN diode as variable resistor. And, then we used 3 PIN diodes to design a variable attenuator.

But I did mention to you about the problem part the problem with that is that the voltages have to be controlled properly. So, that the resistance values vary according to the attenuation desire. So, I also talked about one another simpler configuration, where one can use a branch line coupler terminated with 2 identical PIN diodes and just by changing the bias voltage, we can vary the value of attenuation. Then, we talked about a MESFET and the IC which can be directly used as a variable attenuator. So, in the next lecture, we will see more applications of PIN diode and the application which we are going to talk about would be microwave switches.

Thank you very much.