

**Microwave Theory and Techniques.**  
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**Module - 06**  
**Lecture – 28**  
**Microwave RF Switches: Series and Shunt SPST**

Hello, everyone. Today, we are going to talk about RF Switches you can also call these things as Microwave Switches also. I just want to tell little bit about what is the difference between RF and Microwave. Strictly speaking microwave frequency is from 3 to 30 gigahertz whereas, mobile phones use 900 megahertz or 1800 megahertz or 2100 megahertz depending upon 2 g or 3 g. So, what has happen in the recent years people have started using the term RF in broad sense. Even though RF stands for radio frequency in fact, radio frequency goes to even AM radio and FM radio also.

So, for AM radio frequency ranges from 530 to 1620 kilohertz which is really of the order of 1 megahertz. So, RF in general consists of all of those things. So, RF is lower frequency also and even microwave frequency. So, these days microwave and RF are used interchangeably. So, do not get confused strict definition of microwave is 3 to 30 gigahertz, but nowadays loosely people have started using even the other lower frequency values also as microwave ok.

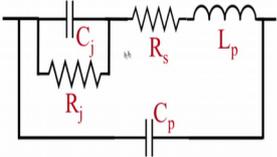
Hence, RF or microwave switches you can say ok. So, let us start with the another application of PIN diodes. So, in the previous lecture we had seen one of the application of PIN diode, where PIN Diode was slightly forward biased and when PIN Diode was slightly forward biased, it behaved as variable resistance. But today we are going to look at the application of PIN Diode as switch where PIN Diode is either completely forward biased or it is reverse bias. So, let us see how we can model the PIN Diode in general?

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## PIN Diode Switch



$C_p$  = package capacitor = 0.1 to 0.5pF  
 $L_p$  = package inductance = 0.1 to 2nH



PIN Diode is Forward Biased (ON)   
 $R_f = 0.2$  to  $5\Omega$  = sum of the resistances of the p and n layers and the contact resistance.

PIN Diode is Reverse Biased (OFF)   
Under reverse bias, charge carriers are completely swept out of the I-layer. The diode presents a high impedance and is predominantly governed by the capacitive reactance.  $C_j = 0.01$  to  $2\text{pF}$  and  $R_r = 0.2$  to  $5\Omega$

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So, this is the PIN Diode, the model of the PIN Diode is given by this particular network over here, what you can see over here? This is a  $C_j$  which is a junction capacitance, in parallel with junction resistance, then there is a series resistance, there is a series inductance, sometimes this is also known as package inductance also and this whole thing is actually put in parallel with the  $C_p$ , which is a package capacitor.

Now, the typical value of the  $C_p$  can be from 0.1 to 0.5 Pico Farad and package inductance can be of the order of 0.1 to 2 Nano Henry. I just want to mention 2 Nano Henry is the real extreme case, most of their time it will be a less than one a Nano Henry. So, when the Diode is forward biased ok. So, here all you do it is apply plus over here and let us say this is a 0 voltage, then Diode will be forward biased. Now, generally speaking for PN junction forward voltage is typically of the order of 0.7 volt.

But, for pi and Diode the forward voltage required is anywhere between 1.5 to 2 volt or even slightly more so, depending upon the PIN Diode specification. And, majority of the time the forward voltage depends upon the width of this particular intrinsic layer ok. So, before you design PIN Diode as a switch, please read the specification what is the minimum forward voltage required? Ok. So, when PIN Diode is forward bias.

So, let us say approximately 2 volt over here. So, when 2 volt is applied over here then the Diode will be forward biased and this entire network can be simply represented by a forward resistance which is  $R_f$ , but I also want to mention many a times in the forward

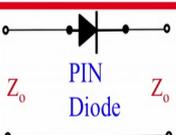
bias we also add series inductor over here also ok. So, do not get confused, later on you will see that we do represent RF in series with inductance ok, but generally speaking capacitance does not come into picture.

When Diode is reverse bias, in that particular case now what happens that it is not conducting. So, this will behave as a junction capacitance, in series with the resistance R r ok. So, typical value of the junction capacitance can vary from 0.0 1 to 2 Pico Farad you can see that this is a very very small value of the capacitance. And, because of this very small value of the capacitance PIN diodes can be used up to very high frequency ok. And, generally speaking again series resistance may be of this particular order.

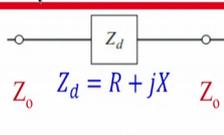
But, again I want to mention that many a times you may actually see that this particular resistance may be even of the order of kilo ohm also. So, again it is very important that you read the specifications of whichever PIN Diode you have chosen.

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### Series Switch (SPST/SP1T)



PIN Diode



$Z_d = R + jX$

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & Z_d \\ 0 & 1 \end{bmatrix} \Rightarrow S_{21} = \frac{2}{A + B/Z_0 + CZ_0 + D}$$

When Diode is Forward Biased

“ON” state  $\rightarrow R = R_f, X = \omega L$ , where L= Series Inductance

Insertion loss ( $\alpha$ ) dB =  $20 \log_{10} \frac{1}{|S_{21}|} = 20 \log_{10} \left( \frac{1 + \frac{R+jX}{Z_0} + 0 + 1}{2} \right)$

$$\alpha(dB) = 10 \log_{10} \left[ \left( 1 + \frac{R}{2Z_0} \right)^2 + \left( \frac{X}{2Z_0} \right)^2 \right]$$



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So, now let us see the application of PIN Diode as a switch. So, first application we are going to look at which is SPST; Single Pole, Single Throw. It is also called S P 1 T single pole you can say one throw ok. So, where do we need a switch ok?

So, first of all let just look at a switch, why we need a switch? I mean you would just think about a simple switch at your home you want to let us say turn on fan or turn off the fan. So, what you do? You just switch it on or you switch it off ok. So, you will get

that particular switch is known as single pole single throw ok. So; that means, on or off the same thing you can say for tube light you want to turn it on or you want to turn it off ok. So, that is a simple switch here we are showing you a first configuration which is a series switch, later on I am going to show you shunt switch and then combination of series and shunt switches ok.

So, a PIN Diode can be modeled as a simple  $Z_d$  where  $Z_d$  is equivalent to  $R + jX$ . Now, depending upon, if it is forward bias then this will be forward resistance plus series inductance, if the diode is reverse bias, then this will be a reverse resistance plus the junction capacitance ok. So, the values of  $R$  and  $X$  may change depending upon the biasing of PIN diode. Please remember that we have to completely forward bias or completely reverse bias ok. And, complete reverse bias is very simple you can just apply 0 volt or sometimes people do apply negative voltage also.

So, the analysis of this is relatively simple. So, we know that for a series impedance we can write ABCD parameters as  $\begin{bmatrix} 1 & Z \\ 0 & 1 \end{bmatrix}$ . So, here  $Z$  is equal to  $Z_d$ . So, from here we can use the conversion from ABCD parameter to S parameter right. Now, we are looking at  $S_{21}$ , but other parameters can be calculated in a similar fashion. So, what is  $S_{21}$  is given by  $2$  divided by  $A + B_{\text{normalized}} + C_{\text{normalized}} + D$ .

So, when Diode is forward bias which is in this particular case switch is on. So, when switch is on forward biased over here, you can say that if it is forward bias whatever is the input given it will go to the output here. And, when PIN Diode is reverse bias, whatever is the input given here practically nothing should go over here ok. So, in the on state  $R$  is equal to  $R_f$  and  $X$  is equal to  $\omega L$ , where  $L$  is series inductance.

So, now, we can find out what is the insertion loss. Insertion loss if you see is defined as  $20 \log \frac{1}{S_{21}}$ . I just want to mention see  $S_{21}$  in general will be negative. Suppose, we give one here it will be always less than 1 ok.

So, here when we take a  $\frac{1}{S_{21}}$ ; that means, insertion loss will be a positive number. So, generally speaking we also say insertion loss is 1 dB or 2 dB, we do not write minus 1 dB or minus 2 dB. So, since  $S_{21}$  has a negative dB value. So,  $\frac{1}{S_{21}}$  will have a positive insertion loss. So, now, let us substitute the value of  $S_{21}$  in this particular expression. And, we know, what are the ABCD parameters? So, let us see quickly here. So,  $\frac{1}{S_{21}}$  so, this thing will go up.

So, we have A, A is 1 plus B by Z 0 b is Z d; Z d is R plus j X. So, R plus j X divided by Z 0 plus C; C is equal to 0. So, we have 0 plus D which is equal to 1. So, that comes over here. And, now this can be little bit simplified in a sense that separate the real and imaginary components so, you can see that this will be 1 plus 1 2. So, 2 divided by 2 this term will be 1 and then this is R divided by Z 0 divided by 2. So, that will be R divided by 2 Z 0. So, that is a real component square and the imaginary component will be X divided by 2 Z 0 square of that.

Now, in reality the magnitude of this will have a square root ok, but that square root means there will be half term here. So, this should be a half, that half has been taken this side. So, that becomes 10. So, this is 10 log this particular expression over here ok. So, for given values of R equal to RF and X equal to omega L, you can find out what is the insertion loss of this particular switch. Ideally, we want insertion loss to be close to 0 dB ok, but in practice it will never be 0 dB as we had seen that R has a finite value, X has a finite value. So, insertion loss also will have finite value. So, let us see now what happens when Diode is reverse biased.

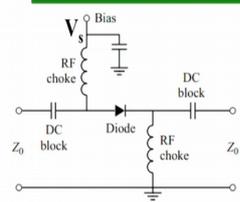
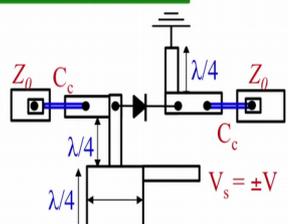
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## Series SPST Switch Realization

When Diode is Reverse Biased  $\rightarrow R = R_r$  and  $X = 1/(\omega C_j)$

Isolation ( $\alpha$ ) dB =  $20 \log_{10} \frac{1}{|S_{21}|}$

$$\alpha(dB) = 10 \log_{10} \left[ \left( 1 + \frac{R}{2Z_0} \right)^2 + \left( \frac{X}{2Z_0} \right)^2 \right]$$



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When Diode is reverse bias now R is equal to R r X is equal to 1 divided by omega C j. So, instead of calling now insertion loss as in the case when switch was on now the switch is off. So, we define it as isolation ok. So, that means, what is the isolation between input port and the output port? Ideally we would like isolation to be infinite ok.

But, practically 20 dB or 30 dB or 40 dB isolation would be there one has to see what is the minimum isolation requirement for a given application.

So, again isolation expression is same as before, the only difference is now that instead of  $R$  equal to  $R_f$  put in the earlier case, now we are going to put  $R$  equal to  $R_r$  and instead of  $X$  putting in the earlier case as  $\omega L$ . So, we put now  $X$  equal to  $1$  over  $\omega C_j$ . So, attenuation expression is exactly same as before, only difference is for forward bias this will be  $R_f$  and this will be  $\omega L$ , for reverse bias this will be  $R_r$  and this will be  $1$  divided by  $\omega C_j$ .

Now, let us see how we do the biasing of the PIN diode? So, let us see the biasing configuration. So, here this is a you can say port 1, this is port 2, and this is the DC voltage which is applied. So, that is a bias voltage we can see over here there is a RF choke, then there is a Diode and then this is a RF choke which is going to ground. So, the DC voltage goes through here and goes through over here and is then finally, connected to ground here.

So, you can see that there is a capacitance connected from the voltage to the ground. This capacitance is basically to kill the ripples as well as the transients. In fact, many a times we put multiple capacitors instead of a single capacitance over here. And, these multiple capacitances can be of the order of let us say 1 micro farad which is for smoothening out the ripple, and we also may put 10 Nano farad and even a 100 Pico farad these are basically to take care of that transients, because remember it is a switch will be going from on to off or off to on.

So, a lot of transients will come into picture and these transients are at very high frequency. So, you need small values of capacitances to take care of these transients. So, what is RF choke? Actually, RF choke is nothing, but a high value of inductor. Now, typical values of the inductor should be chosen such a way that the impedance of the inductor should be at least 500 ohm or more. Why 500 ohm or more? The reason for that is  $Z_0$  is equal to 50 ohm. So, this particular thing should be at least 10 times of that. So, you can take as 500 ohm maybe maximum 5000 ohm, but not more than that, do not take a very large value of inductor because these inductors at very high frequency may act as a capacitance ok.

So, why we need a large value of inductor? The reason for that is that if we do not put a large value of inductor. Then, at AC frequency, if this is not very large this will provide a path to the ground here. Remember for AC DC voltages act as ground. So, the ac input here will get short circuited through this particular inductor. Similarly, over here we need to put a large value of inductor. So, that at a given ac frequency this inductor will act as a open circuit. We need coupling capacitor here to block the DC voltage going from here to the input side or going towards output side.

So, these are also known as coupling capacitor or DC block capacitor. And, the typical value of these capacitances again should be at least one-tenth of this particular impedance here. So, this is 50 ohm the impedance should be less than 5 ohm, but even if you take  $Z$  equal to  $1$  by  $j \omega C$  as even 0.5 ohm or so, it is good enough ok. So, anything between 0.5 ohm to 5 ohm is recommended. So, you should know what is the frequency of operation? At which you are designing a switch accordingly you calculate the value of the capacitance.

Now, over here there is a still 1 small problem in this particular circuit ok. And, what is that small problem, see here we are not able to limit the value of the current. In fact, for practical circuits we should also put a series resistance over here, which should control the current flowing through the diode ok. So, in fact, in the next slide I will show you, a series resistance which is put over here that will limit the current flowing through this particular diode.

But, let us see how we can realize this particular configuration using micro strip line? So, let us see here this is a 50 ohm line. So, width of the line has to be calculated corresponding to  $Z_0$  equal to 50 ohm. So, this is input you can say this is output and there is a coupling capacitor connected between this line and this here. So, simply you solder a coupling capacitor here, you solder a coupling capacitor over here. Now, what you see over here? There is a no RF choke, here it shows RF choke which is inductor.

But, over here RF chokes are not shown. So, let us see how RF chokes have been avoided? So, let us look at here there is a voltage  $V_s$ , which can switch from plus  $V/2$  minus  $V$ , but as I mentioned earlier you can switch  $V_s$  from plus  $V$  to 0 volt, it will still work. So, now, let us see what happens here? See a narrow strip line has been used over here so, which acts as a inductor. So, inductor will provide a high impedance path  $Z$  is

equal to  $j\omega l$  and for narrow line we know that the inductor will be large, hence impedance will be large.

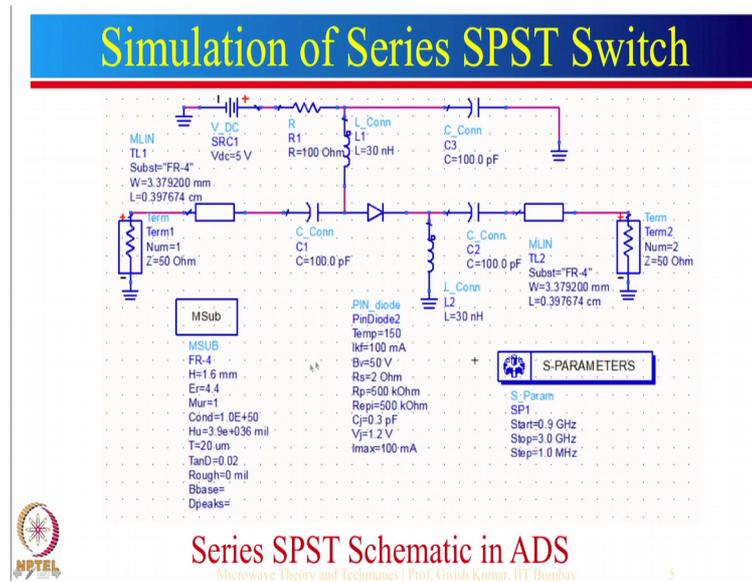
Now, let us see how this capacitance is being realized? So, you can see over here this particular thing acts as a patch capacitance. So, we know that patch capacitance provides capacitance from the top substrate to the ground plane. So, this acts as a patch substrate going from the voltage  $V_s$  to ground. Now, you can see here this length has been chosen as  $\lambda/4$  this length has been chosen as  $\lambda/4$ . What is the reason for that? See, this is an open circuit a  $\lambda/4$  line will actually have a input impedance at this port as 0.

So, this is open this will act as a short, then there is another  $\lambda/4$ . So, short here will act as open circuit. So, at the design frequency open will become short and then it will become open. So, if this is open whatever is the input we are giving that will go to the output. Let us see how this RF choke has been realized. Again this has been realized by using a  $\lambda/4$  line so, this is a short here. So, short will act as open circuit. So, there will be a no power dissipated in this particular thing.

So, what is the limitation of this particular configuration? The limitation of this configuration is that it will have a limited bandwidth, because this length will act as  $\lambda/4$  only at certain frequencies ok. Think about double the frequency, if it is double the frequency then this length will become  $\lambda/2$ . So, short will act as a short circuit here. So, input will not go to the output it will get shorted over here ok. So, the limitation of this particular configuration is that, it will have a limited bandwidth, but for many applications for example, if you are designing something for let us say wi fi ok, wi fi has a bandwidth of only about 4 percent. So, this particular configuration will be very suitable.

Similarly, if you are designing for let us say GSM 900. Again at GSM 900 bandwidth is just about 7 to 8 percent. So, this type of configuration is very suitable for narrowband applications. And, you can see that component cost is very small in this particular case here. Now, as I mentioned that this is not the circuit which we always use, we do use resistance so, that we can limit the current flow through that.

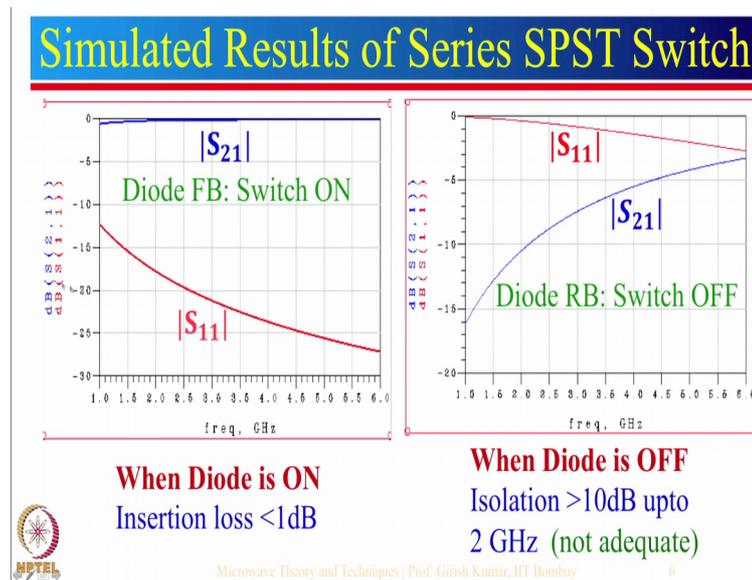
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So, here is a Series SPST simulation using ADS software. Now, it may be little difficult to read all the numbers over here, but I will just try to tell you quickly here. So, here is the biasing voltage and there is a resistor you can see over here, which is basically to control the current, you can choose higher value of resistor also depending upon the Diode specification. Then, you can see that we have used over here  $L$  equal to 30 Nano henry which acts as a RF choke at microwave frequency, then there is another inductor.

So, the path for dc will be from here to this inductor, then diode and it will be right over here. This is a coupling capacitor at the input side coupling capacitor at the output side. So, let us see the result of this particular circuit.

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So, now when the Diode is forward bias so, then switch would be on. So, when the switch is on what do we want? Whatever is the input it should go to the output? So, we would prefer  $S_{21}$  to be as small as possible. So, you can see over here this is the response from 1 gigahertz to 6 gigahertz, you can see that  $S_{21}$  is close to 0 dB. In fact, you can see over here in session losses, less than 1 dB over this entire band.

Now, you might wonder why there is a more loss over here. Actually the reason is not that the switch was bad, the reason for that is we have used coupling capacitor as only a 100 Pico farad. If, we use 1 Nano farad capacitance, then this will become flatter also. So, depending upon whatever is the frequency of operation you desire. Now, corresponding to this  $S_{21}$  you can see this is the  $S_{11}$  plot over here. You can see this is a minus 10 dB this is about minus 15 dB. So, you can see that reflection coefficient is good over this entire bandwidth.

But, now let us see, what is the performance? When the switch is off? Ideally what do we want we want  $S_{21}$  to be equal to 0 ok, but in a reality what we are getting let us see. So, when the Diode is reverse bias ideally switch should have been off; that means, nothing from input side should go to the output side, but let us see what is happening here, frequency varies from 1 to 6 gigahertz. You can see that isolation is just about a minus 16 Db. And, as the frequency increases you can see isolation here is only about minus 10 dB and here isolation is extremely poor.

So, you can see that this particular configuration is not suitable to provide good isolation. So, as I have mentioned over here isolation is just greater than 10 dB up to about 2 gigahertz. So which is not adequate, so in fact you should never ever use this particular configuration.

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## Shunt SPST Switch

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ Y & 1 \end{bmatrix}$$

where  $Y = G + jB$

$$\alpha(dB) = 20 \log_{10} \left| \frac{1 + YZ_0 + 1}{2} \right|$$

$$= 20 \log_{10} \left| \left( 1 + \frac{GZ_0}{2} + j \frac{BZ_0}{2} \right) \right|$$

$$\alpha(dB) = 10 \log_{10} \left[ \left( 1 + \frac{GZ_0}{2} \right)^2 + \left( \frac{BZ_0}{2} \right)^2 \right]$$

$\alpha$  corresponds to insertion loss when the diode is R.B. or switch is "ON"  
 $\alpha$  corresponds to isolation when the diode is F.B. or switch is "OFF"

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Let just see another configuration where diode is used in shunt configuration this is known as shunt SPST switch. Now, this thing can be modeled as shunt admittance and we know that for shunt admittance ABCD parameters are given by 1 0 Y 1, where we can now represent a Y as G plus j B.

So, by using the same concept we can now find out the insertion loss or isolation by using the same expression. So, which is given by alpha in dB is 20 log 10. So, you can now recall that this expression is 1 divided by S 2 1. So, this expression is nothing, but ABCD normalize values ok. So, we can see what is A A is 1, what is B B is equal to 0? What is C? C is y multiplied by Z 0, plus d which is 1 divided by 2. So, now, we can separate the real and imaginary terms.

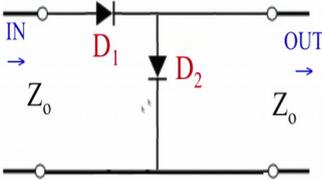
So, Y is equal to G plus j B. So, we write it in this fashion and then take the magnitude of this particular expression. So, this is the expression for shunt SPST switch. So, here alpha corresponds to insertion loss when the diode is reverse biased please notice, that this is now different compared to the previous configuration. So, this is different than series switch. When the diode was in series when, that was on input will go to the output.

But, here things are different; here when the diode is on this thing will act as a short circuit. So, ideally nothing should go over here.

And when diode is off; that means, when it is reverse bias then this will act as an open circuit. So, everything from input side should go to the output side. So, please notice this particular thing that, now insertion loss is when diode is reverse bias. When this is reverse bias, then switch is on and in on condition we defined as insertion loss. When the switch is off and when it will be off when diode is forward bias in that case it is isolation. So, by using a shunt configuration, you have to use opposite of the series configuration, for series we have to do forward bias for on switch here we have to reverse bias for on switch. Now, let us look at the combination of series and shunt switches here.

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## Series Shunt SPST Switch



A better switching performance can be obtained when both series and shunt diodes are used in a single circuit.

Switch is ON: when  $D_1$  is ON (FB) and  $D_2$  is OFF (RB)

Switch is OFF: when  $D_1$  is OFF (RB) and  $D_2$  is ON (FB)

FB: Forward Bias  
RB: Reverse Bias



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So, we have 2 diodes  $D_1$  and  $D_2$ . So, let us see when switch will be on, switch will be on when  $D_1$  is forward bias or on and when  $D_2$  is reverse bias or you can say it is off. So, when we forward bias  $D_1$  and reverse bias  $D_2$  then input will go to the output side, when switch will be off, when  $D_1$  is reverse bias you can see over here and when  $D_2$  is forward bias. So, FB here stands for forward bias RB stands for reverse bias.

Now, how do we do the analysis of this particular configuration? So, again we can use ABCD parameters. So, for this particular thing you can write ABCD parameters as  $\begin{bmatrix} 1 & Z_0 \\ 0 & 1 \end{bmatrix}$ . And, for this particular thing you can write ABCD parameters as  $\begin{bmatrix} 1 & 0 \\ Y & 1 \end{bmatrix}$  multiply the 2 matrices and get the combined ABCD parameters.

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### Series Shunt SPST Switch (contd.)

$$\text{Insertion Loss} = \left| \frac{1}{2} + \frac{(Z_o + Z_h)(Z_o + Z_l)}{2Z_o Z_h} \right|^2 \rightarrow \text{Switch is ON}$$
$$\text{Isolation} = \left| \frac{1}{2} + \frac{(Z_o + Z_h)(Z_o + Z_l)}{2Z_o Z_l} \right|^2 \rightarrow \text{Switch is OFF}$$

Configuration	Insertion Loss (dB)	Isolation (dB)
Series	0.147	8.3
Shunt	0.063	7.5
Series-Shunt	0.108	20.2



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And, from that we can actually find out the insertion loss and isolation. Now, I just want to mention a few things over here. So, what you will notice over here, that this is similar expression, we have used the same thing as before, but there is a only 1 small difference where I want to bring your attention, you see over here it is written as  $Z_h$  and this is written as  $Z_l$  ok.  $Z_l$  corresponds to low impedance  $Z_h$  corresponds to high impedance ok.

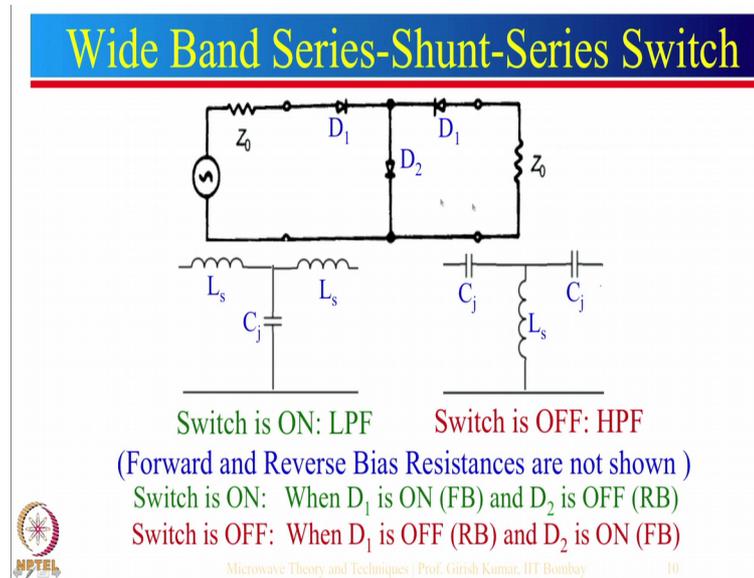
So, just recall now for the series component, when that is forward biased and the shunt is reverse bias; that means, if it is reverse biased impedance will be high for series, it will be low impedance ok. So, this is the insertion loss, when switch is on and this is the isolation. And, if you see the 2 expression there is a only 1 small change between these 2 expression and that is this is  $Z_h$  and this is  $Z_l$ . So,  $Z_h$  is high, if it is high this component will be small hence insertion loss will be small. If  $Z_l$  is small; that means, this component will be large and hence isolation will be large.

So, just to give you a little bit of an idea about insertion loss and isolation of series switch shunt switch and combination of series shunt switch, you can see for series switch insertion loss is of the order of 0.147, for shunt switch it is of the order of 0.063 for series shunt insertion loss is about 0.108. So, you can see it is a relatively small number.

Let us see for isolation. For series isolation is about 8.3, for shunt it is about 7.5, for series shunt it is about 20 dB. So, one can get a decent isolation by using series shunt

configuration. In fact, there is a only 1 problem with this series shunt configuration, that is it is not symmetrical with respect to input and output. So, instead of just using series shunt here is an switch which consists of series shunt series diodes ok.

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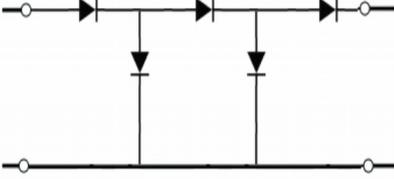
So, let us see how this particular switch works? So, for the switch to be on  $D_1$  should be forward biased  $D_2$  should be reverse bias and for the switch to be off  $D_1$  should be reverse bias  $D_2$  should be forward bias.

Now, for reverse bias we can represent the diode as capacitance and for forward bias we can represent the diode as inductor, resistances are not shown over here just to show you what this configuration looks like. So, this configuration also looks like a low pass filter. And, when the switch is off this will be a reverse bias. So, that can be represented as capacitance and this is forward bias. So, that will be represented as inductor. So, this looks like a high pass filter.

So, basically we are switching between low pass filter response to the high pass filter response. And, in general when you switch from low pass filter to high pass filter response, that configuration is known as wide band configuration.

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### Wide Band 5-element Series-Shunt Switch



- Isolation is better than 3 device up to 19GHz
- 20dB isolation is obtained up to 16.3GHz for 5-devices and 20dB isolation is obtained up to 12.4GHz for 3-devices
- Instead of using PIN Diodes, MESFETs can be used.

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Now, instead of using 3 one can use 5 of these elements. So, you can see that there are 3 series element 2 shunt element, and just to tell you the comparison. So, isolation for this configuration is better than 3 elements up to about 19 gigahertz, one can obtain about 20 dB isolation up to 16 gigahertz, for 5 devices up to about 12 gigahertz for 3 devices.

Now, instead of using PIN diodes 1 can also use MESFET. So, by using combinations of these diodes, one can actually realize wideband switch also. So, just to summarize, today we have discussed about PIN Diode switches, where these PIN diodes have been either used in series configuration or shunt configuration or series shunt series shunt series configuration. And, by using multiple diodes in series shunt combination we can obtain very wide bandwidth.

So, depending upon the application, how much isolation is required and what is the frequency range? You can actually decide to choose 1 element or up to 5 element PIN diode. So, in the next lecture we will talk about SP 2 T which is known as single pole double throw and some of the other applications. So, with that.

Thank you very much, see you next time bye.