

Microwave Engineering
Professor Ratnajit Bhattacharjee
Department of Electronics and Electrical Engineering
Indian Institute of Technology Guwahati
Lecture 22 - PIN Diodes and Control Circuits

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PIN diode and its equivalent circuit

A PIN diode contains an intrinsic or lightly doped layer in between the P and N layers.

Addition of intrinsic region reduces the junction capacitance since P and N regions are further apart.

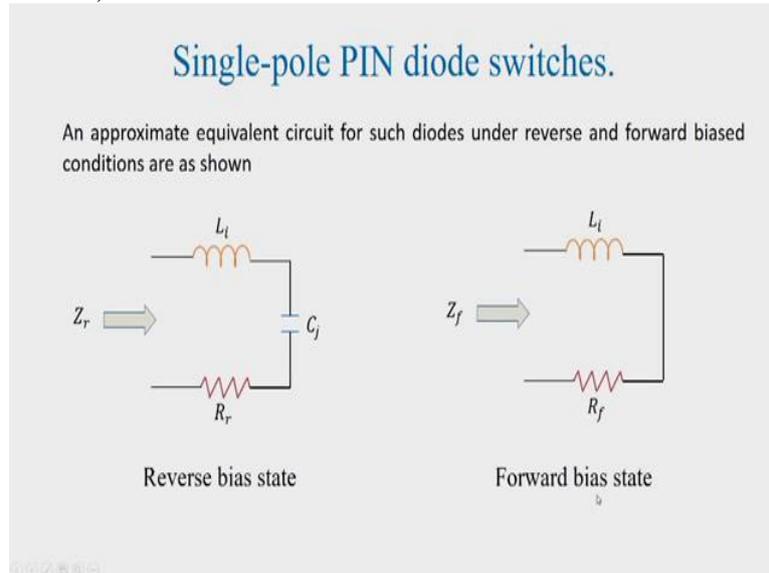
It makes the forward conductivity of the diode a much more linear function of diode bias current.

Under reverse biased condition, the diode impedance becomes high due to a small series junction capacitance.

Under forward bias, the junction capacitance is not present and the diode is in a low-impedance state.

In this lecture, we discuss PIN diodes and control circuits. So, a PIN diode, it contains an intrinsic or lightly doped layer in between P and N layers, and that is why the name of this diode is PIN. The addition of intrinsic region reduces the junction capacitance since P and N regions are now further apart. The introduction of this intrinsic region also makes forward conductivity of the diode a much more linear function of diode bias current. Under reverse bias conditions, the diode impedance becomes high due to a small series junction capacitance. Whereas under forward biased condition the junction capacitance is not present and the diode is in a low impedance state. So, this is in brief how the diode behaves under the reverse and forward biased conditions.

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We represent an approximate equivalent circuit for such diode under reverse and forward biased conditions as shown in the figures. So, this is the diode simplified equivalent circuit. So, we have L_i as the inductance of the Lid. C_j is the junction capacitance, and R_r is the resistance of the device under reverse biased condition. In the forward biased condition as we have said, this C_j is not there, and the resistance value of the device also changes, and it is represented by R_f , and therefore the equivalent circuit becomes L_i in series with R_f .

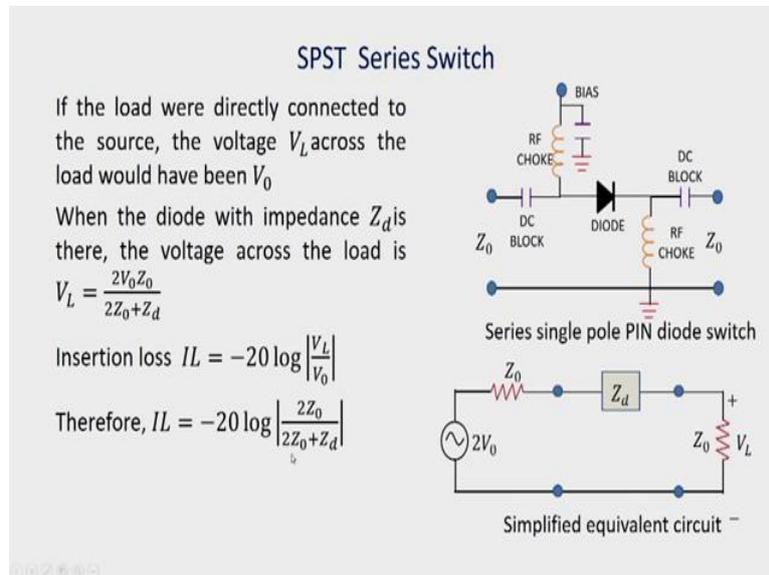
Now since this device offers high impedance in the reverse-biased state and low impedance in the forward-biased state, therefore, this device can be used as a switch, and the impedance of the device can be controlled by changing the bias of the device. And therefore, switching action can be obtained. We will start our discussion with a single-pole PIN diode switch. This is also called 'SPST', Single Pole Single Throw.

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$$V_L = \frac{2V_0 Z_0}{2Z_0 + Z_d}$$

Insertion loss $IL = -20 \log \left| \frac{V_L}{V_0} \right|$

Therefore, $IL = -20 \log \left| \frac{2Z_0}{2Z_0 + Z_d} \right|$



So, we consider a single pole single throw or SPST switch, the schematic of which is shown in the figure, and this is a series switch because here the diode element is connected in series. We can see that this diode is inserted between transmission line, and we have this P side of the diode is connected to the bias through an R_f choke. The purpose of this R_f choke is to provide a high impedance for the signal and a DC. This inductor will be a short circuit. So, this choke will prevent flow of signal towards the bias source. Also, we have a DC block here, because this DC Voltage should not go to either source or to the load. So, we have DC blocks.

Similarly, the N side of the diode is grounded through another R_f Choke. So, this will prevent the signal from going to ground rather when the switch is on, or the diode is in a low impedance state. Signal will flow from the source towards the load.

A simplified equivalent circuit without these biasing arrangements are shown in the figure here, and here we can see that we have a source and let $2V$ naught be the signal provided by this source, Z naught is the source impedance, and this diode is connected between load which is also Z naught. Now this is a series switch, and as we change the bias to this diode, its impedance can be changed; either it can be made high impedance or low impedance, and essentially it will act as a series switch. Now suppose, if the switch were not there, the load were directly connected to the source then we would have got a voltage V_L which is given by $2V$ naught

divided by Z_0 plus Z_0 that is $2Z_0$, into Z_0 , that means half of this $2V_0$. That means the load voltage V_L would have been V_0 .

When this diode is present, at that time, the diode can be modelled by its equivalent impedance Z_d . And the voltage V_L becomes $2V_0 Z_0$ divided by $2Z_0 + Z_d$. Now the insertion loss IL is defined as if you V_L is the voltage when the diode is present, V_0 would have been the voltage if the load was directly connected to the source. So, insertion loss is minus $20 \log V_L$ by V_0 . And from this expression, we can calculate V_L by V_0 and once we substitute this the insertion loss becomes minus $20 \log$ mod of $2Z_0$ divided by $2Z_0 + Z_d$. So, this is the insertion loss for a series switch.

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For the simplified equivalent circuit,

$$V_L = 2V_0 \frac{Z_d || Z_0}{Z_0 + Z_d || Z_0} = V_0 \frac{2Z_d}{2Z_d + Z_0}$$

Therefore,

$$IL = -20 \log \left| \frac{2Z_d}{2Z_d + Z_0} \right|$$

For both the switches,

$$Z_d = \begin{cases} R_r + j \left(\omega L_i - \frac{1}{\omega C_j} \right) & \text{for reverse bias} \\ R_f + j\omega L_i & \text{for forward bias} \end{cases}$$

SPST Shunt Switch

For the simplified equivalent circuit,

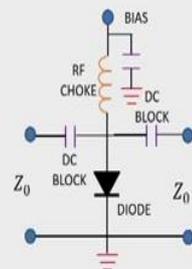
$$V_L = 2V_0 \frac{Z_d || Z_0}{Z_0 + Z_d || Z_0} = V_0 \frac{2Z_d}{2Z_d + Z_0}$$

Therefore,

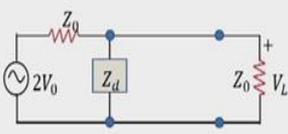
$$IL = -20 \log \left| \frac{2Z_d}{2Z_d + Z_0} \right|$$

For both the switches,

$$Z_d = \begin{cases} R_r + j \left(\omega L_i - \frac{1}{\omega C_j} \right) & \text{for reverse bias} \\ R_f + j\omega L_i & \text{for forward bias} \end{cases}$$



Series single pole PIN diode switch



Simplified equivalent circuit

Let us now consider another single pole single throw switch configuration, but this time the diode is connected in shunt. And we see that when the diode is in high impedance state, then the signal will flow from source to load; it will not go through the diode. Whereas, when the diode is biased, and it is in the low impedance state, in that case signal in the ideal case if the diode impedance is too low, all the signals will be reflected from here, and it will not go to the

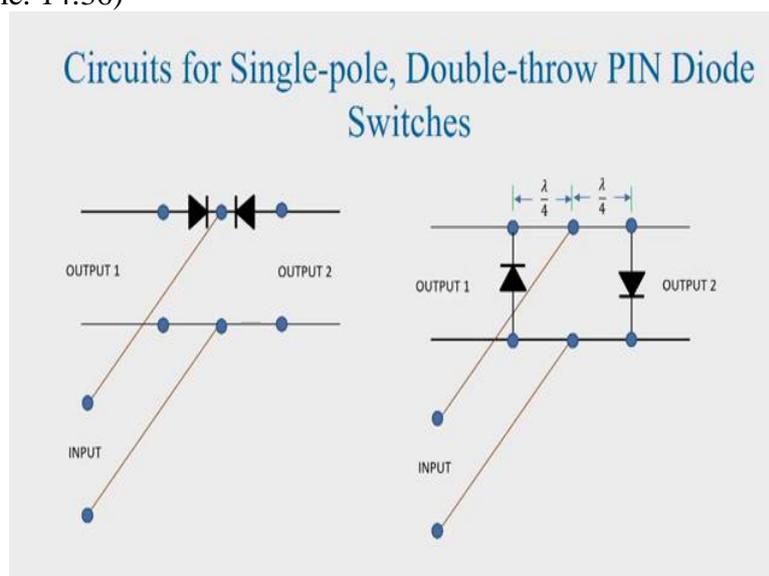
load, and therefore, we have a switching action here. Either the signal goes from source to load, or it is reflected back by the diode, and no signal reaches the load.

As before, this RF choke blocks the flow of signal towards the DC bias source by providing a high impedance whereas a DC is short-circuited and therefore the bias voltage is transferred to the diode. In the light of this discussion, we can draw a simplified equivalent circuit as shown in the figure, and we find that Z_d is now connected in parallel between the source and the load.

For this simplified equivalent circuit, we can calculate V_L to be equal to $2 V_{naught}$ and then Z_d parallel Z_{naught} divided by Z_{naught} plus Z_d parallel Z_{naught} and this becomes $V_{naught} \frac{2 Z_d}{2 Z_d + Z_{naught}}$ and once again had the load been directly connected to the source in the absence of the diode, we would have got, a voltage V_{naught} across the load and therefore, we define insertion loss to be equal to $-20 \log \left(\frac{V_L}{V_{naught}} \right)$ and V_L by V_{naught} we can now write, $\frac{2 Z_d}{2 Z_d + Z_{naught}}$.

So, for both the switches we find that when diode is reverse biased, at that time Z_d is given by $R_r + j \omega L_i - \frac{1}{j \omega C_j}$, this comes from the equivalent circuit of the diode, simplified equivalent circuit of the diode we discussed and similarly under forward biased condition, Z_d becomes $R_f + j \omega L_i$. So to determine the Insertion Loss for the on and off condition we need to calculate by substituting the values of Z_d at the design frequency for reverse and forward biased conditions. These parameters, R_r , L_i , C_j , and R_f these are available from the manufacturer datasheet for particular diode.

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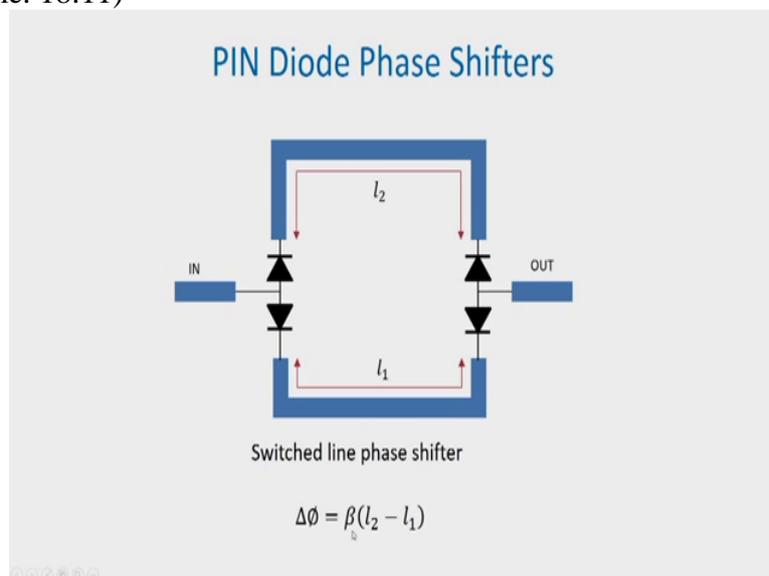
So, we have seen SPST type switch. Now let us consider, SPDT or single-pole double-throw type switches, so this is a switch where we have 2 diodes, and this is the input port, this input

signal may be connected to either output port 1 or output port 2 by making the corresponding diode on and the other diode off. We have not shown any biasing circuitry here. So when this diode is on, and this diode is off, so we will have the signal from the input port will go to the output port 1. And for the other combination that means when this diode is off, and this is on, the signal can be connected through output port 2, and therefore this switch gives us connection where this switch can be connected either to output port 1 or output port 2. That means it is an SPDT switch.

Let us see another way in which SPDT switch can be realized. Here, in this case, the diodes are connected in parallel, and we are using lambda by 4 sections. So, suppose the diode in the output port 1 that is off and the other diode is on. In that case what will happen, when this diode is on its impedance is very low, so ideally it is a short circuit and this lambda by 4 sections will transform it to an open circuit at this junction and therefore signal will flow from input to output port 1 and no signal will flow in output port 2.

Similarly, when we change the order of biasing, we make the diode connected in port 1 short and the diode connected in output port 2 open. In that case, no signal will flow to output port 1, and the signal will flow to output port 2. So, it becomes essentially a single pole double throw switch.

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PIN diodes can also be used in designing phase shifters. So, we see that this type of phase shifters are essentially switched line phase shifter. By switching on one set of diodes, we can bring a transmission line section of a given length between the input and output. For example, when these two diodes the lower two diodes they are made on, transmission line section L_1 is

connected between input and output. While when the upper two diodes are made on, then the transmission line section of length L_2 is connected between the input and output. At that time lower two diodes are kept on the open condition.

And therefore, when the signal travels between input and output through first path, so a differential phase shift can be produced in the signal traveling from input to output depending upon whether it is going through transmission line of length L_1 or transmission line of length L_2 and this differential phase shift $\Delta\phi$ it is given as $\beta(L_2 - L_1)$.