Millimeter Wave Technology
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Module 6
Lecture No 30
Active Devices (Contd)

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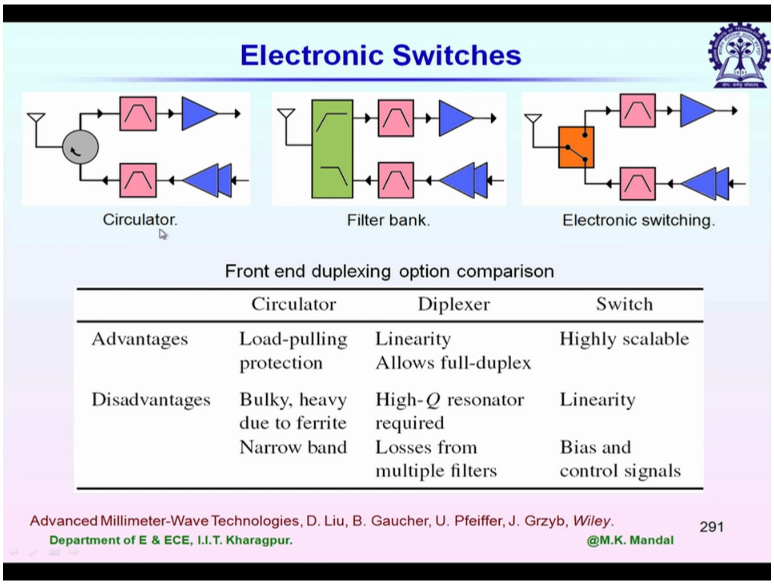

So next example is electronic switches, now electronic switches we will be using to connect a line or to isolates another line. And not that before electronic switches we did not have this type of application, we have some other alternatives also, so let us first discuss what are the basic characteristics of these different types of techniques, which are used to isolate input and output. The first example here based on circulator, so in this typical example one single antenna is connected to the transmitter side and the receiver side and now when this signal from transmitter side it goes to circulator, circulator it directs the signal to antenna and if any signal is received by antenna, then circulator it will direct in the same direction to receiver in a clockwise direction it is showing, so that is how we can isolate receiver and transmitter, so at any time communication is possible or it is a full duplex system.

Next, this is one example of the diplexer, so here diplexer or diplexer it is formed by using filter bank, one frequency is used for transmission and another different frequency is used for reception, so again it is a full duplex system and it can isolate transmitter and receiver at any given time. And the third example is by using switches, so in this case we can see that the single antenna, it is connected to transmitter side or receiver side and its connection depends on the state of switch. So, 2 important characteristics, it should have very good isolation between the input side and output side or receiver side and transmitter side because transmitting power it is very high, it can be of the order of a few watt and receiver side typically receiver it is of the order of nano watt or even less than that so there might be very good isolation between the transmitter to receiver otherwise, there will be leakage.

And also when the switch it connects one line, let us say transmitter antenna it should provide very low insertion loss, so this low insertion loss and high isolation they are the characteristics of any solid-state based switch. Also, we see that it is not a full duplex system, when we are using the antenna for transmission we cannot receive any signal because the receiver path is open. So here are comparison of the advantages and disadvantages of these 3 different types of technologies. Circulator we have load pulling protection, so right-hand side whatever you connect whatever impedance may be it does not have any problem to left-hand side, but it has the disadvantage that it is bulky because it is because it is made of some ferrites device so it needs biasing arrangement, it needs some magnet so that is why it becomes bulky, expensive and typically this is also a narrow band device.

Next is diplexer, its advantage is its linearity, so whatever power we use low-power or high-power, it will not give you any non-linear property, so this is the main advantage of diplexer and also it allows full duplex system. But the disadvantage is that it, we have to design 2 band pass filters having 2 different frequencies and now let us say 2 frequency bands they are closely spaced, so the rejection level at these 2 bands for these 2 different filters should be as high as possible. Sometimes the specified value it can be 80 dB or more. So from filter theory already we have seen that then it should we should use very high Q resonator to design this narrowband filter with very high attenuation rate. And if we go for very high Q or low loss then we have to increase the size of the filter and it would become very bulky and expensive.

Next switch, it is highly scalable in fact, it is possible to fabricate inside any integrated circuit in VLSI technology we can fabricate hundreds of switches together. But main problem is its linearity because in most of the cases it would associate with some PN junction or even let us say Schottky diode and all of them are associated with some sort of nonlinearities. So typically if we go for a high-power applications, in that case it will generate harmonics and signals itself it will be distorted, so linearity is a big problem for this type of switches. And not only that, we also have to provide biasing arrangement and the control signals. Already we have seen for the PIN diodes sometimes how problematic it can be so biasing current also it can be very high typically sometimes tens of mili-ampere. Now in a system if we have hundreds of switches, so you can imagine how much power it will consume.

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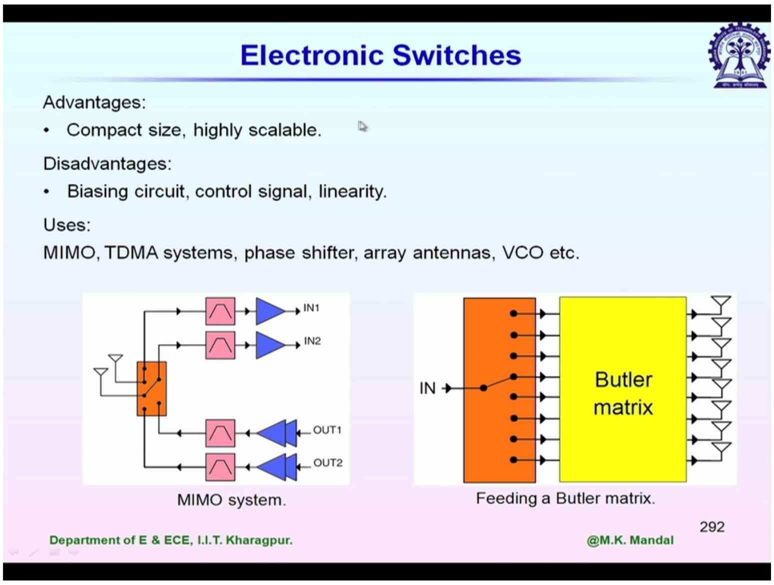

So in this class we will mainly concentrate on different types of electronic switches, so because of their advantages compact size and since they are highly scalable, but already we have seen the disadvantage is that we need biasing circuit, control signal and linearity is a problem. They are typically used in MIMO structure, TDMA system, phase shifters, array antennas, voltage controlled oscillator, et cetera. Here is a schematic example of a MIMO system, we are using two antennas and we have different receivers and transmitters, so we are using multiple multi-throw switch here and that will connect to one antenna to one receiver side or ONe transmitter side depending on requirement, so we are using a switch bank here.

Another example, this is a passive component butler matrix, it is used for phase array antennas. Inside the butler matrix we have a combination of several branch line couplers, passive phase shifters, crossovers. Now the order of the butler matrix, it is 2 to the power n by 2 to the power n, so we have 2 to the power n number of input lines and 2 to the power n number of output lines. Now antennas, they are connected to this all output ports and the RF input at a time it is connected to one of these 2 to the power N input by using a switch. Now how it operates, okay so let me just discuss a few basic points on phased arrays.

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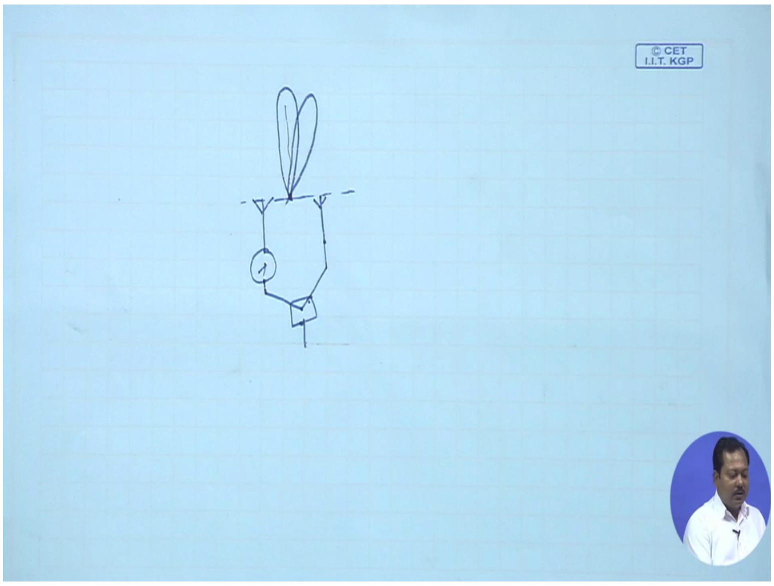

So let us say we have one 2-antenna system and this first antenna is connected to a phase shifter and the second antenna we are using as the reference antenna. Now the resultant beam direction, it is in broadside direction when the phase difference between 2 antenna feed is 0. Now if we introduce a phase shift between these 2 antennas, then beam direction will change and this change or new beam direction it depends on the phase shift value. So for an arrays of N antennas we assume it is a linear array in that case we have to maintain the same progressive phase difference between successive antenna to direct the beam in a particular direction.

Now if I go back to butler matrix, so for butler matrix when let us say the input is connected to the first input, then we have a typical phase distribution and because of that we have a progressive phase shift between the output points. If the input is connected to second point then this progressive phase shift will change and the beam direction will change. If we connect to third input point of the butler matrix then again we have a phase distribution among the output points so we have a new beam direction. So that means for a 2 to the power n input or 2 to the power n output lines, we have 2 to the power n possible beam directions and at a given time the actual RF input is connected to one of the input ports of the butler matrix, so we need a filter bank at the input side to control the beam position. So these are some examples of applications of electronic switches.

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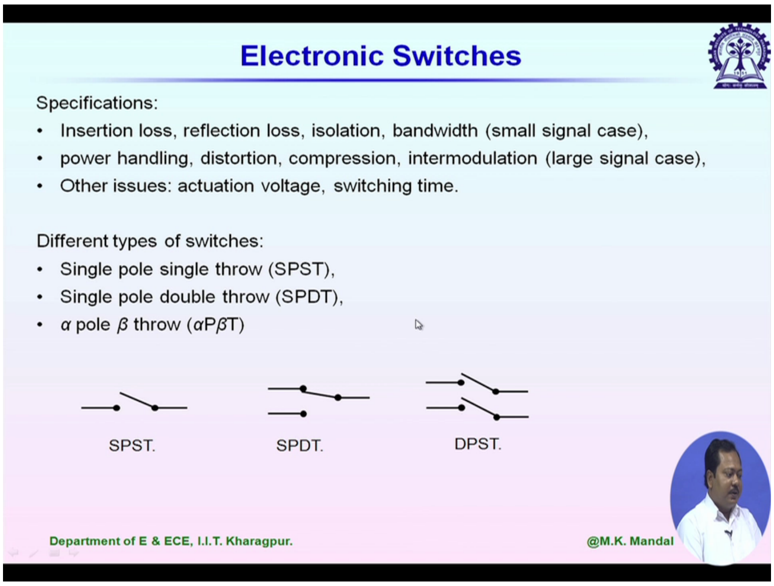

Now switch specifications, for small signal case the main characteristics are insertion loss so this is the loss between input and output, reflection loss seen at the input terminal, isolation when the switch it is off we are expecting very good isolation between input and output and then the bandwidth of operation. But when we go for large signal high-power case, in addition to all these points we have to consider some extra points one for example, what is the highest power handling capability. Next, what distortion it produces, then what is the 1 dB gain compression point, if we keep on increasing the power then output power at some point can decrease, then what is the effect of intermodulation. So since because of the nonlinearities we may have distortion or intermodulation effect and why it is so important because it can generate some other frequency components, which can interfere at the receiver side, so we have to be very careful about these points when we go for high-power applications.

Now, different types of switches according to the number of points to which this switches connected and the number of points where it can connect. It can be named as single pole single throw switch, in this case the switch is connected to just 1 point or it has one pole or ONly one switching position is possible, one single ON or OFF or we call a single throw position or simply SPST switch. The next one is single pole double throw switch, so switch that is connected to one point and it can connect either the first line or second-line, so 2 throw positions are available, we call it SPDT switch. In general we can define Alpha pole Beta throw switch or Alpha p Beta t switch.

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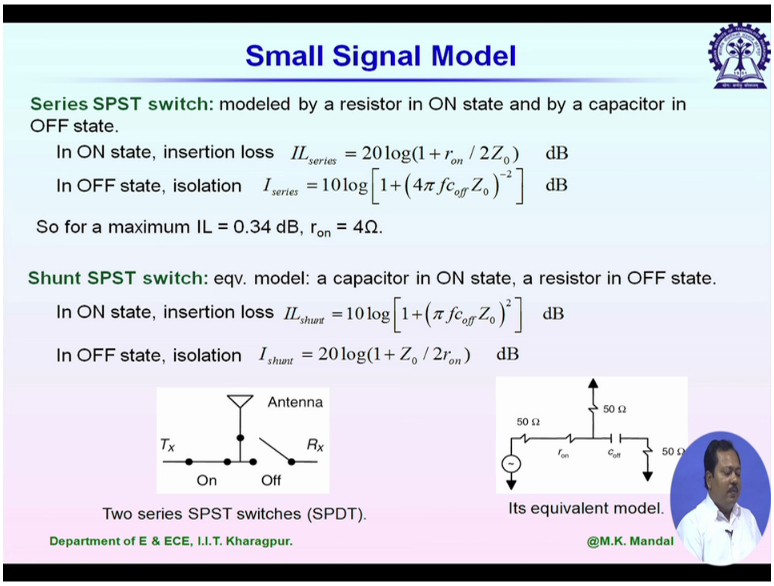

Now small signal model of a switch, already we have seen that a PIN diode or a Schottky diode we can use as switch. Typically, PIN diode is used at low frequency operation and switching speed is low and Schottky diode is used for very high frequency switching. Now, when the diodes are in forward biased condition in simplified form we simply represent by them a resister of small value of resister and when they are in reverse biased condition, we replace the diodes by a small value of capacitor so this capacitor value and the resister value is defined by the companies, it depends on fabrication procedure and the materials they are using. Now how to connect the switches in practical applications? We can connect them in series configuration, we can also connect them in shunt configuration, in the previous example we use PIN diode in shunt configuration.

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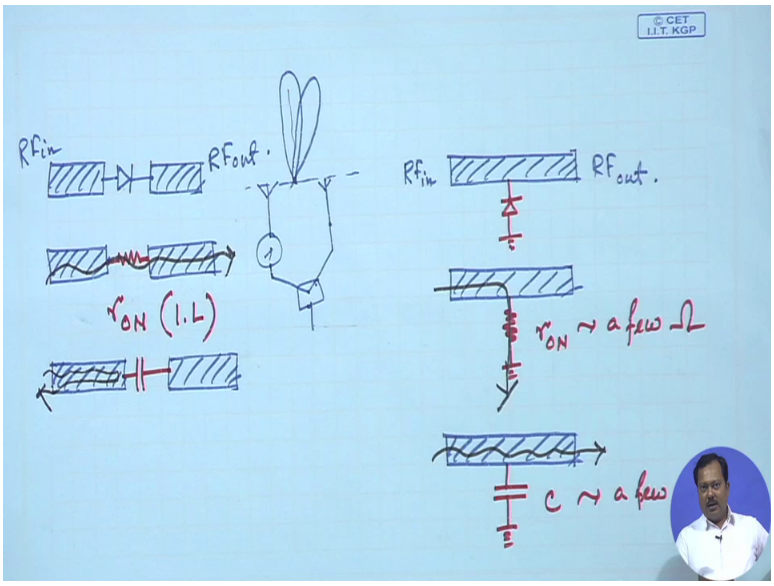

So in shunt configuration when the PIN diode switch is on that means we will be representing the PIN diode by a small value of resister, then it will be simply RF signal it would be grounded, so let me draw a diagram better. So let us say we have a microstrip line, I am showing just the top view of the microstrip line and this left-hand side is the RF in point and the right-hand side it is RF out point, and now I am using a switch in series configuration sorry in shunt configuration, so it is connected between the microstrip line and ground. Now when the diode is ON, in that case we can represent the diode by a small range equivalent resistance r ON, typically r ON is just a few ohms. So in this case what will happen, since the resistance is just a few ohms so RF signal whatever coming from left-hand side it is grounded through the register and we have very good isolation between input point and output point since we do not have any microwave signal or millimetre wave signal present at the output.

Now consider the second scenario when this diode is switched OFF. In that case we can represent the diode by a small value of capacitor, so C typically a few Picofarads so in that case since it is a small value of capacitor, so equivalent reactance will be very high for the RF signal and whatever RF signal we have it will simply pass from left-hand side to right-hand side or we have direct connection between the input and output, so this is in shunt configuration. We can use the same diode in series combination as well, so in that case the switching condition will simply change, so how to connect in that case, we have the same microstrip line but now we are using diode in series combination, so we have RF in left side, a load may be RF out right-hand side, when the diode is switched ON we will be representing the diode by a small value of resistance.

So when the resistance is connected, since it is a very small value it will connect simply left-hand side to right-hand side, so r ON in series it will give you some insertion loss and we see in this case, left-hand side is connected to right-hand side you can compare this situation with the previous one and we have transmission from left to right, just opposite what we have seen in previous case. Now let us say the diode, it is in OFF condition so we will represent the diode by a small value of capacitor here and since we have very small value of capacitor, it is associated with very high reactance and we have high impedance as seen by the RF input port, we have input reflection from this capacitor and we have very good isolation between the input and output point. Now the question is that, let us say one type of switch is given, it can be one PIN diode or it can be one Schottky diode then should we use in series configuration or shunt configuration, which one should we prefer?

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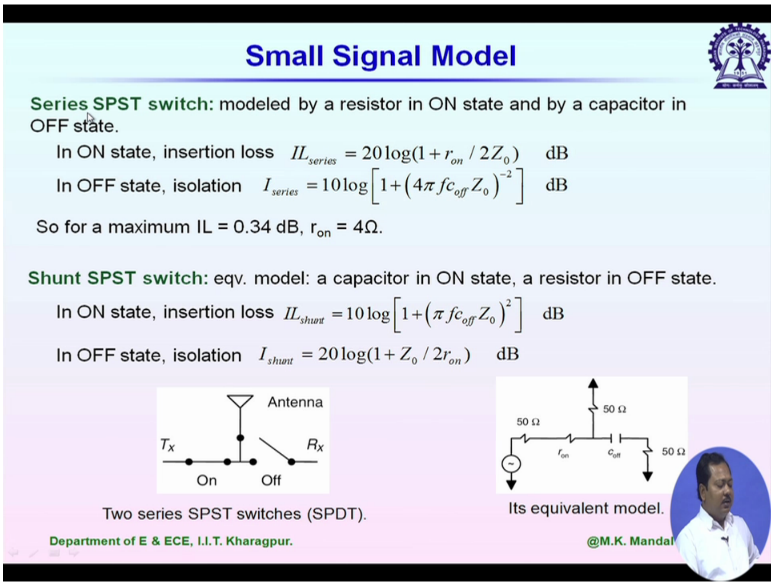

Then we have to do some analysis and after analysis the conclusion is that in shunt configuration if I use a single diode, it would provide better isolation compared to that in series configuration considering that the shunt capacitance typically a few picofarad and ON resistance is a few ohms. So how we do the analysis, so let us see we are considering SPST switch let us first consider series configuration, so as I discussed it is modelled by a resister in ON state and by a capacitor in OFF state. So in ON state then looking at the circuit whatever I have drawn previously, we can easily calculate what is the S 21, so if I go back to my drawing so we can consider it as a 2 port device right, where we have port 1 here, port 2 here and this is the section of transmission line, this is another section of transmission line and in between we have a resister connected to ground.

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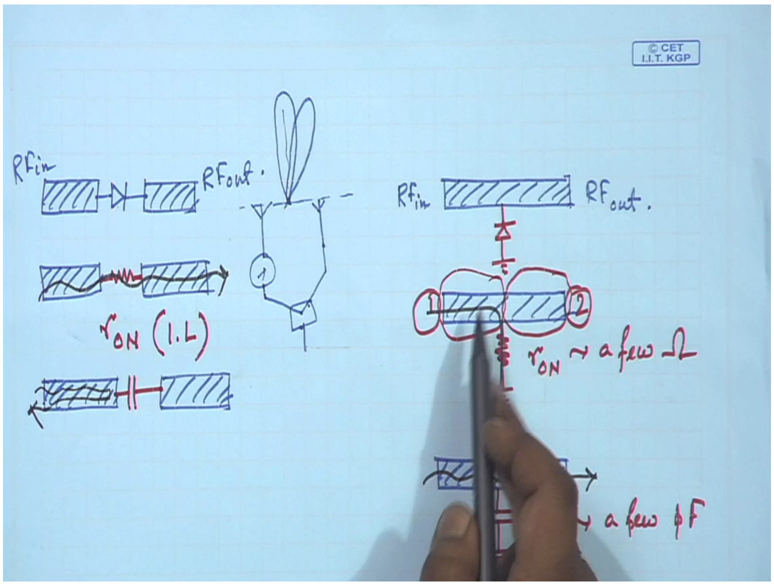

So simply by multiplication of ABCD matrices and then converting it to S parameters, we can calculate what is the S 11 and S 21 of this arrangement. Obviously, when we implement any switch there will not be any one single PIN diode or Schottky diode, in addition to this we should have DC blocking and RF blocking arrangement and for that we have some additional capacitors and inductors, but at RF frequencies those capacitors or inductors we will be representing by short-circuit or inductor by open circuit and capacitor by short-circuit. So not only for this case, for the second case also we can calculate what is the S 11 and S 21. So let us say the Port impedance, it is given by Z 0 in that case when the switch is ON, we are considering series configuration now.

So in series configuration when the switch is ON, left-hand side is connected to right-hand side and we replace the switch by a few ohms resister, which is r ON. If you calculate S 21 that is equal to in dB 20 log 10 of 1 + r ON divided by twice Z 0, and in OFF state that means when the switch is replaced by a small value of capacitor, if I calculate S21, so isolation I series that is 10 log 1 + 4 Pie f c off Z 0 hold to the power - 2 in dB, so we have actually one half term 1 square term here because of that the 20 log it becomes 10 log, so a typical example for a maximum insertion loss of 0.34 db, r ON equal to 4 ohms. If I look at the expression, insertion loss it depends on r ON, isolation it depends on c off and operating frequency. So if I increase the operating frequency for a given switch, what we expect, decrease isolation because capacitive reactance it decreases with increase in frequency.

Now let us consider shunt spaced switch, in this case we are using the PIN or Schottky diode in shunt configuration. So in ON state now we have to represent diode by a capacitor that means in this case left-hand side would be connected to right-hand side and we call the switch is ON, but diode is OFF and S 21 or insertion loss in shunt IL shunt that is equal to 10 log 1 + pie f c off Z 0 equal to the s square in dB. And in OFF state, isolation I shunt 20 log 1 + Z 0 by twice r ON. So we see here, now insertion loss it becomes a function of frequency whereas, the isolation it is a function of r ON, so for very high frequency operation we have to be careful depending on the values of r ON and c off and we can choose a proper circuit implementation, proper implementation scheme, it can be series or it can be shunt.

So already I discuss that for a few picofarad capacitance and considering that a few ohms r ON, mostly in shunt configuration these switches provide better isolation. So here are some examples, we can design SPDT switch by using a SPST switch here, the example is shown here. One antenna, it is connected to transmitter side and also receiver side, so depending on switching condition we can direct signal from transmitter to antenna or antenna to receiver and this is the right-hand side it shows the simplified equivalent model. We are representing the ON condition by r ON and OFF condition by c off and transmitter side, so at millimetre wave frequencies or even at microwave frequencies, if nothing is specified it is 50 Ohms system. Or left-hand side that is why it is represented a 50 Ohms, right-hand side it is also represented by a 50 Ohms load, antenna input impedance when matched that is also 50 Ohms.

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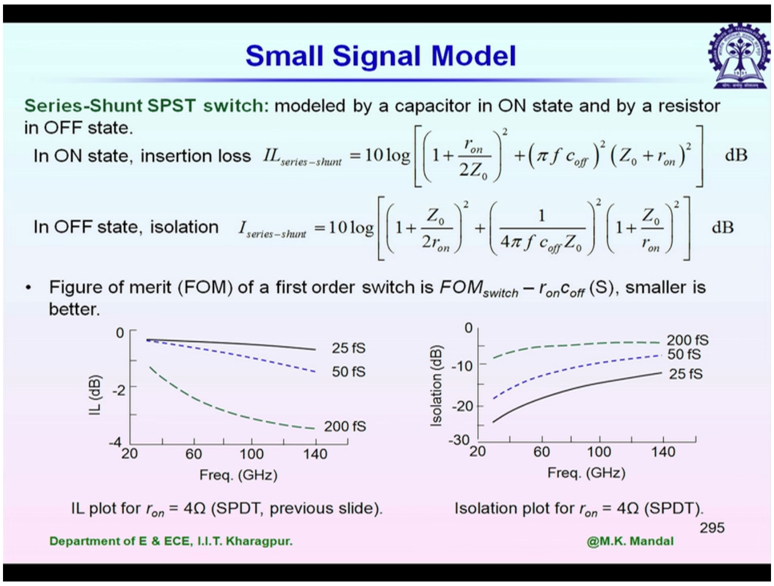

Now, how to improve the isolation for a given switch because it is a problem at higher frequencies? A PIN diode let us say is providing a very good isolation of 40 dB at 1 gigahertz, if I use the same PIN diode above 30 gigahertz, isolation it can degrade just 2-3 dB so isolation improvement is a challenge for any given switch. So next step, if we have two PIN diodes or two Schottky diodes, we can use them in series-shunt configuration to improve the isolation value, so what we will be doing here, let us say the switch we are going to use in series-shunt configuration, so one PIN diode we will be connecting in series configuration and another one in shunt configuration okay, so let me draw it.

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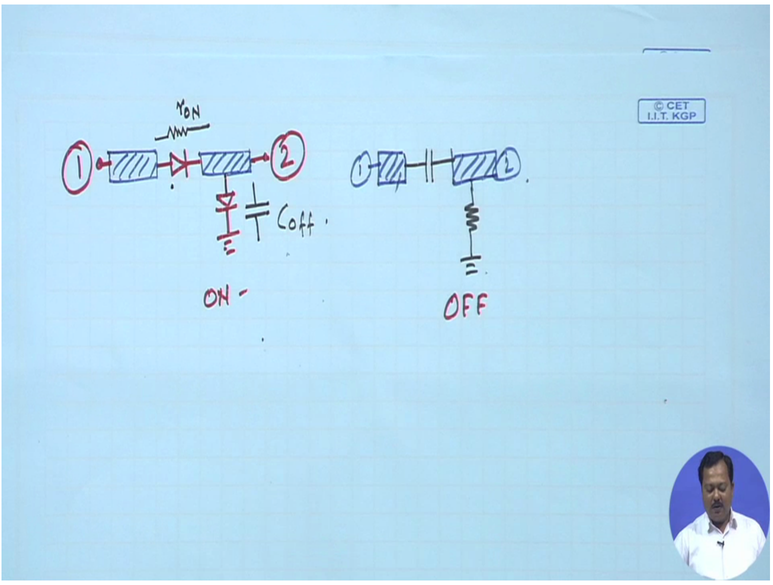

So this is the microstrip line top view, one diode will be used in series configuration and the second diode we will use in shunt configuration and together it behaves as a single switch SPST switch. Now, if I want to connect left-hand side to right-hand side then what should be the conditions of the diode? I want to connect left-hand side to right-hand side when the switch is ON, so in ON condition this diode, it should be replaced by a resister r ON small resistance value, so this diode should be in forward bias condition and this diode it should provide good isolation, so we should represent the diode by a capacitor c off or the second diode it should be in reverse bias condition.

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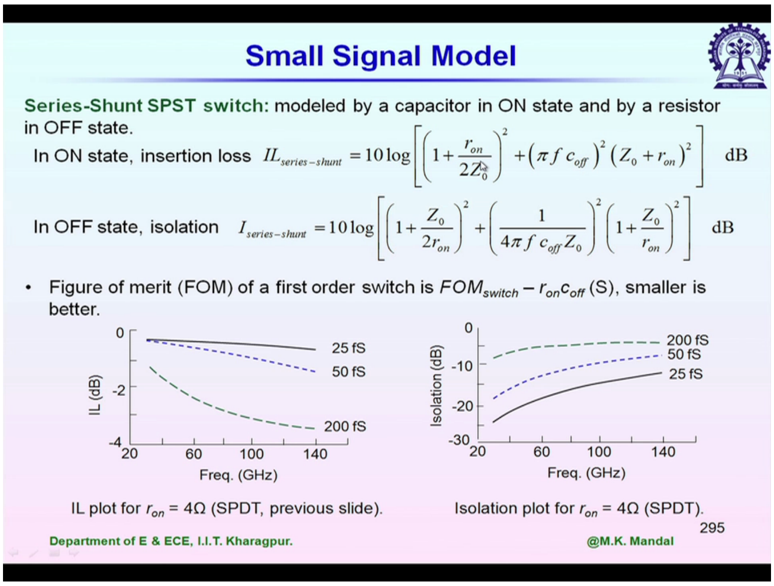

Then in OFF state, it is just opposite in OFF state then this first diode it should be in reverse bias condition and the second diode it should be in forward bias condition, so we have isolation due to first diode and further isolation for the second diode that is how we can improve isolation here, but insertion loss it will degrade. But anyway for any practical application we mainly look at the difference between the insertion loss and isolation, so now again if we calculate S 21 for this case, in ON state insertion loss or S 21 is given by this expression, it now becomes the function of both r ON, c off and frequency. And the isolation or the switch is OFF in that case S 21 is equal to 10 log of this function, so it is also a function of frequency, capacitance and r ON series resistance.

So for any given switch, how good it is to understand that, we define a parameter we call it figure of merit for a given first-order switch r and c, so this is simply r ON multiplied by c off just like one r-c Circuit the only the unit is second time constant, but r in ON state, c in OFF state, so smaller is the figure of merit better is the switch, here are some comparisons. So insertion loss versus for different figure of merits, so we see that for 25 femtoseconds r ON c OFF at even 140 gigahertz the insertion loss is below 1dB, for 200 femtoseconds it degrades to almost 4dB, we had considered r ON equal to 4 Ohms. Now right-hand side figure it shows the variation of isolation, for 200 femtoseconds you see at 30 gigahertz, isolation at least we have 7-8dB but at 140 gigahertz it is less than 5dB we do not have any isolation.

If we go for much better switch 25 femtoseconds let us say, in that case at least we have 13 to 15 dB isolation at 140 gigahertz. So isolation, insertion loss, both depends on figure of merit r

ON into c off, okay so next day we will continue we could not finish the switch here, so next day we will continue another 10-15 minutes on switch then we will start the millimetre wave propagation path, thank you.