Microwave Theory and Techniques
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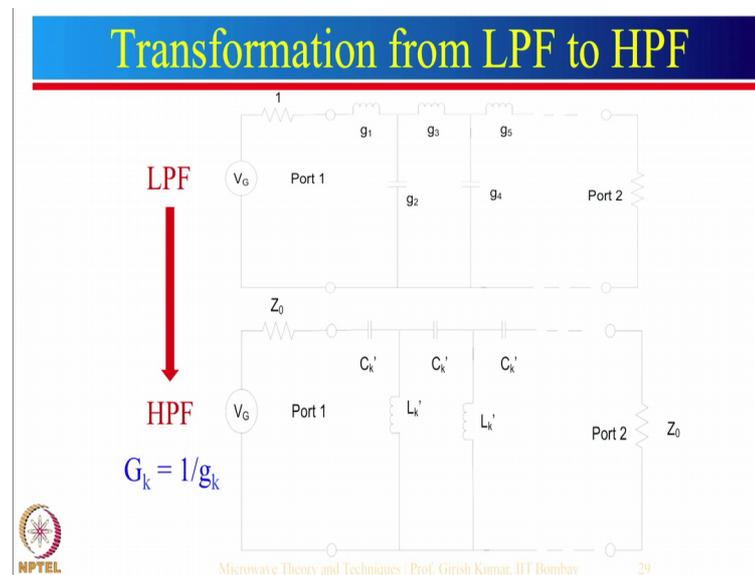**Indian Institute of Technology, Bombay**

Module - 05
Lecture - 25
Microwave Filters - V: Coupled Line and Tunable Band Pass Filters

Hello everyone. In the previous lecture we had seen how low pass filter can be transformed to high pass filter.

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So, for example, if you want Butterworth or Chebyshev high pass filter. Then, we start the design with corresponding Butterworth or chubby shape low pass filter and all the g parameters. And, then what we need to do? We need to do 2 things.

First is all inductors in case of low pass filter will become capacitors. And all capacitors will become inductors. And for the high pass filter the capital G parameters can be simply obtained by 1 divided by g k where g are the parameters corresponding to low pass filter.

And, once you get the new G parameters were C s and L s, then you can use the impedance and frequency transformation to get the values of C s and L.

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And, from low pass filter to band pass filter transformation, what we need to do? Every inductor is actually replaced by a series inductor and capacitor. And every capacitor is replaced by parallel inductor and capacitor. Then, we had seen an example of band pass filter at 100 megahertz where, we had modified the components.

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So, then we saw third order Butterworth band pass filter design at 100 megahertz. The process is again simple that you with a Butterworth low pass filter, and then transform

inductor and capacitor in the low pass filter to the corresponding parallel or series combination for band pass filter.

So, this was the realized circuit. However, that original design circuit was then change to the available practical values of inductors and capacitors.

And, this is the corresponding PCB, where I had mention that these are the plated through hole, and number of plated through holes are created here also. So, that it provides proper shorting to the ground.

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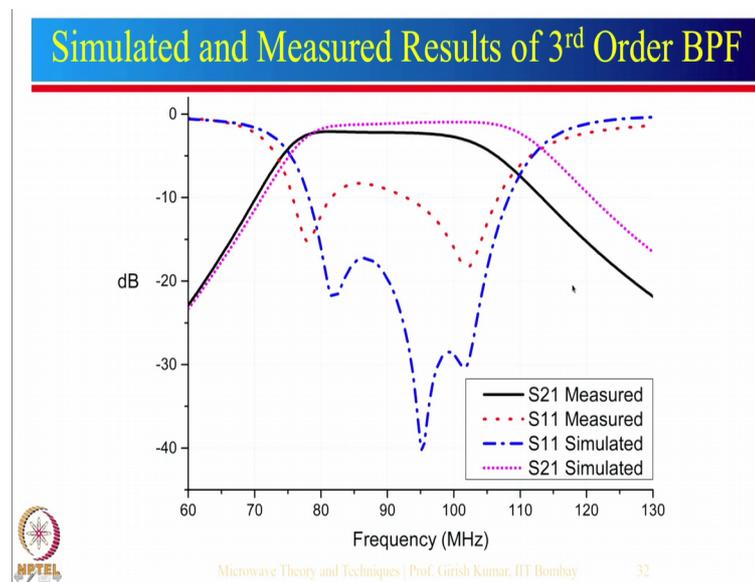
Then, we had seen both simulated and measured results we did noticed that for measured results, there is a small difference in the frequency in fact, most of the time we will see that there is a degrees in the frequency, this is mainly because of the all that printed circuit board provides parasitic inductances and capacitances.

So, when you are designing band pass filter you must consider, that there may be some parasitic inductances and capacitances associated with the PCB so, you must take corresponding precaution.

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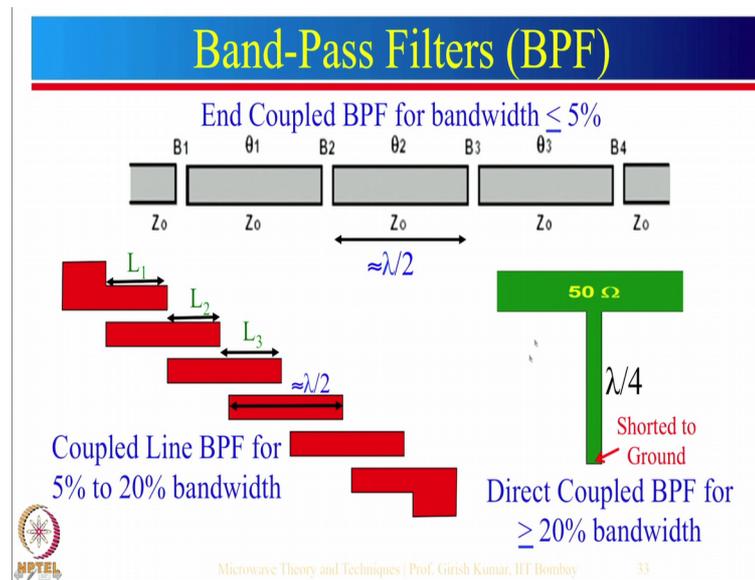
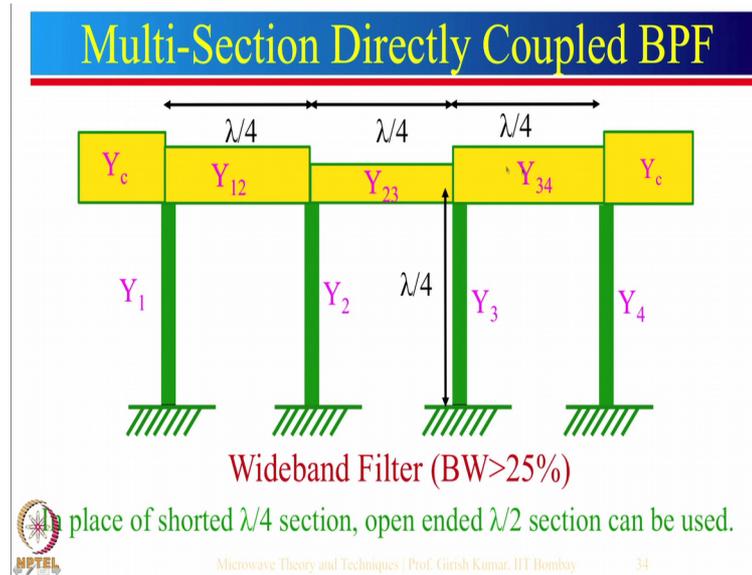Then from here we are shifted to the next concept where we had the microstrip lines to realize band pass filter we talked about end coupled filter, where coupling is done at the end of the resonator. I did mention that this is good for Bandwidth less than 5 percent, because coupling is relatively week. By using coupled line, we can increase the coupling between different resonators and then bandwidth can be increased from 5 percent to up to about 20 percent.
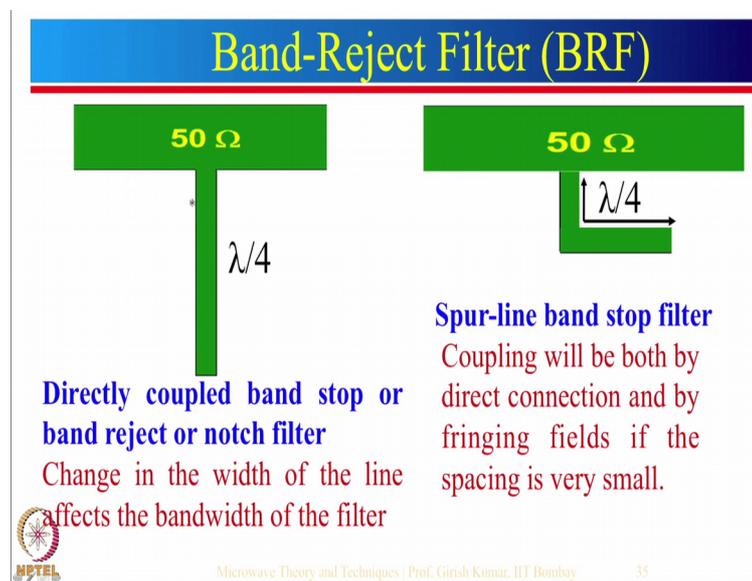
For larger bandwidth generally direct coupled band pass filters are use and again to look at the simple concept. If, there is a short at the end of a lambda by 4 length, then short will act as an open circuit. So, input will go to the output side.

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Multi-Section Directly Coupled BPF

$\lambda/4$ $\lambda/4$ $\lambda/4$

Y_c Y_{12} Y_{23} Y_{34} Y_c

Y_1 Y_2 $\lambda/4$ Y_3 Y_4

Wideband Filter (BW>25%)

In place of shorted $\lambda/4$ section, open ended $\lambda/2$ section can be used.

So, this as a single section this is an example of multiple section. So, multiple lambda by 4 sections have been used which are shorted at the end. Of course, instead of using lambda by 4 shorted section, you can also use open ended lambda by 2 section.

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Band-Reject Filter (BRF)

50 Ω   50 Ω

$\lambda/4$

$\lambda/4$

Directly coupled band stop or band reject or notch filter
Change in the width of the line affects the bandwidth of the filter

Spur-line band stop filter
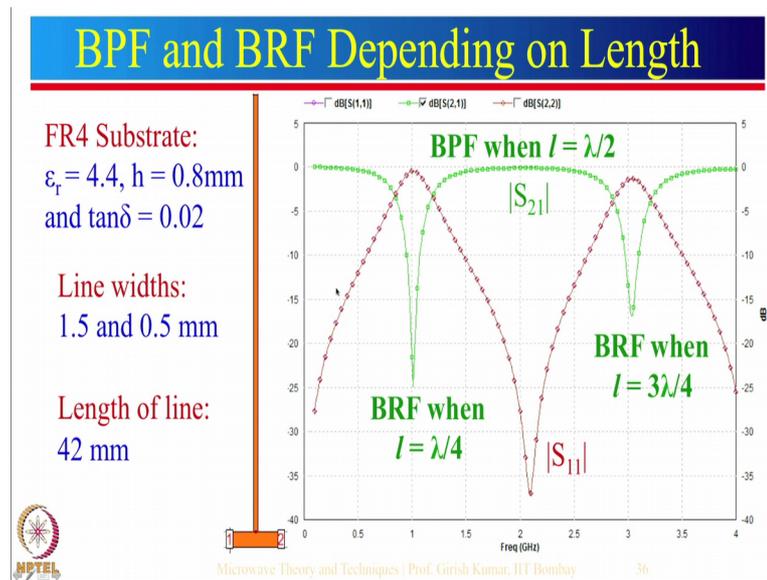Coupling will be both by direct connection and by fringing fields if the spacing is very small.

We looked at the design of band reject filter; we can use same line length of lambda by 4, but instead of shot circuit over here if you make it open.

So, if it is open and if the length is lambda by 4 open will act as a short circuit here. So, nothing will go from here to here.

Then, we had taken the example, where we had a simple transmission line going from pot 1 to port 2 and then resonator was connected and you can see over here. So, corresponding to 50 ohm line impedance, we had calculated the line width which is 1.5 mm that corresponds to the chosen FR 4 substrate, width of this particular resonator was taken as 0.5 mm.

And, a length of the line was taken as 42 mm. So, I had shown you the response first look at this S 2 1 response. So, you can see that this is the S 2 1 response. So, when this length becomes lambda by 4 and if the length is lambda by 4 here is an open circuit open circuit will act as a short circuit. So, nothing will go from 1 to 2.

So, you can see that the output which is S 2 1, it is very very small, you can see the number here is around minus 25 dB. Then at double the frequency this length will become lambda by 2. So, you can see that around 2 Gigahertz, when this length becomes lambda by 2.

So, open here will act like open over here. So, whatever is the input will go to the output you can see here this is a band pass filter. Now, at triple the frequency, which is around 3 gigahertz, we can see that length becomes now 3 lambda by 4. The response becomes of that of a band reject filter. So, this is the corresponding response for S 1 1.

So, when nothing is going to the output everything will reflector. And, if everything is going to the output nothing reflects back. Now, you can see over here for band pass filter bandwidth obtained is very large. And, you may have application where we want smaller bandwidth.

So, let us see how we can get smaller bandwidth we will see the effect of the width now.

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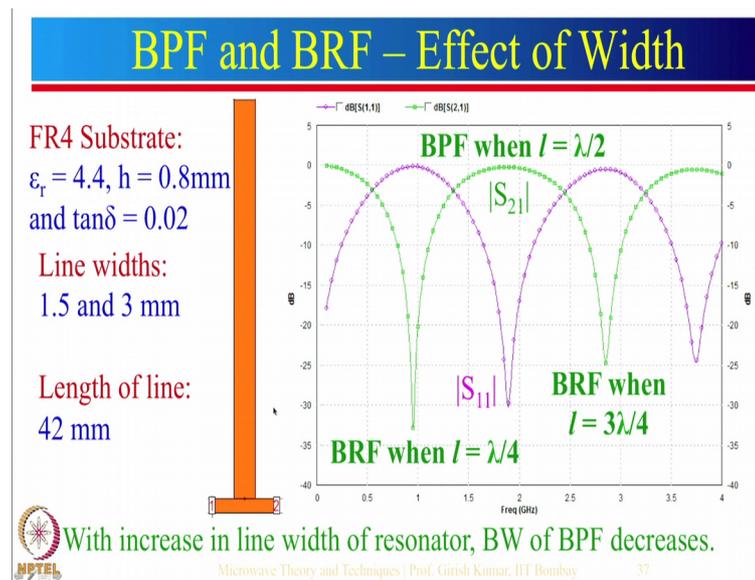
So, in this particular example there is only one thing which we have changed, instead of 0.5 mm width here that has become now 3 mm. And, when the width is increased you can see now that the bandwidth of the band pass filter has reviewed.

So that means, by increasing this width here, we can actually speaking decrease the bandwidth of the band pass filter. So, let just take another example, where we have simply replace this open circuit by short circuit. So, please recall here around 2 gigahertz it is acting like a band pass filter, around 1 gigahertz it is acting like a band reject filter, but now when we do the short let us see what happens.

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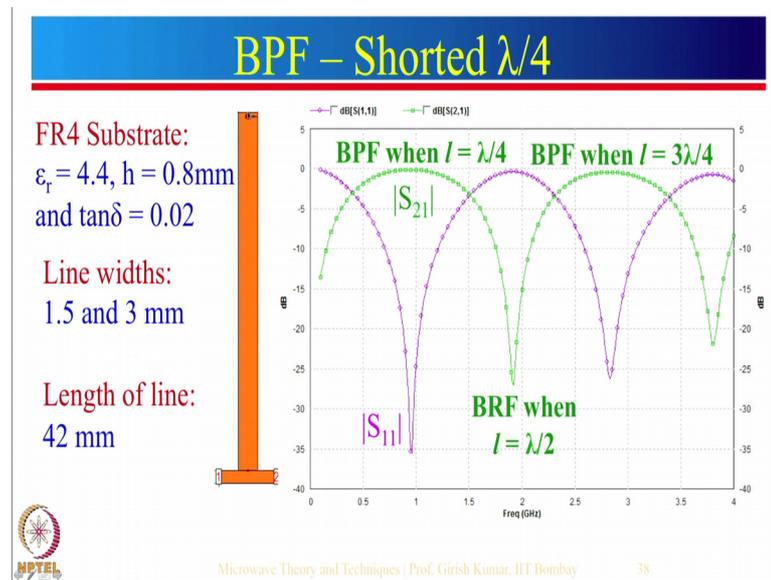
So, when this is shorted you can see that at length equal to n lambda by 4 this becomes band pass filter the reason for that is when this is shorted and if the length is lambda by 4 short will act like open circuit. So, whatever is the input goes to the output. So, this is the band pass filter response at double of this particular frequency.

It will act like a band reject filter, because short here will act as a short when the length is equal to lambda by 2. Again this particular configuration will act like a band pass filter, when length is equal to 3 lambda by 4; that means, approximately triple of this particular frequency.

So, we can see that this particular configuration will go from band pass filter to band reject filter, to band pas filter and then band reject filter. Now, this may not be practical most of the time, because suppose you are passing the frequency let us say in one gigahertz region, but it will also pass the frequencies in 3 gigahertz region also.

So, let us look at some alternate solutions for this particular problem. So, here is a band pass filter using 2 lambda by 4 shorted coupled line.

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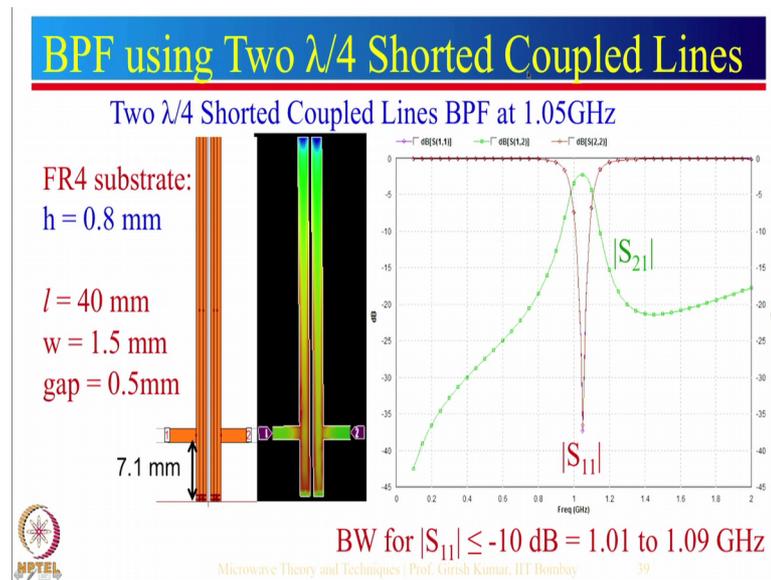
So, let us see what we have here. So, here this length is actually taken as lambda by 4 and over here we have a short circuit we have a short circuit over here. Now, we have to actually decide where to feed this particular resonator.

So, you can see here that this is short circuit. So, at short circuit input impedance will be equal to 0, because we know that impedance is nothing, but voltage divided by current. So, at short circuit voltage is equal to 0.

At this particular point impedance will be very high, because again impedance is v divided by I and here current is equal to 0. So, impedance is 0 here impedance is very high over here. So, somewhere in between we can find a point where the impedances of the order of 50 ohm.

So, we have to do little bit of a design and then optimisation also. So, here is a 50 ohm line feed input here, here is the output at this particular point. Again, we have use as before FR 4 substrate.

In this particular case length is equal to 40 mm for here to here the reason is the band pass filter has been designed at 1.05 gigahertz, previous case the design was around 1 gigahertz. So, since frequency has increase length has to be reduced slightly. So, here gap between the 2 resonator is of the order of 0.5 mm. So, this is the current distribution for this particular configuration.

The analysis has been done using ie 3 D software. So, let us see what this current distribution shows over here? So, blue colour here shows 0 current and red here shows maximum current. So, we know that this is an open circuit corresponding to open circuit current will be very small or negligible, which is represented by blue colour this is short circuited here current will be maximum. So, that is shown by the red colour and you can get the field that, this whole thing is varying from very small current to very high current.

So, you can say that this is nothing, but if we take a wave form like this. So, from 0 to peak will be lambda by 4. So, this lambda corresponds to lambda by 4. So, let us see now the response of this particular configuration. So, this is S 2 1.

So, you can see that this is acting like a band pass filter. And, since most of the power is going from input to the output side you can see that S 1 1 is very good, you can see that the reflected power is very vey small as S 1 1 is even less than minus 30 dB.

However, you can see one small problem over here and that is there is a insertion loss, you can see that this value is not close to 0 dB, but it has a finite loss. So, why there is a insertion loss. The reason for that is where feeding this particular resonator.

And from this resonator coupling is happening through the gap, which is coupled to this particular configuration and then power goes over here. And, we have taken a lossy substrate which is a glass epoxy substrate.

So, if we use a relatively good quality substrate then this insertion loss can be reduced. Neither thing what you can see here, that after this decrease it is increasing. In fact, I will just tell you that at around triple of this particular frequency. This will gain become more lighter band pass filter ok, but you can see that the response here is relatively good, that the transition from here to here is still not very fast. So, instead of using 2 section over here.

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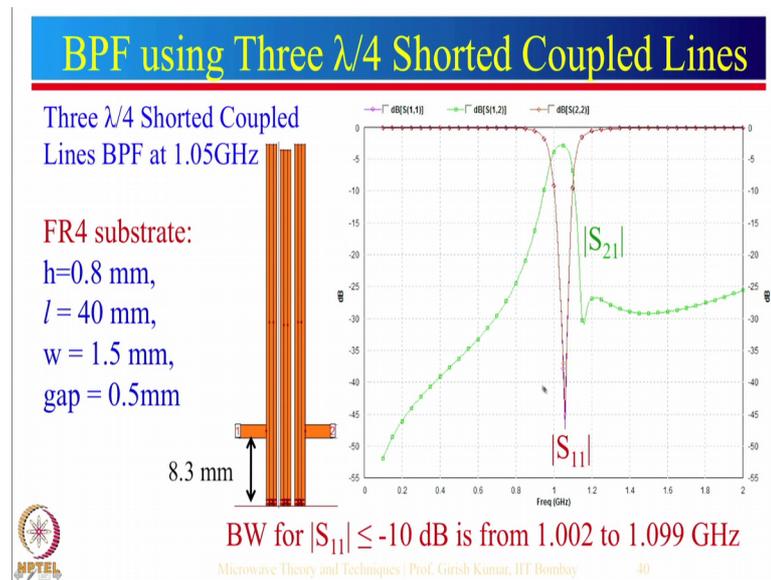
Now, let us see what happens if we use 3 lambda by 4 section. So, again you can see here one section here another section here the middle length here is slightly optimize.

So, that S 1 1 becomes better the coupling is done from here to this particular port here. Even the feed point had to be modified slightly; you can see that earlier this number was slightly different; now the number has change.

So, little bit of optimization has to be done to optimize the reflection coefficient, I can give you little bit of a hint instead of always looking at S 1 1 try to look at the input impedance plot on this mid chart. So, then if the input impedance on this mid chart shows that the impedance value is small; that means, that the port here is relatively closer to the short point here because impedance is small.

So, suppose when you start doing the simulation you may not know where to put this particular thing. So, you may take some arbitrary value, but you should know that this is 0 this is very large. So, 50 ohm should be relatively closer to 0, but let us say we took this particular point to feed here and take the output from here. So, look at the input impedance value, suppose instead of 50 ohm it is coming have to be let us say 40 ohm.

Then, you shift this particular thing above it where impedance will be higher. Suppose at this particular point you find input impedance to be 60 ohm, then you shift the port little bit down here where impedance will be relatively small.

So, let us see now what is the response of this 3 section coupler. So, you can see there now the response is relatively steeper and compare to then we have taken only 2 lambda by 4 section. So, you can compare that you can see that, this is much below compare to the previous one, but again I want to tell you all these things will start resonating again at around triple of this particular frequency.

Now, that may not be desired for several application. So, in that particular case what you need to do, you may have to put a band reject filter at third order filter or maybe you can integrate a low pass filter. So, which will attenuate higher frequencies?

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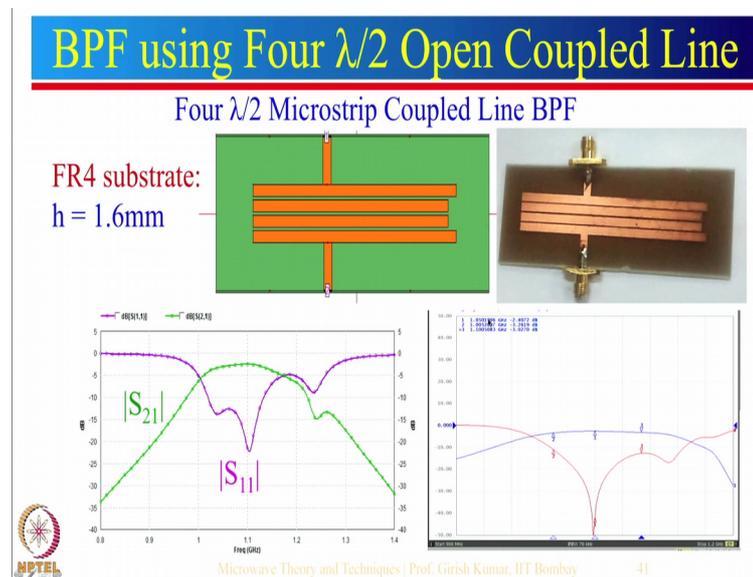
Now, let us just take an another example, it is not always that you should take lambda by 4 shorted line. Here is an example where we have taken an example of 4 lambda by 2 open coupled line. So, the length over here now is lambda by 2. Now, let us see how we have chosen the feed point.

I just want to mention here you have to be very careful where to feed, you first should understand what is the field distribution? So, over here and now since the length is lambda by 2 t is open circuit this is open circuit. So, current will be 0 over here; that means, impedance will be very large over here the current is 0 impedance is very large. At this particular point we can say that the impedance will be close to 0. So, this is a 0 impedance this is maximum impedance and this is maximum impedance.

So, compare to this particular 0 point here you can find the 50 ohm point somewhere here, you can go to this side it is a symmetrical configuration. So, it does not really matter you can chose either way. So, by using this particular configuration you can see that you got an S 1 1, which is fairly good over the desired bandwidth.

So, this is the simulated configuration, here we have done the fabrication of this particular thing. So, that is measured response. That the 2 responses are actually reasonably ok, it is just that this scale is different than this particular scale over here. Otherwise matching is reasonably good.

Now, may a times we do not take these lambda by 2 resonators as straight line, because this will occupy larger space. And, there may be space restrictions in some of the application. So, in that particular case instead of using this straight lambda by 2 resonators, you can us bend configurations also.

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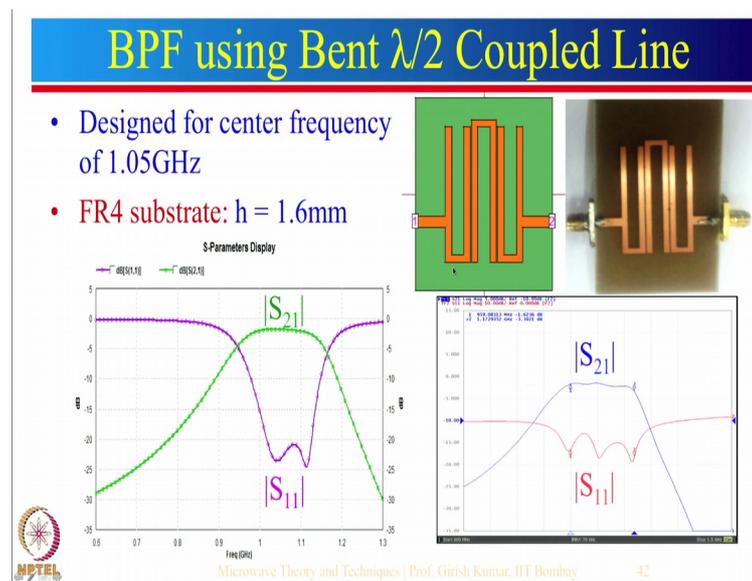
So, here is an example where instead of using straight configuration, we have actually use U shaped resonator. Now just to tell you this configuration is similar to the previous configuration, the design frequency is around 1.05 Gigahertz.

So, in this particular case here this is lambda by 2 length, then there is a another resonator put over here, then there is a another resonator and this is the output and input feed points. Now, how do we chose again the feed points again recall. So, this is lambda

by 2. So, current will be 0 here, current will be maximum here, current will be 0 here corresponding to a maxima of current voltage will be 0. So, impedance will be 0 here, impedance will be maximum.

Here so, between 0 and maximum impedance we need to optimize, this particular location where we get approximately 50 ohm impedance matching. So, you can see here this is the S 1 1 response, you can see the matching is fairly good everything is less than minus 20 dB in this particular region.

So, this is the response for S 2 1, you can see that there is a small insertion loss, we can see here this is 0 dB this is about minus 5 dB. So, there is an insertion loss of the order of minus 2 dB or so.

So, this has been again fabricated. So, this is the fabricated PCB and this is the measured response you can see here this is the S 2 1, which look similar to this particular response over here. And, this is corresponding S 1 1 response. So, this is a minus 10 dB line you can see here.

And, this is the response for S 1 1, you can see that the matching is fairly decent over the bandwidth, which is given by this particular section here. You can see that relatively it is a flat response in this particular pass band.

Now, there are many applications where you have to tune the frequency. So, in that particular case you cannot use fixed microstrip line, because fixed microstrip line will give you the fixed response you cannot change those things ok. Of course, when we did the inductor and capacitor realization, which was the lump element realization, there of course, you can put tunable inductor or tunable capacitor, but again the problem becomes at how you do the tuning of multiple section?

So, instead of using those tunable inductors or capacitors and many a times those inductors and capacitors are tuned manually. So, somebody has to change the value of inductors and capacitors manually. So, instead of using manual changing we can use varactor diode for changing the frequency.

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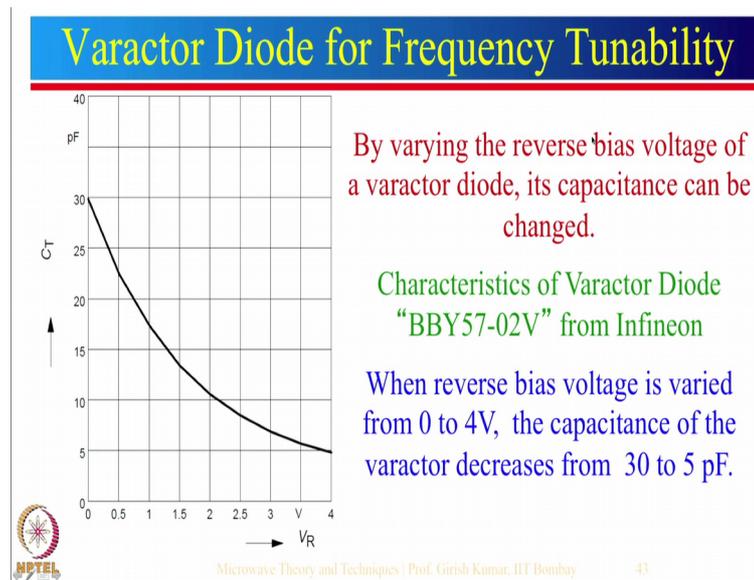
So, let us first look at what is really a varactor diode. Now, the details of varactor diode will be discussed in the next lecture, but today I will just tell you what are the specifications of a given varactor diode? Ok.

So, here is a varactor diode from infineon a number is given here. So, let us see what is the response of this particular varactor diode. What you see along X axis here that is a reverse bias voltage. And reverse bias voltage is change from 0 to 4 volt.

And, this is the corresponding capacitance. And, you can see that if the reverse bias voltage is 0 volt here. The capacitance value is 30 Picofarad and as the reverse bias voltage increases from 0 to 4 volt ah. The capacitance value decreases from 30 Picofarad to around 5 Picofarad.

So, the biasing circuit for the varactor diode is shown in the next slide.

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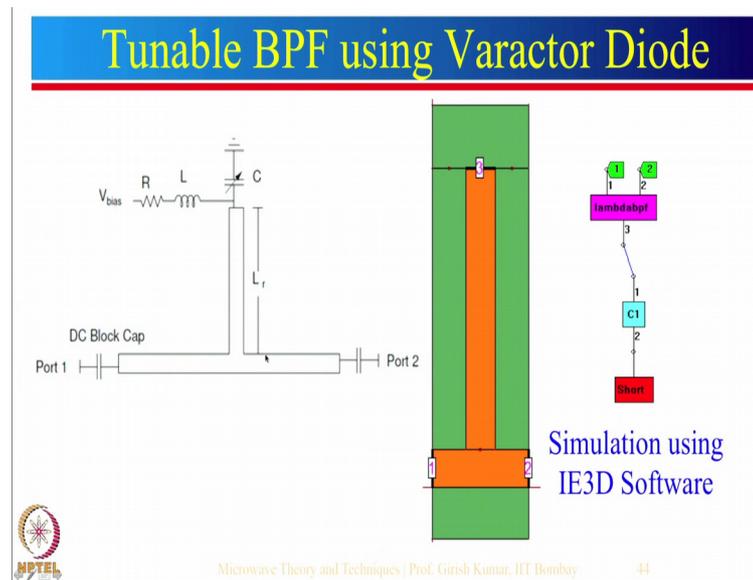
So, here we have taken an example of a simple filter. So, let us see here what we have done this is the port one, you might see that we have actually quoted DC block capacitance I will tell you that why we have quoted. So, this is that input going to the output. We have that length, which we are taken an example and at the end of the length we have put a Varactor Diode.

So, as I mention Varactor Diode is actually nothing, but a variable capacitor. So, this is the biasing circuit for that particular varactor diode. So, let us see what we have here this is the V bias, where is a series resistance inductor, which is connected to this particular varactor diode.

Now, let us see here what should be the value of R end inductors? See that depends upon now, what is the current required for this particular varactor diode? So, you have to study the specks of the varactor diode they will actually tell you that you need a biasing current of 1 miliampere or may be 0.1 miliampere or 10 miliampere depending upon diode to diode.

So, please check what is the biasing current N required for that? Accordingly chose the value of the R, this inductor here basically is acting more like a chock that means very high inductance. So, here we change the bias voltage, let say we had seen that if it is a 0 volt the capacitance for this particular thing will be 30 peak of error and if this V bias voltage is around 4 volt.

Then the capacitance offered by this particular varactor diode is 5 Paek of error. And, you can see here now we have put a resistor here, basically this is for limiting the current inductor here is nothing, but a RS chock or in general we take a large value of inductor.

So, that it acts as an open circuit corresponding to this AC signal. Otherwise, if you do not put this particular here this AC signal may get shorted through this DC bias.

Now, why do we capacitance over here? The reason we put these capacitor is. So, that this DC voltage should not go to the input side or should not go to the output side hence we put the DC block capacitance. Now, what should be the value of this block capacitance.

Now, just I will force of you questions for you to think about. So, this be a 1 microfarad. So, this be a 100 microfarad. So, this be a 1 Nanofarad. So, this be a 1 Picofarad. So, what is the right value for DC block capacitance? Now, just you tell you the purpose of this Dc block capacitances that this should at as a short circuit at the desired frequency.

So, then we know that z is equal to 1 by j omega z. So, larger the value of C smaller will be z. So, intuitively we may think, that let us go to this capacitor as 100 microfarad or 1 microfarad. I just want to tell you those are not right values of the capacitances, because these capacitances do not work at microwave frequency.

See at microwave frequency majority of these capacitance as may, even work like an inductor ok. See all these capacitors have parallel resonances and all these inductors are series resonances. So; that means, up to certain frequency it will work as inductor, beyond that frequency it will act as a capacitor.

So, the right value for these coupling capacitors would be that you calculate, what is the corresponding impedance at a given frequency. So, we know that the input ports are generally 50 ohm.

So, this impedance should be always less than 5 ohm, because this is 50. So, 5 ohm at least will be 1 tenth of that, but generally speaking if you chose this impedance to be around 0.5 ohm to 1 ohm it is more than sufficient. So that means, if you are operating at 1 gigahertz, you are not going to choose 1 microfarad or 100 microfarad, even 1

Nanfarad will be slightly on the higher side 100 to 500 Picofarad will be good choice to connect over here.

Similarly, for inductor here, inductor should act as an open circuit. Now, z is equal to j omega L. So, intuitively again we thing inductor should be as large as possible, gain I want to tell you if you take let us say 1 microhenry. A 1 microhenry inductor may not even work at 1 gigahertz it may behave like a capacitance. Why a inductor behaves as a capacitance you think about that there is a wire like this here.

So, we always think about that inductance. What about the capacitance between each turn. So, generally speaking that is negligible at lower frequency, but at higher frequency, that become comparable.

So, generally speaking most of these inductors have series resonances. So in fact, after a certain frequency, they may not work as an inductor. So, again choosing the right value of inductor is very very important. So, what is the criteria for choosing the inductor?

As, I mention z is equal to j omega L. So, for they given frequency we know what is omega, choose the value of z which is 10 times greater than the port impedance. So, we know that port impedance is 50 ohm. So, chose the value of this z greater than 500 ohm, but definitely not greater than 5 kilo ohm.

So, correspondingly chose these values. So, please understand this thing these are very very important thing at microwave frequencies, that how carefully you chose the values of inductors and capacitors.

So, now, so, what we have done here? So, this particular thing has been simulated using I 3 D software. Now, in the I 3 D software we have not simulated the DC biasing circuit all we have simulated here is this is the input port output port. So, we have assume that this particular thing will act as an open circuit. So, the only thing which we have taken here is that this is a variable capacitance. So, for the simulation what we do we take a input port output port.

Here we take a another port over here that is for simulation. Then in the software we do the change. So, this port 3 is deleted and there what we so, we connect a capacitor C 1, which corresponds to the varactor diode capacitance. And, then that is shorted to ground

as you can see here this is shorted to ground. So, now, let us see what is the result of this particular configuration.

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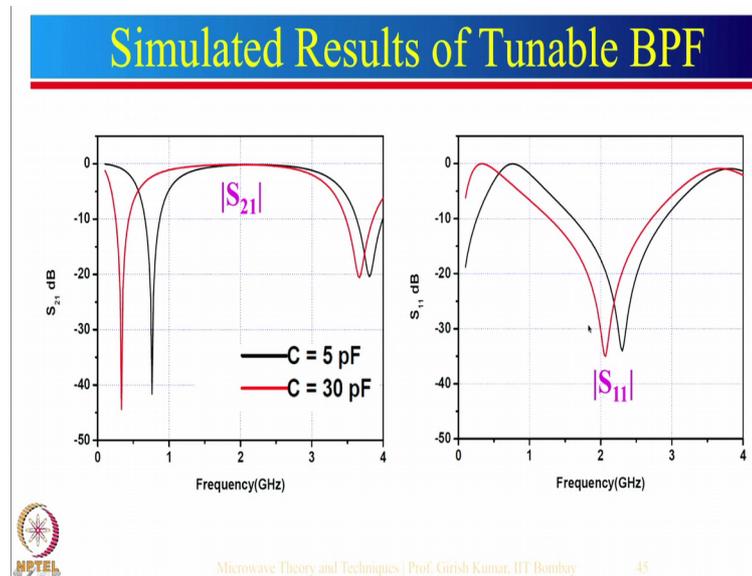
So, this is the S 2 1 response for 2 values of the capacitance, C equal to 5 picofarad C equal to 30 picofarad. And, you can imagine in between response for different biasing. C equal to 30 picofarad corresponds to reverse biasing voltage as 0 volt and C equal to 5 picofarad corresponds to reverse bias voltage of 4 volt.

So, you can see that this is the response of the S 2 1. So, black colour here is the response for C equal to 5 picofarad red colour responses for C equal to 30 picofarad.

So, you can see that the band is shifted may be more clear picture you can see from S 1 1 plot. So, corresponding to this if you look at the S 1 1 plot, we can see that as the capacitance decrease from 30 to 5 picofarad. So, this is 30 going to 5.

So, if the decreases what will happen to the resonance frequency just think about a general concept omega 0 is given by one by square root of L c. So, if C decreases frequency will increase. So, you can see that as C decreases from 30 to 5 frequency decreased. You can also see corresponding response of S 2 1 for band reject filter also.

So, as I had mention a length will act as a band pass filter or band reject filter, when the equivalent length becomes lambda by 4. Here, I want to mention that it is not precisely lambda by 4 length, length is loaded by the capacitance. So, the capacitance value is

fixed for a given biasing condition. So, please do not think that now it is not precisely half of this value.

The reason for that is the lengths are not lambda by 4 or lambda by 2 these are loaded line lengths. So, the ratio is not 1 is 2 2 or if you look at this one here is a band reject filter this is also band reject, but this value is not 3 times like this here. Because, the reason for that is this is not lambda by 4 length only, it is a loaded line. So, for the loaded line response will be different.

But, you can see that it is very clear cut over here that as the capacitance decreases from 30 to 5 resonance frequency increases from here to here. So, you can think about this particular portion as a band reject filter or this particular portion as a band pass filter, and again it acts as a band reject filter.

So, by using the concept of the varactor diode, you can do the tuning of the band pass filter or band reject filter. So, I just showed you one of the examples.

You can use multiple section and by using multiple sections and the multiple varactor diode, you can do the tuning over a larger bandwidth or over a larger range.

So, with that we conclude filters in the next lecture in fact, one of my t a will give a lecture on different types of diodes. After, that I will come back and talk about some of the applications of those diodes such as attenuators switches and phase shifters. So, till then work hard enjoy your life and we will see you next time. Bye.