Microwave Theory and Techniques
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Module – 05
Lecture – 23
Microwave Filters – III: Microstrip Realization, Transformation from LPF to other Filters

Hello, in the last two lectures we have been talking about mainly low pass filter realization using Butterworth and Chebyshev responses. So, we had seen that for Butterworth filter or also known as maximally flat filter the responses relatively plat in the pass band, but the transition from pass band to stop band is relatively slower than the Chebyshev filter which has equi-ripple in the pass band, but the transition from pass band to stop band is relatively faster.

And, then we had seen how to calculate the g parameters for Butterworth filter as well as for Chebyshev filter for Butterworth filter g parameters can be obtain in a very simple manner whereas for Chebyshev filter we have to do little bit more calculations. However, instead of doing the calculations you can use the tables given in the various books or in the literature and then we had looked at the comparison of the low pass filter realization using Butterworth and Chebyshev filter.

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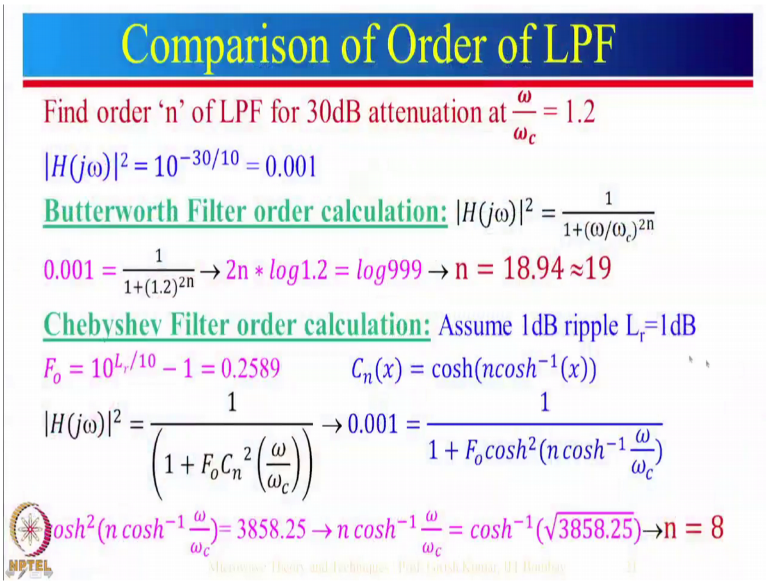

So, in the last lecture we had discussed this particular example here, where we had taken an example of 30 dB attenuation at omega by omega c equal to 1.2, and we had seen that if we use Butterworth filter we need a filter order equal to 19, whereas if we use 1 dB ripple in the passband for Chebyshev then we need a filter order equal to 8. As I mentioned that if you take this as 0.5 dB ripple in that case number of order will be more than 8, but definitely much lesser than 19 and also now show you the responses for these two particular cases and I am will also tell you what is the disadvantage of using 1 dB ripple.

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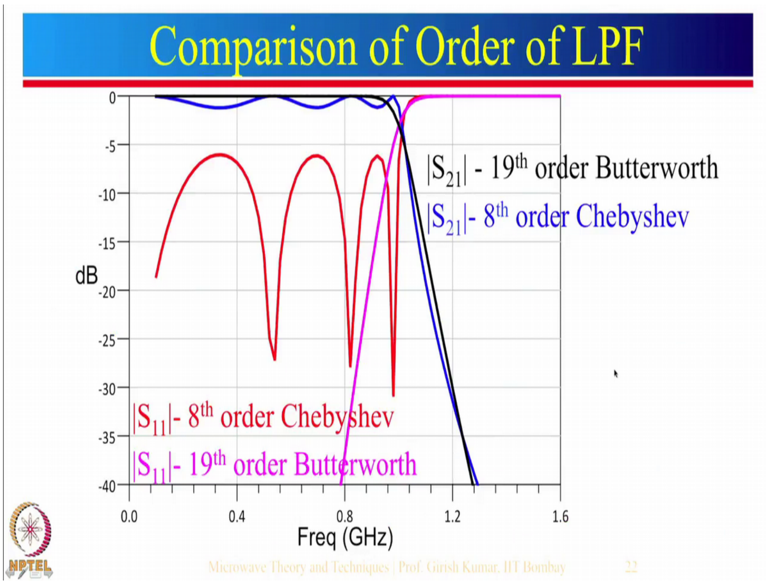

So, here is the response of the two types of filter realization one using Butterworth another one using Chebyshev and for Butterworth we have use a 19th order filter, for Chebyshev we have use 8th order of filter over here and you can actually see that the response for these two cases let us look at the response of the two filters for S 21 first, ok. So, you can see this black color you can see it is maximally flat in the passband and this is the response in the stop band if you look at the response of 8th order Chebyshev filter whether ripple equal to 1 dB in the passband. So, you can see that this is 0 this is minus 5 so, this is corresponding to 1 dB, ok.

So, you can see that there are ripples and this is the transition. You can see that in the transition region and specially if you recall what we had taken the frequency ratio as omega by omega c equal to 1.2 you can see this is 1.2 we designed it for omega c equal to one and corresponding to this point you can see that the attenuation is of the order of minus 30 dB. So, you can see that these two filters will give you somewhat similar response specially at the attenuation level, but let us see what is the response in the passband as for as the S 11 are concerned,.

So, this is the S 11 for 8th order Chebyshev, you can see this is the response over here. You can see that S 11 is very poor this is of the order of approximately minus 6 dB. The reason for that is this design was done for 1 dB rippled. So, corresponding to 1 dB ripple this is what it would be. That is why I had told you if you take 0.5 dB ripples so, this will be 0.5 dB then S 1 will comes somewhere around minus 10 dB. So, that is the disadvantage of a Chebyshev filter if you design for a ripple of 1 dB in the passband, whereas you see the response of S 11 for Butterworth filter you can see that it is keeps going down down down only, right.

So, this is the main problem with the Chebyshev filters that is why we do not recommend that you design a Chebyshev filter for more than 0.5 dB ripple in the pass band.

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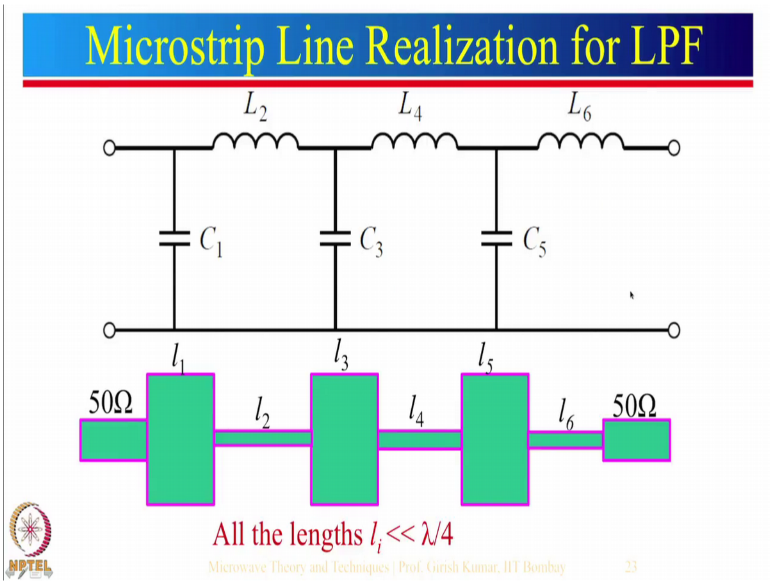

So, now let us see something different. So far what we had done, we had actually found out the values of C 1, L 2, C 3, L 4 and so on and these values were obtain first what we did we found out the g parameters, and it does not matter whether you have use Butterworth filter or whether you have Chebyshev filter all you need to do what is you need to find out the g parameter. So, in this case the first parameters since we have taken as c 1 so, this would have been g 1, g 2, g 3, g 4 and so on.

Now, when you look at these capacitance values or inductor values, you might have notice as we did it in the previous example these are very different values and they are not readily available and as you go to the higher frequencies specially these components values will become very small and they may not be readily available in the market also. So, specially at microwave frequencies instead of using these lumped L, C elements you can realize all of these things using microstrip line.

So, let us see how we can do this particular thing. You have to recall simply the concept which we discuss that is small transmission line, if it is terminated in a short circuit it realizes inductor and a small transmission line if it is open circuit at actually realizes a capacitance. So, let us see how we can use that concept over here. So, first let us see C 1; C 1 is between this line and the ground. So, this C 1 can be replace by this simple patch over here. So, this patch will have a capacitance with the respect to the ground plane. I just to tell you, so, this is the top view of this low pass filter, underneath of this low pass filter we will have a ground plane.

So, think about a printed circuit both. So, that will be a bottom will be a ground plane and on the top or you have to do it is etch out this particular pattern of course, in this particular pattern it is very important to determine all these lengths l 1, l 2, l 3, l 4 and all these widths over here for l 1, l 2, l 3 and so on. So, I am going to tell you now step by step process.

So, now let us see we need to realize C 1, ok. You can think realization of C 1 in two different ways. So, first thing we will look at is the parallel plate capacitance. So, parallel plate capacitance will be from the top to the bottom, ok. So, the parallel plate capacitance for this particular thing will be given by length l 1 and if you said w 1. So, the parallel plate capacitance for a rectangular shape is given by epsilon 0, epsilon r area divided by h. So, here for a given substrate we know what is epsilon r and we know what is the thickness which is h. So, the area of that particular patch will be nothing, but equal to l 1 multiplied by w 1.

Now, here the problem is not over yet the reason for that is that there will be some fringing fields for this particular patch over here. So, you do not take the physical dimension to realize the value of C 1, what you have to do it is you have to take the practical values corresponding to the fringing field. So, what will be the effective dimension? So, you have to think about the affective dimension will be nothing, but fringing field will be there. So, we can say that instead of l 1, we take l 1 affective instead of taking w 1, we take w 1 affective and that should be equivalent to the capacitance C 1 now, this is the one way to look at it.

Now, let us just look at the other part which I said think about a transmission line concept. So, now, this particular line is actually terminated in a very thin line a very thin line will have a very high impedance. So, you can approximately think about that this particular line is terminated into when open circuit situation, you can think about that this transmission line of length l 1 is terminated into a very high impedance line which can be thought of as an open circuit.

So, here just to tell you few design steps here in general we take the width of this particular patch here which corresponds to the capacitances to be much lesser than the impedances of these inductors. So, just you tell you since this is of the order of 50 ohm input and output line typically we take the impedance of these lines; that means, the width is calculated for corresponding characteristic impedance of may be 10 to 20 ohm. So, that is a general design concept, you do not take less than 10 because then the width will become very very large.

So, now comes the part of the inductor we know that a very thin line represents an inductor, but you can now again apply the concept of the transmission line. So, let us say this inductor is terminated in a relatively low impedance. You can see that this particular transmission line is terminated into a low impedance value. A low impedance value can be approximated as a short circuit of course, approximations are required, but these things can be optimize later on when you do the simulation.

So, a capacitor is between this one and the ground plane then we have a series inductor. So, this length here and the width so, generally speaking we take a very high impedance corresponding to this line length l 2 and why we take very high impedance? The reason as I mentioned that this high impedance will appear as open circuit for this particular transmission line and these we take low impedance of the order of 10 to 20 ohm, they will appear as a short circuit for this particular transmission line.

So, generally again to repeat you take the impedances of this 10 to 20 ohm and generally impedances of the line lengths l 2, l 4, l 6 you take anything greater than 100 may be 100 to 150 ohm. Of course, you can take 200 ohm also, but that is not very practical because corresponding to 200 ohm impedance the line width may be of the order of 0.1 to 0.2 millimeter depending upon the subsets specifications. So, generally we try to limit these impedances to about 100 to 150 ohm and these impedances to 10 to 20 ohm.

So, you can see that first step would be is that you find the g parameters for a given Butterworth or Chebyshev filter then you use the frequency and impedance transformation to get these values and then corresponding to these values you can find out the dimensions of these patches. So, just you tell you one way to do this particular thing is C 1 is equal to epsilon 0 epsilon r multiplied by l 1 effective into w 1 effective divided by h. Alternatively, you can apply the transmission line concept also since we are making an approximation this is terminated in open impedance. So, for this particular thing you can think about input impedance at this particular point z n is equal to nothing, but z 0 divided by j tan beta l 1, which is equal to 1 by j omega C 1.

So, z 1 corresponding to this impedance your assuming may be 10 ohm or 20 ohm, then correspondingly you can find the length l 1. For this particular case over here for finding length l 2 or l 4, l 6 what you really do? Since this particular line is terminated in a relatively low impedance you can think about that as a short circuits. So, for a short circuit here input impedance is given by z input equal to j z 0 tan beta l 2, which is equal to j omega l 2, ok. So, we know already l 2 we can find out the value of small l 2 over here because you are choosing the value of z 0 between 100 to 150 ohm.

Now, do not get confused with the z 0 because I am using z 0 for different things here, but just to tell you this is the input and output here. So, z 0 for this two is 50 ohm z 0, for this is 10 to 20 ohm, z 0 for this is between 100 to 150 ohm, ok.

Let us see now microstrip realization for elliptic filter.

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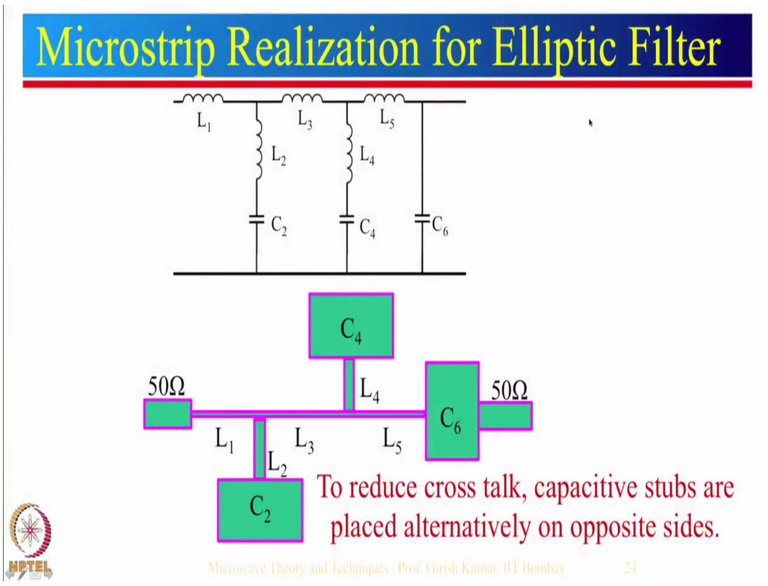

So, far I have not discussed much about elliptic filter in fact, most of the time people do not use elliptic filter at lower frequencies. The reason for that is as follows what you can see that the series inductors are very similar to maximally flat or equi-ripple case you can see here L 1, L 3, L 5. However, the shunt capacitance is now replaced by a combination of inductor and capacitance. So, why we do this thing here the reason for that is that if you look at the impedance of this. So, impedance of this will be equal to what z equal to j omega L 2 minus 1 by j omega C 2.

So, at a frequency omega 2 equal to 1 by square root of L 2 C 2 this particular impedance will be equal to 0. So, now think about when the input is coming from here inductor, through the inductor it will go through, but then this is preciously shorted. So, this particular thing is generally done not in the passband at all so, the value of omega 2 to be chosen which is greater than omega C where we want largest attenuation in the stop band.

Let us see f c is equal to 1 gigahertz then you can take corresponding to this f 2 may be 1.1 or 1.2. So, correspondingly choose the value of L 2, C 2 then you put another null at frequency corresponding to this here. So, that frequency if we term as say omega 4 which is 1 by square root of L 4 and C 4. So, this will provide another null in the stop band just imagine here. So, if this is the response for a filter so, we will have a elliptic filter response ripples in this one then it will come down to close to 0 value corresponding to this frequency omega 2, then it will go up, it will go to 0 corresponding to the frequency. So, it will again go to 0 corresponding to the frequency given by 1 by square root of L 4 C 4, ok. So, that is how you can provide sharp attenuation in the stop band.

Now, as I mentioned generally we do not do this kind of a realization at lower frequencies because component cost increases, but in microstrip these inductors and capacitors can be realized in a very simple manner let just see step by step here is a series inductor L 1 which is realized by this transmission line then we have a inductor in series with capacitance and that is going to the ground. So, this inductor is realized by this thin line of length L 2 terminated with the patch which corresponds to the capacitance C 2 and this patch will have a parallel plate capacitance between the top layer and the ground layer. So, that will provide the shunting or you can say the grounding part. Then we have a L 3 which is realized by this series transmission line and then L 4 C 4 you can see that L 4 is this inductor representation and C 4 is represented by this particular patch.

Now, you can take these two things on the same side also, but I have shown it on the opposite side mainly to reduce the cross talk between this because what happens if this particular thing is taken on this side. So, you can see that try to imagine then this will be very very close to this particular patch here. So, there may be a coupling between the two capacitance C 2 and C 4 because of the fringing field and that may change the values.

So, just to avoid the coupling between this and this one here it has been put on the other side. However, if there are space restriction you can always try to put on the other side, but ensure that the gap between the two is greater than 2 times the substrate thickness, if you do that coupling will be relatively small.

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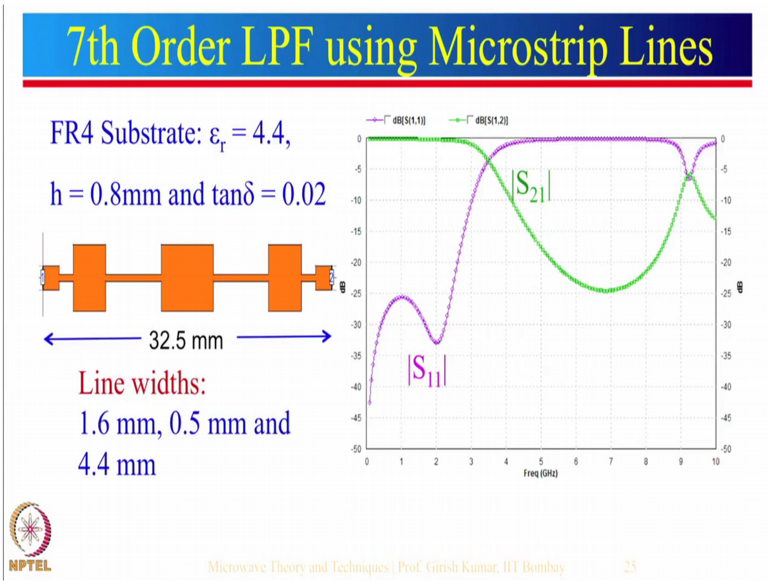

Now, let us see the practical example of the filter. So, here we have a 7th order low pass filter using microstrip line and here we have use the relatively low cost substrate which is FR 4 substrate epsilon r 4.4, h 0.8 mm and tan delta is 0.02. You can actually see that this particular thing has been designed at a frequency around 3.5 gigahertz or so you can see that is the transition thing here. So, at this particular point S 2 1 is minus 3 dB S 11 is also minus 3 dB over here.

So, this design was done for approximately Butterworth response, but you can see that a Butterworth response would have S 11 continuously going over here. There is a small ripple over here there is a very very small ripple over here also, but that is more because of not a complete optimization of this particular configuration, but you can see that this S 11 is less than minus 25 dB so, which is acceptable for almost all practical application.

Now we can see that this entire 7th order filter is fitted within 32.5 mm dimension. So, you can see here that this one here realizes the series inductor. This one here shunt capacitor, series inductor, shunt capacitance, series inductor, shunt capacitor then series inductor over here and one thing I have also want to mention that the first component will be identical to the 7th component, second is identical to 6th, third is identical to 5th and this is the central component over here.

Now, just to tell you what we have chosen over here the line widths are 1.6 mm this 1.6 mm corresponds to 50 ohm impedance over here, then we have chosen 0.5 mm to realize the inductor and 4.4 mm is use to realize the capacitor. Now, let us see the response. Now, we see little interesting thing over here and that is it behaves as a nice low pass filter you can see that it is passing the lower frequency and then the response is going over here, we can see that it is providing the attenuation here let us say about 20 dB or so, at this particular frequency.

But, after that you can see that the response is going up, and then coming down. So, it almost looks like that in this particular area it is behaving more like a band pass filter or if you just look at this particular response then it looks like this is something similar to a high pass filter. So, why all these things coming into picture the reason for that is since we are realizing inductors and capacitors using transmission line and I had mentioned that all these lengths must be less than lambda by 4 to realize inductor or capacitor.

Now, what happens at higher frequencies as frequency increases then lambda will start decreasing. Now, these lengths are actually fixed. So, if the lengths are fixed what will happen? Corresponding to the smaller value of lambda these lengths will not become greater than lambda by 4 and the moment these lengths become greater than lambda by 4, you can say that this particular length here if this is greater than lambda by 4 which is terminated in let us say a short circuit this length will start behaving like a capacitance. So, a capacitance in the series path will actually behave more like a high pass filter. So, that is what is happening this particular things starts behaving like a high pass filter.

Then why a band pass filter in this particular region? The reason why it is behaving more like a band pass filter where these lengths become equal to lambda by 2. So, when the length becomes equal to lambda by 2, they start acting like a resonator. So, resonator is nothing, but more like a band pass filter. So, when I talk about band pass filter, then you will understand these things in more clear terms.

So, then the next question comes well we wanted to design a low pass filter, but here we have kind of a high pass filter or band pass filter and so on. So, that means, at this particular frequency it is behavior is very bad or you can say it is a pathetic low pass filter at that particular frequency region. So, I just want to tell there is a solution to every problem. So, what one can actually do that you design a low pass filter something like this over here there is a no inductor, there is a no capacitor.

Now, what we can do actually here that at this particular frequency where you can see that it has gone up to as high as minus 5 dB which may not be desirable. So, sometimes what we do we actually put a band reject filter at this particular frequency. Suppose, if you put a band reject filter at this particular frequency which is you can say that greater than 9 gigahertz band reject filter size will be very very small. So, this entire response instead of going like this will actually go like this over here. So, many a times combination of these concepts can be used.

So, now I am going to show you a another example how this low pass filter has been integrated with a high pass filter to realize one of the practical problem given to us.

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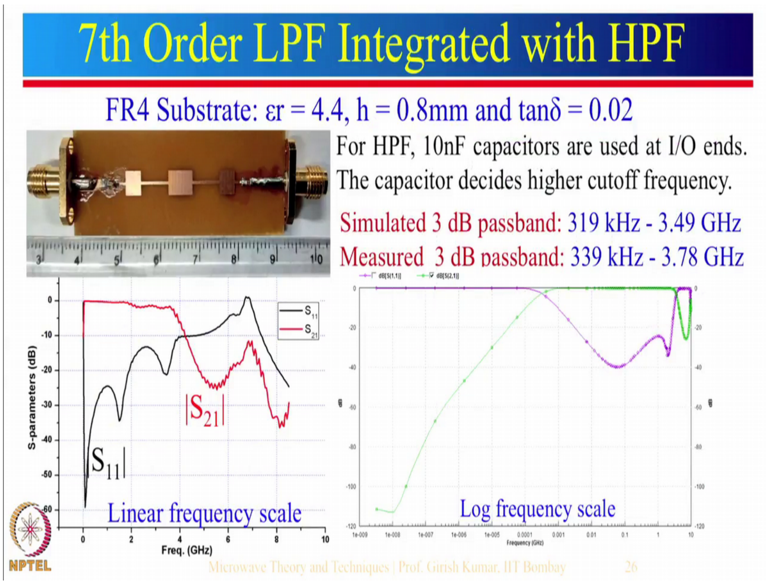

So, here is a one example which is a 7th order low pass filter integrated with high pass filter. In fact, before I talk about all these things let me tell you in fact, we had actually got one of the problem and the problem which was given to us by one of the labs was that they wanted a very broad band filter, ok. Filter which works from roughly around 300 kilohertz up to about close to 3.5 gigahertz now that is a very very broad band band pass filter, and when we talk about band pass filter you will realize at this particular filter is extremely broad band.

So, well we did look into the project will did look into the problem and then we found a very very simple and unique solution. So, what we did actually? We designed a low pass filter with a cutoff frequency of around 3.5 gigahertz you can see that this is the response for that. So, what we did? We designed a low pass filter with the cutoff frequency of approximately 3.5 gigahertz, then along with that low pass filter we actually added a capacitor at the input and the output stages over here and to realize that high pass filter we had actually put a 10 nanofarad capacitor, ok. The value of this capacitance was calculated for the given value of around 319 kilohertz.

So, just you tell you how we did that. So, we know that the cutoff frequency is given by omega is equal to 1 by RC. So, here the source impedance and load impedance has both are 50 ohm each. So, what we did we put the capacitance of 10 nanofarad, 10 nanofarad and you can calculate for this particular combination you will see that the cutoff frequency comes out to be this particular number over here. So, let us see the first simulated response then we will see the practical response.

Now, just want to tell you here this is a log frequency scale over here. So, first of all let us see the transmission coefficient which is given by this green color over here. So, you can see that this has a behavior of high pass filter. So, it is blocking all the lower frequencies. So, from here to here you can see that it is behaving more like a band pass filter and then this is over here there is a dip and it goes up little bit above here. So, this response is exactly same as what I had shown you in the previous slide for the low pass filter realization.

So, now this one here is given in log frequency scale. Here is the fabricated thing you can see what is the size of this particular filter and these are the measured results and just I want to mention here this is the linear frequency scale and this is a log. So, n log each one of these divisions are increasing by 10 times ok, but here it is a 0, 2, 4, 6, 8, 10 gigahertz.

So, try to imagine that in your mind. So, you can see here that close to 0 frequency there is a sharp transition which is actually corresponding to this one over here. This is somewhat similar to a low pass filter response and this thing peak which we had seen earlier over here is what is coming had this particular point here and this is the response for the S 11. So, you can see that corresponding to this S 11 short up, but in this entire particular region over here where most of the power is going from here to here reflected power is very very small.

So, that is how we actually realize the practical problem of a band pass filter by combining a low pass filter response with the high pass filter response. So, now let us just see how we can find out and design other type of filters.

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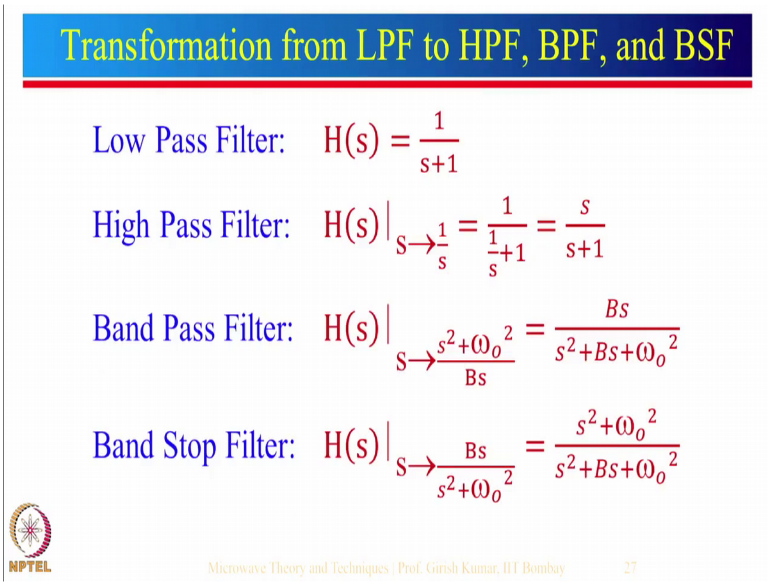

So, we can actually used the g parameters of low pass filter and by using those g parameters of low pass filter we can actually design a high pass filter, band pass filter and band stop filter. Let us first look at the concept part ok. So, we had seen that for a low pass filter H s is given by 1 divided by s plus 1. Again, you can do some quick checking over here put s equal to 0, so, that will be 1 by 1 ok. So, H s is 1 at low frequency put s equal to infinity 1 by infinity is 0. So, the response is 0 at very high frequency.

Now, how to get high pass filter? So, high pass filter if we just use a very simple transformation instead of putting s here if you put s as 1 by s then what will happen. So, let us substitutes s as 1 by s. So, 1 divided by 1 by s plus 1 this becomes the transfer function of high pass filter. Again, quickly check put s equal to 0. So, at s is equal to 0 this will be 0; that means, at lower frequency output will be 0. When s is infinity this term will become 1; that means, at very high frequency response is equal to 1.

Now, for band pass filter what we do, we use the transformation something like s 2, s square plus omega 0 square divided by B s. Omega 0 is the center frequency of the band pass filter B is the bandwidth of the bandpass filter. So, if we substitute s equal to this here in this particular expression so, s put over here simplify this is what is the transfer function of band pass filter. Again, you can make some quick check put s equal to 0, if s is equal to 0 this whole term will become equal to 0. If we put s equal to infinity what will happen this goes to infinity, this will be infinity square. So, you can say it will become 1 by infinity it will become 0. So, that means, the output is 0 at lower frequency, output is 0 at very high frequency. So, in between it will go up and come down. For band stop filter you actually use reverse of that so, instead of s transformation like this you use reverse of that so, this is B s divided by this here.

And, if you substitute this value of s in this expression it becomes like this here. Again you can use the concept of put s equal to 0 and then you put s equal to infinity and you will see that in fact, for both s equal to 0 as well as for s equal to infinity it is equivalent to approximately 1 and at the center frequency omega 0 output will be very small.

So, in the next lecture we are going to see how to realize from a low pass filter a high pass filter or band pass filter or band stop filter. So, just you summarize so, today we discuss about the practical applications of the filters we actually saw that the response of the Chebyshev filter and Butterworth filter and 19th order Butterworth filter is almost equivalent to 8th order Chebyshev filter, but the Chebyshev filter had a problem that it had a 1 dB ripple in the passband.

And, then we also looked at how to practically realize a very broad band band pass filter by integrating a low pass filter with the high pass filter and in between we also saw how these lumped elements can be realized using a microstrip configuration so, then you do not need a inductor or capacitor simply by using microstrip line you can actually design of filter. In fact, we will use the same concept of microstrip line to realize high pass filter or band pass filter or band stop filter also. So, thank you very much. We will see you next time, bye.