Millimeter Wave Technology
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Module 6
Lecture No 23
Passive Components (Contd)

So, next we are going to discuss how to determine the external quality factor and the coupling coefficient by using full wave simulator. So what is the importance of this work that let us say you have calculated some external quality factor, now you need to implement the filter. But then what should be the physical dimensions of the filter? So what we do, we 1st do a parametric study for a given resonator and then plot the variation of Q external versus some parameter, then once we have that requirement so we need this particular Q external then from that previous abbreviation what already we plotted, from that we find out the values, similarly for the coupling coefficient. The 1st do a parametric study by using full wave simulator and plot the coupling coefficient versus let us say gap between regulators.

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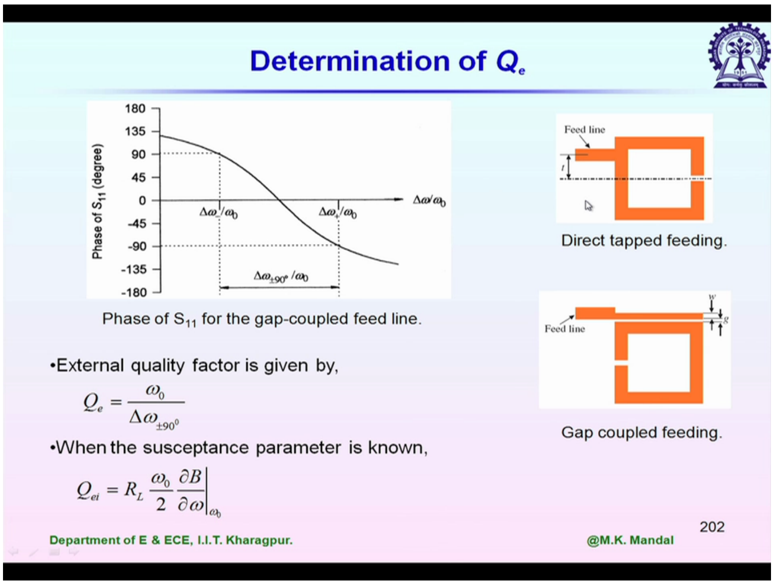

Once you have that lot, then you calculate your matrix and then matrix from the matrix element now the required ones, from the required once you choose the gap which you already have from the plot. So we will start with the determination of Q e, you see we are showing is an example 2 microstrip resonators, it is called open strip resonator, it can be even one straight lambda G by 2 resonator also. Now, we can directly connect feed line to this resonator as shown in this 1st figure and in the 2nd figure it is coupled by a gap, so electromagnetic power it is coupled to the resonator through this gap, it can be coupled via electric field or magnetic field. Now, now if we change the thick point in the 1st design then accordingly the external quality factor will change or you can say in other words, power loss from the resonator into feed network it will change, so it is a function of this separation T.

Similarly, in the 2nd case, Q external it is a function of this gap G between the thick line and the resonator. Now, if I increase the gap in that case what I expect that power coupled from resonator to feed line or better to say power loss into feed line, it will decrease with increasing gap or in other words, Q external will increase, so Q external, it decreases with smaller gap value, now how to calculate it? Simply we draw this structure in any full wave simulator and then plot the S 11 mainly its phase (())(3:25) So here one example is shown here, the phase of S 11, it is a function of frequency, so if I place my input port exactly at this point where this coupling start, then it crosses 0 at the resonant frequency, but practically it is not, so there are always will be shift, so what you have to do?

You have to 1st find out the resonant frequency of this resonator and note down what is the phase of s 11 at that particular frequency, then go left-hand side + 90 and right-hand side - 90 and note down these 2 frequencies represented by Delta omega - and Delta omega +. From that we have the Delta omega + - 90 bandwidth and Q external, it is simply then omega 0 divided by Delta omega + - 90. Now, if you can calculate input impedance as seen by your feed line, then we can also calculate Q external mathematically. It is equal to R L into omega 0 by 2 into Del Del Omega of B at Omega 0, but for the 1st structure you can directly calculate the input impedance because from this input point you can see it looks like 2 open stub, one open stub on top, one open stub bottom and they are in parallel at this peak point.

So we can easily calculate then what is the input impedance sent by the feed line and we can calculate the external quality factor for the 1st example. But for the 2nd example it involves a gap and it is really difficult to represent the gap mathematically, it can be done but the procedure is complicated so it is better to calculate the Q external by using the full wave simulator. Now what we do, we calculate Q external for different cap, let us say you start from G = 0.05 millimetres then, at a step you change it to G = 5 millimetre, for each and every step what is the Q external value and plot it with G. Now once you have the requirements, Q e1 and Q en, now already you have the plot then from the plot you choose the gap value.

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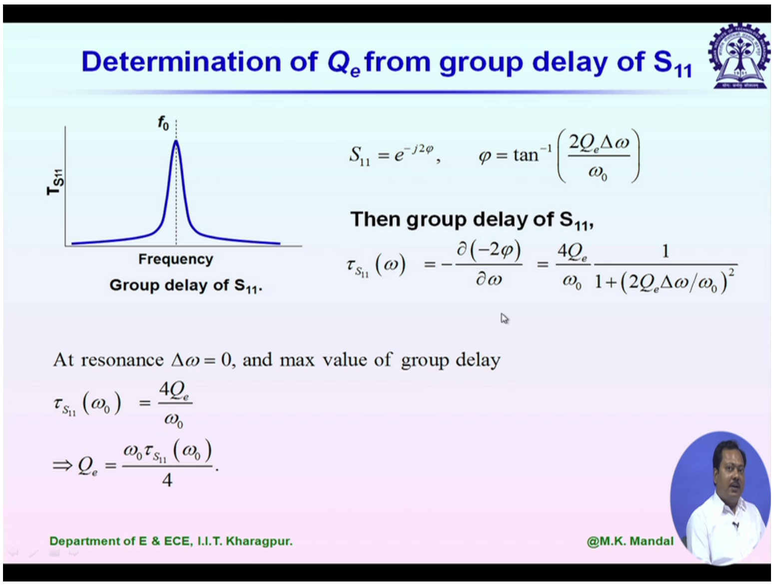

So, how to determine the resonant frequency? So, at resonant frequency power is coupled feed line to resonator. If I plot magnitude of S 11, will be expecting one dip in S 11, but sometimes that dip of S 11, it is influenced by other parameters, the feed length and other things, so it is suggested to observe the group delay plot and find out where delay is maximum that will give you the resonant frequency. So what we are doing here, we are simply calculating the group delay of S 11 Del Del omega of and plot it versus frequency and it is maximum at the resonant frequency. So from the maximum point you note down what the resonant frequency is, then once you have the resonant frequency, you note down what is the phase value at resonant frequency.

Let us say it is + 10 degree, then you go left-hand side + 90 so +100. Right-hand side, - 90, so where - 80 degree, note down these 2 frequencies and then you have Delta omega + - 90, calculate Q external.

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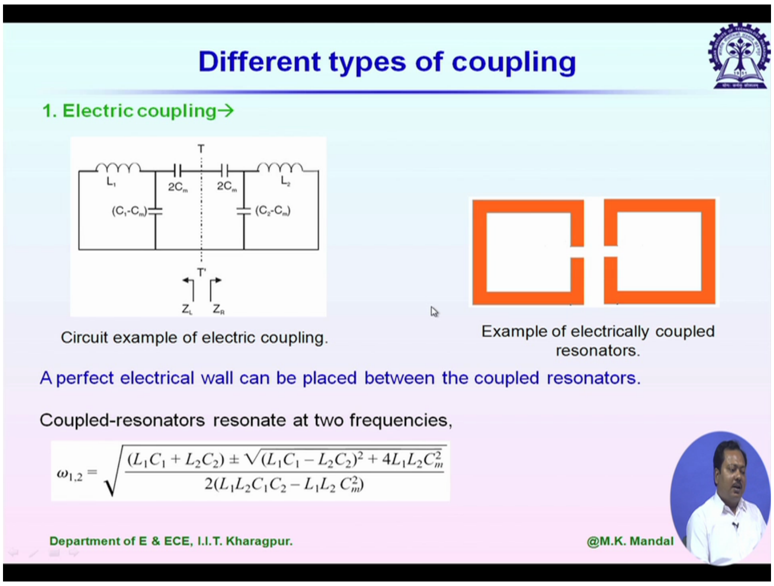

Now coupling, how to determine the coupling coefficient, before that let me discuss about different types of coupling. Again, I am giving you microstrip line example, even at millimetres wave frequency we can use microstrip line to some extent, so this one again we are showing open loop resonator and these gaps, they are facing each other. In this case the energy is transferred from one resonator to another resonator by changing electric field and we call it electrically coupled resonator systems in equivalent circuits, then this coupling it is since it is through electric field we can represent it by capacitor. So in this figure you can see, one isolated resonator it is represented by L 1 C 1, but for this coupled system let us say we have this capacitor connected between 2 resonators, which represent the coupling it is given by C m.

And since we are representing it into two symmetrical parts we are representing it by twice C m and C 1 it becomes C 1 - C m. And in this case this coupled system, it will have 2 frequencies, so one single resonant frequency, it will split into 2 components omega 1 and omega 2, it can be given by this expression one is due to + C m, another is due to - C m. Now, how to determine this coupling coefficient by using any full wave stimulator?

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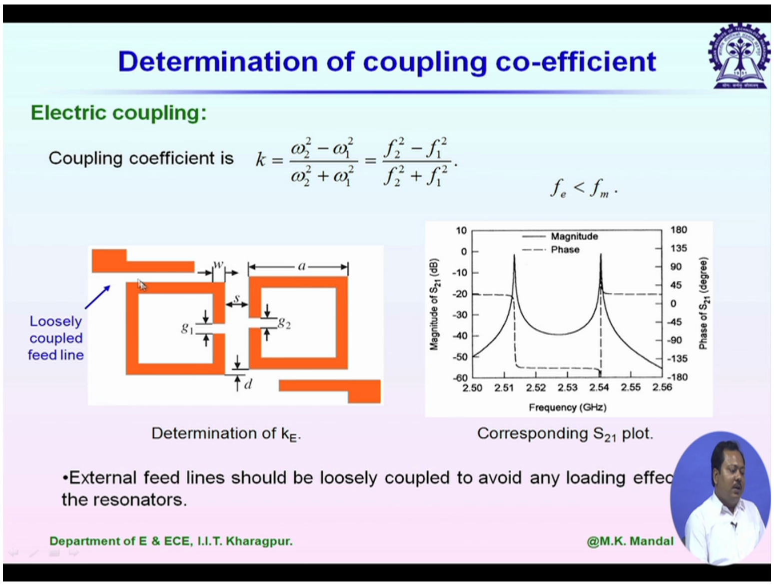

So you see, we are using the same coupled open loop resonator, but we have to excite the resonator to obtain the S 21, we can determine the coupling coefficient from S 21 plot. We are using port 1 with a feed line, port 2 with another feed line and we are using gap coupling. Now these resonators, it should be isolated from rest of the world for this coupling coefficient calculation, but without these feed lines you cannot make excite the resonator. So practically what we do, we use a large gap here and we assume that they are loosely coupled or we use loosely coupled feed lines and these feed lines do not affect the resonant condition of this couple system. So in that case if I plot S 21, whatever we obtain from any full wave simulator, you can see the plot here magnitude of S 21 in dB versus frequency.

We have 2 peaks, these 2 peaks represent now that 2 resonant frequencies of this coupled systems. Let us say, the 2nd one is F 2, the 1st one is F 1, then coupling coefficient k this is equal to F 2 square - F 1 square divided by F 2 square + F 1 square. Now between these 2 peaks at 1 resonant frequency this coupling, it will be electric coupling and at another resonant frequency the coupling, it will be magnetic coupling. For electric coupling case, this lower resonant frequency here actually we have electric coupling and at higher resonant frequency we have magnetic coupling. Okay, so what is electric coupling, what is magnetic coupling, let me discuss a little more before.

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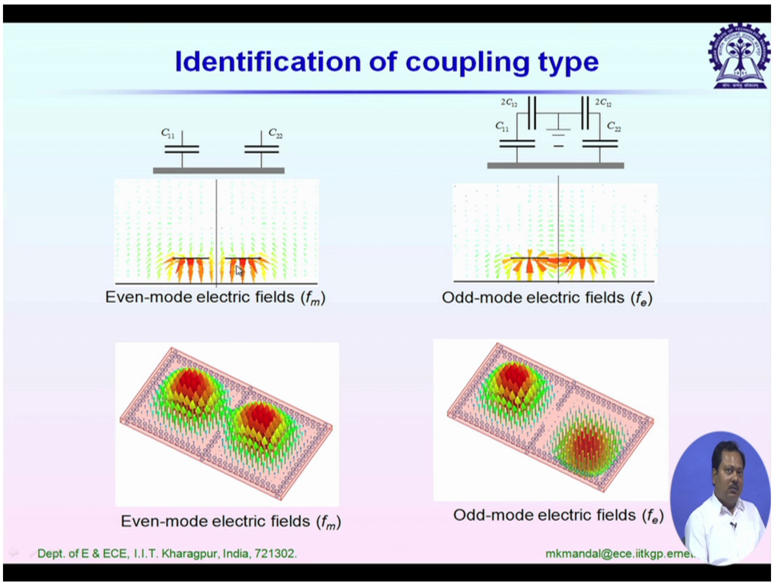

We know the couple microstrip line, already we discussed in even-odd mode theory analysis. When they are excited in same field with 0 phase difference, so this is the electric field plot just below this strip, you can see the vector electric field; they are in same direction, so there is no phase difference between 2 EM signals. And now, if I consider one plane in between these 2 strips, what is the orientation of electric field on this midplane? This is parallel, that means we can place one open circuit plane or 1 PMC here and we call it F m or magnetic coupling because we know there is no electric field penetration from left hand to right-hand side, we call it even mode excitation or magnetic coupling.

And right-hand side now, the same couple microstrip line but now we are exciting it in odd mode condition, so left-hand side you see electric field it is from bottom to top and right hand side, it is top to bottom and because of that we have some winching electric fields in between coming from right to left and now on the midplane, which is symmetrically placed between these 2 strips, electric field it is exactly perpendicular or this plane you can call it a shorten plane or PEC perfectly electrical conductor. And now it is clear that this coupling is due to electric field, we call it electric coupling similar situation also exists in web guide technology.

For this particular example, I am showing actually SIW, we have 2 cavities they are coupled to each other through one window Iris, so this chain obvious they represent short wave and inside we have die electric, so it is a dielectric cavity bounded by PEC all-around and between 2 cavities we have a small opening, so power is coupled from cavity 1 to cavity 2 through this opening. And now you see in this left figure, look at the orientation of electric field, they are in same direction, so on this midplane again we have even mode like situation, right. So we can place one PMC and we call it magnetic coupling and in right hand side figure, look at the electric field orientation, in cavity 1 it is bottom to top and in cavity 2 it is top to bottom.

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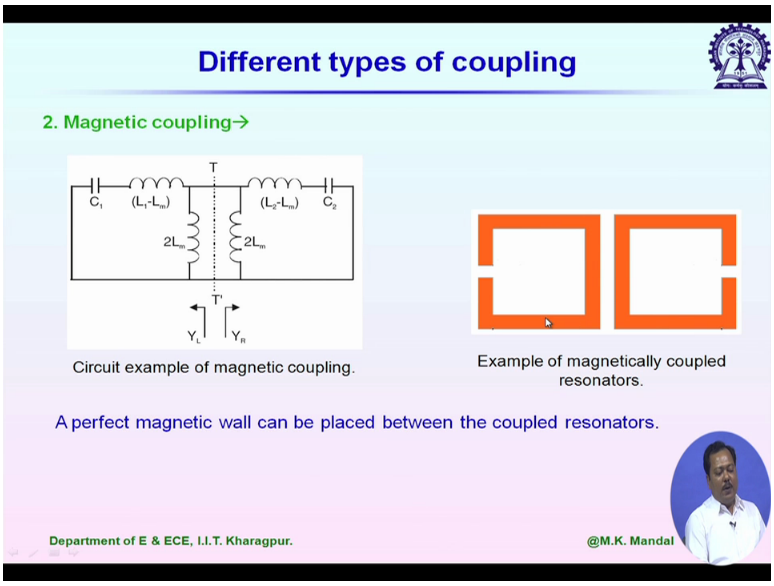

So the orientation of electric field is different and if I consider a symmetrical plane in between, it can be shown that electric field direction is perpendicular on that and it behaves like PEC and it is electric coupling. So, for a coupled resonators system so we have 2 frequencies, if at lower frequency it is electric coupling this coupling is due to electric field, we call it electric coupling and the lower frequency, it is due to magnetic field then we call it simply magnetic coupling.

So for open loop resonator, you see if we just change the orientation of open loop resonator, then it becomes magnetic coupling, we can also analyse the structure, you can see at open end, so at resonant frequency, length of this open loop it is Lambda G by 2, at these open ends we have electric field maxima current minima and at the mid length, current maximum electric field minima. So obviously the coupling where the current maxima electric field minima, we do not expect any electric field coupling and it should be due to magnetic field. And for this magnetic coupling what we do, we represent in equivalent circuit this coupling by ah mutual inductance L m and this is the equivalent circuit.

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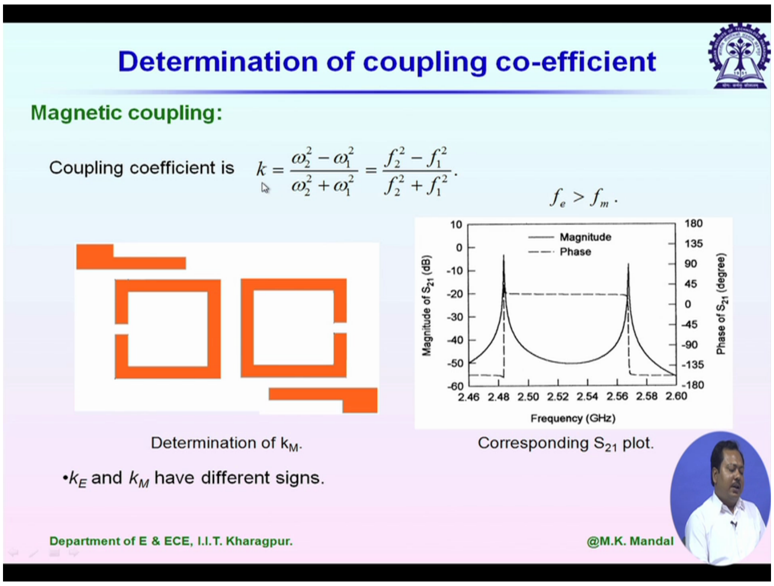

So exactly same procedure to calculate K simulate the structure, remember to take loose coupling for this feed line to resonator coupling and then you simply plot S 21. Once you have F 21, F 1, calculate the coupling coefficient from this formula. In coupling matrix, we represent K e and K e with different signs, so if K e is positive for example, K e is usually represented by negative number.

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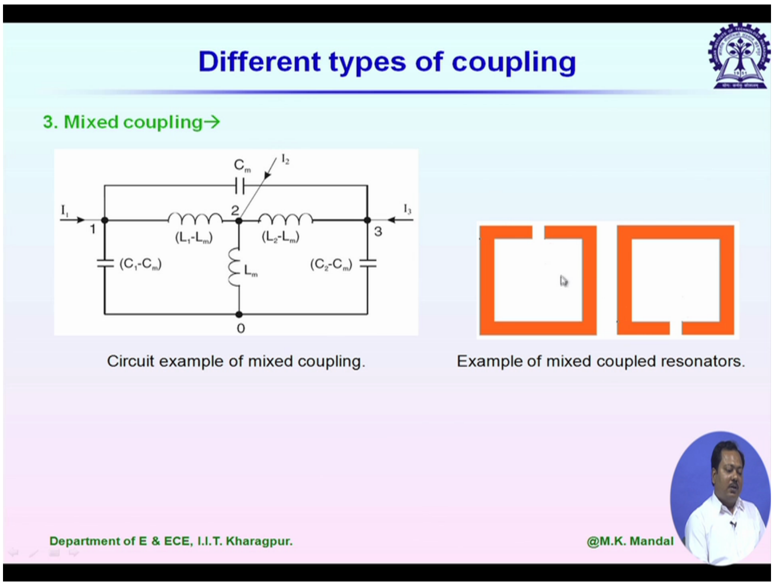

Sometimes we may face mixed coupling, so coupling is let us say for this example, it is due to both electric field and magnetic field and sometimes what happens for some given gap let us say not for this example, I have some other example, yes this one.

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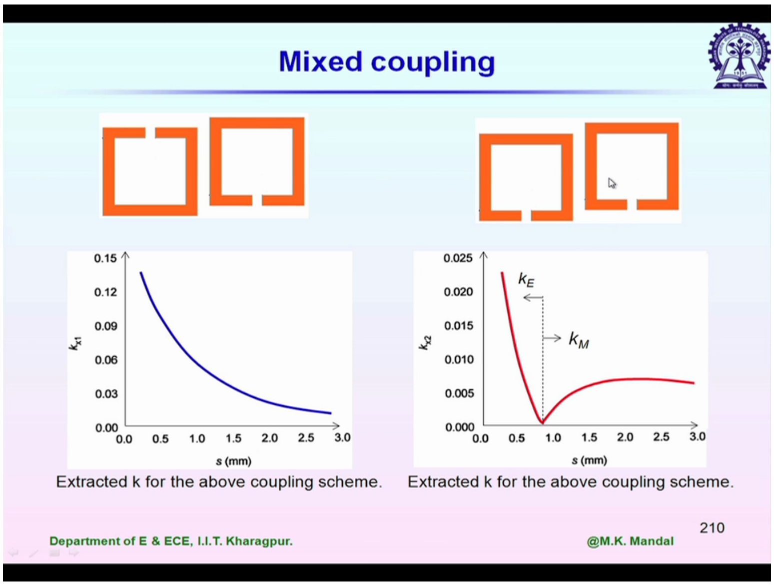

So right-hand side figure you see one interesting things, we are plotting coupling coefficient for different separation or gap between 2 resonators, so here it is being changed from let us say 0.2-0.3 millimetre to 3 millimetres and for each and every separation we are calculating K from full wave simulation by noting down F 21 and F 1 and then plotting it. Now it is interesting to say that 1st coupling coefficient, it decreases at some given value let us say for this particular example 0.9 or 0.95 it is becoming 0 and then again increasing. It is due to opposite behaviour of K e and K m, so at this point of 0.9 or 0.95 millimetres, K e and K m, they cancel each other away and at lower frequencies it is electrical coupling, at higher frequencies it is magnetic coupling.

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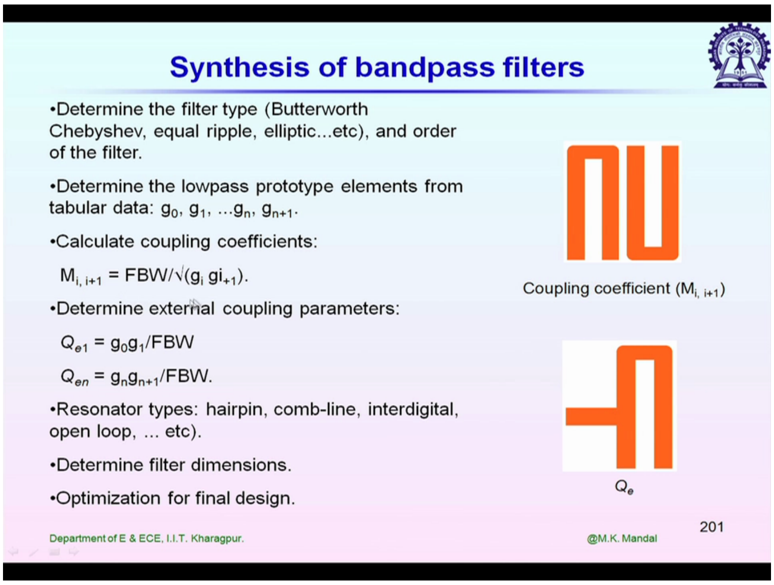

And for this left-hand side figure, it is always mixed coupling and the coupling coefficient you see it decreases with increase in separation. Now, once you have this plot so in the synthesis state if we go back you see, we will be having different M ij values that nothing but coupling coefficient with different resonators, so you can then calculate what is the gap required between 2 resonators for the required coupling coefficient from this matrix.

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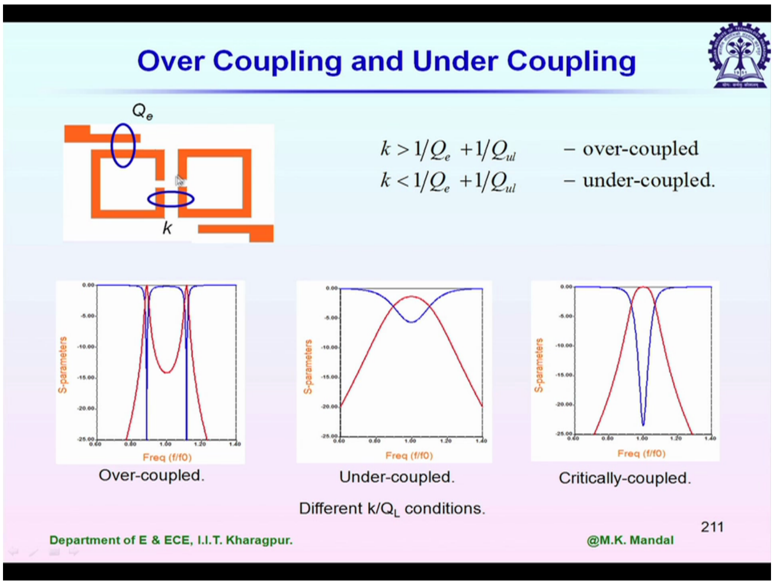

Now, I will show you some examples of over coupling and under coupling case. So we are considering a simple 2 resonator filter system, this is the input feed line, this is the output feed line and in between the 2 we have 2 resonators and from this configuration you can see we are using electric coupling. Now, coupling coefficient is determined by gap between 2 resonators and the external quality factor, it is determined by the gap between feed line and the resonator. Now, we may have depending on the Q e and K values for a given system, we may have 3 different scenarios; case one, we call it over coupled condition when K is greater than 1 by Q e + 1 by Q ul, where Q e, this is the external quality factor and Q ul, this is the unloaded quality factor of the resonator.

And in the 2nd case we call it under coupled case, when K is less than this value. So you see, this is a typical situation over coupled scenario, this Red Line, it shows the S 21 plot, so from this coupling K, it is more than the required 1 by Q e. Or you can say, this is the input matching an output matching for this response is really poor and S 11 in between these two frequencies, it goes up and touches 0 dB. So to bring it down what we have to do, we have to decrease Q e value or we have to decrease further this gap, feeding gap and then only you can take it up, this S 21 take it up and input matching can be improved. In the 2nd example, this is under coupled scenario, so where we are using small gaps for the feed lines that mean Q e is smaller than the required value and coupling coefficient then we have to increase or the coupling gap we have to increase to obtain the higher S 21 at the mid band.

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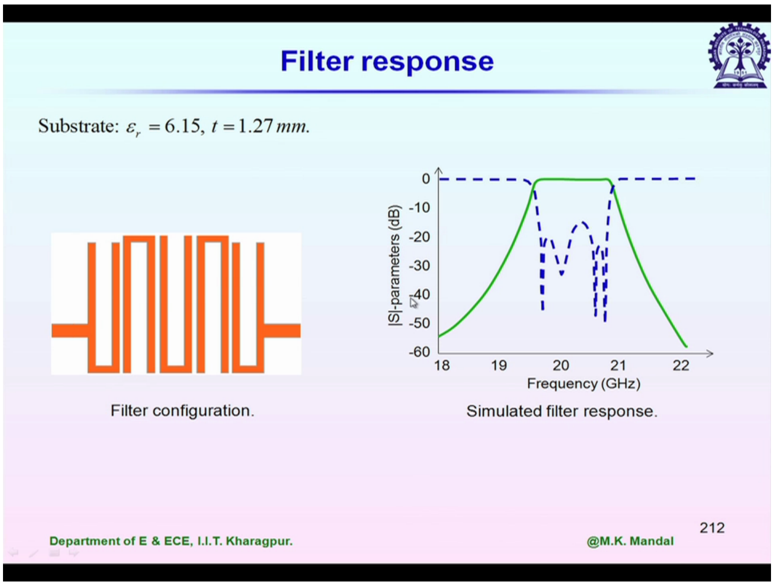

And the 3rd case when we have specifically coupled scenario, in this case actually K is equal to this 1 by QE + Q ul and can see, 2 resonances they become 1 resonance, they merged. So in practical situation what we prefer, it should be little over coupled. So this is one example, this is one higher pole filter response using high band resonators and this is the simulated response without considering any loss so that means considering PEC and lost (()) (22:49)equal to 0, so you see after optimisation how the band pass filter response looks like.

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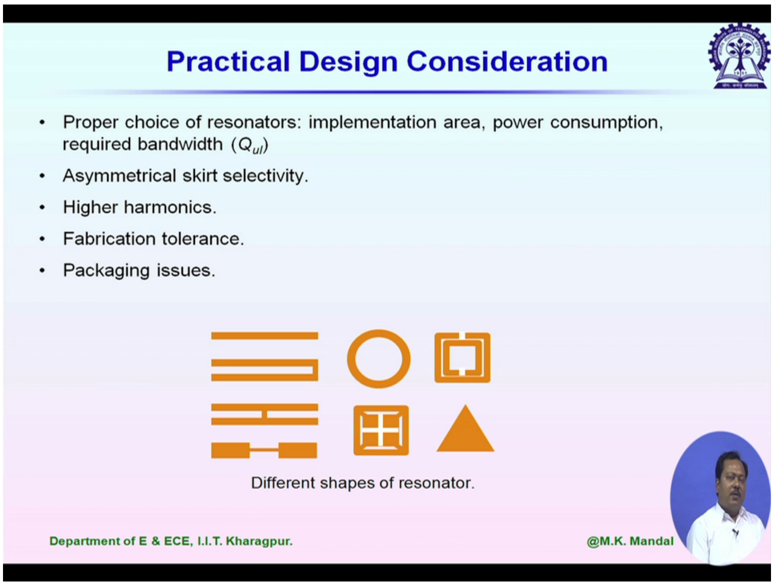

Next is, practical design considerations, so we have already let us say so what are the steps? 1st step is filter synthesis, so we have to find out the coupling matrix, required external quality factor, then the implementation scheme, let us say already you have determined what are the gaps required between different resonators, what are the gaps required for the feed lines. Even after implementation, you will see that the response to, it is not coming the desired response, it is far away. So after implementation we have to do some sort of optimisation, so once you implement just by using this coupling matrix and whatever the plot you have, you are very close to final result, but it is not the final result so to obtain that you have to use some sort of optimisation.

Now, for practical implementation you have to consider many other points. For example, while you are fabricating the filter structure you always some tolerance, so let us say you want a gap of 0.12 millimetre, but your PCB fabrication process it may not support that accuracy, it can be anything between let us say 0.1 to 0.15 millimetre, so error of 0.03 millimetre. So because of that error, your pass band response will deteriorate, so in your simulation you have to consider this all this worst condition cases and then find out even after that your filter is working or not. So in this example whatever I have shown till now all based in microstrip line technology, then when we should use microstrip line or when we should use rectangular waveguide or NRD or dielectric disintegrator, how to determine those factors.

So they are determined from (())(25:21) requirements, power handling capability, power handling requirements for example, let us say we have to design a filter for Radar transmission application, where power level can be asked as high as 1 kilo watt, obviously we cannot use microstrip line we have to go for rectangular waveguide. Another example, let us say we need a very narrow bandwidth at millimetre wave frequency, let us say we just need 0.5 or 500 megahertz bandwidth filter at 60 gigahertz, we cannot design that in microstrip line technology because filter loss, pass band loss, it depends on loaded quality factor resonator as well as the fractional bandwidth of the filter.

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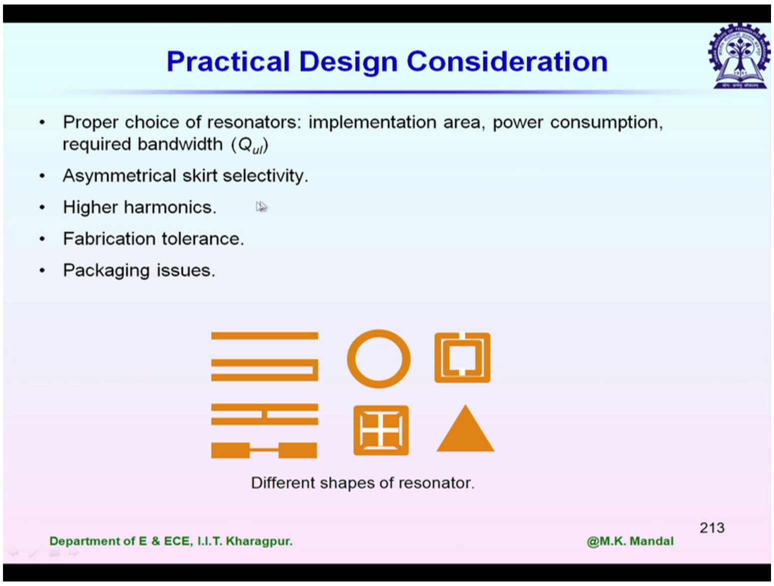

So we have actually relationships I will show you later and many other factors like asymmetrical skirt selectivity, so it happens due to the difference in even and odd mode velocities, the left-hand side and right-hand side role of their different, the rates are different so you have to be careful about that otherwise, we have to use some sort of that minimisation technique that will give you almost symmetrical response. Next, in filter theory we did not consider higher harmonics, what about the higher harmonics? It can appear just next to pass band and packaging issues finally. So we have to use some sort of shielding or packaging finally and that should not affect the filter performance.

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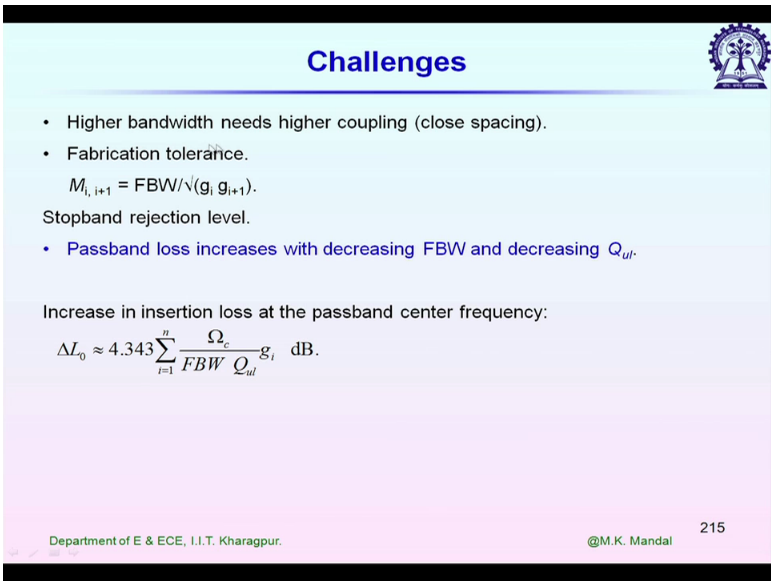

So the challenges, higher bandwidth needs higher coupling (close spacing). One way, instead of using side-by-side monitors we can use actually broadside coupling to have higher coupling value and then fabrication tolerance already we discussed because the gap it changes due to fabrication tolerance, then coupling coefficient changes and if the coupling coefficient changes than the bandwidth and everything changes.

So similarly, stop band rejection level also depends on fabrication tolerant and now pass band loss, it increases with decreasing fractional bandwidth and decreasing Q ul, unloaded quality factor. We have a close form expression for that, Delta L 0 mid band loss, this is approximately 4.343 submission I = 1 to n, n is the order of the filter and Omega C divided by FBW into Q ul into G I in dB.

So it depends on fractional bandwidth, obviously order of the filter and the unloaded quality factor, so it is stored energy inside the resonator it decreases or in other words, if the loss from the resonator increases, then we have lower unloaded quality factor, it will give you high loss. Not only that, if you increase number of resonators to obtain in higher attenuation you have to increase number of resonators, so in that case again loss will increase and another important parameter sometimes we forget it also depends on sectional bandwidth.

Of the same resonator if you are asked to design of filter with fractional bandwidth of 1 percent and somebody else let us say using the same resonator to design a filter fractional bandwidth 10 percent, you will be facing more loss, your FBW is just 1 percent. So sometimes it is so negative that you simply cannot use microstrip line at millimetre wave frequency because of this increased loss due to smaller FBW requirement. Okay so now we will take a break that we will start other passive components, thank you.