CMOS RF Integrated Circuits

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Module - 02
Passive RLC Networks
Lecture - 06
Other Matching Networks

Welcome to lecture 6, C MOS RF Integrated Circuits, we were disusing matching networks, in particular we had discuss the L match in quite detail, and then we decided that the L match might not be the end of the story, because there are only 2 degrees of freedom. So, this is what we had done in the previous lecture, we found that the L match uses 2 components, an inductor and a capacitor, and the ratio of the source to load resistance, that is the transformation ratio, that determines the Q of my network.

Once the Q of my network decided, the value of the inductor is decided, once the value of the inductor is decided and at a given frequency the value of the capacitor is also decided. So, we do not have any freedom to choose the q, given the transformation ratio that we desire given the centre frequency, everything else is frozen in the design, so this was the drawback that we were working with in the previous class. And the solution was that we said that instead of having 2 components lets go for 3 components, and we drew these 4 networks, we call them the pi match and the t match. So, these 4 networks presumably could solve my problem, and today my plan is to discuss both of these networks, and more networks if necessary and we will put a close to this entire topic, so the pi match.

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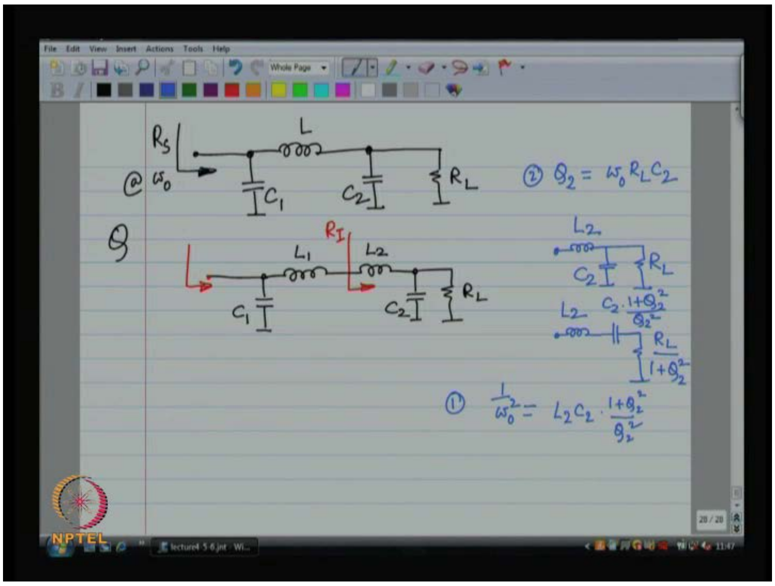

Let us consider this first, I like this particular 1, because, so between this and this I preferred this for a reasons that you will find out soon, so this is my plan that I have got 1 inductor, 2 capacitors. And I want the total input impedance looking in from the other end to be equal to R S at omega naught for maximum power ((Refer Time: 03:19)) and I want a certain quality factor of the entire network. I do not want quality factor to be determined by the rid transformation ratio or anything else, quality factor is a given, omega naught is a given, R S and R L are given, this ratio is also given.

So, this is my situation, now how you can conceptualize this network is as follows, let us split L into 2 pieces L 1 and L 2. Now, at omega naught I am going to plan to make the impedance looking in from in front of L 2, let us call this R intermediate, so I plan to make this impedance looking in from in front of L 2 to be purely resistive at omega naught. And at omega naught I plan to make this impedance also look purely resistive, so to do that what you can think of is as follows you have got a network, that looks like this.

So, C 2 parallel with R L can be transformed to a series combination of C 2 and R L, so what happens to C 2 first of all what happens to R L, does the impedance of R L increase or decrease. The impedance of R L decreases by the Q, what is the Q in this case, Q of this particular sub network let us call it Q 2 is equal to omega naught R L C 2 remember larger the R L larger the Q, because R L is in parallel with C.

So, R comes in the numerator, so this is my quality factor of the network, now R L is going to decrease, because you are going from parallel to series, so at omega naught instead of R L you are going to see R L divided by 1 plus Q 2 square. What is going to happen to C 2, C 2 is also going to change how was is it going change is it to increase or decrease, when you go from parallel to series the impedance is going to decrease.

So, C s is going to be equal to C p times 1 plus Q squared by Q squared, so the impedance is going to decrease means the capacitance is going to increase in the series case, little bit. And you choose L 2 and C 2 such that, L 2 and C 2 resonate at a the chosen frequency, so 1 by omega 0 squared is equal to L 2, C 2 times 1 plus Q 2 squared by Q 2 squared, so this is 1 design equation.

So, you make keep this design equation in mind and basically you choose C 2 accordingly, you also have to keep this design equation in mind. Now, next what I am left with, I am left with a resister, suppose inductor and capacitor resonate with each other at omega naught, then the series combination of inductor capacitor becomes equal to 0 impedance it becomes a short circuit. So, as a result I only see the resistance R L by 1 plus Q 2 square, so at omega naught what I see is as follows.

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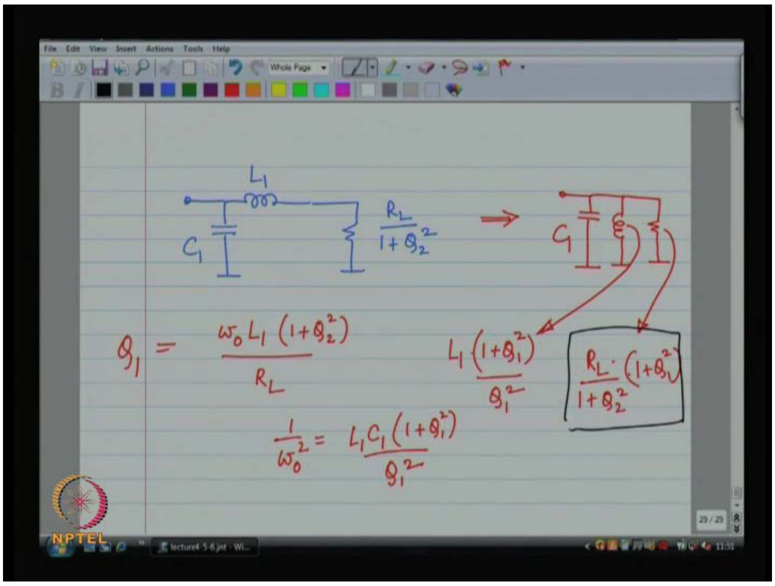

This is what I see at the frequency omega naught, now we can further transform is L 1 is in series with a resistor, so this can be transformed into a parallel combination of an inductor and the resistor. And what is going to happen, this is going to transform into capacitor instant with inductor, instant with a resistor, and the value of this resistor is going to be R L by 1 plus Q 2 squared times 1 plus Q 1 squared.

The value of the resistance is going to increase, when it goes from series to parallel, yes and what is going to happen to the value of the inductance this is going to decrease, no this is also going to increase marginally. What is the value of Q 1, in this case Q 1 is fully determined by the inductor and the resister, here is transforming inductor is series with resistor to inductor in parallel with resister.

So, at omega 0 Q 1 is going to be equal to the smaller the resistance more the cube, so L is going to come in the numerator resistance in the denominator, this is the Q 1 that we are talking about. So, this is what we have got, and next step we have to make sure that the new inductor, cancels out with the capacitor C 1. So, we have to make sure that omega 0 squared is equal to L 1 C 1 1 plus Q 1 squared by Q 1 square, so once we make sure of this, the inductor in the capacitor resonate out, when we are in shunt with, it is a shunt parallel resonant circuit. So, it is an infinite impedance. So, it is as good as it not been there, so you see only the resistance which is R L times 1 plus Q 1 square divided by 1 plus Q 2 square, so this is the final resistance that you see and you have to make R S equal to this quantity, this is basically the idea.

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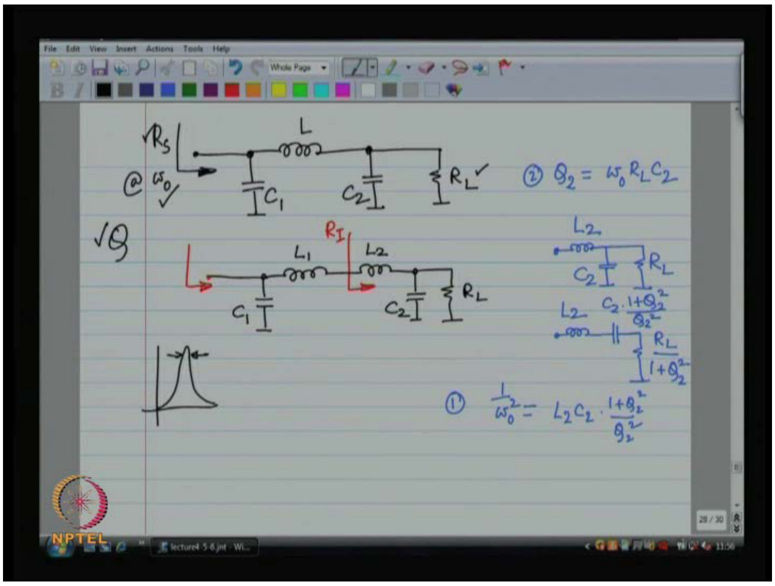

Now, in basically in 1 step you are increasing, you are a decreasing the resistance then you are again increasing the resistance, yes, so you have to choose your Q 1 and Q 2 in a fashion that it satisfy this. Suppose, Q 1 and Q 2 are both large quantities, in that case this basically simplifies to R S equal to R L times, Q 1 square by Q 2 square, and also what else simplifies these inductors and capacitors simplify considerably. Basically, the value of the inductors and capacitors are more or less the same, so omega 0 squared equal to 1 by L 1 C 1, and that is equal to 1 by L 2 C 2, L 1 plus L 2 is the total inductors. What else is missing here, Q 2 is how much, and Q 1 is omega naught L 1 times 1 plus Q 2 square by R L, now we have all of these equations, now what is missing this is 1 big piece of information that is missing, the Q of the total circuit is missing.

So, when we started of, we said that I know R S, I know R L, I know omega naught, these are all design parameters and I want a certain Q, why do I want a certain Q, because I want a certain band width over all band width of my matching circuit. So, I need at certain frequency it matches perfectly, and around that frequency over a little band width it matches somewhat.

So, I want to define what is the range of frequency over which it matches somewhat, so the net characteristics is going to look like this, so I want a definition of this that is my band width, that is the band width of the matching circuit. It matches over that band approximately, it matches perfectly at only 1 point, but approximately over a range of frequency, so that is my overall Q. So, what is this quantity if I have a circuit which has C 1 C 2 and L, what is the overall band width of the match, any thoughts, you can think of it this way let us try to work this out from first principles, this is an important idea.

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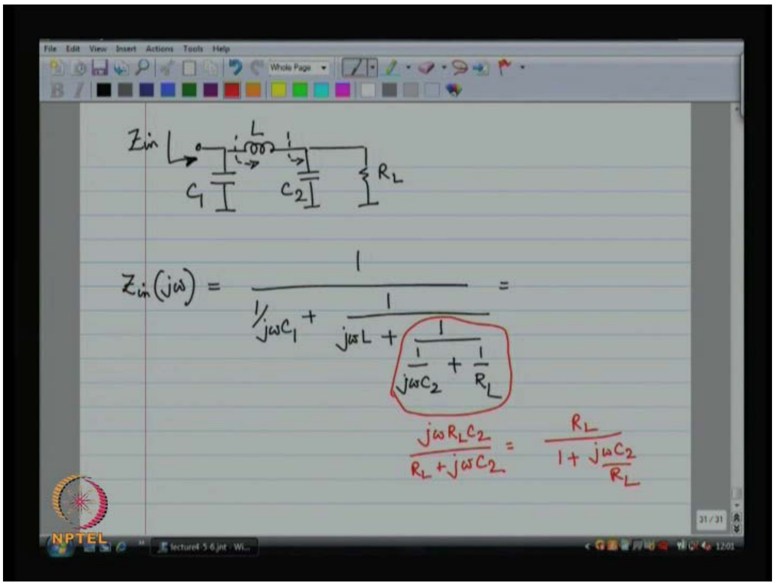

So, my input impedance Z in, that is equal to the capacitor parallel in with some other stuffs, so that is what I am writing down over here, what is the other stuffs it is an inductor in series with some other stuffs. And that is basically a resister in parallel with a capacitor, so the net quantity can be simplified to what, so first of all let us try to simplify this lower most quantity, this is yes, and actually it is never written in this fashion.

It is usually simplified and written in this notation, so at high frequencies the impedance is 0, at low frequencies, at low frequencies the impedance seen is R L does that pop out of this, so I should not write it in this fashion. So, this is how we like to write it, so at low frequencies the impedance is R L, and at high frequencies as omega tends to infinity have made further mistakes, as omega have made mistakes in the, so please correct this.

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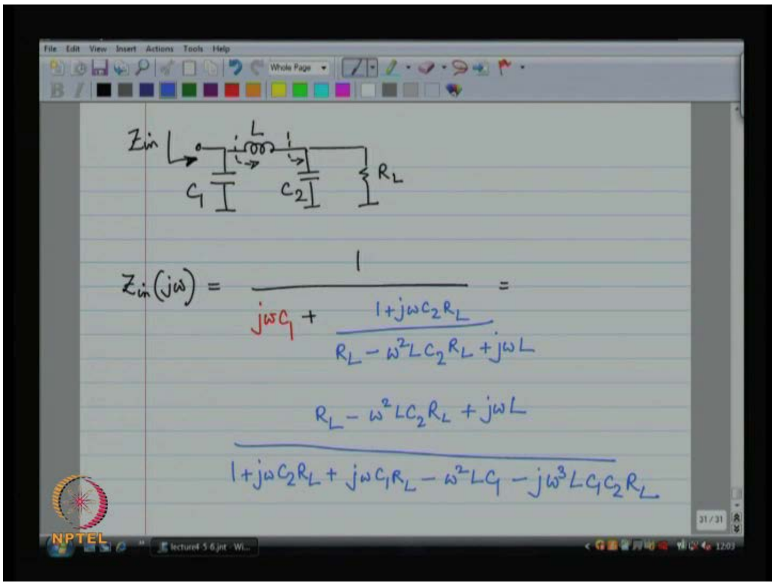

So, we write this in this fashion, that is why was not coming to, so this sanity checks always what come, so always are needed when you do manipulations. And then let us try to simplify this entire term over here, and there you will basically get 1 plus j omega C 2 R L divided by R L minus omega squared L C 2 R L plus j omega L. So, the next step is to make the further simplification, and then we shall get R L minus omega squared L C 2 R L plus j omega L in the numerator. And in the denominator we are going to get 1 plus j omega C 2 R L plus j omega C 1 R L minus omega squared L C 1 minus j omega cubed L C 1 C 2 R L, so this is my final expression.

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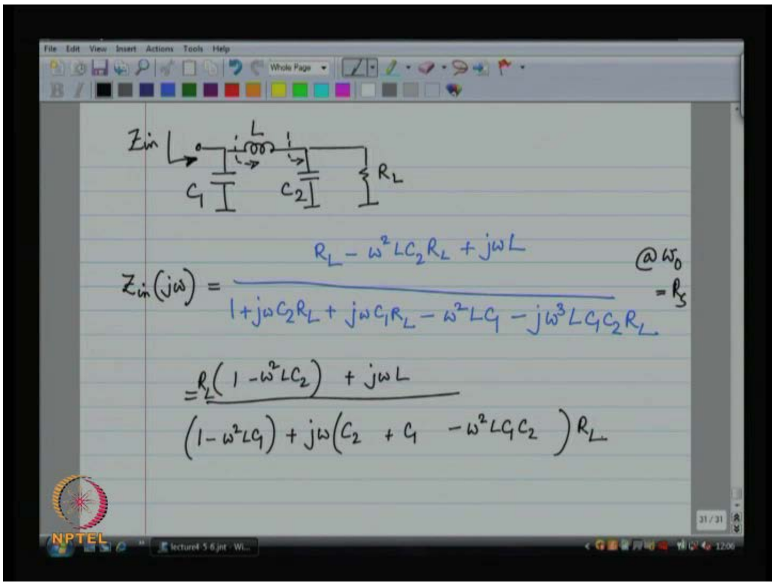

And this final expression at omega equal to omega 0, what is our plan our plan is that we have made this final expression such a fashion, that at omega equal to omega 0, this final expression is equal to R S, this is what you have done by your designs strategy. Now, assuming that we have already achieved that, let us look at a few issues over here, how R u going to compute the band width.

So, this can be further be simplified you are right, this can be further simplified into having a real part and in imaginary part, so I can club real and imaginary parts in the following fashion, this will simplify a little bit, this will also simplify little bit. So, I have clubbed real in imaginary parts together, and then what you do, you multiply the numerator by the complex conjugate of the denominator, and then when the real part and the imaginary part are equal, that frequency is going to give you the 3 dB cut of point.

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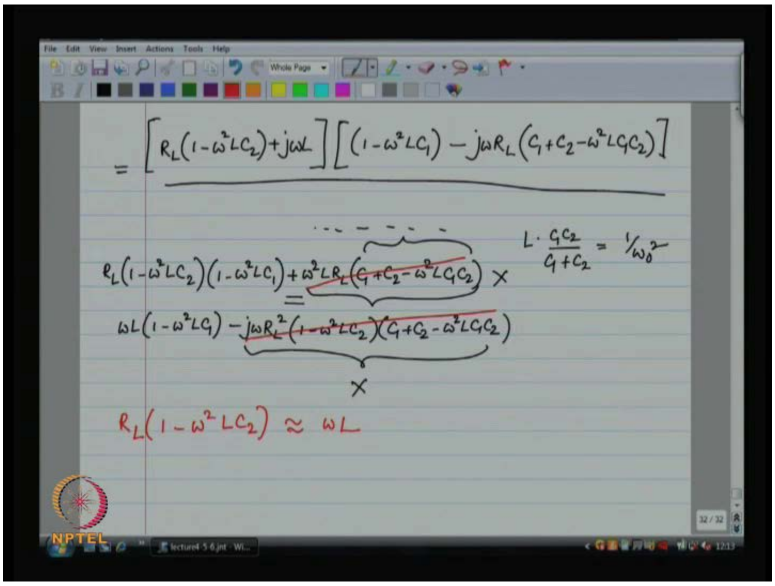

So, let us take a step and do that, so this is what I have, and the real part has to be equal to the imaginary part, that will give me my 3 dB cut off, so let us do a little more work, and what I am going to get is as follows plus j times minus j is plus 1. So, this is the real part, and the imaginary part of the numerator is something of this fashion, and what we are saying is that when the real part is equal to the imaginary part, then at that particular omega is that is my 3 dB frequency.

So, when these 2 quantities are equal, first of all what is the relationship between omega 0 squared, and L and C 1, and omega 0, this is what we know and L 1 plus L 2, we know to be equal to L. So, we know this, so it is almost like C 1 instant a in series with C 2 has to resonate with L something like this, of course assuming that Q is large, so what is this quantity in that case, you see why we did this.

This quantity is approximately equal to 0, at the centre frequency at omega naught at omega naught this quantity is approximately equal to 0, so around omega naught this entire quantity is going to be very, very small. So, this entire term is of no use to me, this entire term is also of no use to me, we like being engineers, so we make a lot of these approximation first of all the big approximation here is L 1 does not really resonate with C 1, L 2 does not really resonate with C 2.

What resonates are a little different, these are actually my equations, but we assume that Q is large, so we made that engineering approximation first. Then the second engineering approximation that we are making over here, is that around the centre frequency these quantities are still going to be very, very tiny, so given that both this and this can be thrown out. Once, you throw these 2 quantities out, you realize that the other 2 quantities are got be to be more or less equal, which means once again we get some cancellation which means that R L times 1 minus omega squared L C 2, as got to be approximately equal to omega L.

So, what does that mean, can we find out omega, thus this remind you of something, yes it does remind us of something that is the cube of the network, so the way we compute the, so this is what you are going to get. It does not matter we just solve for this quadratic equation find out the 2 omega, and that is the end of the day, end of the story for us, and you can the way we solve for band width is exactly the same you end up with the exact same equations and this is the Q in that case.

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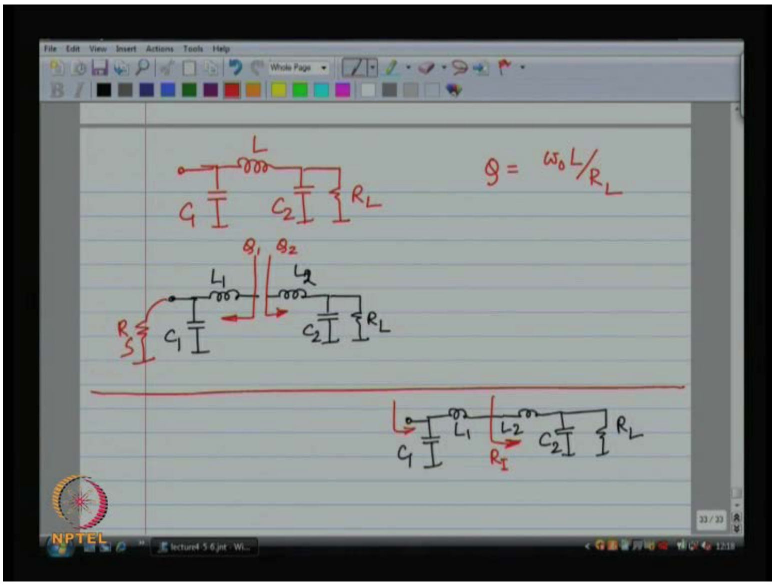

So, this basically tells me that the net cube of my circuit, this was my circuit that we started from, this basically tells me that the net cube is omega naught L by R L, it is almost as if I have a series combination of L and R C 1 C 2 etcetera are accessories. So, that is the net Q of my circuit, is there another way to see this happening, well another way to see this happening is to examine this from the centre.

So, we split it into 2 portions, so the Q looking in to the right side is something, the Q looking in to the left side is something, what is the Q looking into the left side, now you know what it is. So, Q looking into the right is something, Q looking to the left is something and the total Q is some of these 2 Q's, so that also gives you the same result, that Q is going to be almost equal to omega naught L by R L.

So, what have we got, so far, what we have got is a technique that is as follows, so first we transform R L into some into mediate resistance looking in from here, this intermediate resistance is smaller or larger than R L it is smaller than R L. Then we transform that intermediate resistance into a larger resistance looking in from here, so we go down first then we come up to the desired value.

So, I needed a certain transformation ratio let us say, I first go down by a factor of 1 plus Q 2 squared, then I go up by a factor of 1 plus Q 1 square, and reach by target. So, this is this strategy, the net Q is the sum of Q 1 and Q 2, so you have got a little bit of freedom over here, Q 1 can only be larger than Q 1, and the total Q can be larger than Q 1 and Q 2.

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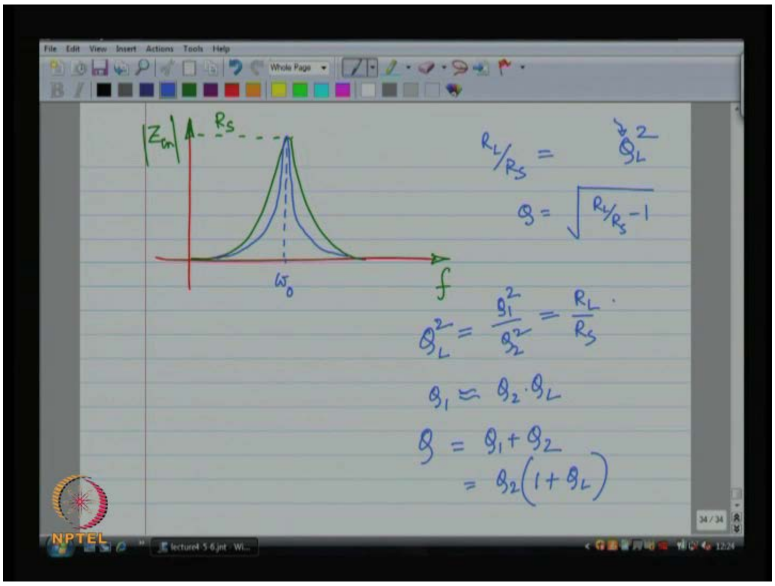

So, suppose with an L match this is what you are getting, this my frequency axis, this is Z m, this is what you were getting with this L match, with a pi match you can make the Q sharper, you cannot make it broader unfortunately. So, once omega 0 is decided, once R S and R L decided, then the L match is fixed where as with the pi match, you can tweak around the little bit you can play around with L 1 and L 2, because we are going a step down and then coming a step up.

So, you can play with the values of Q 1 and Q 2 and you can come up with a an different value of the total Q, this different value is going to be larger than the earlier one. So, far, so good, why is the different one going to be larger, why not brought it is like this that, for the L match case R S by R L, R L by R S is 1 plus Q square, this is for the L match. So, Q is something like this, in this case what we are doing is we are going step down first, so we have 2 numbers Q 1 and Q 2, Q 1 is making the resistance smaller, Q 2 is going to make the resistance larger. The opposite actually Q 2 is making the resistance smaller first, and then you are going larger with Q 1, so R L by R S is 1 plus Q 2 Q 1 square by 1 plus Q 2 square something of this fashion.

So, looking at the 2 equations that you have got R L by R S is the same, so for the earlier 1 you need the certain Q here assume Q 1 and Q 2 are large, so this is what you have got.

So, the ratio is pair of the ratio of Q 1 and Q 2 is comparable to the earlier Q, which means that if Q 1 is something, then Q 2 has to be earlier Q times Q 1 or wise versa, so something like this. So, Q 1 squared has got to be Q 2 squared times Q L, and the net Q is Q 1 plus Q 2, so it is definitely more than the Q of the L match cannot be less, so you will get a much sharper match in this case fine, so far, so good. Now, comes the question why do did I favor this particular network, the reason why I favor this network is because of parasitic, so you might have heard of parasitic capacitances in earlier courses.

So, whenever you have 2 objects there is a parasitic capacitance between these 2 objects, or whenever you have 1 object you have the parasitic capacitance between that 1 object and the reference potential, that is ground. So, these networks that I drew, let us consider this particular network it is very hard to make this, because whenever I place L 2 there is automatically going to be a parasitic capacitance between the load and ground. There is automatically going to be another parasitic capacitance here, where as in this case if I have these parasitic capacitances, they can be lumped inside the capacitors.

So, C 1 and C 2 can absorb these parasitic capacitances, and once I figure out what these parasitic capacitances are going to be high basically design in such a fashion, that C 1 and C 2 are, so much less. I mean the desire total capacitance minus the parasitic I design it in that fashion, so that is why kind of prefer this particular design has oppose to the next one. Next one is going to give you the identical, it is an identical situation with the next one, you have now have to split C into 2 series capacitors each of these capacitor are going to be smaller, than the original larger than the original one.

Then there is the T match, what is the T match do well the T match is which one will I favor, will I favor this one or is this going to be favored or this going to be favored you. This is going to be favored more, because whenever I place that inductor over there, automatically there is going to be parasitic capacitance to ground, which I will be very hard press to figure out what to do with it. Whereas in this one, this parasitic is taken care of there is also a parasitic capacitance here, which I have to worry about, and this is also parasitic capacitance here which is something I will have to worry about, but let us worry about these things later.

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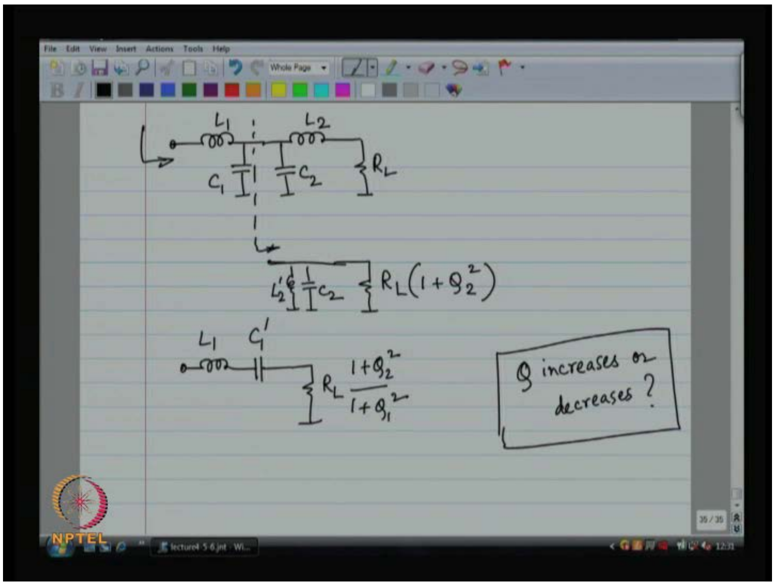

So, let us look at this T match briefly, so it is the same strategy as before, I split up this capacitor C into C 1 and C 2 they are in parallel, and now I have got L 2 and series with R L to an inductor in parallel with the resister, now I am going up. And I make sure that C 2 resonates out with L 2 prime at the frequency omega 0, so I can delete C 2 and L 2 prime both, and now from this point this is what I see.

And, now I have got a parallel combination of a capacitor and resistor, this I will transform to a series combination of a capacitor and a resistor, which means that I will have to go down in terms of resistors. So, what is going to happen is something like this, so once again very similar design equations, and you basically have to figure out the values of Q 1 and Q 2, such that you get the desired transformation ratio between R S and R L.

If both Q 1 and Q 2 a large than this certain approximations can be made, and L 1 and C 1 prime is little different from C 1, but as long as Q is large C 1 is almost equal to C 1 prime. Similarly, C 2 is almost going to be equal to C 2 prime, L 2 is going to be almost equal to L 2 prime, so L 2 prime as to resonate with C 2, L 1 as to resonate with C 1 prime. All of these resonators have to resonate at omega naught, the chosen frequency of match, once they resonate out everything is clean, and you just see that desired resistance. Now, the question mark here is does this increase the Q or decrease the Q, this is something you need to find out as homework.

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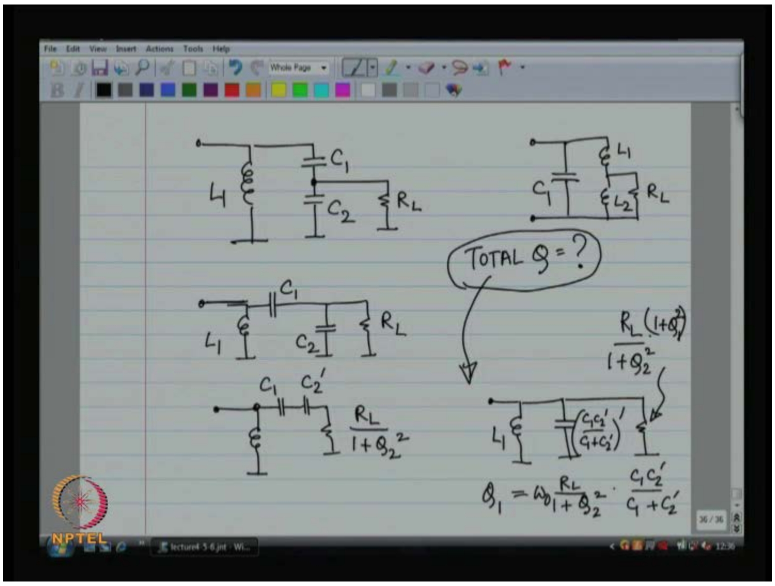

So, total Q, so please do this as an exercise, then there are a couple of other matching networks that are interesting, these are called tapped inductors or tap capacitors, almost it looks like a pi it looks like this. And redraw this in this fashion, but we call it tapped, this is called a tapped capacitor match, and similarly there is the tapped inductor match which looks like this. And which one is preferable, what do you think is preferable, most probably it the tapped capacitor going to be preferable, because it lambs into it the load parasitic capacitance.

So, how do you conceive of this, how I mean how do you how are you going to imagine this, so the tapped capacitor match we are going to split up C 1 into 2 series capacitors, is that, no it is not. What you have to do is think of the ratio C 1 by C 1 plus C 2, that is actually what is going to give you the transformation ratio, so the older technique of splitting up the middle 1 into 2 pieces is not really going to work here. In any case think of it in this fashion, you are going to transform C 2 in parallel with R L to a smaller series resistance, and a capacitance at the frequency omega naught, and now you have C 1 in series with C 2 can be lambed together as one big capacitor. And, now once again you can do the series to the parallel transformation, where Q 1 is equal to yes, so the series combination of the 2 capacitor and the resistor.

That Q you have to worry about and this inductor and the capacitor need to resonate at the desired frequency, so you have to put the inductor such that, it resonates out with the value of the capacitor. Of course, you choose Q 1 and Q 2 accordingly, so the question for you is what is the total Q of this network, you have to figure out, this could be something that you need to do, you need to figure out by yourself.

So, the total Q once you figure it out, whether the Q is going to increase or decrease, and how can play with, so let us do the brief recap of what all we did. We basically started of with the pi match circuit, and we broke up the inductor into 2 piece L 1 and L 2, and first we were stepping down the resistance, then we were stepping up the resistance. So, the net transformation ratio was 1 plus Q 1 squared by 1 plus Q 2 squared, so this was the net transformation ratio that I was going to work with and as a result, I found that the Q that I can get from this is much, much more then the ordinary Q's that I can get with the straight forward L match.

So, this is the lesson learned from this, parallel exercises we can do with the T match exact same methodology, and a different exercise could be the tapped capacitor or the tapped inductor matching network. So, with this we are going to close this chapter this entire module on R L C networks, so under R L C networks we studied, basically we studied the parallel to series and series to parallel transformations. And then we studied a lot of different matching networks, so thank you, and we are going to start a new module after this.