CMOS RF Integrated Circuits
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Module - 02
Passive RLC Networks
Lecture - 05
Matching

Hello and welcome back to CMOS RF integrated circuits, today lecture 5 this is part of the second module on passive RLC networks, today we are going to discuss matching. So, far in the last 4 lectures you might have heard of this ward several times, so we have said we need to match the load to the characteristic impedance of a transmission line or we have made statements like, we need to match the source impedance to the characteristic impedance of the transmission line or we have made statements like we have to match the load to the source impedance to get maximum power transfer. So, we have made this statements several times, and today we are going to start learning about how to do such a thing, how to achieve such a goal.

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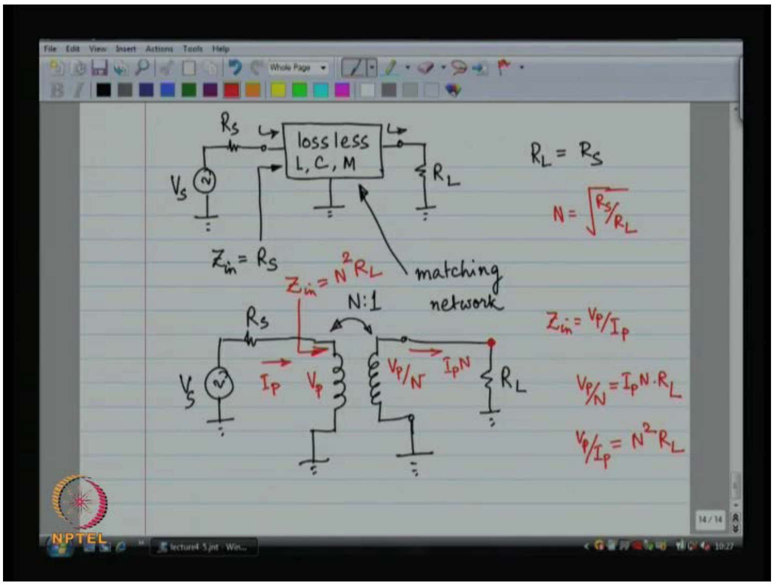

Now, let us consider the following let us say I have a source which has which is in separable from source resistance, and I have a load. Now, for maximum power transfer given R S, R L has to be equal to R S, this is for maximum power transfer, what if R L is not equal to R S, what do you do you given up. Alternatively what we could do is we could conceive of a network in between this network is made purely out of loss less elements.

What do you mean by loss less elements, inductors, capacitors if you need transformers, mutually inductances any element does not consume power. So, this does not mean that you can use transistors, you cannot use registers, you cannot use transistors, diodes non-linear components anything that consumes power you cannot use this inside this network. So, suppose I do this, suppose I make a loss less network I put it in between the source and the load like I have drawn, and suppose I make sure that the impedance looking in to the loss less network, at the point I have shown.

This impedance is equal to R S, suppose I can achieve this if I manage to achieve this, then I will get maximum power going into the loss less L C or L C transformer mutual inductor loss less network. So, maximum power is transfer into this network, now this network is made out of components that do not consume any power, so all of that power is delivered to the load. So, I still get maximum power transfer from the source to the load, so the design of these loss less networks is called matching network.

Now, let us try to understand this, what if inside this loss less network I basically used a transformer an ideal transformer, we all studied transformers in your circuit theory courses hopefully you have. Now, if the transformer has a terms ratio of N, in terms of the primary 1 term of the secondary or vice versa I mean let us just choose this, let us say that the term ratio between the primary and the secondary is N is to 1, N can be less than 1 all right.

What is the input impedance that I see looking into the primary, how do you figure this out well it is a what you might remember is that if the primary voltage is V primary then the secondary voltage is going to be V primary by N. If the primary current is I primary, then the secondary current is going to be what I primary times N because, power needs to be consumed. So, the power delivered to the transformer on the primary side it is I P times V P the transformer does not consume in any power, it delivers all the power to the load.

So, the power deliver to the load is V P by N times I P by N which is again V P times I P all right, so that how it works. So, the transformer is the loss less network, now given these circumstances what is the resistance, what is the impedance that you see looking into the primary. You apply a voltage V primary and you see that the current I is primary right, so the impedance looking in to the primary is V primary is by I primary right.

And what is the relationship between V primary and I primary, we know the relationship at the load, at the load V primary by N equal to I primary times N times R L. So, therefore, V primary by I primary is N square times R L, so therefore, Z in is equal to N square times R L. And what you can do, you can choose N to be equal to square root of R S by R L, if this is the relationship of N that you choose, then you get exactly what you need, you get Z in is equal to R S you get maximum power transfer into the primary of the transformer.

All the power deliver to the primary of the transformer goes to the secondary and therefore, to the load because, the secondary also does not consumed any power right is this with everyone all right, what is the catch here, what is the big problem, why we need to study matching networks. if it is so easy, if I already finished of topic in 5 minutes, the got to be a catch can be so easy.

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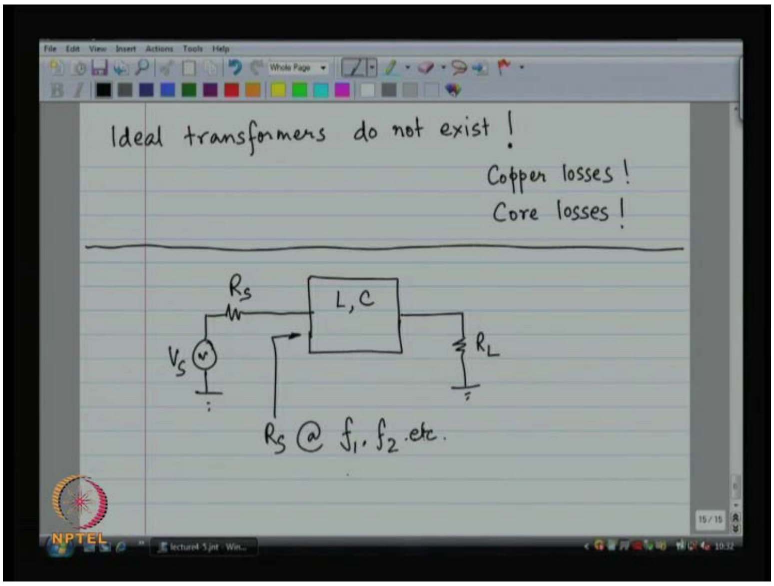

The catch is that I assumed that I have got an ideal transformer, does not exist impossible to make an ideal transformer we going to study transformer later on. But, it is not possible right, second thing is transformers also consumed power, it is impractical to say I am, going to make transformer dose not going to consume power, they are going to be copper losses, there are going to be core losses. So, because of this things transformer is not going to be loss less any moiré right.

Each between each winding of the transformer, there is going to be parasitic capacitor between the primary side and the secondary side, there is going to be parasitic capacitance. So, the transformer is a mess, the ideal transformer is a just a mathematical entity, it is not possible to make such things all right, so wish for an ideal transformer it is not possible. So, therefore, we have to continue our study of matching networks, now if I have a network which is made out of the inductor and the capacitor in front of a load registers, is it possible to have the input impedance to be a registers.

It is not possible why not because, there are frequencies at which the input impudence will be inductor, they are frequencies at which the input impedances will be capacitive right, it is never going to be that the input impedance is going to be R S all the time unless there is no L N C R L is already equal to I which is trivial case. But, otherwise it is just not possible to have the input impedances equal to R S all the time at all frequencies, what is possible is to make a network which are discrete interesting frequencies wants in the fashion that I have shown.

So, it is possible to select certain discrete frequencies is call than f 1, f 2 etcetera, only at these frequencies the input impedances of entire network is actually equal to R S. At other frequencies do not know what is going to happen, important is these frequencies discrete it is not a range of frequency discrete frequency fine. So, it is possible like we saw in the earlier discussion we were trying to transform, inductor and series with the registers inductor with parallel with the register is possible to do that act a discrete frequency, not at all frequencies. Similarly this networks can be transformed into a register at a discrete frequency all right, so given that what can be the easiest network that we can think.

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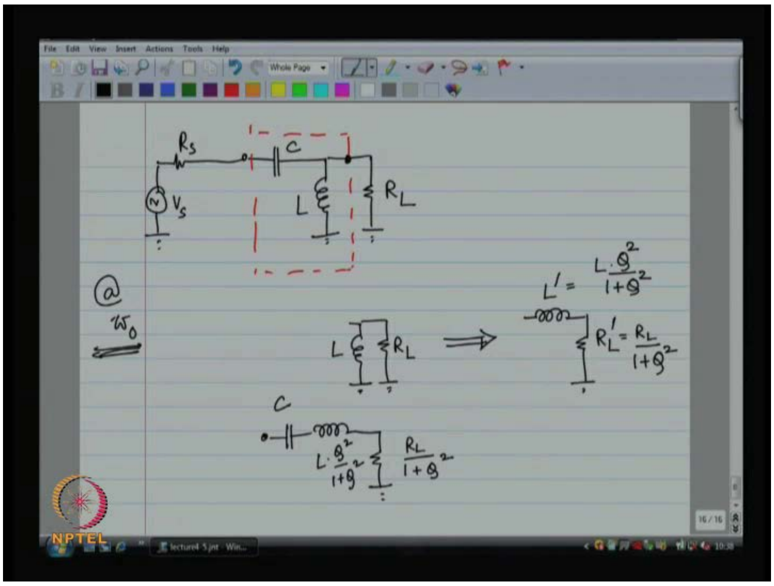

Let us think of the following, so this is the matching network I got an inductor, I have put in inductor to the parallel to the register, and I got a capacitor in series with that. Now, we can transform the inductor in parallel with the registers to a series combination of an inductor an a register at a given frequency, let us says I choose the frequency omega 0 all right. So, let say I choose this frequency omega 0, then the inductor in parallel with the register can be transformed to an inductor in series with the a register.

And what is the relationship, what is L prime, R prime, R L prime go back to the discussion in the previous class, this is what we have done in the previous class you remember, we had an inductor in parallel with a register which we could transformed to any inductor in series with the register and vice versa. And the relationship between L S and L P was over here the relationship between R S and R P was an over here.

Before we going to what is Q, let me finished the story and then we talk about the Q over here do not even try to guess what is Q it is. So, we do this transformation, so it is conceivable to do a transformation inductor in parallel to register, to inductor series with the register. Then the network that we end up with is a capacitor in series with the inductor, in series with the register. Now, at omega naught if I place a capacitor such that at omega naught this capacitor resonates with the series inductor. Then the series combination of the capacitor and the inductor becomes an impedance of 0 zeoms at omega naught, which means that what I see as my load is R L by 1 plus Q square.

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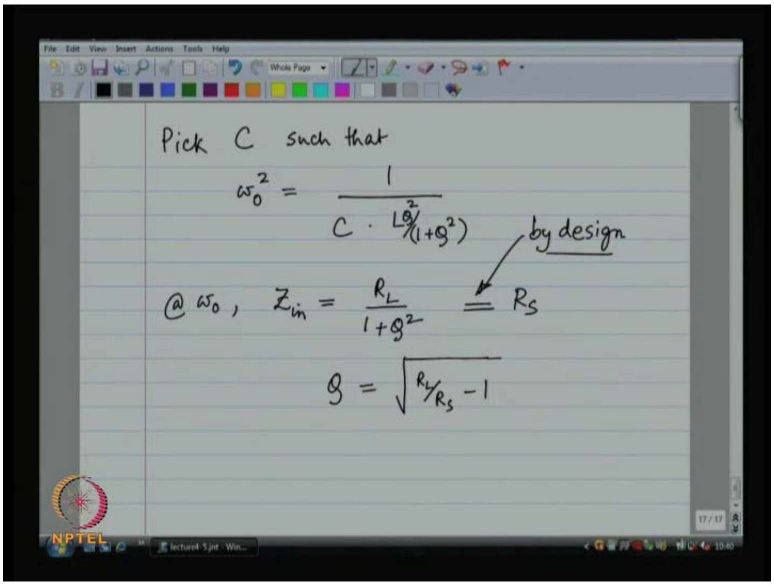

So, pick C such that at omega naught ((Refer Time: 19:44)) this is the relationship pick C in this passion, and then C and L resonate they will find combined impedance of 0 ohms at omega naught. And therefore, all that you are going to see is R L I am right, so if you do such a thing then your load resistance at omega naught is going to be R L by 1 plus Q square. So, looking in over here what I see is R L by 1 plus Q square I want this quantity to be equal to R S, so therefore, I want this quantity I want the input impedance of the network equal to R S. So, by designed R S should be equal to R L by 1 plus Q square for maximum power transfer therefore, Q is going to be equal to square root of R L by R S minus 1 that is correct. So, you compute the Q, so this is how we go about to do this proceeding with our story.

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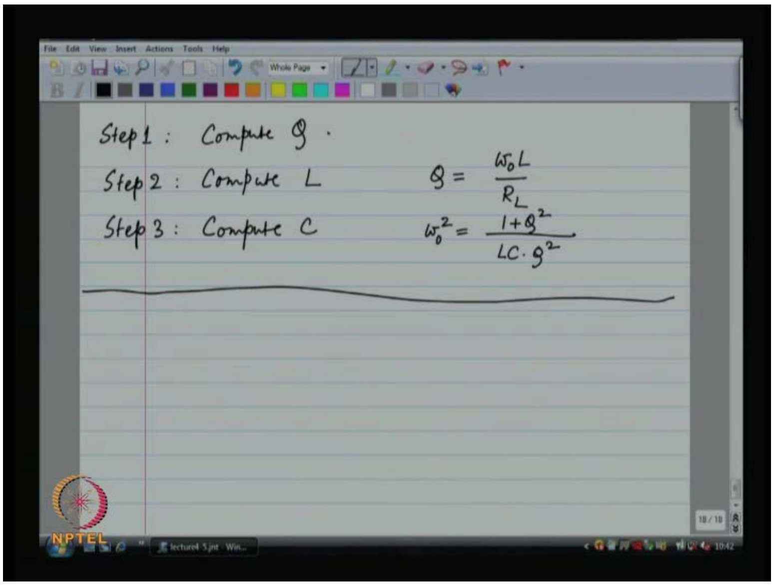

Number 1, compute the Q dot, Q is going to be this, step 2 compute L, what is the relationship between Q and L inductor is parallel with the register, the Q is omega naught L by R L right. So, L is going to be Q times R L divided by omega naught that act a chosen frequency omega naught, and step 3 is compute C we want back words in our derivation in our explanation. So, C is this C is going to follow this equation you know L Q and omega naught, so you figure out what C is all right.

What is the problem, what is the biggest problem is that step 1, step 2 and step 3 what is the problem in step 1, what happen if R L is smaller than R S, if R L is smaller than R S then I do not get a meaningful number of Q I get Q to be imaginary in which case we are struck. So, this techniques works only when R L is greater than R S, so when R L is less than R S we have to figure out some other matching network, this matching network is not going to do my job.

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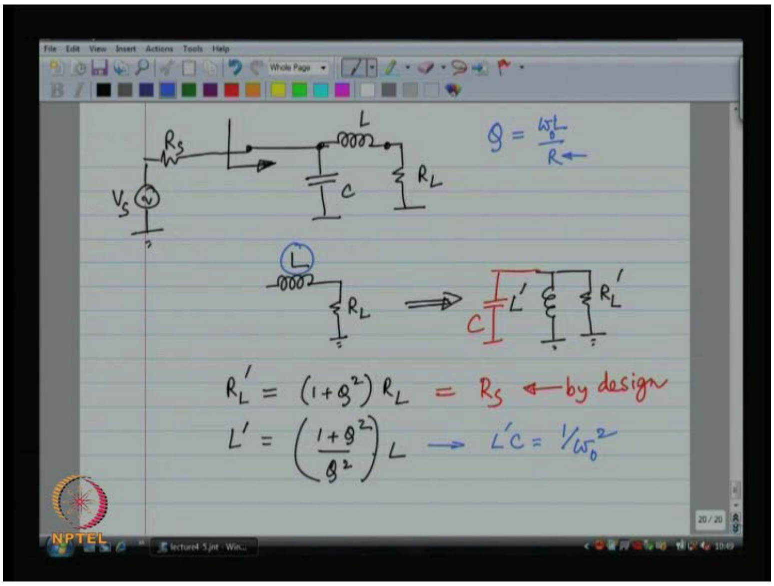

So, what else can you think out, we just pick something on and just move work it something else up. Let us pick up this here I can transform the series combination of the inductor and R L into a parallel combination of a inductor and some other register, and the expression for that it also quits straight forward it is exactly the converse of the old expression.

So, all right, so this was exactly opposite of the old expression I do not need to rewind back all the way to previous class to figure this out, easy way to remember these expressions is just follows, the inductor value is hardly going to change. So, is going to be 1 plus Q square by Q square or is going to be Q square by 1 plus Q square, Q is large. The resistance value needs to be small if the series resistance it needs to be large if it is a parallel resistance, so accordingly you figure out whether it is divided by 1 plus Q square or multiplied by 1 plus Q square fine.

So, we transform the inductor in series with the register to inductor parallel with the register. And now I need L prime and C is resonate with each other at omega naught, so if C and L prime is resonate with each other at omega naught, then the parallel combination of L and C L prime and C is an infinitely large impedance. Which means that you do not need to consider it at all, which means that all that your left in your network is R L prime right.

So, therefore, by define R L prime has to be equal to R S for maximum power transfer, so therefore, you can figure out what is the value of Q that you need. Once you figured out what is the value of Q you need you can figure out what is the value of L because, L in series with R L means what does it mean that the Q is going to be equal to R by omega naught L no exactly opposite omega naught L by R I think this is wrong, how do you remember which formula is forward.

When you have inductor in parallel with register, the largest the resistance the more than the Q really do not want the register to be there at all, you want infinitely large impedance instead of the register for infinite Q. So, therefore, when inductor in parallel with register, resistance comes in the numerator which means Q increases are the resistance increases. When you have inductances series with the register, when you decrees the resistance, when you make the resistance short circuit you get infinitely large Q. Which means that you need the register in the denominator that is how you keep in your mind, what the correct formula for Q should be, correct result should be. So, Q is going to be omega knot L by R, so therefore, I can compute the inductor value that I need this inductor value, then C and L prime should resonate L prime is 1 plus Q square by square times L all right.

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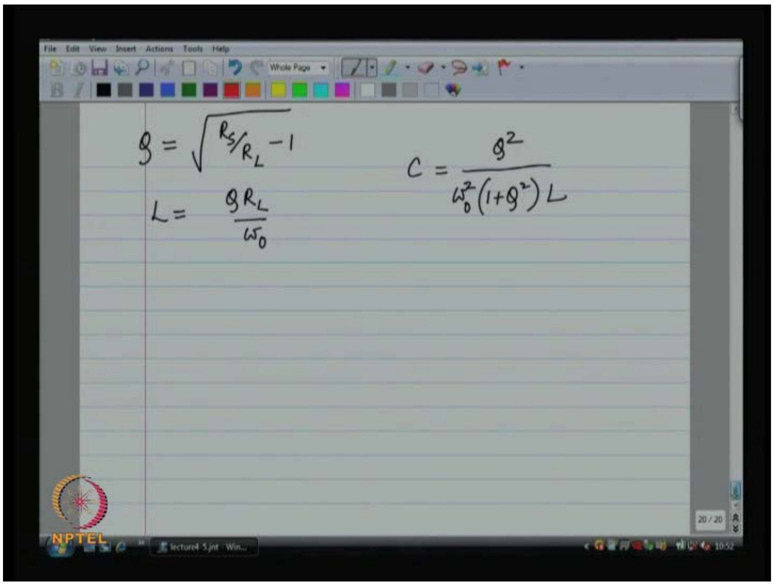

Does this work or these flow here ((Refer Time: 31:12)) something like this, so one of the problems here, this matching network does not work when R L is more than R S. In which case the previous matching network works, this matching networks works only when R S is more than R L fine.

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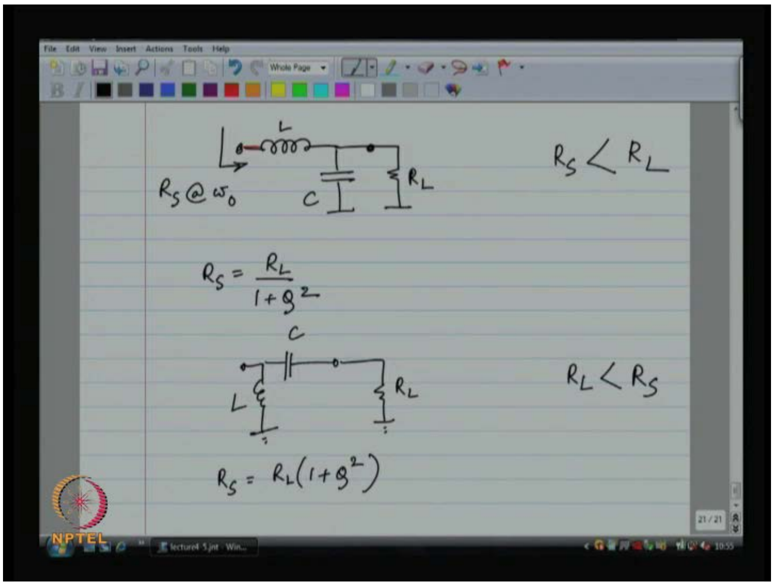

What else can be do, we can also conceive of doing playing with our networks, we can also conceive of doing something like this, as our matching networks. And the derivation for this is also quite revel, you just have to transform R in parallel with C to R in series with C, the value of C is not going to change much, the value of the resistance is going to go down by 1 plus Q square.

And this capacitor, this transform capacitor needs to resonate with the inductor, and at we chosen frequency omega naught. And when we dose the resistance in inductor at omega naught, then what value see is the resistance R L divided by 1 plus Q square that is all you see like. So, this is also going to work, so Q is always going to be more than 0, which means Q is real number which means that R S has got to be less than R L for this to work.

And alternatively you can also conceive of this, and it straight forward to show that this will work only when R L is less than R S. So, here the series combination of C and R have to be transform to parallel combination of C and R and then C should resonate to the transform capacitor should resonate with the inductor value to get infinitely large impedance open circuit, the remaining resistance will be R L times 1 plus Q square. So, R S have to be equal to R L times 1 plus Q square, which means that R S has to be more than R L for this to work. So, we have four matching networks all of these matching networks are broadly called the L match.

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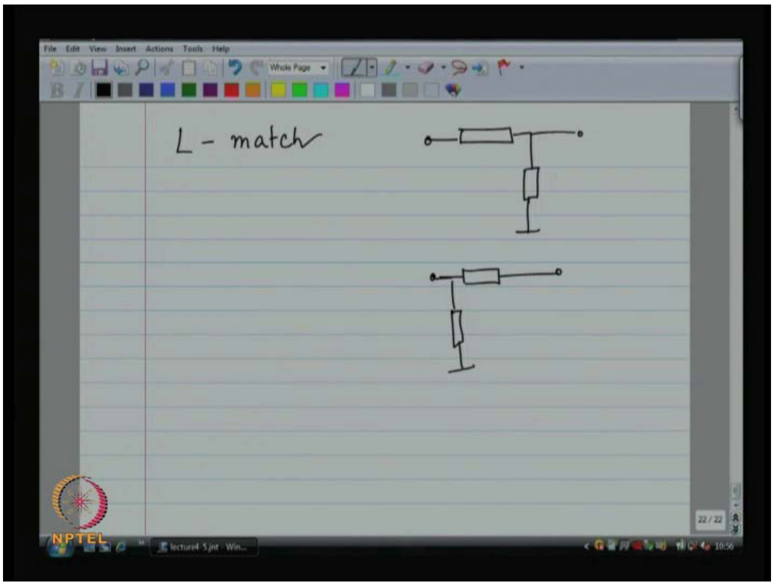

So, this is no more space to write over here, but all of those are called the L match, L is not because of inductance L the is because of the shape of the matching network. So, it either looks like this or it looks like this, and if you turn your head in certain directions this patterns are going to look like and L the alphabet L. So, it is called an L match is this spend our studying of matching networks not quite, there are a lot of problems with this. Let me do a numerical and that will kind of illustrate the problems, so this is going to be numerical, suppose we are talking about the transmitter inside your cell phone, and suppose we are talking about GSM.

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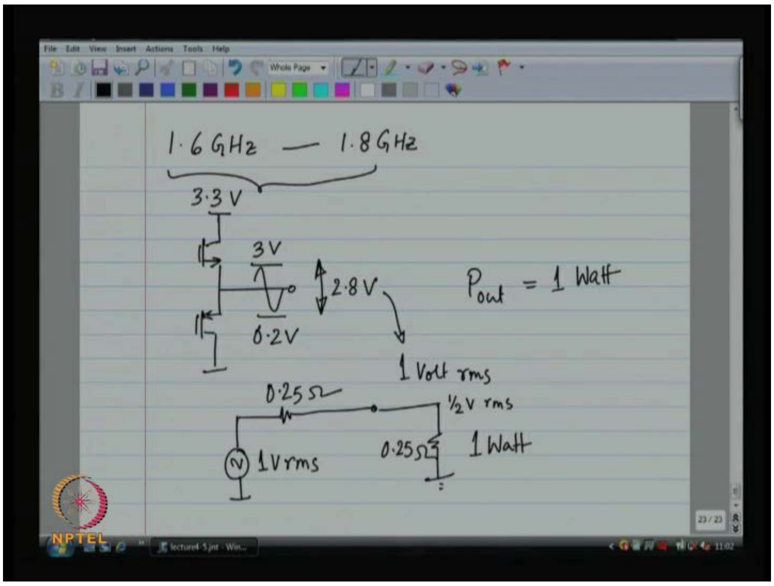

And one of the bands of GSM is from 1.6 gigahertz to let say 1.8 gigahertz numbers might not be exactly accurate, but let say this is the case. So, the cell phone needs to transmit in any channel over the entire band, so the basic station you tell the cell phone at exactly what frequency to transmit, and that frequency could be anywhere between 1.6 and 1.8 gigahertz suppose this quite avoid band.

And the output of my transmitter is basically a power amplifier, and the power amplifier at the end of the amplifier put preassembly look something like this. So, you got an output over there and suppose I have a 3.3 volt supply, then may be this output can spin peak to peak from 3 volts to 0.2 volts, which means that the peak to peak spin is 2.8 volts. And suppose that the best station by far from the base stations, and your required to pump out power of 1 volt suppose this is what we are working with.

Now, the first question is I have got 2.8 volts peak to peak what is; that means, that means it is 1.4 volts amplitude. That means, r m s it is about 1 volt 1.4 divided by root 2 that is about 1 volt r m s I am choosing easy numbers for my numerical might not be the case when you do your numericals, but I am doing a preparing paper, so all right. So, I have got 1 volt r m s signal, I need to pump out 1 watt of power watt needs to be my source register, watt needs to be my load resistance.

And here of course, you need to assume that you are doing maximum power transfer because, that is the best case right. You write a if you make a source resistance lower and lower, you will being more and more, but that comes at cost right, it was making a source resistance more I am sorry you can make keep making the source resistance less and less and you will keep winning more and more, if you have a open the source resistance, but really making the source resentence is less this is not a good idea.

Because; that means, that your power amplifier will need to be burning more and more current right, you need to have larger and larger area requirements for the power amplifier to have such a low volts source resistance, lower and lower source resistance. So, I want to know what is the maximum source resistance, what is the load resistance such that I get 1 watt of power on the load.

So, to do that you have to have maximum power transfer, which means the source resistance should be equal to the load resistance. So, if this is R and this is R then I get a half of volt over here r m s, which means V square by R has to be equal to 1 watt half V whole square divided by R has to be equal to 1 watt. So, 1 has to be equal to 0.25 ohms thank you, so this is the case when you get maximum power transfer, to reduce the source resistance further indeed you get more power out, you get even more power out. But it is, not advisable because, reducing the source resistance further and further is just going to blow up the size of the power amplifier all right.

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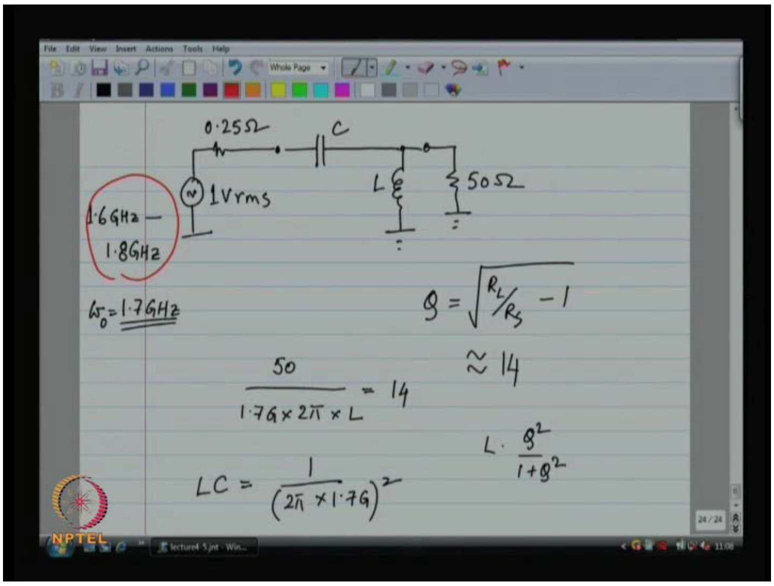

So, this is what I have got, I have got a system which puts 1 volts r m s signal it has a source resistance of 0.25 ohms right. Unfortunately the load is not 0.25 ohms, the load is the antenna which is broad casting the massage, antenna look like 50 volt ohms resistance. So, I need a matching network in between that matches the source to the load right great, now one pick about the source, the source can range frequency from 1.6 gigahertz all the way to 1.8 gigahertz.

So, let us say I chose the centre frequency at which it should be a perfect match at, so my center frequency is 1.7 gigahertz at which I want a perfect match, at the other frequencies is wont be a perfect match, but you know will be doing quite well fine. So, suppose this is the case then I plan to make matching network, I have got a large load resistance a small source resistance I need to transform the large resistance into a small resistance. So, I need to put something in parallel with it could be L and it could be C does not really matter.

So, L in parallel with R transform to more or less the same L in series with much smaller R right fine, so far, so good. And what is the Q that is the first step right, something like this times the R S by R L because, R S is less than R L, so that is power equal to R L is 50, R S is 0.25. So, R L by R S about to 200, so square root of 200 is about 14 square root of 199 is about 14, 196 is 14 square.

So, I need a Q of about 14 which tells me what is the exact value of the inductor right, once you know the Q we can figure out the exact value of inductor 1.7 gigahertz times 2 pi that is my omega naught. So, omega naught times L, so the resistance divided by omega naught times L is about 14, so L is about 50 divided by 1.7 giga divided by 2 pi divided by 14. So, what about that number that is your inductor value, if you have calculator this can be computed I do not have 1 fine.

So, you compute the value of L that is the second step, and then the third step is this L is going to transform to another inductor which is going to be about L into Q square by 1 plus Q square. So, Q square is 199 1 plus Q square is 100 that is about the same L, so the value of L remains more or less unchanged, when you transform it from parallel to series. And then this inductors needs to resonate with the capacitor at we chosen frequency. So, C times L should be 1 by omega naught square, and from this you can figure out what is the value of C that you need all right. So, what is the problem here, the problem is this the band width of my circuit is related to Q right.

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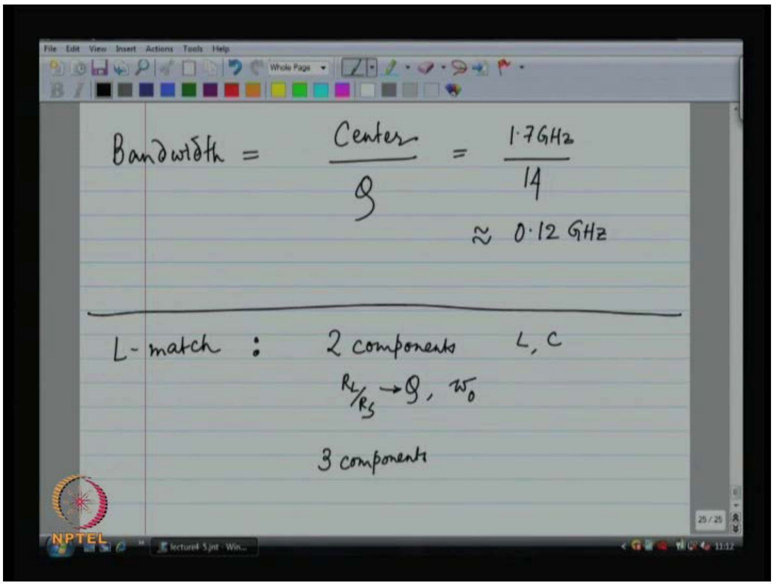

So, what is the band width is the centre frequency divided by Q, so we have got 1.7 gigahertz are center frequency divided by Q is about 14. So, my band width is a little about 0.1 gigahertz that is the total width of the band in which I will be able to transmit reasonably good amount of power, the match is going to be reasonably nice right. The desire band width is 0.2 gigahertz, the band width that I am getting is 0.12 gigahertz which is significantly lesser, so this is my problem right.

So, once you start saying that know I want to have control over the band width over which I should be able to broad cast power right, then you cannot do with this L match. So, the L match has 2 degrees of freedom it has 2 components, one inductor and one capacitor right and you need, so to think about the mathematics right and you have some design equations, and there are two unknowns. So, you can at max accommodate 2 equations because, if you have more than two equations you need a third unknown.

So, what are the two equations related to the first equation, the first design equation is related to Q, and the second design equation is related to the centre of frequency. And the Q all to happens to be directly related to the ratio of the load on the source resistance. So, once you have given the ratio of the source resistance, and your given the centre of frequency your done, the design is frozen you cannot do anything to trick the band width or the Q or anything else it is all frozen.

So, what can be do well the way I described at the solution is simple, I need a matching network which has 3 degrees of freedom, which means the need to be 3 components not 2. So, if I have 3 components then I will have 3 degrees of freedom, may be these 3 components are L 1, L 2 and C may be they are C 1, C 2 and L I do not know, and the 3 degrees of freedom are R l by R S Q and omega naught. Now, Q is related to band width, so therefore, you can also say R L by R S band width and omega naught; however, do please.

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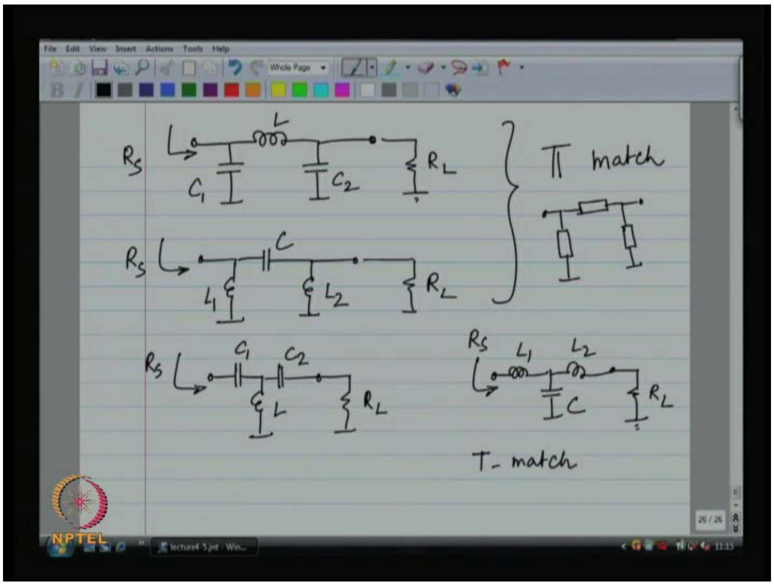

Such matching network could look like this, they could also look like this, you could also have something like this or like this. ((Refer Time: 55:12)) So, these two are called the pi match because, somehow the matching network looks like the capital Greek pi, this looks like a Greek capital pi the letter pi. And the bottom two are called T match because, they looks like the capital T alphabet T, so far today in the class in this particular lecture, we studied the L match which looks like an L, and then there are the remaining 2 pi match and the T match.

And the reason why we will probably will have to go for pi matches or T matches are because, we need an extra degree of freedom the band width. So, with this we are going to close this today’s lecture, we has studied the L match in quite details we also did kind of numerical examples of probably, why you do not want to matching etcetera practical scenario. And I also pointed view towards the motivation of the development of the pi match or the T match, thank you we will close this lecture.

Thanks.