Introduction to Electronic Circuit
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Lecture 35
Small signal Amplifiers (Contd.)

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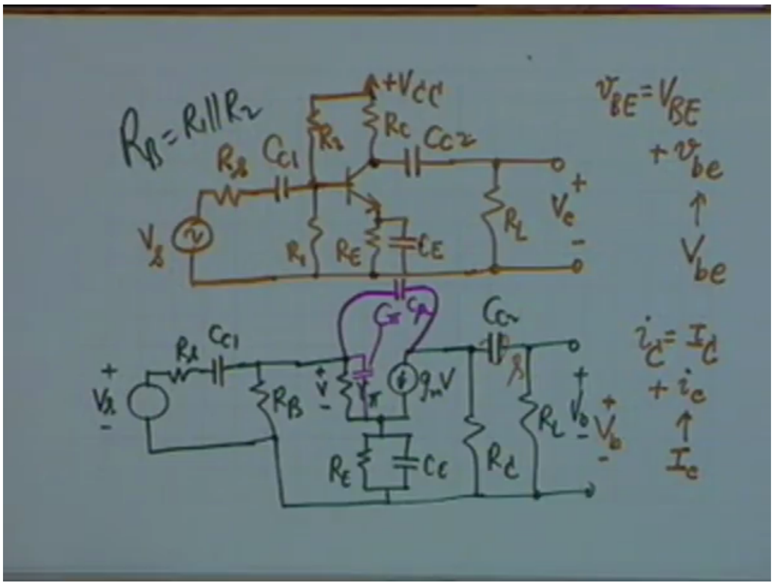

35th lecture and the topic is small signal amplifiers, as I have drawn last time a typical BJT amplifier, a complete BJTamplifier looks like this, let me draw it once at least RE and CE, there is an RC and this voltage is class VCC. The load is coupled to the transistor by means of a capacitor called CC2 coupling capacitor number 2 and this is RL, the actual load the signal voltage is taken from here and obviously this voltage shall be purely incremental voltage of the AC voltage.

Now we have adopted the notation that if I say VBE this is the total base emitter voltage this is equal to the DC base emitter voltage capital V sub capital BE plus small v sub small b small e this is the AC input voltage. Now we shall adopt the notation we have already done that. That was the single part root mean square value shall be denoted by the RMS value of vbe if it is sinusoidal shall be denoted by capital V subscript small b small e.

For example if we are concerned with the collector current i sub capital C, well, it is the sum of I sub capital C this is the DC value plus small i subscript small c it is AC value and the RMS value of this shall be denoted by capital I subscript small c, okay. This is the notation that you shall follow and therefore what should we call this voltage? This voltage root mean square value.

We will only write root mean square values now, it should be called V sub small c then, that is all. It is a voltage of this point with respect to, no, respect to ground because CE is short, CE makes our each short and therefore this is the voltage, wait, okay, VCE or VCG ground is a same thing, so you should call it Vc, simply Vc, alright. And we will note down a polarity, this polarity shall be related polarity, alright.

For example if V sub capital B is positive then you know that V sub small c shall be negative there is a phase change, well, this will be clear in the subsequent discussions then the base circuit is biased by means of R2 and R1 and the base circuit is coupled to the voltage source or current source.

Let us represent this by a general source, a general source has an internal resistance Rs and the voltage if it is AC then we shall say small v subscript small i v input or small v subscript small s and if I want to only write the RMS values. We will write this as capital v subscript small s, we shall follow this discipline throughout. For example the AC base current shall now be denoted by capital I subscript small b that means the root mean square value of the signal voltage.

And as I have repeatedly told you we can divorce signal quantities from DC quantities and therefore we can analyze by means of this small signal model of the transistor. There are 3 capacitor's CC1, CC2 and CE. 2 of them CC1 and CC2 are coupling capacitors, they double the AC to the transistor, this couples the collector voltage to load, so these are coupling capacitors and C sub E is a bypass capacitor, it bypasses the AC to ground, so that nothing drops across R sub E.

Now if I follow the hybrid pi models strictly than my AC incremental equivalent circuit we like this and try to draw with me. What we have is, we are representing every quantity by means of its RMS value. So Vs then in Rs then CC1 the coupling capacitor and then as far as AC is concerned from this point to ground R1 and R2 come in parallel and we have chosen to call R1 parallel R2 as R subscript capital B, RB is the parallel combination R1 parallel R2, Parallel combination R1 and R2, alright, RB.

Then comes the base, from the base to the emitter it is rpi, alright. Then RE and CE, well, there is a parallel combination we will see the effect of this RE and CE this terminal comes here, alright. RE and CE and then this voltage, if I call this voltage as capital V, this voltage is capital V voltage across rpi then at the output you have gm times capital V this is the collector terminal and from collector to ground goes a resistance R sub C and then from the same point collector, a capacitance CC2 goes to RL and this voltage is V sub c or V0 the output voltage, okay.

In order to determine the performance characteristic of this amplifier, that is the amplification property, what we have to find out? By circuit analysis we have to find out V0 by Vs that would be the gain of the circuit, we have to find, in general you see because there are resistance is as well as capacitances this gain would be a complex quantity. It would be a complex quantity either to replace the capacitors by 1 by g omega c.

To be fair to make this circuit at applicable at all frequencies we should introduce the terms the capacitances which are internal with transistor. If this circuit is to represent high frequencies for example we should introduce the Cpi, C pi is across rpi and another capacitor we should introduce between this point and the collector this is Cmui, alright. If we introduced these 2 then this circuit is complete.

It can represent low frequencies it can represent high frequencies it can also represent medium frequencies and the most convenient calculation for gain comes at medium frequencies. At medium frequencies, while the frequencies are defined, medium frequencies are defined as the frequencies neither too nor too high these are frequencies at which the effect of capacitances can be ignored which means that at medium frequencies CC1 , CC2 and CE should act as a short-circuits.

Medium frequencies are those at which CC1 the 2 coupling capacitors and the emitter bypass capacitor the 3 act as short-circuits and the internal capacitances which are very small at medium frequencies they act as open that is Cmui and Cpi they act as open and therefore at medium frequencies which is also called the mid band are equivalent circuit.

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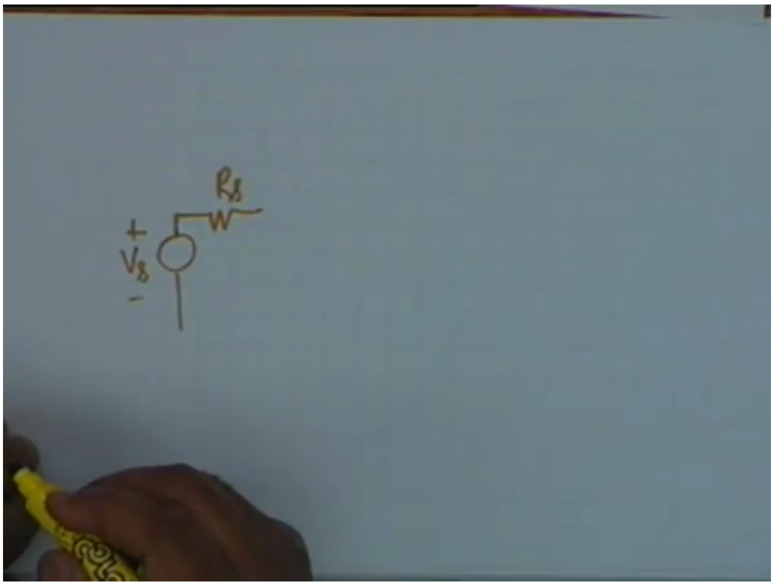

If we follow this carefully our equivalent circuit would be Vs then Rs CC1 will act as a short then we shall have RB in parallel with rpi, now ri comes across RB because RE is assured, CE is assured and therefore rpi comes across RB and this voltage is v, okay. Then we have gmV no capacitances Cpi is ignored, Cmui is ignored and we have gmV in parallel R sub C than the capacitor CC2 also acts as a short-circuit and therefore this is R sub L and this voltage is V0, this is the situation and the mid frequency range sometimes called mid band equivalent circuit, mid band frequency range.

Well, I should mention here and if you plot the gain, that is if you plot V0z by Vs versus frequency Omega then in general for the RC coupled amplifier the curve looks like this. That is at DC again is 0, why is it 0 at DC?

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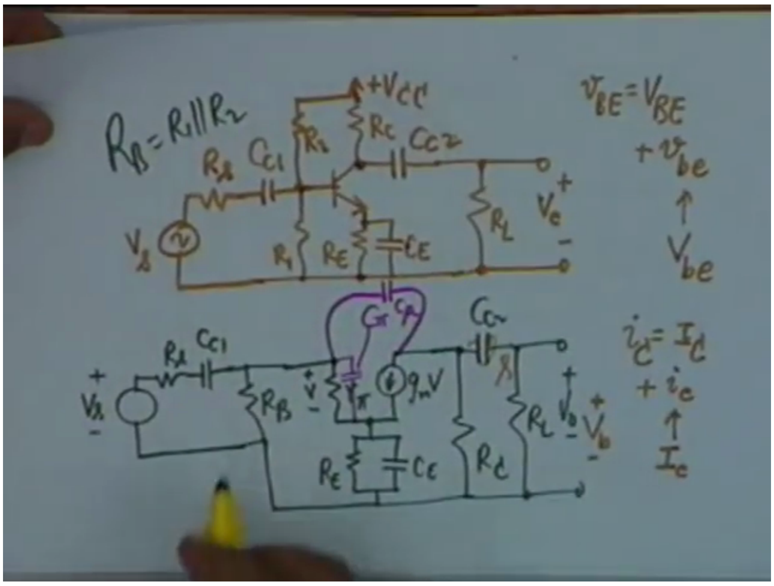

Because this coupling capacitors refuse to pass DC, alright. This coupling capacitor, this coupling capacitor, so at DC nothing reaches the transistor, transistor does not amplifier, alright. That is why the gain is 0. As the frequency increases these 2 capacitors, they become often less and less impedance and therefore signal passes to the transistor and the transistor does amplify, so the gain rises.

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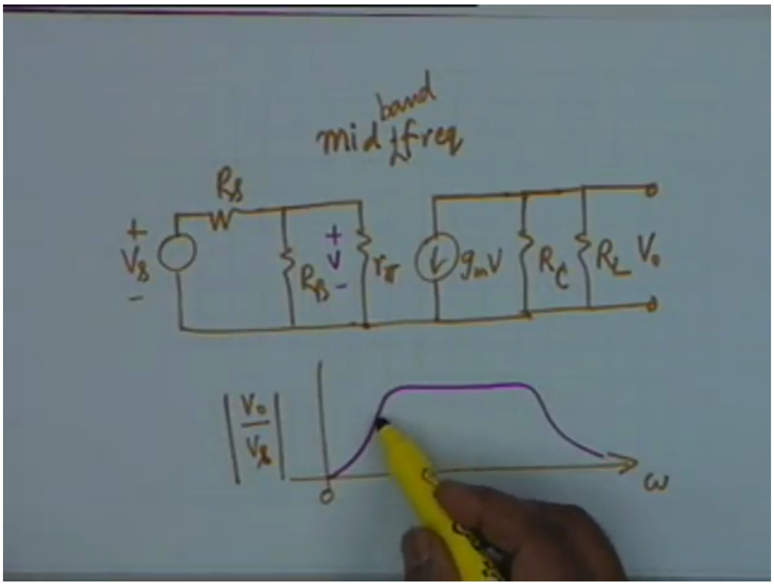

Then around, let us say there is a set of frequencies at which the gain is a constant, the gain can be a constant only if there are no capacitances in the circuit which means that this is the mid band frequency range. This is the mid band, mid band range and then as the frequency is increase the coupling capacitances and the bypass capacitance they remain short because they react the impedance is 1 by Jay omega C.

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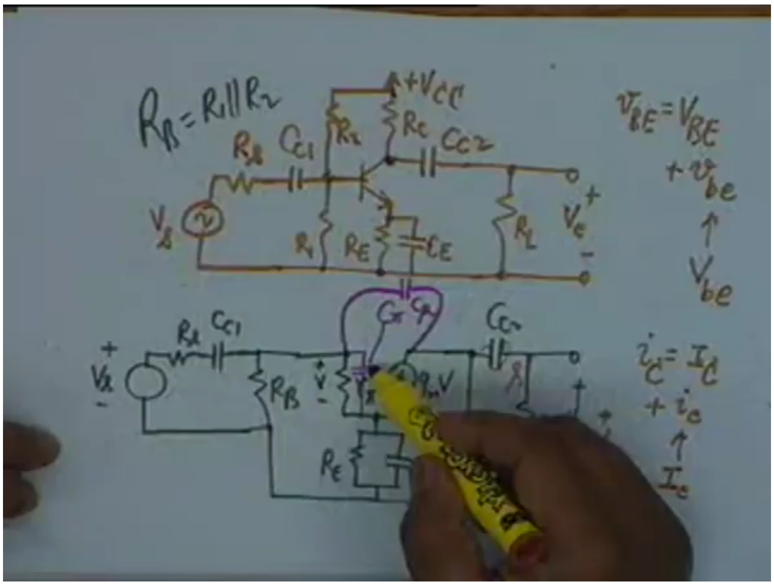

So the higher the alley frequency, the lower is the impedance they remain short but what we had assumed as open that is the 2 internal capacitances Cpi and Cmui they now show their treat and therefore their effect then dominates and it is because of these 2 capacitances that the gain once again falls, alright. So it is a well shaped curve, this region, the region from 0 to the beginning of the mid frequency is denoted as the low frequency region.

And the region the frequency range from the end of the mid band to in finite frequency theoretically is the high frequency band and you know that in such a characteristic not only the mid band gain is important, mid band gain we should denote by A0 but also the 2 frequencies at which the gain falls below the mid band value by 1 by root 2 and therefore this value is A0 by root2 there are therefore 2 frequencies, and we call omega L and the other we call omega H.

Omega L is called a low frequency cut-off this is a frequency and the omega H is the high frequency cut-off that means between omega L and omega H the gain remains 70.7 percent of its mid band value. I was told you that the gain is usually expressed in terms of decibels and decibel gain is 20 log 10 of A and log10 20 log 10 of 1 by root 2 is approximately minus 3 therefore if the mid band value is taken as the reference then this level is 3 decibels below the mid band value.

If the mid band value is taken as 0 decibels then this is minus 3BB this point and this point. Is that point clear? Did I not discuss decibels earlier? Oh, I did not, okay. The gain, you see the gain could be a very large quantity it may vary from 0 right up to let say 10 to the 5 or 10 to the 6 and it is very difficult to represent such a large dynamic range and therefore what you do is, you compress the range by a logarithmic transformation.

For example if A that is from 1 to let say 10 to the 5, then at 1 the value is 0 20 log 10 A and at 10 to the 5 it is simply 100. So what you represent is 0 to 100, instead of 1 to 10 to the power 5.

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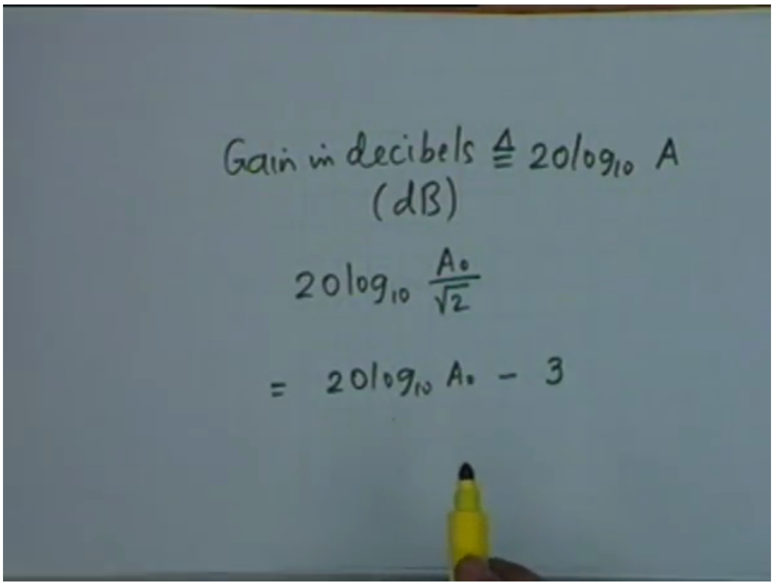

So you compress the range and therefore gain is always in electrical engineering practice, gain is expressed in decibels D E C I B E L S and if is it (()) (16:15) small v capital V the definition is that this is 20 log 10 of gain as a number, alright, 20 log 10 A. And you see if the if the gain is A0 by root2 then it is simply as you know 20 log 10 A0 minus 3 half of log2, log2 is 0.30103, alright. Is this clear? 20 log 10 A 0 minus 20 log 10 of root 2, 20 log 10 of root 2 is approximately 3, actually this 3.0103 we ignore that.

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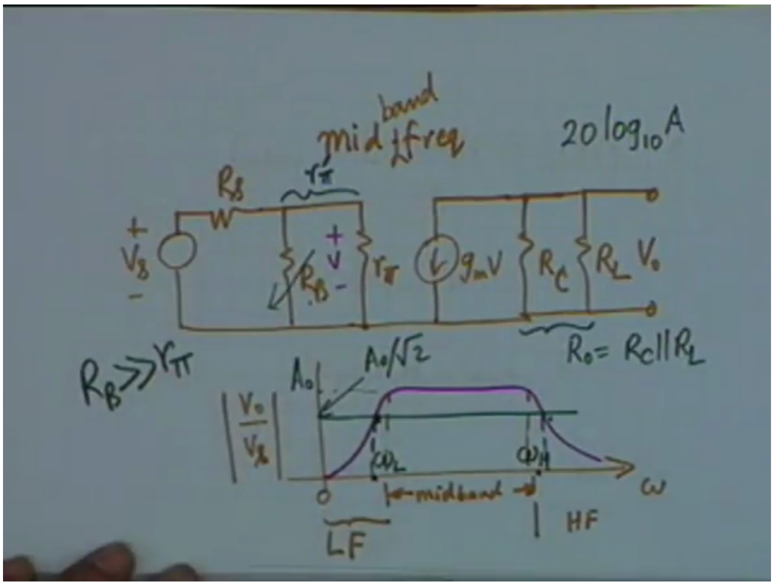

And therefore these are frequencies, omega L and omega H these are frequencies a**t the** at which the gain is reduced by 3 decibels and this omega L and omega H therefore I have got another game, one of the names is low frequency cut-off, high frequency cut-off or they are also called free db points that is the frequencies at which the gain is down by 3 decibels 3 db points omega L and omega H, alright.

We shall calculate what omega L and omega H is for the RC coupled amplifier but at the present time we are concerned with the calculation of the mid band gain, mid band frequency range by definition is 1 in which the effect of all capacitances can be ignored which the coupling in bypass capacitances are shorts and the internal capacitances Cpi and Cmui are open, alright.

If that is the case then this becomes the equivalent circuit and it simplifies the equivalent circuit by noting that RC and RL are in parallel and we can is this by R0, let us call this R0 is equal to RC parallel RL. You also notice that RB and rpi are in parallel and if RB and rpi are comparable then you can combine the 2 and you can call this resulting 1 as rpi prime that the usual design consideration is that RB is usually much greater than rpi, rpi is the order of the k and Rb would be of the order of the 10k and 1 is to 10 can be considered as much greater than.

And therefore in our subsequent calculations we shall ignore the effect of RB. If needed if your design is such that RB is comparable rpi then you simply combine the 2 that is you take instead of rpi you take rpi prime is a parallel combination of RB and rpi and therefore our equivalent circuit then simplifies to the following.

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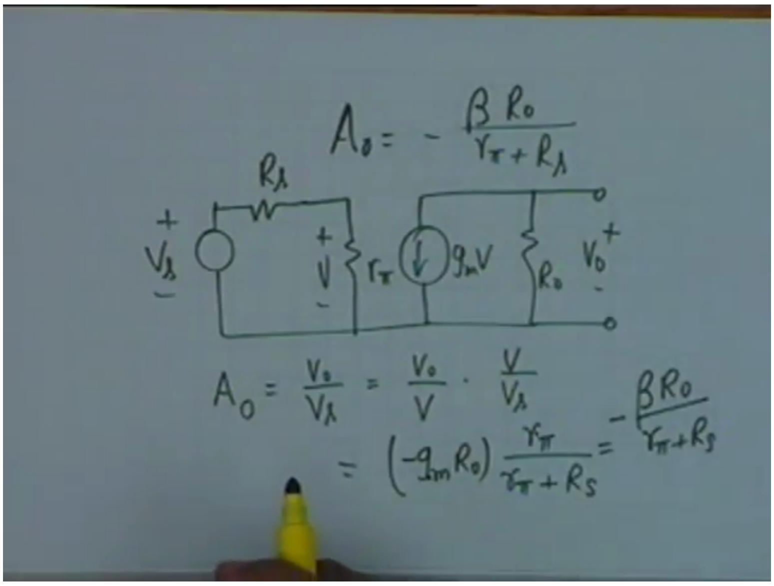

We have Vs Rs, Rs is the source resistance then we have rpi this voltage is V then we have gmV and simply R0 this is equal to V0 and you notice that the gain A, we are calculating the mid band gain and therefore I would subscript 0, A0 is v0 by Vs which I can write as v0 by V multiplied by V by Vs, is it okay? V0 by Vs I have written as V0 by V multiplied by V by Vs.

What is V0 by V? You see this current flows through R0 and therefore V0 will be equal to minus gmV times R0 and therefore V0 by V is simply minus gmR0 and V by VS is simply a potential division that is rpi divided by rpi plus Rs you see that gm and rpi come as a products now the product is beta and therefore I can write this as minus beta R0 divided by rpi plus Rs you can see what happens if capital RB it cannot be ignored then rpi shall simply be replaced by rpi prime which is the parallel combination of rpi and RB, so this is a simple formula for the mid band gain that is minus beta R0 divided by rpi plus Rs.

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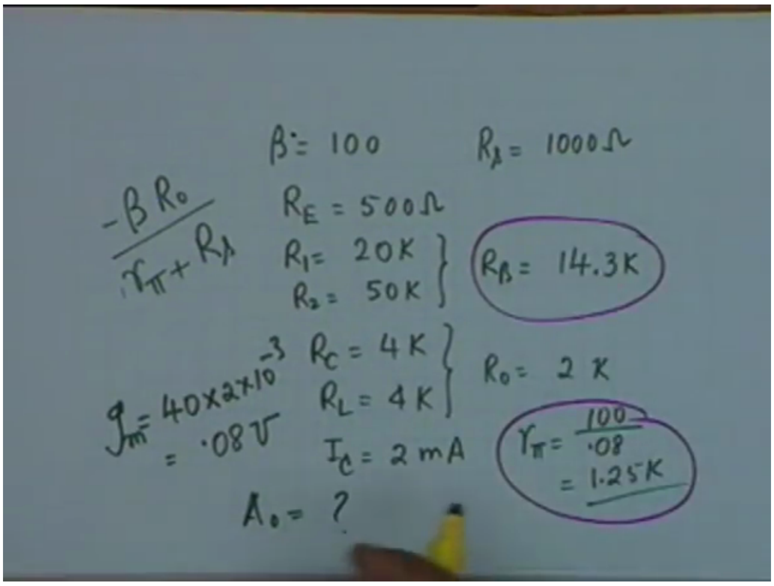

Let us take some typical values, for a certain transistor 2m series, beta is typically 100, the source resistance typically is 1k 1000 ohms. RE is of the order of 500 ohms, RE does not enter into the mid band calculation because RE is (()) (21:58) by capacitance which is sufficiently large R1 is 20k, R2 is 50k therefore RB is how much? 20 times 50 divided by 70 that is 14.3k, alright.

RC is let say 4k, RL is 4k, so that R0 is simply equal to 2k, R0 is a parallel combination of the 2 and I sub C the collector current is given as 2 milliampere, alright. You are required to calculate the mid band theory A0. Obviously for mid band gain calculation minus beta R0 divided by rpi you understand the meaning of the minus sign because the output voltage is out of phase with the input voltage, okay. rpi plus Rs therefore indeed the value of rpi, we have been given the value of beta.

And we know what is I sub C is, that is the quiescent collector current and therefore can calculate the value of gm, gm is 40 times I sub C therefore 40 times 2 times 10 to the minus 3 which is equal to 0.08, is it okay? And therefore what is rpi then beta divided by gm therefore 100 divided by 0.08, have I made a mistake? So how much is this? 1.25k, alright. That is correct 1.25k and you notice that indeed 1.25k rpi is small compared to RB which is 14.3, 1 order of magnitude difference is good enough for much greater than. So we can indeed ignore this.

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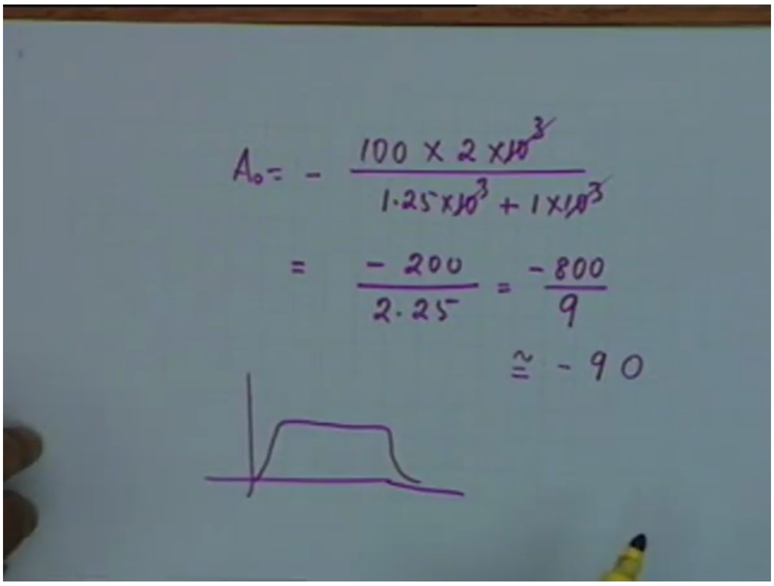

Now if we substitute this value, so we can indeed ignore this, now if we substitute these values in the mid band gain and I get A0 as equal to minus 100 beta, R0 is 2k 2 times 10 to 3 divided by rpi which is 1.25 times 10 to the 3 plus Rs which is 1 times 10 to the 3, so 10 to the 3can be ignored this is minus 200 divided by 2.25. In this minus 800 by 9, yes and as you can see this is approximately equal to minus 90, alright.

Approximately it is slightly less than 90, 89 point something but this is the typical mid band gain, you can get a gain of 90 to 100 and if you couple another stage you can get 8100 in 90 times 90, alright. Many large gains are indeed possible. Now let us look at, it is the mid band situation, mid band situation as I said is a situation in which the gain remains approximately a constant, why does it remain constant? Because effect of capacitances can be ignored, alright.

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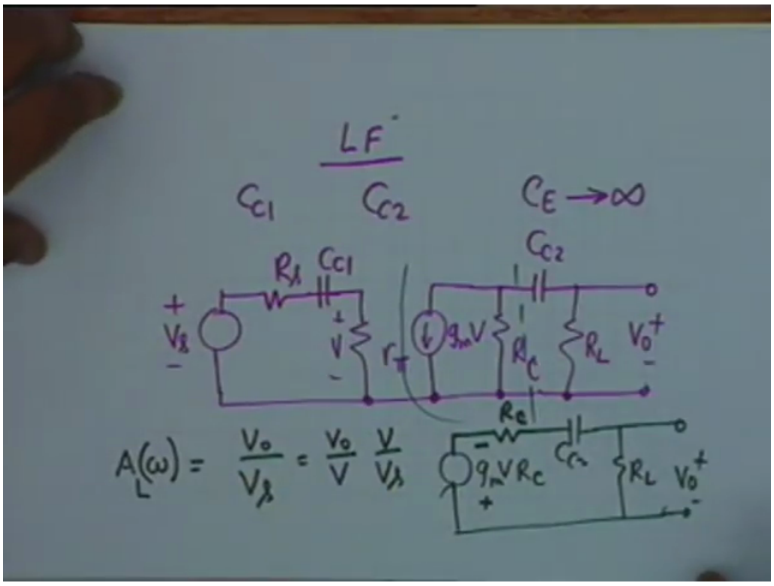

Let's look at the new frequency situation, what happens at low frequencies? At low frequencies the internal capacitances of your transistor can be ignored but the coupling capacitances must be taken into account and also the bypass capacitor. Now since there are 3 capacitances to be taken into account, 3 capacitances CC1, CC2 and CE circuit analysis becomes a bit complicated.

Also 1 tends to get lost into mathematics of the algebra of the situation 1 tends to get loose site of the physical situations, so what we will do is, for an engineer it is very important, it is very convenient to consider one at a time, one effect at a time. We shall be shall be a little more prudent, we shall be a little more flexible and say 2 at a time, let us take the effect of CC1 and CC2 into effect.

Which in effect means that CE we are assuming go to infinity, the largest possible CE we put there and therefore we look at the effect of CC1 and CC2 (()) (27:18) and if you draw the equivalent circuit then the RMS value of the signal Rs then there is a CC1 the coupling capacitance, we have the rpi and this voltage is V. You see the advantage of having V instead of current I sub B.

Then we have gmV and we have gmV in parallel with Rc then we have the second coupling capacitor CC2 and the load resistance RL this is V0. Now unlike the mid band situation we cannot combine RC and RL because CC2 is not a short it offers appreciate all impedance, impedance can be comparable to that of RC and RL therefore we cannot consider this but we can do one thing very interestingly we can replace this part by (()) (28:30) and therefore what we can do is than RC and RL will come in series, you see the point.

So what we can do is this part I can write as gmV times Rc, this is the open circuit voltage with what polarity? Minus plus then the (()) (28:51) resistance is RC then we have CC2 and we have RL, the output circuit can be represented like this and this is V0, alright. Let the input circuit remain as it is. We have to calculate the gain, the gain A, now A is a function of frequency Omega.

So we say A function of frequency, alright. And since we are considering no frequencies we say AL omega, this L stands for low frequency gain. In the previous case when we calculate the mid band gain we should have written a subscript of m but 1 prefers to write A0 this is conventional, at mid band gain where it is a constant you write A0. So AL omega now is V0 by Vs and this is the circuit that has to be analyzed now.

Input part is this, output part is this and the analyses can be done by inspection just by looking at the circuit because you see V0 by Vs can be written as V0 by V multiplied by V by Vs.

Now let us look at this circuit once again and calculate these 2 quantities separately now equivalent circuit let us draw it again Vs, Rs, CC1, rpi and this voltage is V, then you have, no I am sorry, gmVRc is a voltage generator now with this polarity minus plus and Rc, CC2, RL and this is V0. You can see that V0 is equal to minus gmVRc, alright. Minus gmVRc then a potential division RL and RC in series with CC2.

Therefore it would be RL divided by RL plus RC plus 1 over g omega CC2, is it okay? I write this is my inspection, okay. Now I can do a bit of simplification, you see minus, let us write V0 by V this is what I want, I want V0 by V, so let us write V0 by V this is minus gm, look at the same simplification I have RC RL then for the denominator let me take RL plus RC out, alright.

Then I get 1 by 1 plus 1 j omega CC2 RL plus RC, is it all right? Now do not you see that this is simply the parallel combination of RC and RL and therefore I can write this as minus gm R0 divided by 1 plus now I introduce a term omega 12 by j Omega? I introduce a term omega 12 where I define omega 12 as 1 over CC2 RL plus RC. You see the definition is, that it is inverse of the time constant of the circuit.

What is the time constant? Product of capacitance and resistance, RC and RL are in series and therefore the time constant of the output circuit is given by CC2 RL plus RC and the reciprocal of that I express I give the symbol omega 12 then my V0 by V becomes minus gmR0 divided by 1 minus now I have take j up 1 minus j omega 12 divided by Omega, alright. This is the low frequency gain as far as the output circuit is concerned.

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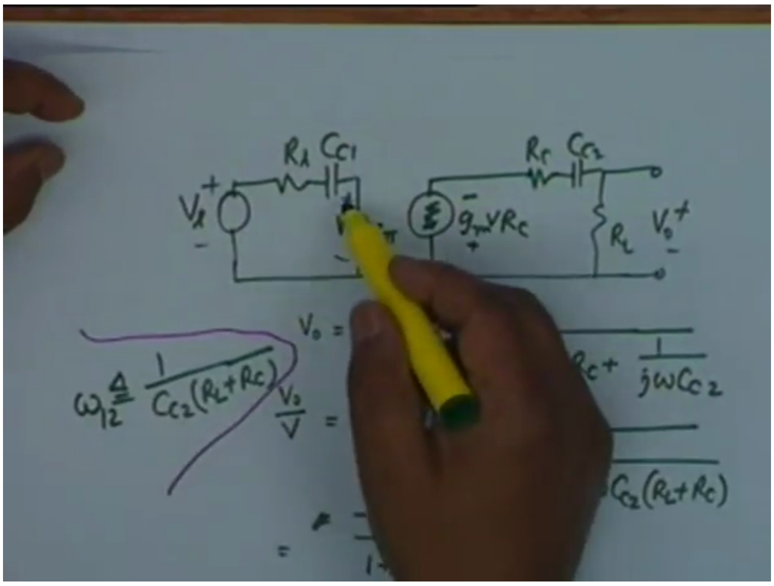

We have however a task of finding V by Vs and if you notice this circuit as I have done earlier V by Vs is simply a potential division between rpi and Rs and CC1.

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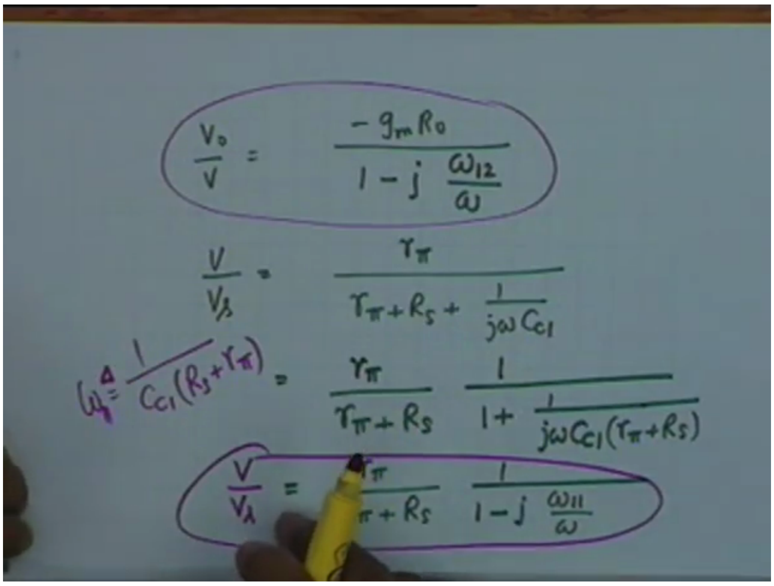

And therefore I can also write that down by inspection that is rpi divided by r pi plus Rs plus 1 over j omega CC1, this I now write as rpi divided by rpi I take this out, alright. And then I can write 1 divided by 1 plus 1 over j omega CC1 rpi plus Rs, any objection? Is that true? Have I distorted anything? Not yet, alright. So I prefer to write this in the form rpi divided by rpi plus Rs 1 minus j, 1 by j is minus j and then I write omega 11 divided by omega, alright.

Omega 11 divided by omega is omega 11 is now defined as the time constant of the input circuit, reciprocal of the time constant of the input circuit which means CC1, input circuit is CC1 in series with Rs plus rpi, alright. This is omega 11 is defined as the reciprocal of the time constant of the input circuit, alright. Now if I substitute these 2 values that is V0 by V this expression and V by Vs this expression and I multiply the 2 then I get V0 by Vs that is the overall gain.

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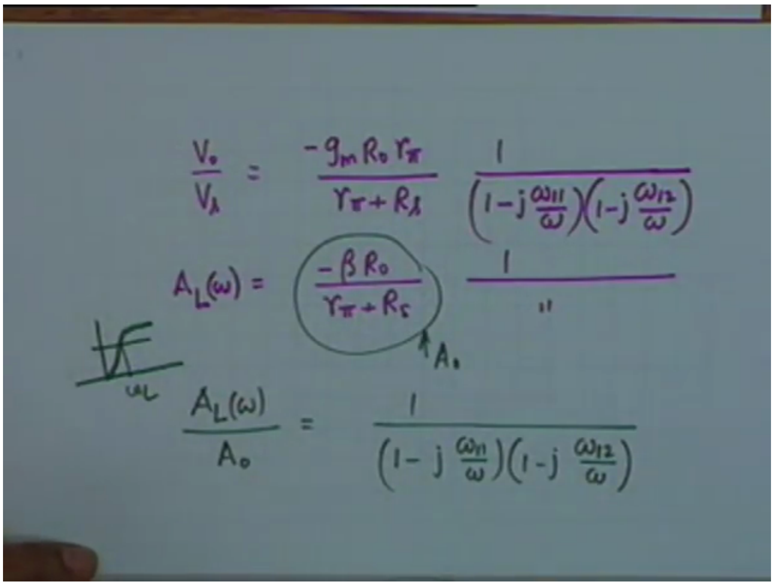

And this obviously V0 by Vs becomes equal to, if you notice carefully minus gm R0 I think the constant term of the other expression rpi given by rpi plus Rs, alright. Then I have 2 terms 1 minus j omega 11 by omega 1 minus j omega 12 by omega, is that clear? And if you notice the constant term here you see that gm rpi is beta and therefore this is minus beta r0 divided by rpi plus Rs times 1 over these 2 terms.

This is AL omega the low frequency gain as a function of frequency. What do you recognize this as? This is the mid band gain that is A0 and therefore the normalised gain that is Al omega divided by a 0, if we normalise again with respect to A0, it is simply given by one by one minus j omega 11 by omega 1 minus j omega 12 by omega, it is a product of 2 terms like this and you notice that if omega, what is the value at Omega equal to 0?

Obviously this is 0 and as omega increases, the gain increases, when omega becomes large compact omega 11 as well as omega 12, gain becomes 1 it simply becomes 1, right? And therefore it does explain the rise of gain from 0 to the mid band value A0. The question now is where is omega L? What is the frequency at which the gain is 3BB down the mid band value.

3 would be less than the mid band value or 1 by root 2 times the mid band value. Well, strictly what we have to do is, we have to take the magnitude and equate that to 1 by root 2 you will get a quadratic equation omega to the power 4, engineers do not like to solve equations electrical engineers in particular try to find a shortcut, what we will do is the following.

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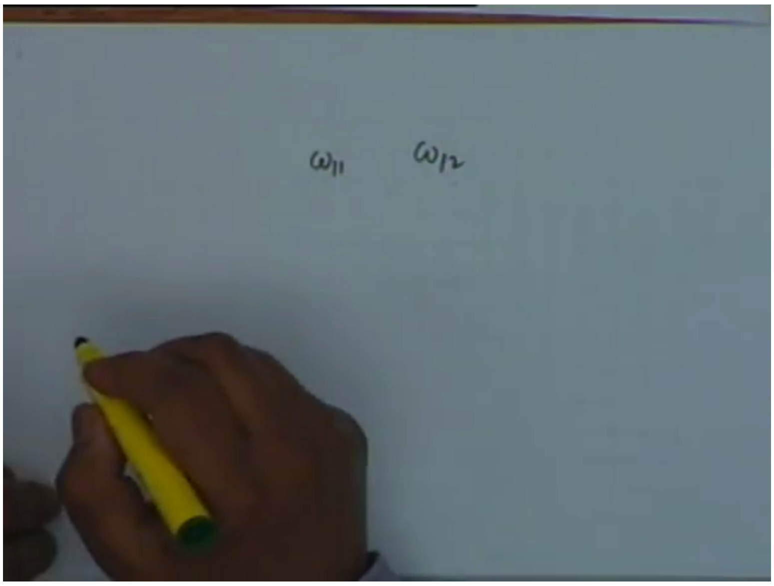

He says alright I have 2 frequencies omega 11 and omega 12. Suppose they are several times apart from each other, let say omega 11 is greater than omega 12 and maybe greater than is let say of the order of 3 times, what is the square of 3? 9 and much greater than means in electrical engineering is 1 is to 10.

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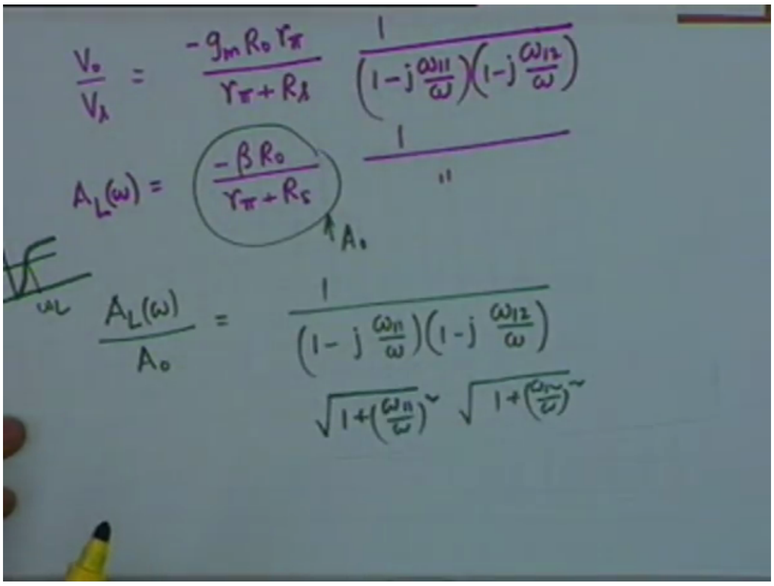

Now in this case you see when I take the magnitude, what is a magnitude of this term? Square root of one plus omega 11 by omega square, now the other term is 1 plus omega 12 by omega square. If one of these terms is approximately 10 times the other term then obviously one can ignore the other term and this qualitative argument it can be strictly put on quantitative terms.

This qualitative argument says that which one...

“Professor -Student conversation starts”

Student: because you are multiplying…

Professor: Yes.

Student: subtracting or adding sir.

Professor: Okay.

“Professor-Student conversation ends”

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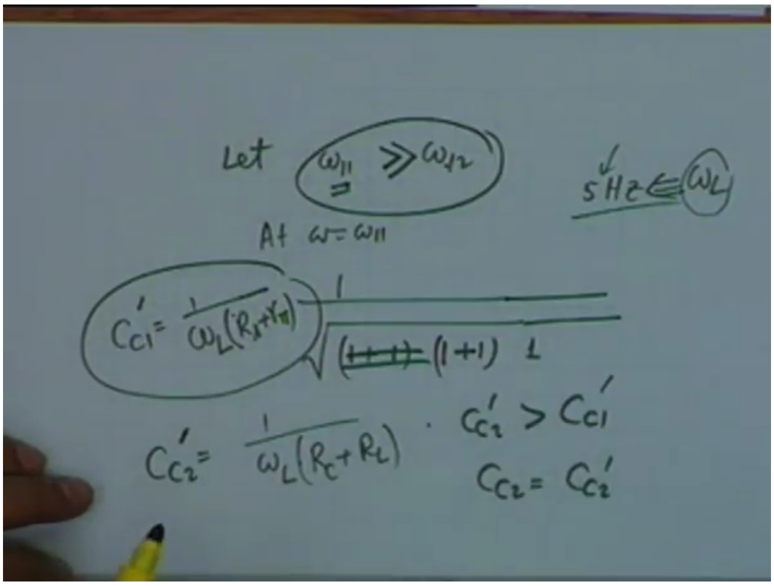

Let us say that omega 11 is much greater than omega 12, let this be the case, okay. Then at omega equal to omega 11, what is the value? What is the magnitude? Magnitude is square root of 1 plus 1, okay. And the other one is approximately 1? And therefore omega 11 determines the low frequency cut-off, is that clear? This is the point that I was making, if one of them is much greater than the other, I will come to what is much greater little later.

If one of them is much greater than the other than the greater one determines the low frequency cut-off. Now how much greater? In practice 3 times is good enough because the quantity is involved here not as omega 11 but omega 11 squared, alright. If one is 3 times the other, 3.3 times approximately than the square shall be one order of magnitude apart and therefore 3 times greater is good enough, alright.

So what one does is the following, given a circuit, if you see that omega 11 and omega 12 before by at least a factor of 3 and you take the higher one as the low frequency cut-off, as have shown in here, the higher one, alright. On the other hand if they are comparable, if this much greater than sign does not hold, suppose one of them is 10 hertz and the other one is 15 then we have to solve this equation exactly, the quadratic equation there is no other way but that is hardly even the case.

What an engineer does, engineers like new IIT graduates they design, so you are told by the boss we want a high fidelity stereo amplifier whose low frequency cut-off is let say 5 hertz, you are told that audio frequencies go from 16 hertz to 16 kilohertz but if your amplifier satisfies only this the drums, the left-handed (()) (42:45) in particular which is very rich in low frequency that sound is lost, alright.

If you want a very high fidelity stereo amplifier then you must go down to about 5 hertz is the low frequency cut-off alright. You have to design an amplifier with 5 hertz cut-off then what you do is, you find CC1, okay. You find CC1 prime let say from whatever the specified omega L is, what is omega L if low frequency cut-off is 5 hertz?

“Professor -Student conversation starts”

Professor: What is the value for omega L?

Student: 5.

Professor: No, omega L.

Student: 10pi.

Professor: 2 pi times 5, you must not big mistake.

“Professor-Student conversation ends”

So what you do is, from the specified Omega L you find out CC1 the coupling capacitor 1 which would be omega L times, what is the resistance? Rs plus rpi you calculate this capacitor, alright. Then you get calculate the other capacitance CC2 prime, are you following the design process? Given if the omega L is specified you calculate the necessary values of CC1 and CC2 each satisfying this value of omega L.

How do you find CC2? Not I am not putting CC2, I am putting CC2 prime because the design values will be different, alright. So what I do is CC2 prime, I also calculate from the same omega L, I say omega L, what is the resistance as I said? RC plus RL then from these 2 I find out which one is larger. Suppose CC2 prime is larger, if this is larger CC2 prime is better than CC1 then what I do is, I put CC2 equal to CC2 prime whatever the calculative value is, alright.

And I increase the other capacitor that means 5 times 3 is a good figure but to be on the safe side I increase 5 times, what does that mean? It means that omega 11 shall now be at least 5 times less than omega 12 and that is what omega 12 shall determine below frequency cut-off, is the design process clear? We shall illustrate this by means of an example, mind you we have not talked about CE at all so far.

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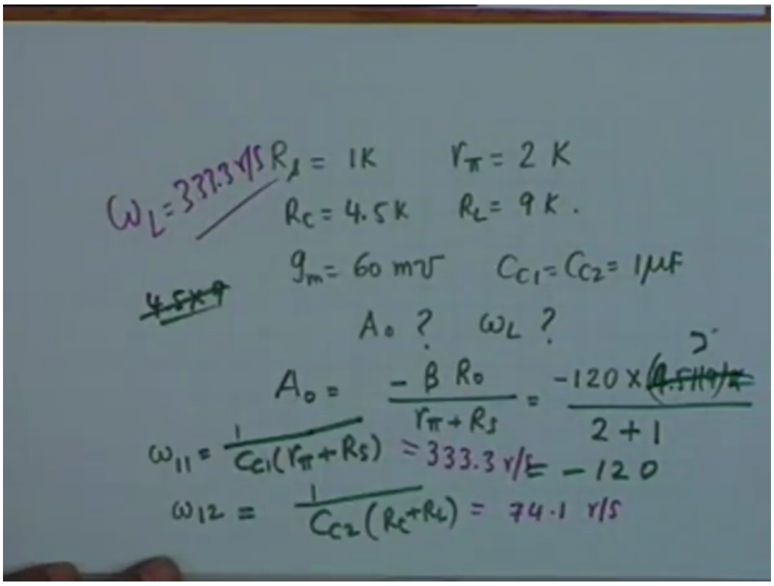

What will be the value of CE? We will consider that also a moment but let us consider example first. Suppose you are given amplifier in which Rs is 1k, the source resistance is 1k the same design data but to give variety let us say rpi si 2k, Rc is 4.5k and RL is 9k, gm is let us say 60 millimoh, what does this correspond to? I sub C, yes, so what is I sub C? 1.5 milliampere.

If gm is specified then you know what is I sub C, if I sub C is specified then you know what is gm, gm is 60 milli moh and CC1 and CC2 both are specified as 1 microfarad. You are required to find out 0 that is the mid band gain and omega L? Alright this is not a design problem, this is a analysis problem. Now obviously what you can do is A0 is minus beta, if you remember R0 divided by rpi plus RS and you simply substitute.

Is beta given, no beta is not given, rpi and gm are given, so beta must be 120, is it right? 60 times 2 is 120, k and millimoh they cancel each other 120 R0 is 4.5k parallel 9 K divided by rpi is given 2 (()) (47:35) in k because it will cancel 2 plus Rs is 1, so I can forget about k. What is the parallel 4.5 and 9? Oh! Its 3, so 3 by 3 this is simply minus 120 than with the given CC1 and CC2 calculate omega 11 and omega 12.

Omega 1 1 as you know is 1 over CC1, rpi plus Rs and omega 12 calculate as 1 over CC2 Rc plus RL and during this calculation one finds that omega 11 comes as 333.3 radiance per second and omega 12 comes at 74.1 radiance per second. Well, this is about 5 times, is not that right? This is about 5 times this and therefore your omega L is equal to 333.3 radiance per second, alright.

This was the example of analysis, now if you want to design we will consider the design problem along with that of emitter bypass capacitor and it is at this point that we should take a 5 minute break, we reassemble at 500.