Analog Electronic Circuits
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Lecture – 63
Multi-Transistor Amplifiers: Cascode Amplifier (Contd.) – Numerical Example (Part A)

Dear students, welcome back to our online NPTEL certification course on Analog Electronic Circuit. Myself, Pradip Mandal from E and EC department of IIT Kharagpur. Today we are going to talk about Multi Transistor Amplifiers; namely, in fact this is continuation of our previous lectures. So, today we will be talking about Numerical Examples of Cascode Amplifiers.

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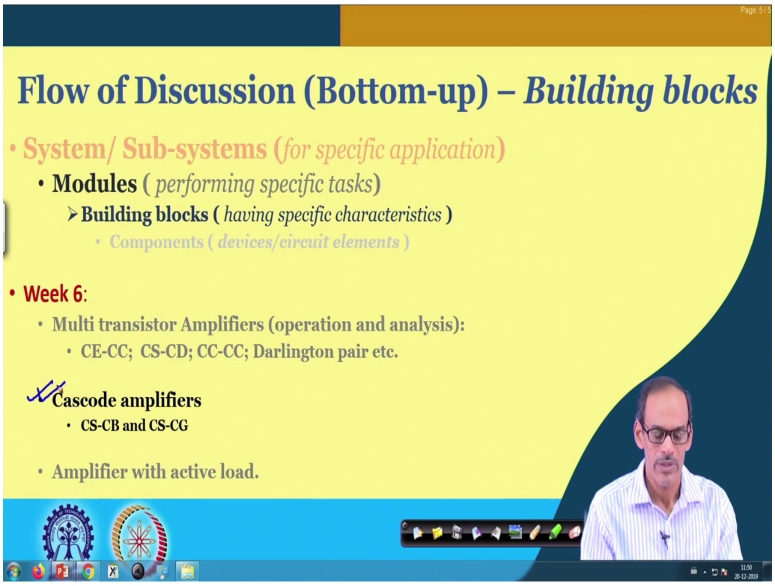

So, compared to our overall plan, we are in week 7, 6. And as I said that we already have discussed about the analysis and construction of cascode amplifiers and today we are going to detail of some numerical examples.

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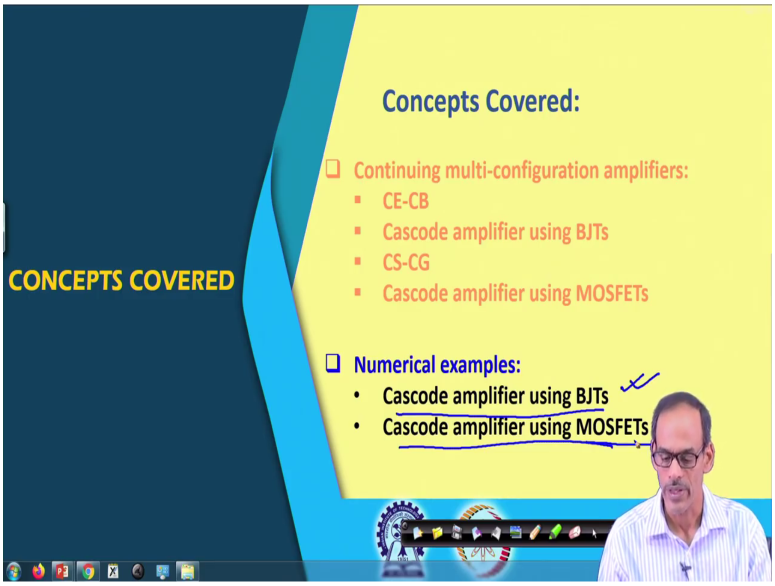

So, the coverage of a today's lecture it is primarily cascode amplifier using BJT and cascode amplifiers using MOSFET. We do have two very in depth numerical problem we have said, and most likely we will be discussing on this BJT based on cascode amplifier. So, that gives you some idea that why we go for this cascode amplifier compared to a simple CE amplifier.

And the MOSFET counterpart, what I mean is that similar kind of cascode amplifier can be constructed using MOSFET; and there also we do have very detailed numerical problem. But based on the time availability, I may be giving you some hint, but you have to work it out, ok.

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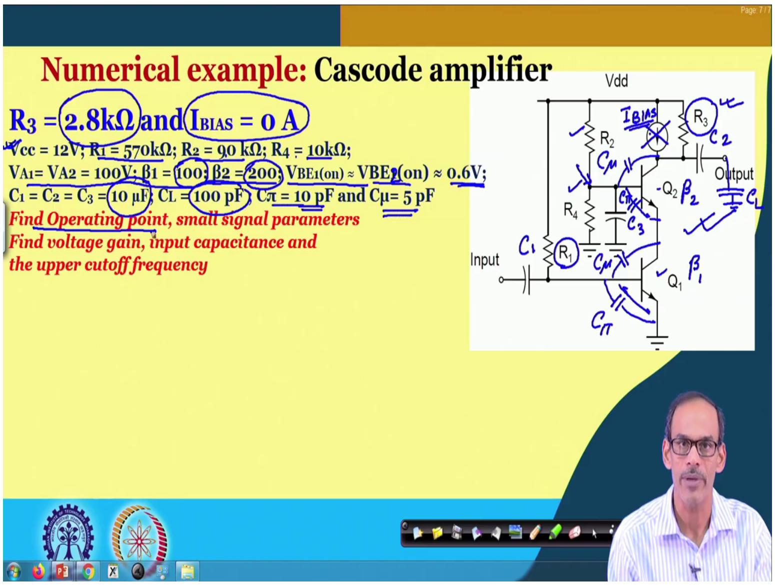

Coming to the cascode amplifier using BJT, so here we do have the numerical problem. This circuit, the cascode amplifier we already have seen before. And today we are giving you numerical value of different bias components, supply voltage, and then the device parameters are given here; similar to whatever the parameter it has been discussed earlier. Namely, early voltage of both the transistors, we are assuming it would be 100 volt; beta or transistor 1, it is 100. Just for a change we are using beta of transistor 2, beta 2 it is 200; on the other hand V B E of transistor 1 as well as transistor 2 both are approximately 0.6.

Now, the different coupling capacitors, signal coupling capacitors or DC decoupling capacitors; C 1, C 2 and then C 3 we are assuming all of them are equal, relatively high around say 10 micro Farad. On the other hand we are assuming that we do have a load capacitance C L connected at the output port, it is say 100 pico Farad. And for both the transistors C pi and

C mu from base to collector are given here; and let me assume that both the transistors C pi, C mu are equal, so we do have C pi here and then C mu here, they are given here.

In the bias circuit on the other hand we assume that, the value of this resistance it is 2.8 kilo and the bias current here I bias for the first part of the example, let you consider it is 0; which means that, we do not have this current source, instead we do have a passive element R 3 and it is value it is 2.8 kilo ohm. Now based on the bias registers we do have here, and then the potential divider here constructed by R 2 and R 4; we do have the other biasing arrangement. And from that we can find the operating point of the two transistors. So, let we first find the operating point of both the transistors and then we will go for the small signal parameters, ok.

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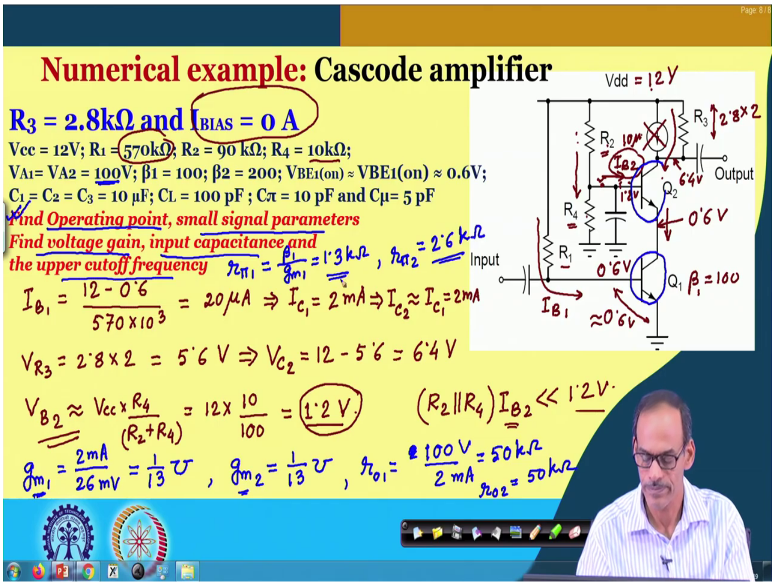

So, to start with let we yeah, let me use different color here. So, to start with we do have here it is supply voltage is 12 volt and then we do have R 1 which is 570 kilo ohm and then we do have the V B E on is approximately 0.6 volt drop. So, from that we can calculate what is the I B 1? In fact, I B 1 it is 12 volt supply minus V B E of 0.6 divided by R 1, which is 570 kilo ohm, so that gives us 20 micro ampere. And we do have beta here which is 100, from that we can get collector current I C 1 equals to 2 milli ampere.

In fact, same collector current is flowing through emitter of transistor 1 sorry transistor 2. So, from that we can also say that I C 2 is approximately equal to it is emitter current, which is equal to I C 1 and that is 2 milli ampere. So, we can say that this current 2 milli ampere of current, it is also flowing through R 3 and we do not have this current source; as we said that the bias current we are assuming here it is 0. So, the drop across this R 3, it is 2.8 multiplied by 2, right. So, the voltage drop across this R 3 equals to 2.8 k into 2 milli ampere, so that gives us 5.6 volt; which implies that, the voltage at the collector of transistor 2 V C of transistor 2 equal to 12 minus 5.6, so that is 6.4 volt.

On the other hand we do have a potential divider constructed by R 2, R 4 and then 12 volt supply. So, from that we can say, the voltage at the base of transistor 2 ignoring the this base current compared to whatever the current we do have within this potential divider; we can say that, V B 2 it is 12 volt, that means in the V c c multiplied by R 4 divided by R 2 plus R 4. So, that is 12 multiplied by 10, we do have 10 here and we do have 100 here, so that is giving us 1.2 volt.

As I said that we are assuming this I B 2 it is very small compared to whatever the current is flowing through transistor 2 and transistor 4. In other words before we connect the base terminal, the voltage it was 1.2; obviously once we have this current flowing, this the base voltage it will be slightly dropped. But still we can approximate that the voltage it will be remaining there; because the drop across this the R 2, terminal equivalent resistance R 2 in parallel with R 4 due to this I B 2 which is in fact, 10 micro ampere.

How do I get 10 microampere? Collector current is 2 milliampere divided by it is beta, so that is the I B 2 is 10 micro ampere. So, this is very small, very small compared to 1.2 volt and hence we are considering this V B 2, it is approximately 1.2 volt. So, we do have 1.2 volt here, and then the voltage coming here it is 1.2 minus 0.6, so this voltage it is 0.6 volt. So, we do have 0.6 volt here V B 1 and then we do have 1.2 volt here and then we do have 6.4 volt here. So, that keeps of course, this transistor it is in active region, this is also in active region. So, the circuit it is not having any problem.

Now, so we obtain the operating point or the both the transistors. And let us see what will be the value of small signal parameters namely g m, then r o and R pi of the two transistors. So, let me yeah, I do have blue color now. So, we can say that g m 1 which is corresponding I c current, which is 2 milliampere divided by V T 26 milli volt. So, this is equal to 1 by 13 mole. So, likewise we can get m 2, g m 2, it is also same 1 by 13 mole; because the collector currents they are same, the output resistance r o 1 of the transistor Q 1, it is coming from the early voltage here and then 2 milli ampere of current.

So, early voltage it is 100 divided by 2, so that gives us r o 1 equals to 50 kilo; in fact r o 2 it is also 50 kilo ohm. And using this g m 1 and g m 2 you can say that, r pi of transistor 1 equals to beta 1 divided by g m 1; which is equal to 1 by sorry 100 divided by g m, it is 1 by 13, so that gives us 1.3 kilo ohm. On the other hand r pi 2, since beta is 200 here; it becomes 2.6 kilo ohm. So, now, we you obtain the small signal parameter from the DC operating point and then using that, we can find the voltage gain and then input capacitance, maybe the upper cutoff frequency which is of course, our interest.

So, what is the voltage gain? So, try to remember these values of the small signal parameters to get the voltage gain.

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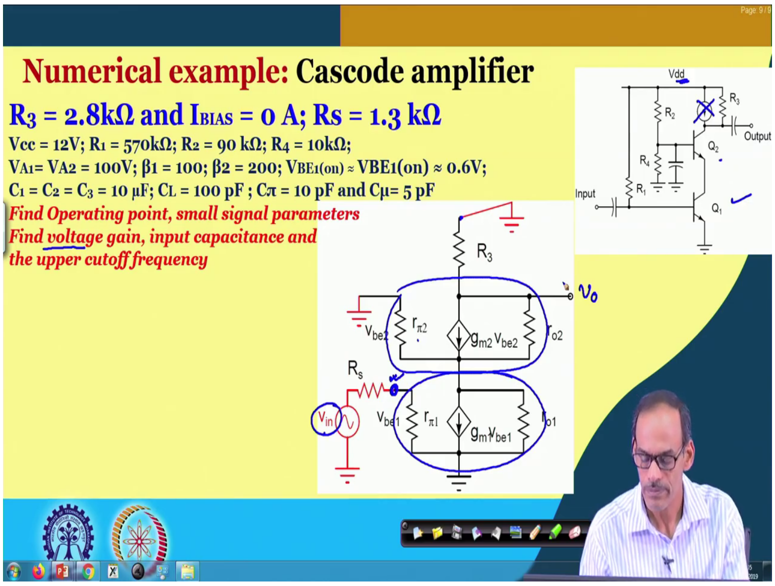

Let me I think I do have, and the next slide I do have the small signal equivalent circuit, yes. So, we do have the small signal equivalent circuit for Q 1 sorry, for Q 1 we do have the small signal model here. So, likewise Q 2 the small signal model it is here; and we know the value of different parameters, so let us try to see what is the voltage gain of this circuit. And of course, this current it is zero or even if it is DC, the small signal wise will be ignoring this; R 3 on the other hand it is connected to the DC supply voltage here which is a AC ground.

So, the voltage coming at this output in terms of V in is our main interest. Before we go into primary input to primary output, let us starts from; start from here and then try to see what is the gain from base or transistor 2 sorry transistor 1 to the primary output of the amplifier, ok.

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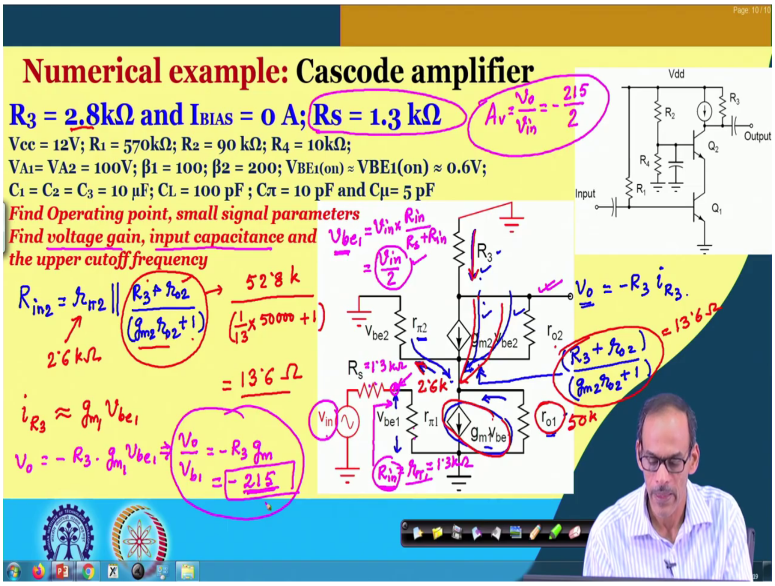

So, what is the voltage gain we get? So, we do have V be applied here and then we do have this current is flowing and this current it is partly coming from r 1; some part of the current is coming from r pi 2 and then this whatever the combined current it is flowing through this device.

So, these three currents I should say, together it is giving us the total current. And depending on the value of this resistance, this resistance and whatever the equivalent resistance we do have; we will be getting the current branch out. And so, whatever the currents we do have here, they are essentially coming from this R 3 and that develops the corresponding voltage here. So, if I know this current flowing through R 3, then if I multiply with R 3 that will be giving us the v o. So, I should say that, v o equals to minus R 3 into whatever the current you do have, let me call this is i R 3.

So, if you look into this circuit and try to see what is the impedance and in fact, you may recall; the expression of this impedance of this kind of spatial active circuit it is R 3 plus r o 2 divided by g m 2 r o 2 plus 1. So, this is the equivalent resistance looking at the emitter. In addition to that we also have this resistance. So, these two resistances together, it is giving us the input resistance of the this second transistor or you may call it is common base circuit. So, R in 2 is equal to r pi 2 - coming in parallel with R 3 plus r o 2 divided by g m 2 r o 2 plus 1. And then of course, you can see that how much the current is flowing through this R 3 that can be obtained.

Now let us see this part numerically and you may recall that this resistance it is 2.6 k. And now let us try to see, what is the numerical value of this one? We do have R 3 which is 2.8 and r o 2 it is 50 k. So, this is 52.8 k divided by g m 2 r o 2 plus 1. So, what is the g m 2? We do have 1 by 13 and then we do have r o 2 which is 50 k; 50 into 1000, plus 1 probably we can ignore and so this is giving us. In fact, I do have the calculation done myself for you, let me see what is the value I got. So, it is very close to 13. In fact, precisely this is 13.6 ohms only. In fact, if you compare this part, this is much higher than one; and here also we can say this is much higher than R 3.

So, if I do that approximation, then I will be getting this part equals to 1 by g m 2. So, no under g m 2 is 1 by 13 and that is why you are getting this resistance is very small. So, since this resistance, this part it is very small, namely only 13.6 ohms; this resistance on the other hand it is 2.6 k and this resistance of course, this is 50 k. So, I should say g m 1 into v b 1, it is primarily flowing through this device. As a result, the current flowing through R 3; namely signal current flowing through R 3 I, which is denoted as i R 3. So, this is can be well approximated by g m 1 v b e 1. So, the output voltage, the output voltage v o equals to minus R 3 multiplied by g m 1 into v b e 1. Or we can see that output voltage v o with respect to base voltage of transistor 1 which is v b e, so that is equal to minus r 3 into g m 1.

So, that gives us again of, again I do have the calculation 215, so that is the voltage gain. Now this is the gain from the base terminal or transistor 1 till the output point. Now if I consider the r is and if I consider this R s is equal to 1.3 k. Why did I take 1.33 k? Just for simplicity that, the input resistance here in this circuit call R in which is r pi 1 and we know that this is 1.3 k. So, if I take this R s is also equal to 1.3 k; then you can say voltage coming at the base or transistor 1 is basically V in multiplied whatever the attenuation offered by R s and then R in. And since both of them are equal; so we can say that v b e, so that gives us v b e of transistor 1 equals to v in multiplied by R in divided by R s plus R in. So, numerically it is coming v in by 2.

So, since v b e it is just half of the primary input. So, now, combining this expression or this value and this equation what we can get that; overall gain A v define as the primary output divided by primary input, so that is minus 215 divided by 2. So, g m, so the overall gain, we are getting it is 107. Now next thing is that the input capacitance. So, let me clear, but then you must remember this values; whatever the values we obtain here, input resistance and so and so.

And try to then calculate the input capacitance.

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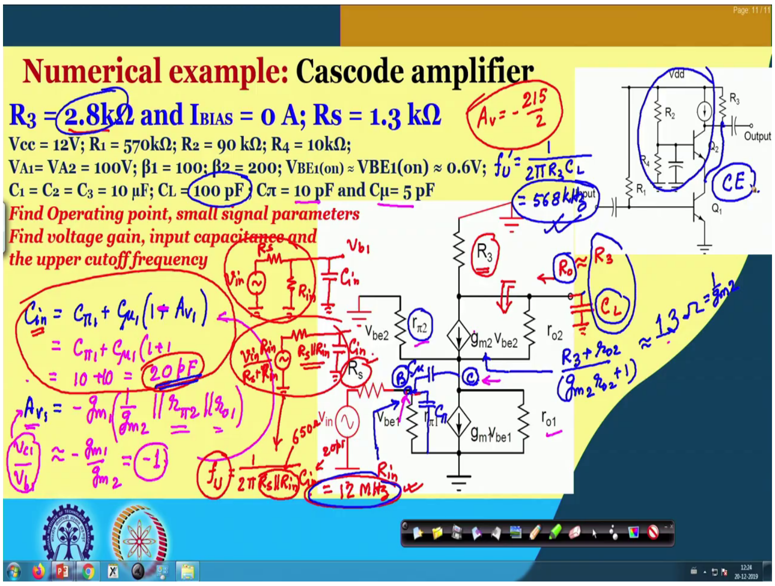

So, C in, input capacitance of this entire circuit looking at the base or transistor 1 which, is equal to we do have the C pi and then we do have the C mu. And then C mu of course, it is bridging the base and the collector terminal of transistor 1. So, naturally this C in, it will be C pi 1 plus C mu 1 multiplied by 1 plus A v 1. So, what is A v 1? It is the gain coming out of the transistor 1, while the load here it is connected. And we know this impedance the load here; load here it is r o sorry R 3 plus r o divided by g m 2 r o 2 actually r o 2 plus 1. And this is of course we already have seen that, this resistance it is 13 ohm. And compared to this 13 ohm, this is very small; in fact, you can directly see that this is 1 by g m 2.

Now once we have this g m 2, this impedance and then the voltage gain A v 1 equals to; basically the gain starting from the base terminal here, base terminal here to this collector terminal while it is driving this load of 1 by g m 2. And it is gain it is g m 1 multiplied by 1 by g m 2. In fact, this g m 2 it is in parallel with r pi 2 and r o 1 also; but then these two parts they are very small, so naturally this is approximately equal to g m 1 divided by g m 2 and this is 1, because both the g m’s they are 1 by 13. And how do we define this gain? This is actually v collector voltage divided by v base voltage of transistor 1, ok.

So, since this, this is 1; in fact I should have a minus sign here, if I am retaining this minus sign. So, that gives us the input capacitance by considering this value here, we are getting C pi 1 plus C mu multiplied by 1 plus 1; and C pi here it is 10 and this is 5, so that gives us 10 plus 10 equals to 20 pico Farad. So, the input capacitance here it is 20 pico Farad. Now this is of course, one of the important point that, the gain of this cascode amplifier you may recall if I consider R s; and then the overall gain, it was minus 215 by 2.

So, you may be wondering that this gain it is not much different from normal common emitter amplifier, so why we go for this cascode amplifier? The answer it is line in this example also, answer it is having two types of circuits; I should say based on the two types of circuits, the answer may be 2. One of this answer it is that, in case if this R 3 it is passive and this resistance is relatively small; then we may not get much advantage in terms of gain. But then if you see the value of the input capacitance, it is quite small; and so the pole getting created by this R s and input resistance and then the C in, that pole it is getting situated at a very high frequency.

So, if I consider the circuit here along with the C in; what you are having the circuit equivalent circuit is, v in followed by R s. And then we do have the equivalent resistance of R in, followed by equivalent capacitance C in and this is the v in. The voltage here it is the v b 1. So, this circuit it can be redrawn by considering this entire portion as equi Thevenin equivalent source; and then we do have Thevenin equivalent resistance which is R s in parallel with R in followed by C in.

So, this resistance and then this C in, it is forming. So, this is v in multiplied by R in divided by R s plus R in, so that is the Thevenin equivalent voltage source. So, this circuit this R c circuit is creating a pole; the pole coming due to that it may eventually limits the bandwidth of the circuit. So, the corresponding circuit the bandwidth may be defined by this frequency say; f U due to this R s and R in, which is 1 by 2 pi multiplied by this R s in parallel with R in into C in.

And if you see that this resistance, numerically this is, in fact this is equal to 650 ohm and this is we do have 20 pico Farad. So, that gives us a cutoff frequency which is equal to close to 600 or something, this is this is quite high. In fact, this is equal to 12 mega Hertz; which means that, this pole, this pole defined by R s in parallel with R in and C in it is quite high. And when you say quite high, we must compare with the other possible candidate defining the upper cutoff frequency, which is essentially the output resistance of the circuit. So, output resistance of this circuit, which is actually defined by this R 3; because the resistance coming from the lower portion it is quite high, so R o it is primarily R 3 and then the C L.

So, what is the value of this the corresponding upper cutoff frequency defined by this R o and C L? Did you call this is f u dash, which is equal to 1 by 2 pi R 3 into C L and R 3 it is given here, C L it is also given here; and if you put the corresponding value, the corresponding cutoff frequency I was getting 568 kilo Hertz. So, if I compare 568 kilo Hertz and then to 12 mega Hertz, definitely this defines the upper cutoff frequency.

So, this is of course you may say that, then upper cutoff frequency it is coming from R 3 and C L; so what is the advantage of having this smaller value of this capacitance? Now to really appreciate this point, what you can do? Let we compare the performance; namely the voltage gain and the upper cutoff frequency for a standard CE amplifier, where we can probably, we can eliminate this part and we can directly connect the collector part, collector of Q 1 to R 3. And then you see that whatever the simple CE amplifier we get, what is its corresponding gain. So, in the next slide we will be talking about that.

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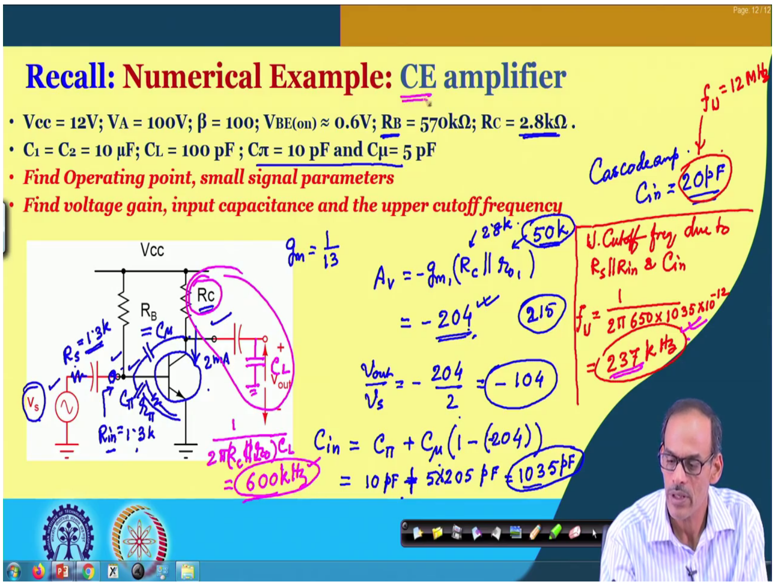

So, we do have say simple CE amplifier and intentionally I have taken the value of different bias elements, particularly R B, it is same as the previous case; and also this R c it is same as R 3, namely 2.8 kilo. Rest of the things are very similar, namely this the C pi and C mu. And you may recall that, the same similar kind of analysis can be done and the corresponding collector current here it is 2 milliampere, and for this case of course, the corresponding g m it is 1 by 13, and the voltage gain A v equals to it is g m of the transistor, and then R c in parallel with r o; whatever this r o we do have and this is 50 k and this is 2.8 k.

So, this voltage gain is of course, from the base terminal to the output terminal. And here we are if you put the corresponding value, we are getting minus 204, if I consider this one; otherwise it may be coming close to 215. But whatever it is, if I consider this resistance; then I will be getting 204. And so, the voltage gain if I consider R s here, the voltage gain of the circuit and if I consider this R s is 1.3 k, which is same as the input resistance R in which is essentially this r pi and r pi it is 1.3 k.

So, if I consider R s is 1.3 k, R in is also 1.3 k; so the gain or attenuation from this point to this point it is 0.5, and from here to here we do have the gain of 104. So, the overall gain v out by the primary input say v s equals to minus 204 divided by 2, this 2 it is due to this attenuation here. So, that gives us 104. So, still it is ok, the voltage gain of this, this CE amplifier it is same as very close to whatever you obtained for the cascode amplifier.

Now next point is that, if I consider the effect of input capacitance on the bandwidth; namely if I consider C pi and C mu, then what kind of what kind of upper cutoff frequency we are getting. Namely if we calculate the C in which is C pi plus C mu multiplied by 1 minus this gain, whatever you say 204 with a minus sign. And then we do have here C pi equals to 10 pico Farad and then we do have C mu equals to 5 and then we do have 205, right.

So, this is plus. So, that gives us how much, 1035 pico Farad. In contrast to contrast to this value, the for cascode amplifier; we got C in, it was 20 pico Farad only. So, now, it is expected that this large value of this input capacitance, it will affect the upper cutoff frequency due to this R s, R in and then the C in. So, let us calculate what is the upper cutoff frequency coming from the C in and then R s and R in?

So, we can say that, the upper cutoff frequency due to, cutoff frequency due to R s in parallel with R in and the input capacitance. So, if I say that this is f u equals to 1 by 2 pi; R s and R in parallel, so that gives us 650 ohm multiplied by 1035 pico Farad. And I have done the calculation, I got the value here it is. So, I got the value close to 237 kilohertz. Now this is very important, earlier we obtained; if I consider 20 pico Farad, the corresponding cutoff frequency you obtained there it was only, it was rather 12 mega Hertz, now it is becoming 237 kilo Hertz.

Now if I consider the other candidate defining the upper cutoff frequency, namely this R c and the C L. And we have seen that the corresponding cutoff frequency defined by R c and C L, namely 1 by 2 pi R c into C L it was; in fact, if I consider this R c in parallel with r naught, this was giving us close to 600 kilo Hertz. So, if I consider R c in parallel with r o, which is the output resistance multiplied by the C L in the denominator. So, this cutoff frequency and if I consider this cutoff frequency, definitely this will be defining; because this is lower than this one.

So, as a result the to summarize that, if I compare the common emitter amplifier and then cascode amplifier; we can say that, for both the circuits the gain it is very close to each other.

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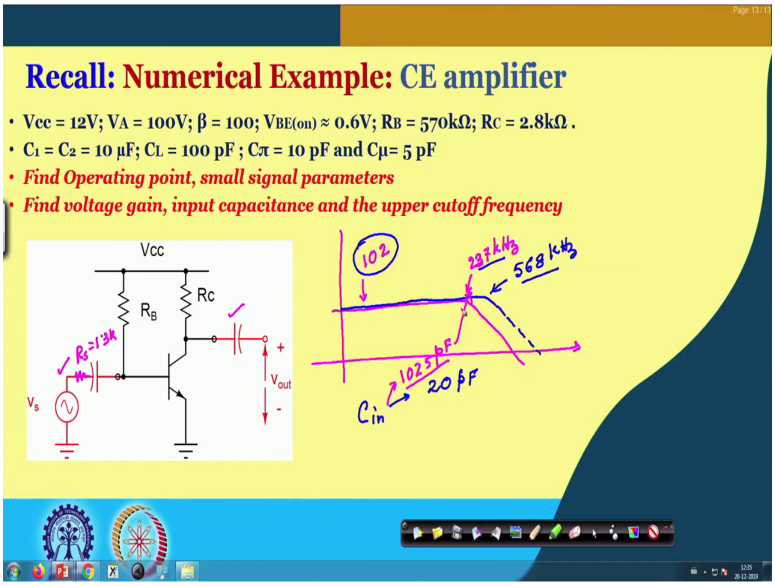

So, the gain if I say that, for CE amplifier gain may be, overall gain it is 102; if I start from here till this point considering the source resistance of 1.3 k. And then the upper cutoff frequency you have obtained here, it was 237 kilo Hertz. On the other hand if I consider cascode amplifier, the gain it was very close slightly higher slightly higher. Note that this is in ratio we need to convert into d v and then the bandwidth here it was remaining; the bandwidth it was defined by the corresponding output resistance and the C L. And this was around 5, something 5 568 kilo Hertz.

And this difference as I say that, primarily due to difference in C in for C in, for cascode it was 20 pico Farad; whereas, for CE amplifier it was 125 pico Farad, so that gives us the lower bandwidth, ok. So, let me take a break and then we will come back to similar kind of comparison again.