Analog Electronic Circuits
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Lecture – 64
Multi- Transistor Amplifiers: Cascode Amplifier (Contd.)-Numerical Examples (Part B)

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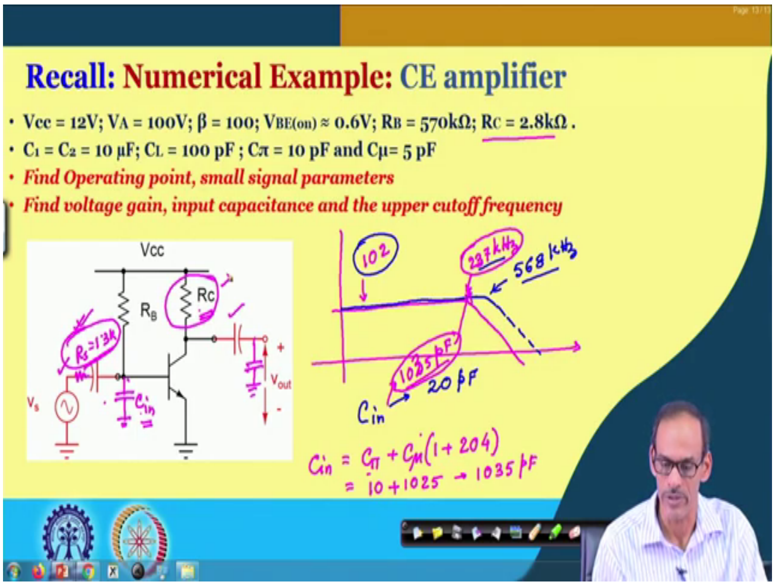

Welcome back after the short break. Before I going to the next topic I must see here that this calculation of the C in I did a small mistake hear, it should be 135 because C in equals to C pi plus C mu into 1 plus 204 and so, here we do have 5 and also here we do have 10. So, I miss this 10 part. So, 10 plus 1025. So, that gives us 1035 pico Farad capacitance.

So, it should be 1035, this calculation remains the same ok. So, far what we have discussed that the advantage of cascode amplifier with respect to standard CE amplifier and namely what you have seen is that in case if you are retaining this passive element for both the cases, then gain wise we do not get much advantage. But then what we have seen that in case if we have the input resistance and the source resistance together forming a significant significantly low frequency pole due to this large value of the C in, then we have seen that the cascode amplifier it is giving some advantage.

Now it may be a situation where this resistance it may be small or whatever the cutoff frequency we are obtaining by this Rs and then C in and R in that may be beyond the upper cutoff frequency defined by RC and the C L. So, far such case you may say that then what is the advantage of cascode amplifier. In fact, cascode amplifier it is having two types of advantages; one is extending the bandwidth as we just now we have discussed particularly in presents of significantly large value of the source resistance, the other advantage which is commonly used is that the increasing the gain drastically.

So, to get the higher gain so, far whatever the example we have considered R C it was only 2.8 k. So, the increasing the capability of the cascode amplifier to increase the gain, it has been blocked by the low value of this RC. Namely if you put a cascode amplifier then its output resistance it is quite high compared to this passive element.

So, to demonstrate the capability of the cascode amplifier to increase the gain first of all let we consider a different situation instead of having this RC if you put some active circuit their, probably then the advantage of the cascode amplifier particularly for enhancing the gain it will be quite prominent.

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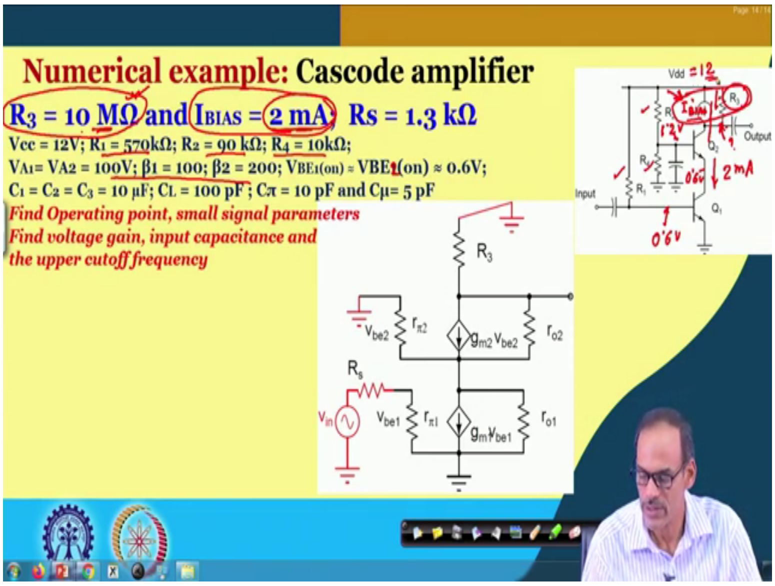

So, to demonstrate that in the next slide what we are going to do we will be getting almost the same numerical problem except we do have a change here. Particularly, if you see the value of this R 3 instead of 2.8 k now we are going to take a big value say 10 mega ohm. On the other hand since we have do have 12 volt supply here and if we are expecting this R 3 it will be supplying the entire 2 milliampere of current; obviously, then drop across this resistance it will be quite high to avoid that problem we consider this I BIAS.

So, I BIAS it is supporting this 2 milliampere of current. So, then you may say that why do you have this resistance at all. Well for all practical purposes while you are implementing this circuit it may be having finites conductance of the current source and whatever the value you have taken here it is feasible particularly if you implement this part by something called cascode current source.

So, later we will be talking about the implementation of the cascode current source for the time being let you assume that the bias circuit we do have here it is having two parts; one is 2 milliampere of ideal current source in parallel with 10 mega ohm resistance. And rest of the things we are keeping same namely R 1 R 2 and then R 4 and so and so and all the bias all the early device parameters also we are retaining same sorry this should be V be 2.

So, what you are expecting from the lower side as we have discussed based on the resistance here based on the (Refer Time: 06:12) R 2 and R 4, the current flow here quiescent current flow here it is 2 milliampere, the voltage here it is 0.6 volt DC the voltage here it is 1.2 volt. So, the voltage here it is 0.6 volt and the voltage coming here of course, we have to see what will be the corresponding voltage.

In fact, if you see the value of the resistances here and if I say that the current here it is 2 milliampere it is getting supported by this bias current, then natural question is that if the current flow through this R 3 it is 0 then drop across this one it will be 0. So, naturally the output voltage it will be 12 volt.

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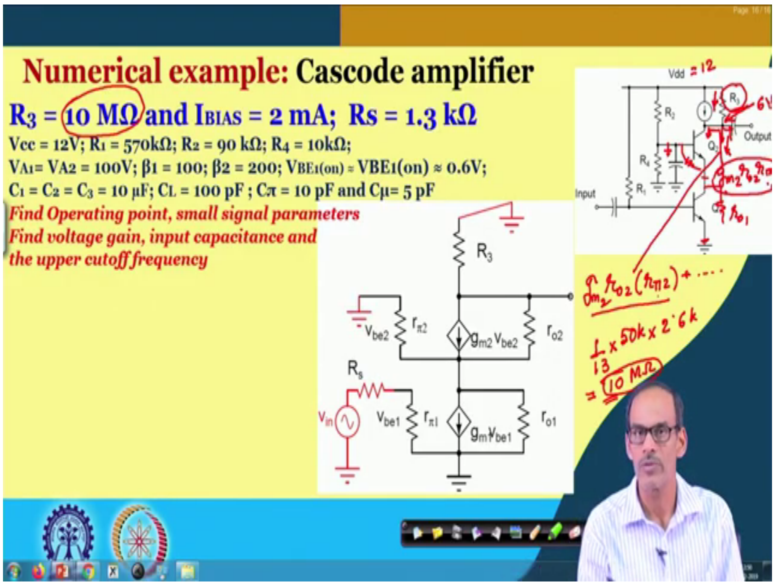

On the other hand if I consider practical circuit and let me use the analysis slight analysis here. If I consider the resistance of this part in fact, this resistance equivalently you can see the value of this resistance it will be roughly gm 2 r o 2 multiplied by r pi 2. If I ignore say or if I consider this node it is connected to ground. So, if I calculate this value of course, for DC we cannot say this is ground, but for the time being let we tolerate such kind of things and if you do so, the corresponding in fact, this r pi is coming in parallel with r o 1.

So, whatever it is the if I consider this resistance here it is r gm 2 r o 2 multiplied by r pi of transistor 2 plus may be smaller entities over which this term it is dominating and if you put the numerical value here particularly if I say this is 1 by 13, this is r o 2 it is 50 k then r pi 2 it is 2.6 k that gives us 10 mega ohm ok. In fact, this is the reason why we have picked up this 10 mega ohm it is not only feasible, but it is also a meaningful value and if I consider the practical value of this resistance, then what about the little current it will be flowing here that current we will also be consumed by the equivalent resistance there.

As a result this R 3 and then whatever the resistance we are expecting here since they are equal. So, that will make this 12 volt and the ground here in fact, getting divided by R 3 and this equivalent resistance and hence the voltage DC voltage coming here it is you can approximate that this will be 6 volt.

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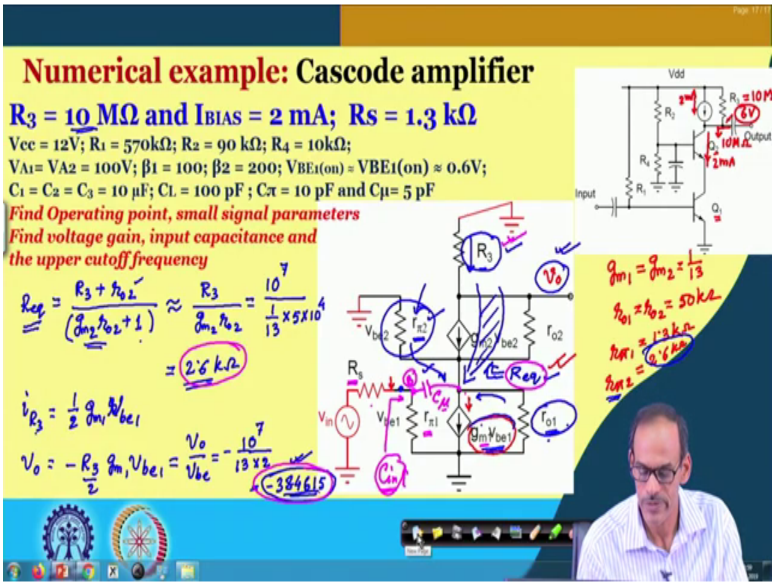

So, in summary if I consider this is 10 mega ohm and the equivalent resistance of this part it is 10 mega ohm and the ideal current here it is 2 milliampere, this is also 2 milliampere. So, then this voltage it will be 6 volt. In fact, this 6 volt of course, we do have some assumptions. And So, there is there may be a scope of debate. So, whether those things are correct or not, but whatever it is we do have this voltage it is maybe in the near vicinity of 6 volt keeping transistor 2 as well as transistor 1 in active region of operation.

So, we can say that for all practical purposes both the devices are in good condition and hence we can move to small signal equivalent circuit. Now in before we go into the small signal equivalent circuit, I like to recall that value of gm 1 and gm 2 both are 1 by 13 then r o 1 and r o 2 both are 50 k and r pi of transistor 1 it is 1.3 k and r pi 2 on the other hand it is 2.6 k right. So, with that if I try to see what is the voltage it is coming here in the small signal equivalent circuit. So, suppose we do have V be voltage here. So, the current flow here it is gm 1 into V be now this current it is coming from r o 1.

So, part of the current it is coming from ro 1, then we do have r pi 2 and also we do have this circuit supplying the current and based on this current here we do have the current flowing through R 3. So, to find the value of this current flowing through R 3 we need to know what will be the relative value of this resistance, we need to find what will be the resistance coming from this circuit and also this ro 1. So, we already have the numerical value of r pi 2 and ro 1, but then let us see what is the equivalent resistance coming from this circuit.

So, this r equivalent as you may recall this is R 3 plus r o 2 divided by gm 2 and then r o 2 plus 1. So, R 3 it is quite high compare to r o 2 and this part it is quite high compared to 1. So, we can as well considered this is R 3 divided by gm 2 and ro 2. In fact, if you put the value here namely 10 mega ohm 10 to the power 7 divide by gm 2 which is 1 by 13 and then ro 2 it is 50 k 5 into 10 to the power 4. So, that gives us 2.6 k ohm. In fact, that is how I have picked up the value. So, this r equivalent it is same as what is a numerical value we do have for this r pi 2.

So, compared to this two resistances this resistance and this R equivalent if I ignore if I consider this resistance is quite high. So, I can see half of this current it is flowing through this part and the other half the current is flowing through this r pi 2 and hence this current flow through the R 3 which is iR 3 is equal to half of gm 1 into r V be 1. So, that give us the output voltage v o equals to minus R 3 into this iR 3 which is gm 1 by 2 into vbe 1. In fact, that gives us vo divided by vb e equals to minus gm 1 it is 1 by 13 and then we do have 2 in the denominator and numerator we do have 10 power 7 and in fact, this value if you see. So, we do have.

So, if you calculate this value, it will be coming roughly minus 384615 it is a big number right. You may recall compared to the a normal CE amplifier the gain it was just a 204. So, compared to that this is very high the basic you know basic philosophy how we get this gain, it is the even though we do have very high resistance here of say 10 mega ohm, we are able to successfully you know flow this at least half of the current through this resistance as a result it is developing a large voltage.

So, once we have this voltage gain then of course, the main advantage it is very clear, but of course, we have to keep in mind that the moment we increase this resistance that also have increase this resistance namely 2.6 k and incidentally that also has increase the miller factor coming for the C mu and what is the consequence? In the corresponding C in got increased.

So, this C in got increased because the miller factor of the C mu got increased now. So, yes we got the advantage, but we need to really calculate whether we made some significant amount of damage on the upper cutoff frequency defined by the input capacitance C in and Rs and R in ok.

So, R s and R in we are taking same. In fact, R in it is also defined by r pi 1. So, Rs in parallel with R in same as earlier case namely 650 ohm, but then we need to see what is the corresponding C in. So, to get the C in we need to know what will be the gain from the base terminal here to the collector terminal of transistor 1 ok. So, please try to recall all these numbers and I am going to create the space for that analysis.

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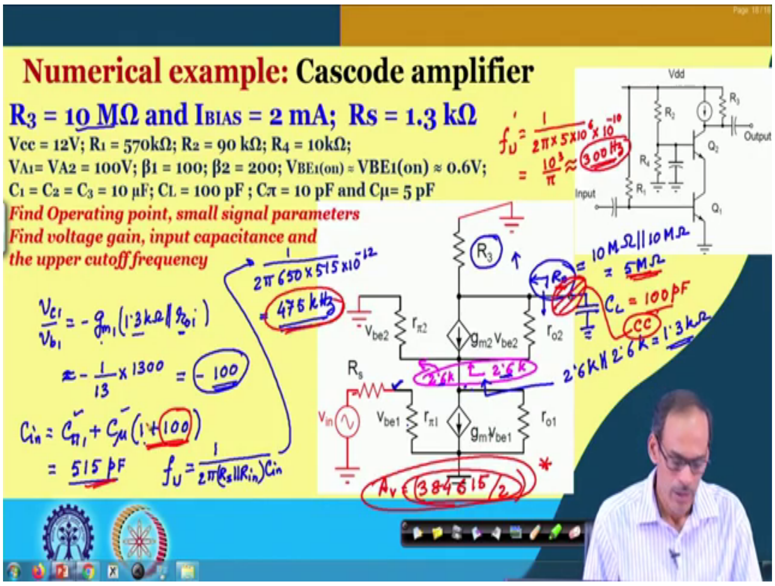

So, what we have said that this r equivalent coming from this part, it is 2.6 k and also we do you have 2.6 k here. So, that gives us the total resistance these two together, it is giving us the total impedance for the lower transistor q 1. So, these two resistances together it is giving us 2.6 k in parallel with 2.6 k is equal to 1.3 k right. So, if I consider the base two collector gain which is essentially if I say that v c 1 by vb 1 equals to minus gm 1 multiplied by this resistance 1.3 k in parallel with this ro 1 which is 50 k ok. So, roughly we can see that this gain sorry. So, this gain you can say that you can drop this part you can retain this one and this gm 1 it is 1 by 13, here we you do have 1300.

So, if I drop this part, the gain it is becoming minus 100. So, what is the conclusion here that, the gain earlier here to here the gain it was just 1 now that gain it got increased to 100 magnitude wise that is mainly because this R 3 it got increased from 2.8 kilo ohm to 10 mega ohm right. So, the input capacitance it is C pi of transistor 1 plus C mu multiplied by 1 plus this 100 gain.

So, that is becoming this is 5 and this is 10. So, we do have 505 here and then we do have 10. So, 515 pico Farad. As a result the upper cut off frequency define by Rs and R in it is 1 by 2 pi Rs in parallel with R in and then multiplied by C in it becomes quite significant.

So, let us I do have the calculation for you. So, we do have 1 by 2 pi 650 and then 515 multiplied by 10 to the power minus 12 and that gives us 475 kilo Hertz and earlier we already have said that the pole coming from the CL and this RO earlier it was quite small, but of course, now this output resistance it is also getting increased because the resistance lower side it is 10 meg upper side it is 10 meg. So, then total resistance here it is 10 mega ohm coming in parallel with 10 mega ohm so, that gives us 5 mega ohm.

So, the now the alarming situation we do have here it is 5 mega and CL equals to 100 pico Farad. So, that defines the upper cutoff frequency. In fact, the corresponding upper cutoff frequency defined by this load capacitance which is 1 by 2 pi into 5 into 10 to the power 6 multiplied by 10 100 pico Farads that is 10 to the power minus 10.

So, what we have here it is 7 3 10 to the power 3 by pi so; that means, this is roughly 300 Hertz only yes. So, the advantage here what we got namely we got very high gain from this circuit which it was I think we already have said that 3 8 the overall gain, it was 3 8 4 61 5. In fact, if I considered this attenuation this divided by 2.

So, that is the gain overall gain, it is very good thing, but unfortunately this output resistance got increased and the corresponding upper cutoff frequency it is the concern. But of course, we have to keep in mind that while we have increase this one the gain, though the miller factor affecting the C mu increases the C in, but the corresponding upper cutoff frequency is the it is not limiting factor for defining the bandwidth of the circuit rather the problem it is elsewhere and this problem this output resistance it is quite high, that can be handle differently namely by placing one buffer circuit here which we have discussed earlier, we can put a buffer circuit here constructed by maybe common collector stage to address that.

So, I should say the cascode amplifier alone is not the solution, we need to put the cc stage, but it is important to make a note that cascode amplifier it is having two important potential it is having the capability to increase the gain by whatever the gain we obtain there multiply may be square of that almost square of that, also it is having the capability in case if you are not looking for high gain it is having the capability to decrease the input capacitance keeping the Miller factor they are small and hence it can be considered for one candidate to extend the bandwidth. But you need to know the situation of yours and then only you can deployed.

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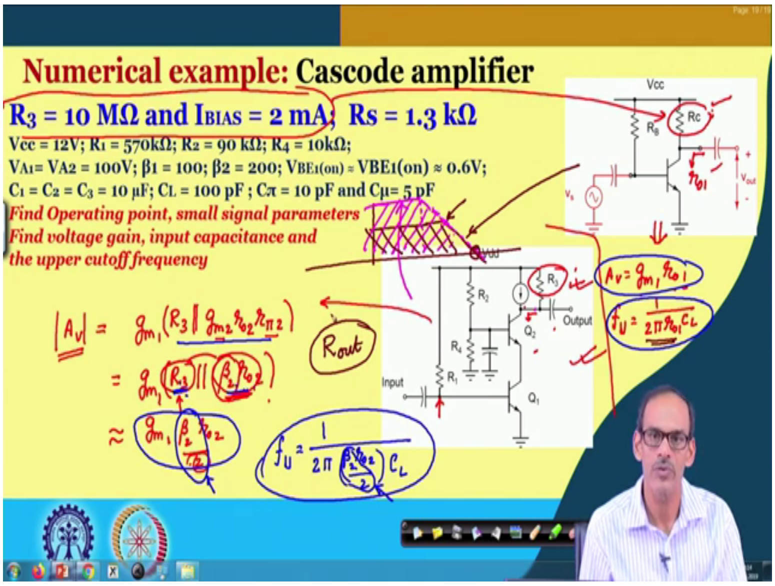

So, for we are talking about cascode amplifier using bjt similar kind of circuit can also be analyzed. In fact, this is what we were talking. So, in case if you are considering the CE amplifier sorry this CE amplifier and then if you compare this circuit directly it will be difficult to compare because this resistance it is high, but then this resistance you cannot make it so, high in case if you are making this is high of course, then here the output resistance it will be defined by r o of the lower transistor.

Of course that will also affect the upper cutoff frequency, but the way this circuit has a affect the upper cutoff frequency, it is quite sever compared to this cutoff frequency. Namely for this case the upper cutoff frequency it is if I make say this circuit replaced by this kind of active circuit for fair comparison, then the gain here it is gm 1 ro 1. So, this is the voltage gain for simple C amplifier and the upper cutoff frequency on the other hand it is 1 by 2 pi r o r o 1 in parallel with very big resistance.

So, that can be ignored multiplied by C L on the other hand for this circuit the gain we obtain there it was quite high it was. In fact, gm 1 multiplied by this R 3 in parallel with whatever the resistance we obtained here.

So, the resistance there it is gm 2 ro 2 multiplied by r pi 2. In fact, you can see that gm 2 and r pi 2 it is nothing, but the beta of the another transistor. So, this is the gain this gain we are talking about the gain from this point to this point without considering Rs and this is becoming gm 1 multiplied by R 3 in parallel with beta of transistor 2 into r o 2. So, while this cascode structure it is helping us to increase the gain to get the advantage of that in the.

So, sorry the cascode structure it is helping us to increase the output resistance by a factor of beta of the cascode transistor to get the advantage of that on the gain if you take this R 3 also in the same order, then only it is meaningful and if I in this numerical example we have considered that this resistance it is in this order and hence it is having a capability of generating a gain which gm 1 multiplied by beta 2 ro 2 by 2

So, assuming that this two are equal. So, that is why we do have factor of 2. On the other hand here the gain it is gm multiplied by ro1. So, the difference if you compare difference of this equation and this equation if you see here beta by two is the factor by which you can enhance the gain.

So, theoretically you can say that gain of this cascode amplifier compare to similar kind of CE amplifier it is a factor of beta by 2. On the other hand of course, the output resistance since this output resistance got increased its cutoff frequency, it is 1 by 2 pi the corresponding output resistance it is parallel connection of R 3 and beta into ro and again if I consider this R 3 in the order of beta into ro. So, we can see that this is beta into ro by 2 multiplied by CL.

Now again if I compare the upper cutoff frequency here and upper cutoff frequency here. So, we can see that the difference here it is beta by 2, but in this case cascode circuit it is having worse performance than the CE amplifier. So, and the the degradation here of course, it is the same factor by which hear the gain it got increased. So, if I pictorially if I compare if I am having the CE amplifier gain say like this and then it is having the corresponding 3 dB frequency or the bandwidth defined by the expression there.

So, this is for the CE amplifier on the other hand if I consider the cascode amplifier, we are the gain it is quite high and then the corresponding cutoff frequency it is lower, but then if you see that the role of here they are finally, coinciding. So, this pink color it is the performance of the cascode amplifier.

So, if I consider the output node and the difference here of these two circuit, then for one case the gain it is increased, but then bandwidth got decreased on the other hand by the same factor for normal c amplifier the gain is lower, but then the corresponding bandwidth is higher and gain bandwidth product it is remaining same. It is intuitively it is also clear that by cascode structure we are essentially changing the output resistance R out and the consequence of increasing the R out is that one is increasing the gain and then with the same factor decreasing the bandwidth as a result the gain bandwidth product for both the circuits remaining the same.

So, that is about the cascode amplifier. So, depending on our application if you are looking for very high gain, but then we can if in case if we are we can tolerate with lower bandwidth, then we will be going for cascode amplifier.

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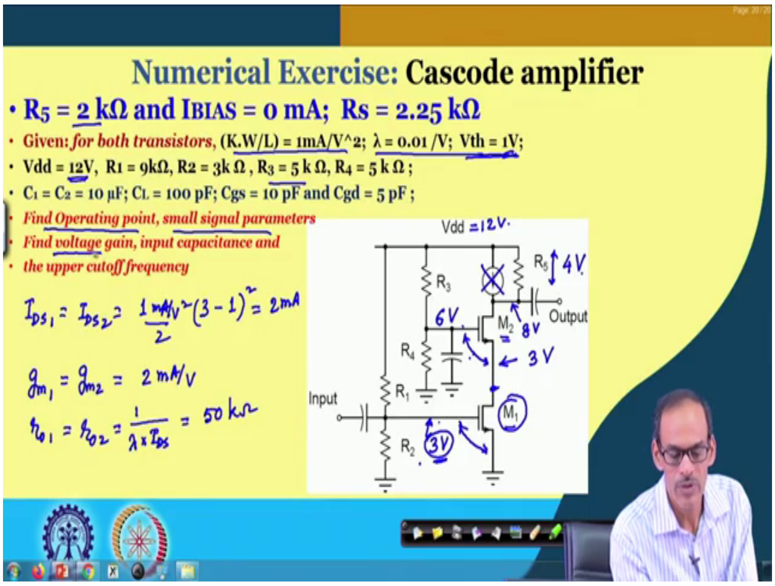

Similar kind of circuit it is also done for the MOS counterpart and the value of different bias circuits given here device parameters are also given here. So, we do have the device parameters are given here for both the transistors we consider transconductance factor it is 1 milliampere per volt square, lambda it is 0.01 per volt, threshold voltage of both the transistor it is 1 volt, supply it is 12 volt and then R 1 and R 2 this potential divider it is such that it creates a voltage here it is 3 volt from this 12 volt.

On the other hand R 3 and R 4 it is creating 6 volt here. So, since the size of both the transistor they are equal and Vth is also equal. So, we are expecting both the devices they will be having equal current. So, naturally the Vgs here and Vgs here we are expecting they should be equal.

So, we do have yes we do have 6 volt here, we do have 3 volt here and so, this is also 3 volt. So, that gives us this is equal to 3 volt. In fact, if you see this node it is 3 volt still this device it is in saturation region because if the gain voltage is 3 volt, its drain voltage it can go lower than its gain voltage by an amount of 1 volt. So, the lower limit of the drain voltage of transistor 1 it is actually 2 volt.

So, definitely transistors 1 it is in saturation region. Now to start with of course, if we have say this Vgs it is a 3 volt the corresponding current I DS 1 equal to I DS 2 equals to 1 milliampere per whole square by 2 into 3 minus Vth is 1 square. So, here again it gives us a current of a 2 milliampere. So, this 2 milliampere it is creating a drop across this R 5 which is 2 k.

So, this is 4 volt we are assuming that this is 0 and so, if we have this drop 4 volt. So, the voltage coming here it is 12 minus 4 so, that is 8 volt. Again transistor 2 it is in saturation region. So, with this of course, we got appropriate operating point of both the transistors, now small signal parameter wise we can calculate gm 1 equals to gm 2 and their values are 2 milliampere per volt, r o 1 equals to r o 2 which is essentially 1 by lambda into the corresponding current 2 milliampere and that gives us again 50 kilo ohm.

So, from that probably we can find what will be the corresponding voltage gain. The analysis small signal analysis here it is very similar to the previous case I should say rather it is simpler compared to the previous case and by analyzing that you can find the gain.

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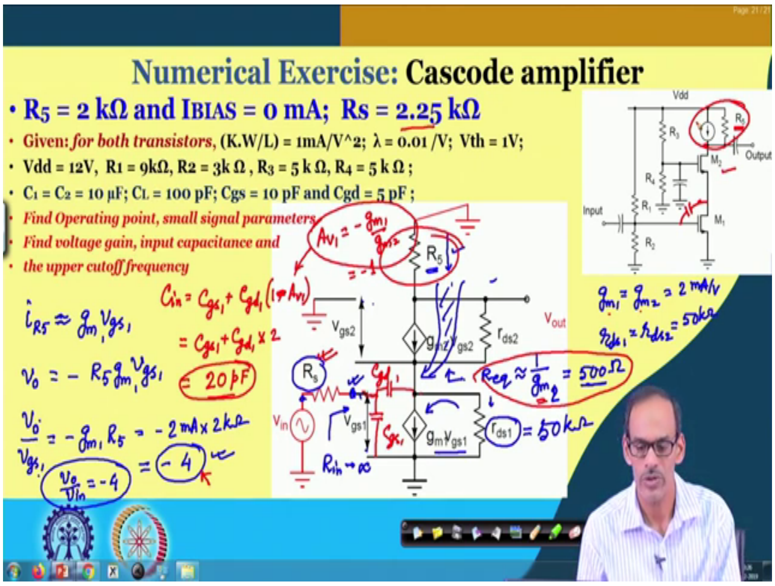

So, let us see in the next slide about the equivalent circuit here and from our previous analysis we see that gm 1 equals to gm 2 equals to 2 milliampere per volt and r d s 1 notation here we are using rds, rds 1 equals to rds 2 is equal to 50 k and the of course, we do not have the r pi here.

So, the circuit that is what I said that the circuit is simpler and at this node of course, we do have the capacitances for gain of course, we can ignore that. So, if we have say vgs applied here, we do have gm 1 into vgs 1 and part of those that current it is flowing through this and also the other part is flowing through this device and this current it is coming from this R 5. So, the again based on the relative value of this resistance and this resistance we can say that major part of this current it is coming from here, because in this case the r equivalent it is essentially one by gm 1 rather gm 2, which is gm 2 it is 1 by gm 2 it is 500 ohm ok.

So, it is of course, significant, but still it is much smaller than this rds 1 which is 50 k. So, we can say that the current flowing through R 5 which is denoted as a i R 5 equals to approximately equal to gm 1 into V gs and then the corresponding output voltage vo equals to minus R 5 gm 1 into V gs 1. So, that gives us the gain starting from its gate to the output, it is V o divided by V gs 1 equals to minus gm 1 into R 5 and gm 1 we have obtained 2 milliampere. So, 2 milliampere multiplied 2 k.

So, that gives a gain of only four as expected MOS transistors they do have 4 gm, so, that is why we do have low gain. So, in case if you really want to use MOS transistor for amplification probably we can look for cascode structure and for that we can increase this resistance. We will see that, but before we go into that let to you also discuss that the input resistance here since it is infinite, even though in presence of this Rs we can say that there is no attenuation.

So, whatever this minus 4 it is also giving us the overall gain. So in fact, I should say that v o divided by v in it is same as V o divided by V gs 1 and hence this is also equal to minus 4. Now next thing is that what is the gain what is the sorry what is the input capacitance? So, that you also see the input capacitance C in equals to Cg s. So, Cgs in parallel with Cgd multiplied by whatever the gain we do have.

So, we do have the Cgs 1 plus Cgd multiplied by 1 plus the gain coming from gate to drain or transistor 1. Now here if you see the gain in presence of R equivalent which is 1 by gm 2 and since this gm 2 and gm 1 they are same we can say that this A v 1 equals to in fact, I should say this is minus. So, minus gm 1 divided by gm 2 and that is minus 1. So, with this the C in we are getting Cgs plus Cgd into 2 and hence again here we are getting 20 pico Farad capacitance. Now this 20 pico Farad capacitance it may create a pole with this Rs.

So, depending on this value of this Rs it may be having its corresponding pole location. So, again we will the analysis it will be similar. So, we will not be going into that discussion, just we like to say that because of the cascode structure since the Cgd here it is not exposed to the output node and hence the Miller factor for this Cgd it is small. So, the input capacitance is remaining low.

So, for high bandwidth application of course, this is having some advantage. Now next thing is that what you are looking for is that if you want to enhance the gain instead of 4 if you want to enhance the again by using this cascode structure, what we have seen for bjt version that this passive element this passive element probably we can try to replace by active circuit, where we can try to take high value of this R 5 and then the corresponding I BIAS.

So, I will be going to that discussion, but let me take a again short break and then we will come back with that numerical problem.