Course name- Analog VLSI Design (108104193)
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Week- 10
Lecture- 29, module-02

Welcome back. So, now it is time to see what a real transistor differential amplifier would look like. So, till now we have been dealing with this structure right and this was going this current was going into some resistance and let us say I for this purpose of this discussion I keep this resistance the drain some arbitrary resistance Rd right. Then let us say this is V1 this is V2 this is Vx. So, this is the small signal equivalent of the structure that we want, it is time to replace the small signal equivalent with its transistor-level equivalent. So, let us do that.

So, let us start with the gm on the left that is gm1. So, clearly it is a transistor. So, we have to apply V1 here, but clearly we cannot apply simply V1 right we have to apply V1 on top of some bias and we know several ways of applying the bias. So, I will not show them explicitly I just assume we know how to apply the bias.

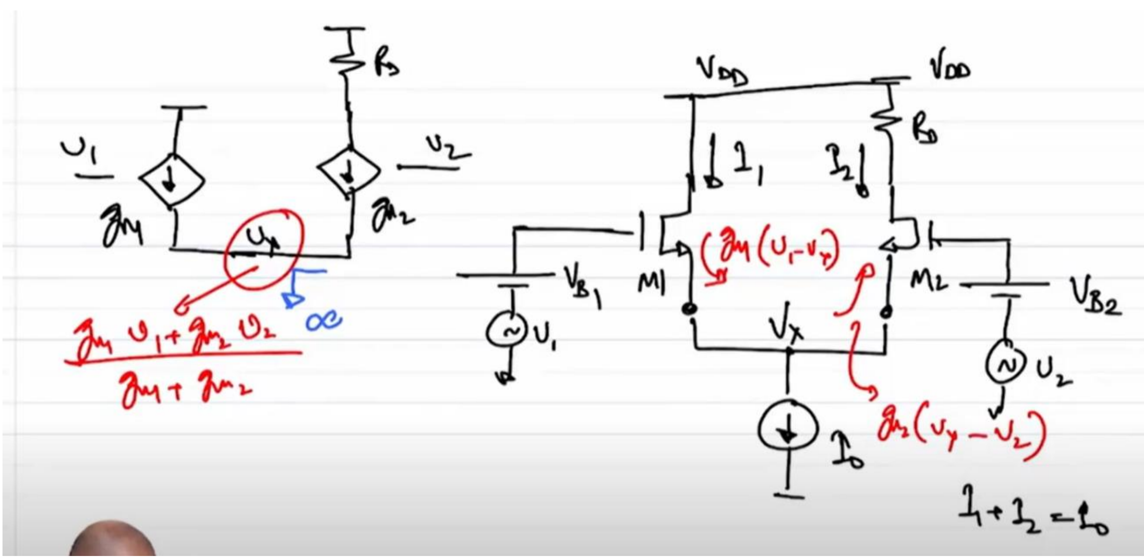
Let us call this Vb and this is V1 ok. So, this has to be Vx this known as Vx. What do we need to do to the drain in the circuit on the left in the incremental model the drain is shorted right. So, in this case it has to be higher voltage and shorted which means that it has to be shorted to Vdd ok. Now, let us switch focus if it all the same one let us switch focus to the gm on the right.

So, this will be again another transistor whose other input will be incrementally V2, but again it has to be some voltage Vb2. So, let me call it Vb1 let me call that Vb2 and this is V2 and we have a resistance connected at its drain and let us call this I mean and other side of the drain is connected to Vdd ok. And what should we do with the sources as far as the two structures are concerned the source sources are shorted. So, let us short them ok. However, if we short them what is going to happen? Firstly in a common source amplifier the source is shorted to ground right, but if we ground each of them right if we short them and ground each of them will this work? This will not work because what is the reason? The reason is in the incremental model then this becomes a ground.

If the in the incremental model this becomes a ground what is the this current will be gm1 times V1 this current will be gm2 times V2 and both of them will go to the ground. We are not going to get the difference of V1 minus V2 right. So, how why is the difference of V1 minus V2 getting generated? That difference was getting generated because Vx was a function of both V1 and V2 right. So, if I go back yeah. So, you see Vx was like gm1 Vi plus gm2 Vf by gm1 plus gm2 right.

So, Vx in this case has to be gm1 V1 plus gm2 V2 by gm1 plus gm2. This is almost like a weighted average of V1 and V2 weighted with the value of its own gm right. So, so, so clearly Vx equal to ground is not possible, but note that more importantly what is there looking downwards from the source? It is an open circuit right. It is an open circuit of resistance infinity ok. So, which means that looking downwards from the source I need to see an incremental open circuit and what contraption do you know that gives you an incremental open circuit? You guessed it right this is a current source right.

So, let us put a current source and let us call this Io ok. So, this is M1, this is M2, this is the voltage Vx and this becomes the this becomes the transistor level schematic of our differential amplifier ok. So, now, it is time to investigate what are these voltages or what I mean what are the effects of this Vb1, Vb2, sizes of M1, M2 and so on correct. We have note that we have already done we have already done the incremental analysis before because this structure came from the incremental analysis correct. So, again just to reiterate what will be the current through this structure, incremental current? Assuming some quiescent current flows into M1 and M2 we do not know how much right now.

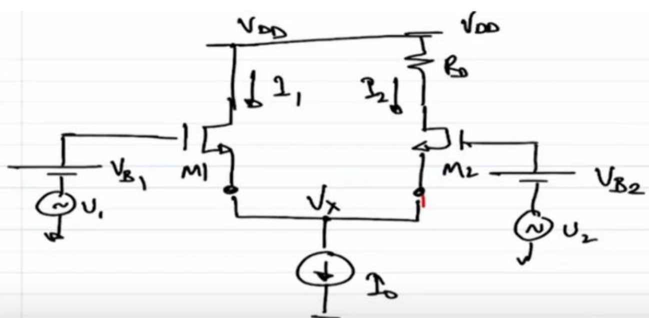


Let us say the quiescent current here is I1, quiescent current here is I2 and of course I1 plus I2 has to be equal to Io and this sets up some gm on M1 and some gm on M2. So, what is the quiescent current through gm1 not the quiescent current I am sorry what is the incremental current through gm1? This is gm1 times V1 minus Vx. What is the current flowing into M2? Note that I have reverse the direction. So, the incremental current flowing into M2 will be gm2 Vx minus V2 and then we equate these two and you will get what we got in the previous module right. So, now time has come to delve slightly deeper into this structure.

So, let us first figure out, let us first figure out what is going to happen if the transistors M1 and M2 are not identical. So, if transistors M1 and M2 are not identical then what can you comment on the quiescent current I1 and quiescent current I2? So, clearly the quiescent current I1 is of mu n C ox W over L of 1 VB1 minus Vx whole squared quiescent current of 2 will be of mu n C ox W by L2 VB2 minus Vx square. Note that I have made an important distinction here, important assumption here and that assumption is that both M1 and M2 are in saturation right. So, for M1 it is quite obvious I mean as long as we can keep BB1 to be one threshold voltage I mean as long as we can keep BB1 difference between BB1 and VDD to be less than one threshold voltage then we are good. It is not particularly evident in case of M2.

However, let us say the transistor M2 had gone into linear what can I do? I can reduce the value of RD to increase the quiescent voltage at the drain of M2 and that would be good right. So, we now we are mature enough to know what to do to get the transistor back into saturation if it is that has gone into linear. So, I will make the assumption here to start off that our transistors are in saturation ok. So, I will make another critical assumption another assumption. An assumption is since these two I mean this looks to be a symmetric circuit right.

I mean as far as the operation of this circuit is concerned or at least the physical nature of the circuit is concerned it looks like there is nothing to distinguish if you apply an input to M1 or you apply an input to M2 right. I can the circuit will essentially behave identically those are the directions of the incremental current will change right and that is why in general even though in general you can choose any values different values of VB1, VB2, W by L of M1 and M2 also need not be the same, but in most cases you will see that we tend to use same values of VB1 and VB2 and same values of W by L for M1 and M2 just because it gives us that symmetry in terms of I can choose which terminal to apply the input to without really thinking what is going to without really thinking of the effect of asymmetry ok. If we do not do that if we do not do that what we need to do we need to ensure that both the term I mean I mean the sizing of M1 and M2 is such that and the sizing of and the voltages V of V1 and VB1 and VB2 are such that we have transistors biased in saturation ok .



$$I_1 = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)_1 (V_{B1} - V_X)^2$$
$$I_2 = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)_2 (V_{B2} - V_X)^2$$

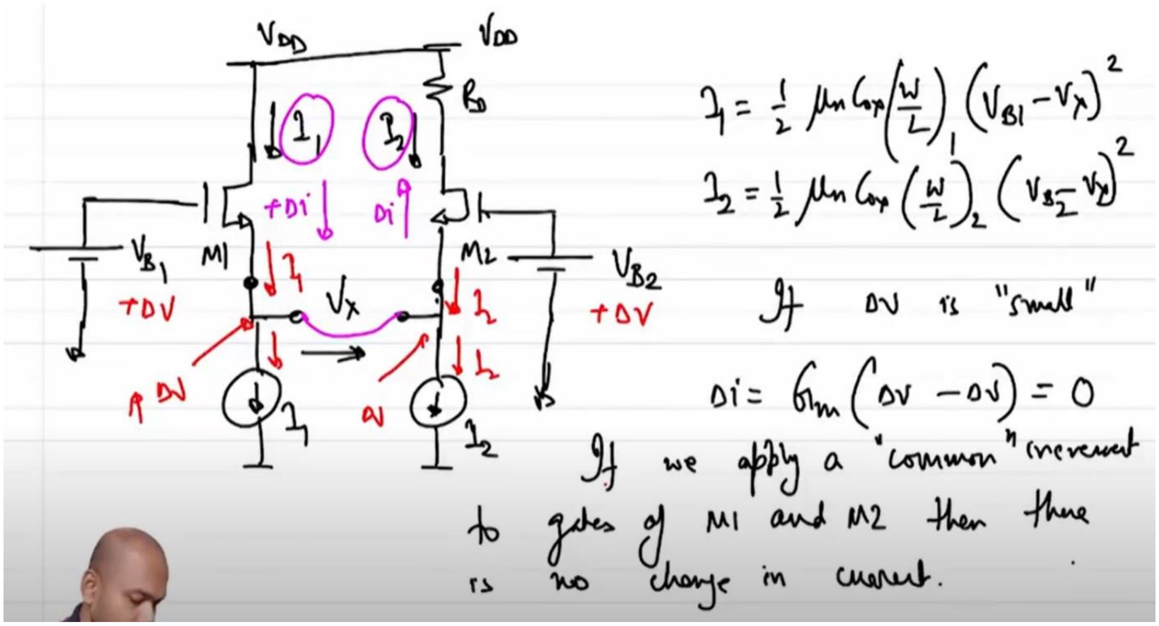
So, to make the point let me ask you let us assume that this our transistors are biased in saturation and VB1 and VB2 are different W by L of M1 and M2 are different. Can you tell me what is going to happen if I increase the volt let us say I do not have the incremental inputs let us say I do not have the incremental inputs and let us say I increase VB1 from VB1 to plus delta V and VB2 to also VB2 to plus delta V.

Now tell me what is going to happen will there be any what will happen to the what will happen to the quiescent currents I1 and I2? Any comment on what is going to happen on the quiescent current of I1 and I2? So, see the easy way to easy way to the most obvious way to think about this is to split this current source I0 into two sub current sources I1 and I2 right. So, let us say I split this current source into two current sources one having current of I1 the other having current of I2 ok. So, if this were the case right if this were the case can you comment on whether I will be having any current any quiescent current through this where connecting the two current sources? Note that note that this choices of I1 and I2 are not arbitrary right. They have been chosen in such a way that in such a way that the quiescent they will support the quiescent current of I1 and I2 through the transistors M1 and M2 right. So, in other words what is the current that is coming through this? This is I1 what is the current that is going out? That is also I1 what is the current coming through this? This is I2 what is the current going out? This is I2 which means that for all practical purposes I can say that this line does not exist right.

Because there was no current through this through this band right. So, now tell me what is going to happen if I increase the gate voltages of M1 and M2 both of them by same amount delta V. So, what is constant? Constant is the current sources I1 and I2. So, they are not going to change right. If they are not going to change then what do you think is going to happen? If they are not going to change then I may as well say that this current is not changing.

So, these currents will not change this I1 and I2 will also not change right. If they do not change I have applied an increment of delta V at the gate however the current I1 remains fixed then what is the consequence? What is the only thing that can happen? The only thing that can happen is Vx of this terminal will also go up by delta V this terminal will also go up by delta V right. So, regardless of whether these two terminals are connected or not right the sources of both M1 and M2 will go up by delta V in order to keep your current constant ok. And I mean note that we did this I did this heuristic hand waving analysis we can also do it using brute force method right. What we can simply do is let us assume this delta V is a incremental input right.

It is a incremental change right. We can also do assuming that if delta V is small within code small right. What will be the change in I1 or let us say if delta V is small and you start off with the assumption that the currents I1 and I2 will change right. If the currents I1 and I2 the quiescent current through M1 and M2 actually changes which means that quiescent current through M1 has to increase and M2 has to decrease or vice versa right. It cannot be both because I mean where will that if both currents increase then which essentially means that the current source since we have a current source at the connected at Vx that will not allow for the increase of current on both M1 and M2 which means either the current through M1 has to increase or the current through M2 has to increase and the other has to decrease.

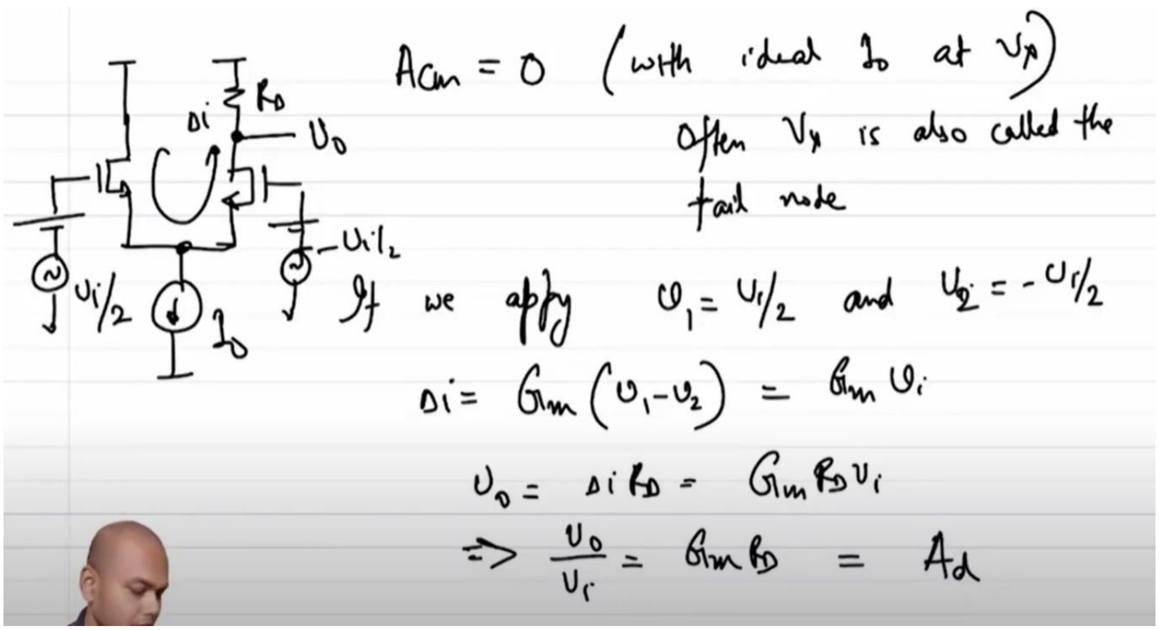


So if we assume the current through M1 increases by delta I right this direction which means the current through M2 will also decrease by delta I which essentially means that the current in the opposite direction of delta I correct. So what is delta I? Delta I is equivalent gm which is the gm1 gm2 by gm1 plus gm2 times V1 minus V2 what is V1 minus V2? Delta V minus delta V which is equal to 0 right. So which essentially means that moment if you apply an incremental input on both sides simultaneously in the same direction right there will not be any change in the quiescent currents right. Another way of saying the same thing is that if we apply a common signal if we apply a common increment to gates of M1 and M2 then there is no change in current and in more technical terms in using more jargon what we call this is this differential amplifier rejects common mode excitation right. So this is a very critical property of crucial property of differential amplifier which has immense use right.

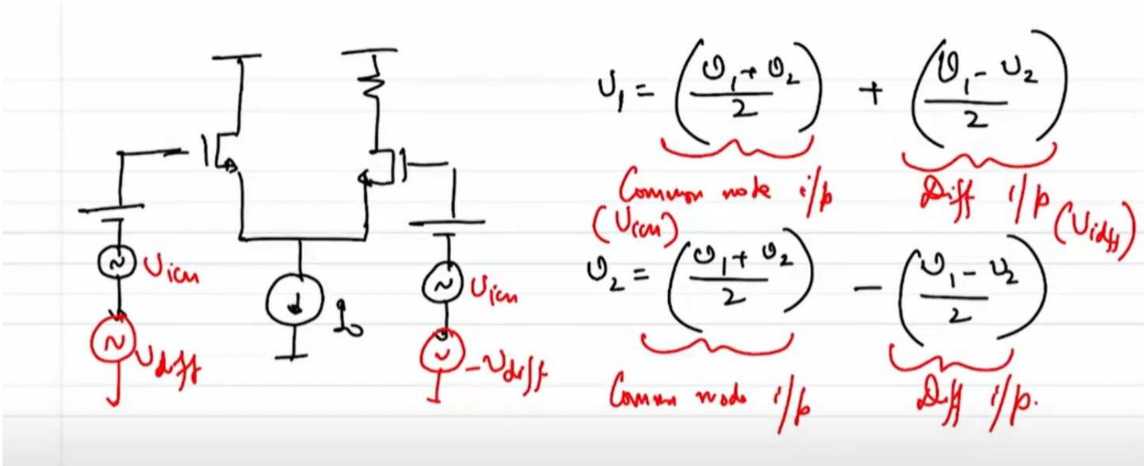
So because now if our differential amplifier is able to give us gain which is equivalent to the difference of two voltages but is also insensitive to any common mode excitation which means that I don't have to set Vb1 and Vb2 very accurately Vb1 and Vb2 can be slightly different as well right and still our quiescent points won't get disturbed too much correct. Okay so another piece of jargon is so this is called often ACM that is the ACM is equal to

0 so with ideal I0 at Vx right. Often also Vx is also called that tail node right so Vx is also called often Vx is also called the tail transistor or the tail node in this case sometimes you will hear me talking about a tail transistor or a tail node which essentially means that anything that is connected to that node Vx okay. So if ACM is 0 what about if we apply a differential excitation let's say we apply if V1 if we apply Vi by 2 or let me say V1 equal to Vi by 2 and Vi V2 equal to minus Vi by 2 right basically I am increasing one side I am increasing the gate voltage of M1 and reducing the gate voltage of M2 that's all I am doing. So what will be the incremental current delta i will be gm times V1 minus V2 that is gm times Vi where will this current flow this current delta i is flowing into Rd and it will create a voltage right so maybe I should draw this up again.

Right so what will this delta i flow not that even if I am sketching it using transistors the analysis that I am doing is a small signal by now we should be comfortable with without replacing the transistor with a small signal equivalent and we will be able to visualize what the incremental model would look like if with even without replacing the transistor with this incremental equivalent right. So if delta i is flowing upwards and it is flowing into Rd what will be the incremental voltage at this node V0 incremental voltage V0 will be delta i times Rd which is gm times Rd and Vi which means again V0 over Vi is gm times Rd



this is often called the differential gain or Ad right so this is called differential gain. Okay so why is this split why do I bother about this differential gain and common mode gain the reason we bother about differential gain and common mode gain is as fault is because of the following reason. So let us say I apply an arbitrary input in V1 arbitrary input V2 here right so note that I can express V1 as V1 plus V2 by 2 plus V1 minus V2 by 2 right it is simple algebra I broke it up and also similarly I can express V2 as V1 plus V2 by 2 plus or rather minus V1 minus V2 by 2 correct. So why is this useful this is useful because in the context of differential amplifier this is my common mode input right this is the common mode input and this is the differential input okay.



So since in the incremental sense our circuit is linear we can use superposition right in the incremental sense our circuit is linear which means we can use superposition which means we can in principle apply a common mode input here that is let me call this VICM and let me call this VID. We can apply a signal VICM and VICM on both sides and we can apply another signal V diff plus V diff and minus V diff on both sides right. We can do both simultaneously or we can do both individually and do our analysis right. So that is one of the reasons why you will see that breaking the input into common mode and differential mode of an of an helps a lot okay. Okay so let us stop here in the next class we will delve deep into some more detail into the properties of a differential amplifier.

Note that we have till now neglected the effects of channel length modulation we will see what is the effect of channel length modulation. Again we cannot assume we have an ideal current source all the time right. So we have to see what are the non-ideal effects that come in if we use a real current source right or by real current source we mean essentially mean that a current source is essentially a essentially a transistor right. So a transistor have will have its own own GDS or own RDS. So we will see what happens to this common mode gain what happens to the differential gain right in the presence of in the presence of these non-idealities.

We will also see how to how to how to size the transistors M1 and M2 in order to get certain quiescent gain and certain quiescent and rather what are the to get certain quiescent current through them and so on right okay. So let us stop here. Thank you.