Course name- Analog VLSI Design (108104193)
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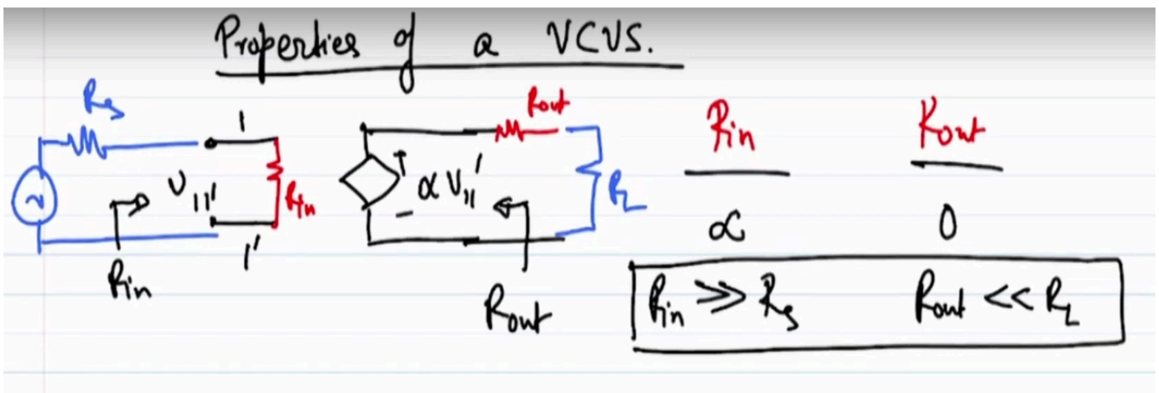
Now, we will come back. So, we have been until now looking at this particular architecture and we were interested to see what was the transfer function between V i and Vo, right? And V naught, where V naught was taken across the resistance RL which is AC coupled to the drain of the MOSFET and the whole purpose was to design a common source amplifier. Now, if you go back few lectures, you will notice that why did this common source amplifier make sense? This common source amplifier made sense because at the output side, right, at the output, so the common source amplifier topology



was essentially this. This is what we wanted our common source amplifier to look like incrementally. This is RL, this is gm times Vgs and this is supposed to be the source, this is supposed to be the gate, this is supposed to be the Vin. And then we saw that we could not do it straight away, so we had to put some resistance Rd here, we had to put some biasing resistance R1 parallel R2, then we had to size them appropriately so that they could not, they were not loading and so on and so forth.

But in essence, this is what we were targeting. And why was this supposed to work? This was supposed to work because all the incremental current at the output stage was supposed to flow into the resistance R L, right. In other words, in other words, other way of addressing the same thing is to say that the impedance looking in into the drain of the transistor was infinite, right. Since the impedance looking into the drain of the transistor was infinite, all the current that was coming out of the transistor was flowing into RL.

Had it not been infinite, then there would have been some current division and you would not probably had gotten a gain the gm times RL, right. Okay, fine. But if we go back, if we go back couple of slides here, couple of slides here, yes, here, so what did we observe? We observed that, we observed something interesting. We observed that if we were trying to figure out the Thevenin equivalent resistance looking into the source of the transistor, what was the Thevenin equivalent resistance that we got? We got it to be 1 over gm, correct. So can you comment on, can you comment on the value of 1 over g m? Is it a large value or is it a small value? Now you might turn around and tell me that, I mean, how do I know what is the large value, what is the small value because they are relative quantities, you have to tell me a reference with respect to which I can tell you which is large or small and you would be absolutely right.

So what is the reference that we have? In a common source amplifier gm RL has to be much much greater than 1 in common source amplifier, right, which means, which means what? 1 over gm is much much less than R L, right, okay. So what does it mean? And in plain English this means that, it means that the impedance 1 over g m, right, is much much greater than the resistance that the common source amplifier is driving, right. So why am I saying this? Because it seems like the resistance looking into the source of the transistor is 1 over g m, right. So can we do something about it? And can we leverage something while looking into the source of the transistor? This might seem confusing at first, but bear with me, what I am trying to say is, let us say you want to create a voltage control voltage source, right. So let us assume if we want to make a voltage control voltage source, what are the properties that we should be bothered about? So let me just simply say, what are the properties of a voltage control voltage source? So a voltage control voltage source is incrementally a voltage control voltage source is what? Is a contraption whose output voltage depends on the voltage across two other terminals, right.

So let us say I call these terminals 1 and 1 prime. So this is V1 1 prime, output is alpha times V1 1 prime, correct. What is the impedance? So what is the impedance of the voltage control? What is looking in impedance? What is the input impedance of a voltage control voltage source? So what is R in and what is R out? In a voltage control voltage source, the R in is the net, correct. And what is R out? It is a voltage source. So what is the R out of a voltage source? It is 0, right.

But by now we already know that, I mean, infinite does not exist, 0 also does not exist. So what is it that we should be asking essentially? We should be asking is, what is meant by infinity? In a voltage control voltage source, the R in, infinity essentially means this is equivalent to saying that R in has to be much much greater than R s, where R s, so if this is R in let us say and you have R s associated with an input. So, this R in has to be much much greater than R s, so that R in does not load the source that it is driving it. Similarly, we know that at the output also there will be some R out, it will not be 0, right. So, R out is an ideal, nothing is ideal, so R out will be there.

So and ultimately this guy is supposed to drive an RL, some output load RL. So what is the constraint? What is the constraint on R out? The R out should be much much less than RL, right. So these are the constraints that a voltage control voltage source would honor. So why am I saying this? The reason I am saying this is that looks like the resistance looking into the source, resistance looking into the source of M1 is 1 over gm, which is much much less than RL. But does that mean that if I connect RL to the source, this guy will behave like a voltage control voltage source? Note that a common source amplifier is not a voltage control voltage source, right.

Why? What is the one of the properties of the voltage control voltage source is, its output is independent of the load that you attach to it, right. So in a voltage control voltage source, the output is independent of RL, right. However, in a common source amplifier, the output is dependent on RL, in fact is directly proportional to the RL, right. So a common source amplifier is not a voltage source, it is in fact a current source, right. That is what is happening here.

The common source amplifier is a current source because all the current is being dumped into RL, right. And the voltage across RL is this current times RL, ok. So the common source amplifier essentially, I mean if I restrict myself to only this part, the stuff within the box is essentially a voltage control current source. But now what we are trying to see is that given that there is a possibility of 1 over gm is much much lesser than RL and 1 over gm is the resistance looking into the source of the transistor, then is it possible to use the same circuit and turn it into a voltage control voltage, right. So the question that we are asking is this.

So let me sketch the incremental equivalent of the same circuit again and then we will discuss, right. So what was the incremental equivalent of the same circuit that we have been using till now. So instead of current source, this goes to ground, we had an input, Rs. Let us assume that the capacitor is shorted and R1 parallel R2 is very high so that it does not load Rs, right. If we assume that what we have at the drain side, at the drain side we had some contraption connected.

Since we are not connecting the load at the drain, I can as well say that only Rd is connected, right and the other side is grounded. And now I have an RL, where is RL connected? I am saying the RL is connected between ground and the source, ok. So this is Vs, this is gm times ggs, ok, fine. So what I am essentially saying is what is the impedance looking in, what was the impedance looking, what was the Thevenin impedance looking in Rth, this we have already seen Rth is 1 over gm, correct, ok. What is the relationship between Rth and RL? So in our case Rth is much, much less than RL, right.

So this is, if this is the output terminal, since this is the output terminal, this is let us say I am taking D out from here, this is the output terminal, then looks like the output side of the voltage control voltage source equation is satisfied. What about the input side? What is the input impedance? R in, R in is infinite, correct, R in is because I am neglecting that R1 parallel R2, R in is infinite, right. So looks like this is the condition for voltage control source. So if this is voltage control voltage source, I would like to investigate more and see what is the output impedance. So output impedance effectively is the Nortonized version of this because ultimately we are interested in Vout over Vi, right.

If you are interested in Vout over Vi, I would like to know what the Norton equivalent is. So in Norton equivalent, what we need to do, we need to find out the short circuit current and what else and the output impedance. What is output impedance? Output impedance you already know, this is output impedance, right. What is the short circuit current? To find short circuit current, what should we do? To find short circuit current essentially we have to basically, let me sketch. To find short circuit current, what should we do? We should replace this output node with a short, right.

Replace the output node with a short circuit. I need to find out, I need to find out what is the current flowing into that short, right. So I need to find out Isc. So what is Vs? Vs in this case is 0, right.

So Vs is 0. Then what is gm vgs? gm vgs becomes gm times Vg. What is Vg? Vg is clearly Vi. So this becomes gm times Vi, correct. So what is Isc? Isc is gm times Vi. What is the Norton's equivalent? Norton's equivalent will be, this is Isc, this is R Thevenin or Rout and connected to the load, correct.

So what is Isc? Isc is gm times Vi. What is Rth? Rth is 1 by gm. What is V0? V0 is Isc times Rth parallel RL, right. Or I can say this is Isc is gm times Vi, right, times 1 over gm parallel RL. So which implies V0 is equal to gm times Vr 1 over gm times RL by 1 over gm plus RL, right, which is equal to, if I multiply with gm in the numerator and denominator, what do I get? I get V0 over Vi is gm RL by 1 plus gm times RL.

$$v_o = i_{sc} \times (R_{th} \parallel R_L)$$
$$= g_m v_i \times (1/g_m \parallel R_L)$$

$$\Rightarrow \quad v_o = g_m v_i \, \frac{1/g_m \times R_L}{1/g_m + R_L}$$

And what did we know? We know that the constraint that we originally had was gm times RL is much much greater than 1, right. That is how we had sized it initially. If this is the case, then V0 over Vi is approximately equal to 1. This is independent of RL, right. You see you are getting a voltage gain, which is independent or rather you are getting an output voltage which is independent of load resistance.

$$\Rightarrow \boxed{\frac{v_o}{v_i} = \frac{g_m R_L}{1 + g_m R_L}} \qquad g_m R_L \gg 1$$

$$\boxed{\frac{v_o}{v_i} \approx 1 \quad (\text{Independent of } R_L)}$$

So what do you call something which is the output is independent of load resistance, this is an ideal voltage control voltage. Now obviously there are two questions that might arise, two very critical questions that might arise is why should I bother making something which gives me a gain of 1, correct? So that is the answer to that is the following. So let us say, let us take a number, let us say we have a voltage source Vi and I have a resistance Rs which comes with the voltage source, we cannot do anything and let us say I have to deliver this Vi across another RL, right. So let us take some number, let us say Rs is equal to 1 kilo ohm and this RL is also supposed to be 1 kilo ohm, right. If this is the case, how will I develop a voltage Vi across RL? Will it develop if I simply connect the input to the output? Clearly it will not because if I connect this RL will load the input contraction because it will load you will have a current that will be drawing through the source and because of that this voltage will become Vi over 2.

Now what are we doing? We are saying we are putting a voltage control voltage source, right, we are putting a voltage control voltage source of gain 1, right between the input and the output, ok and it has a, it has an output impedance 1 over gm. If the output impedance 1 over gm is much much greater than, less than RL then clearly the output voltage will be equal to the input voltage regardless of the value of RL, ok. So hence this is a, there is a use for this type of circuits and this is called a voltage buffer, right. So this is called a voltage buffer. What is the other question that might arise? Before I get into the other question that might arise let me also point out a fact that what is the role of Rd here? Is there any role of Rd? Clearly there is no role of Rd.

That Rd was necessary in a common source amplifier in this case the Rd is not necessary at all. If Rd is not necessary we can essentially get rid of the Rd. And what will be the incremental equivalent? Incremental equivalent will be Rs. Let me put back that R1 parallel R2 now because we would want to make the full blown circuit also. So this becomes RL, right and this becomes incrementally grounded if we get rid of Rd.

So this is gm times Vgs. Note that this is not gm Vg, right. This is not gm times Vg which means this is not gm times Vi. So Vgs is not equal to Vi in this case, right. Since Vs is not equal to 0. So this is you have to be careful while you are analyzing this because this can be a very potential but this can be a place where you might make mistake, right.

Because in a common source amplifier source is grounded we have the habit of always writing the incremental current or the current source to gm times Vi which is not the case always is gm times Vgs. In this case Vs is not equal to 0, right. So you have to be careful and you write gm times Vgs while honoring the fact that the sole voltage is not equal to 0, okay. So this was also bounded, right. So now what is this, what is this drain? The drain is grounded.

The drain becomes incrementally grounded. Since this, since the drain becomes incrementally grounded this, there is a common nomenclature of this. This is also called a common drain amplifier. Or a CD amplifier. This is also called a voltage buffer because you are essentially buffering the input, you are isolating the source from the load and by translating the information of the source to the load.

This is also called in the literature source follower. Why is it called source follower? It is called source follower because incrementally any change in Vg is getting translated to the change in the source voltage. So the source voltage is following the gate voltage. Since the source voltage is following the gate voltage we call it a source follower. So all these three terminologies are very often used in the literature and we will probably be using it also in different contexts as the course moves forward, okay.

So now the second question that I was alluding to that might arise is why do we call this an amplifier at all? Because what is the maximum gain that I can get out of this amplifier? The maximum gain that I can get is equal to 1, but in reality the gain is always less than 1, right. The gain is, the gain is gmRL by 1 plus gmRL. Since gmRL is not infinity, right, so this gain will always be less than 1. If that is the case, why do we call this an amplifier? The reason this can be justified as an amplifier is the fact that this can give you, this can still deliver power. What is the input power? Ideally what is the input power? Pin is equal to 0 if R1 parallel R2 is infinity.

But what is the output power? Clearly output power will be V0 square over RL, right. So Pout will be, so Pin is almost close to 0 and Pout is P0 square over RL average, right, which is approximately Vi squared average over RL. So this can still deliver power. So you are getting power amplification, right. Since you are getting power amplification, this can be still, this still falls under the category of an amplifier, ok.

Ok, great. So now that we, now that we are comfortable with the fact that this can, this can work, right. This has some use. So we would like to see what will be the biasing picture of the, of the same circuit, ok. So what will be the biasing picture? Note that it is the same circuit that we had been using earlier, right, to make a common source amplifier. Just that we are taking the output from a different location.

So let us do that. So I had a MOSFET, current source, input side biased, R1, R2, the input fed through AC coupled capacitor C1, right. Since we do not require RD anymore, I can simply connect the drain VDD, right. So what do I do with RL? So in a common source amplifier, we had a capacitor here, right. If you recall, we had a capacitor here C2 and C2 was tending to infinity. But in this case, do you think we need C2? We surely do not need C2 because if C2 tends to infinity, then the voltage at the source will always be grounded, right.

We do not need C2. If we do not need C2, if we do not need grounded C2, we can as well remove it. But RL has to be connected to the source. So do you think I can connect this RL directly? So clearly, ideally we will, we cannot do this because of what?

Because this current I0 is supposed to flow through this. If I connect RL, then some part of I0 will flow through this. So this will become, this will not become I0, this will be different from I0.

So the biasing of the transistor can get affected, right. So how can I ensure that the biasing of the transistor does not get affected? So this is the time old story. We know that voltage at the source is what? The voltage at the source is Vsq, let me call this, this is equal to Vgq. What is Vgq? Vgq is Vdd R1, sorry Vgd R2 by R1 plus R2 minus the Vgs of the transistor M1, right. While it is biased at the current of I0, which is equal to Vgq minus threshold voltage plus under root 2 I0 by mu Cox W over L, correct.

Everything on the right hand side is known. So we know Vsq. So if we do not want, if we do not want the resistance RL to load the quiescent current of the transistor, what we need to do? We need to ensure that the voltage at this node of RL is also Vg, Vsq. How can I do that? I can put a battery of value Vsq. If I put a battery of value Vsq, then obviously what will be the quiescent current through that battery, it will be 0. But now we also know that this is not something we would like to do.

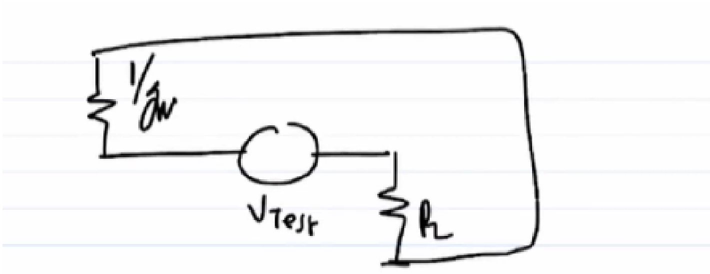
In principle this is possible, but it has implications that we do not want to use multiple batteries, floating batteries. So what is the option? What is the other option? The other option is to put a infinite capacitor, right. What is the value? So let me call this again C2. Let me call this C2 tends to infinity, right. So what under DC condition, what is the current through C2? Under DC condition the current through C2 is 0.

At DC condition what is the voltage at this node? It is 0 at DC. What is the voltage at this node? It is Vsq. So what is the voltage across the capacitor at DC is exactly equal to Vsq which was supposed to be the battery voltage, right. So at AC what is the condition? At AC, at AC the capacitor is supposed to act as a short. Since the capacitor is supposed to act as a short then at the AC picture RL gets connected to the source of M1, correct.

So now, so this seems to be our common drain amplifier. So far so good. But what about the value of C2? Can I, again the same old problem, right, we cannot really put an infinite capacitor. So what should I do? So now what should I do? I should again find out the Thevenin impedance looking at both the terminals of the capacitor. So what will be the Thevenin impedance? So let me, this is the capacitor terminal here.

So I am trying to figure out a Thevenin impedance. So one side is RL. What is the other side? Incrementally, what do I have on the other side? On the other side I have the transistor, this is Vs. What is the drain of the transistor connected to? Drain of the transistor is shorted, correct. So this is gm, what is the Vg? Vg is 0 because I had to short the Vi while we are trying to find out the equivalent output resistance looking into these terminals.

So Vg is equal to 0. So this is gm times Vgs, which is gm times minus Vs, which means I can flip the direction and make this gm times Vs, correct. So what is the, so if I put, so what is the resistance looking up? What is the resistance looking up? So we have already derived this two minutes back. So the resistance looking up is 1 over gm, right. So we must have a voltage source, it must have a voltage source here.



$$R_{th} = \left(\frac{1}{g_m} + R_L\right)$$

$$\tau_2 = R_{th} C_2 = \left(\frac{1}{g_m} + R_L\right) C_2$$

$$\therefore \left(\frac{1}{g_m} + R_L\right) C_2 \gg \frac{1}{\omega_0}$$

The resistance looking up is 1 over gm. So this becomes 1 over gm, this is Vtest, this is RL and this becomes the loop. So what is the, what is the Thevenin impedance? So Rth is 1 over gm plus RL. So what is the time constant associated with C2 is Rth times C2, which is 1 over gm plus RL into C2. So what is the constraint that C2 must follow if C2 has to be, if C2 has to behave like a short circuit at omega 0. So therefore, 1 over gm plus RL times C2 has to be much much greater than 1 over omega 0, which means C2 has to be much much greater than 1 over omega 0, 1 over gm plus RL, right, to ensure C2 acts like a short circuit at omega 0, right.

Okay. So in today's lecture, what did we see? We saw, we analyzed the, we analyzed the value of the capacitance, the value of the capacitance is required in a common source amplifier. When the common source amplifier was biased using a constant current source connected to the source, then we saw that the same contraption can be used, looks like the same contraption can be used like a voltage control voltage source, where the RL is connected at the source and not at the drain. And then also we were able to, then also we analyze the same architecture and we saw what will be the constraint on the value of the capacitance and when the capacitance is, when the resistance is, output resistance is AC coupled to the contraption, right. So in a nutshell, what I would like you to focus on is the fact that the same looking architecture can behave completely differently. In one case, the same looking architecture can behave like a voltage controlled current source or a common source amplifier and just because I have taken the output from a different terminal, right, it looks like it behaves like a completely different beast that is the voltage controlled voltage source or a source follower or a common drain amplifier, right.

So, this can be at times a bit tricky if you are not careful. So I hope that with practice, with the practice in the problem sets that will be posted, you will get, you will get comfortable with the content, right. So, let us see you in the next lecture. Thank you.