Analog Integrated Circuits
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Lecture – 33
Folded- Cascode OpAmp – 2

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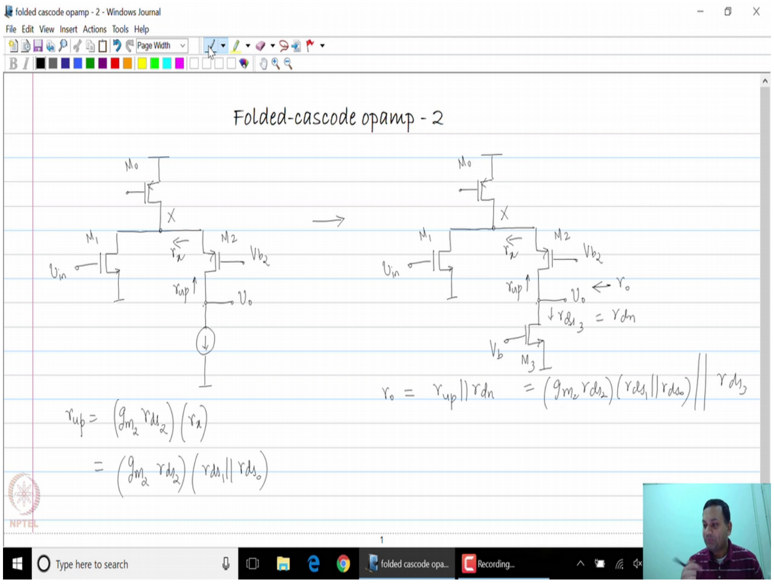

Before we build the full opamp using the folded cascode structure let us take a look at the gain and noise performance of the simple single ended folder cascode structure. So, we will assume that the input is an NMOS anti cascode is a PMOS a device.

Now, we need to do something about the output mode. Now, earlier we had look for simplicities case we have assumed that the output is resistively loaded, but it normally does not make sense because the minute you have a resistive load you really do not need the large output impedance that this particular structure offers right. So, you really want to get high DC gain from the structure. So, naturally you ideally want to use an ideal current source so that you will get the gain of maximum you will get the advantage of maximum gain from this particular opamp.

Now, how do you get up how do you make a current source you of course, cannot make ideal current sources in practice. So, the first thing you try to do is to try to replace that with a transistor. So, please note that the output impedance of this, so maybe I will call that r up, r up is something we need to write down. So, before we you move want to the replacing the current source because this is going to become significant in a few minutes. So, what is the expression for r up. So, as you can see the gate of M 2 is connected to a constant voltage and therefore, M 2 is a common gate structure. You know that any impedance at the source of the common gate structure is multiplied up by the intrinsic gain of the common gate transistor. So, therefore, you expect the impedance to be g M 2 r ds 2 times r x if this node was node x times r x and this is g m 2 r ds 2 times r x is of course, the parallel combination of I Ds 1 parallel r ds 0.

So, this is the impedance looking upwards at the train of M 2. So, this is of course, quite high we. Now, want to use an ideal current source here, but we know we cannot do that. So, let us first try to replace that with transistor with an NMOS transistor because this is a current flowing downwards. So, the first thing we will try to do is to replace it with some V b that it is gate such that this has some correct. Now, clearly this NMOS transistor will now, have some resistance let us say, let me call this M 3 this will have some resistance r ds 3 and therefore, r down will be equal to r ds 3 and the total resistance at the output which is the output resistance r o is r up parallel r down and this is clearly, this is clearly the parallel combination of g m 2 r ds 2 into r ds 1 parallel r ds 0 in parallel with r ds 3. And now, we can see that the impedance looking upwards is of the order of g m r ds square it is slightly lower than g m r ds square whereas, the impedance looking downwards is just of the order of r ds.

It is going to be very different to make a very difficult to make these of the same order and typically what you will find is that r down in such a case will always be how much smaller compared to r up. This is not the best case because you wanted up current source which would have much higher impedance compared to the impedance looking upwards which will give you the maximum gain from this particular stage. So, now it becomes clear to us that you need better current source at the bottom.

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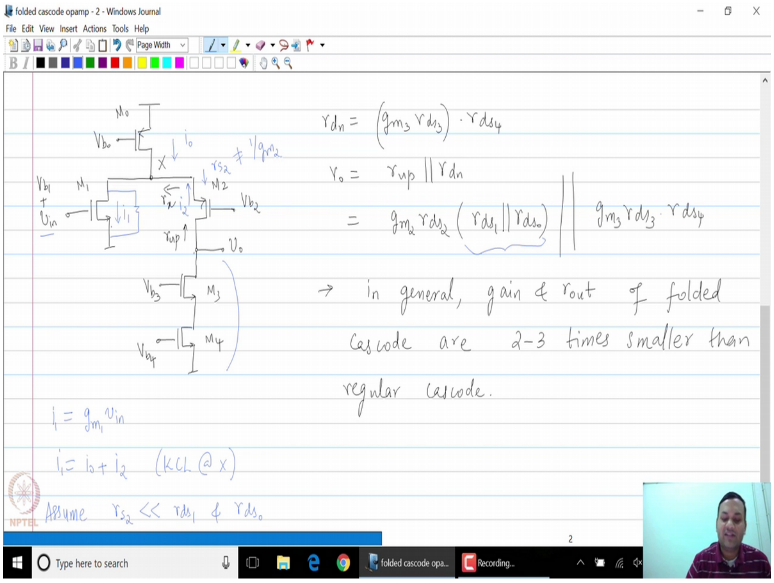

So, now, if you want the better current source you of course, have to use a cascode structure even at the bottom. This will give you an even better output resistance. So, let me call these transistors M 3 and M 4 with gate voltages V b 3 and V b 4. Now, if you use this current source r down will be equal to g m 3 r ds 3 times r ds 4 and therefore, you are overall output resistance which is r up parallel r down will become equal to g m 2 r ds 2 times r ds 1 parallel r ds 0 in parallel with g m 3 r ds 3 times r ds 4.

Now, as you can see this is somewhat close to that of the telescopic cascode, but you just note that because of this particular terms here this gain would be slightly smaller and in general gain and r out of the folder cascode. So, will be around to 3 time smaller then the telescopic version which is the regular cascode (Refer Time: 07:15). So, in general now, when you try to decide all of these r ds values you will find that it is a little bit lower than that of the regular cascode, but it is still much higher than that of the regular one stage opamp this is simple common source structure. But, so this is the template that we are going to use for our analysis. So, this is the 5 transistor structure for the folded cascode single stage, folded cascode single ended folded cascode. So, now we can write the expression for the gain. So, let us assume that a voltage V in is applied to the gate of M 1 clearly that should also include some bias voltage V b 1 the bias voltage at a gate of M 0 should be V b 0.

Now, let us look at what will happen when you apply a signal I am not going to draw the small signal structure because we have now, at a point where we should be able to visualize the small signal structure of each circuit and of slightly more complicated subjects. So, when I apply this V in between the gate source of M 1 you will have a current I 1 flowing through M 1 I 1 should clearly V g m 1 times V in and this I 1 has 2 paths to flow the first path is through transistor M 0 the second path is through transistor M 2 and of course, with the opposite direction since I have already chosen the direction. So, these will be the 2 directions of I 1. So, I 1 should be equal to I 3 sorry I 0 plus I 2 and this is purely from KCL are known x.

Now, part of this correct will of course, flow through M 0 ideally you want to design the circuit such that as much of I 1 flows into M 2 as possible. What is the impedance of the circuit looking downwards at the source of M 2? Please note that the impedance at the drain of M 2 is quite large. So, you cannot assume that the input impedance at, you cannot assume that the input impedance at the source of M 2 is equal to 1 over g m. So, this particular assumption is not valid because you have actually connected a very large resistance at the drain of M 2. So, please note that.

So, the current will split and some form depending on the 2 impedances. Now, this current will now flow through the output node at V 0 the total output impedance is given by r out and therefore, that will give you a certain amount of gain. So, this will give you the small signal gain. So, I will let us assume that we design M 0 such that it has much higher impedance compared to the output impedance of r ds of M 1 and the input impedance is the source of M 2.

So, I am going to call that rs 2. So, that will distinguish it. So, we will assume that r s 2 is designed to be smaller let us say much smaller than r ds 1 and r ds 0. So, there are 3 paths for the current to flow at node x, one of them is the output impedance of transistor M 1 the other is the output impedance of transistor M 0 and the third path is through the you know source of M 2 itself.

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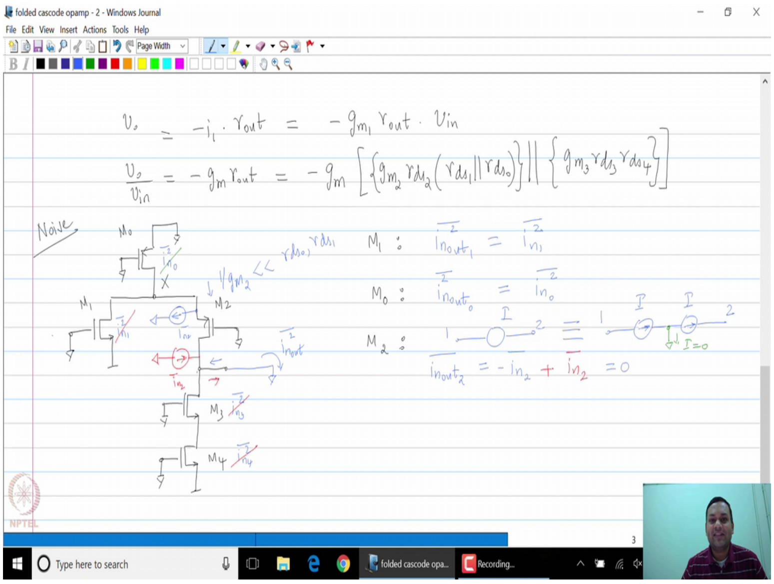

So, we will assume this is true and therefore, the small signal gain V in, we now assume that all of I 1 the circuit has been designed such that all of I 1 close to M 2. So, the small signal gain now, is minus I 1 times r out times r out sorry this is the output voltage is minus I 1 times r out. So, this is minus g m 1 r out times V in. So, V o by the V in which is the small signal gain of the circuit which is minus g m times r out. So, this is minus g m times as we have seen r out as g m 2 r ds 2 into r ds 1 parallel r ds 0 in parallel with g m 3 ids 3 r ds 4.

So, this is the expression for the small signal gain of this particular folder cascode structure and this will give you slightly lesser gain compared to the regular cascode, but this is still larger than the simple comment source structure value would have seen before.

So, now let us look at a noise performance of this particular cascode structure. So, let us first make a copy of this particular amplifier so that we can now, analyze it for noise. So, as always when you analyze for noise the first steps are to apply the appropriate voltage and current conditions in the circuit. So, clearly when you are doing analyzing for noise that you assume there is no input signal because the noise is uncorrelated with the signal. So, therefore, there is no input signal and since to noise is a small signal quantity you assume that small signal equivalent circuits are valid and therefore, the bias voltages at the appropriate nodes will be grounded.

And so far so good. So, now this structure you find that there are actually 5 sources of noise in this circuit and the 5 sources of noise are the drain current noise, i n 1 of M 1, i n 0 of M 2, i n 0 square of M 0, i n 2 square of M 2, i n 3 square of M 3 and they will 4 squared of M 4. So, there are clearly 5 different sources of noise in this particular circuit. Now, let us look at each one of these and figure out if that noise will make its output.

The easiest way we have seen earlier is to short the output the ground and then look at the output short circuit noise current. So, in short circuit condition we are going to look at the output noise we will of course, assume that the noise of each transistor is uncorrelated with each other. And now, we need to find out the mean squared sum at the output know; let us start going to each of these M 1 by 1. So, this is noise analysis. So, if you look at noise of M 1. So, you will find that the noise of M 1 and you do this noise of M 1 we will assume that the other noise forces do not exist and this noise of M 1 flows between the drain and source of M 1.

So, at node x this current has 3 parts of 3 ways to split it can split just like your small signal, it can split through r ds 1, it can split through r ds 0 and it can split through the source resistance seen the resistance seen looking into the source of M 2.

As we have seen earlier just right here we have assumed that we have assumed that r s 2 is much smaller than r ds 1 and r ds 0 so that most of the current flows through M 2 put the output. And clearly since we have designed a circuit such that that happens for the signal you should expect that all of i n’s one squared appears at the output. So, the first component of a i n out square which is in out 1 square is equal to i n 1 square. So, pretty much all of noise of M 1 will appear at the output short circuit. What about M 2? If you look at noise from M 2, if you look at the noise of M 2 that is again a current source which is across the drain source of M sorry noise of M 0 it is across the drain source of M 0 and as you can see from usually from the circuit topology this looks yeah you know i n 0 looks exactly the same as i n 1 square purely from a circuit topology.

You should expect that I M 0 square also has 3 paths to flow through the first one is through r ds 1, the second one is through r ds 0 and the third path is the impedance looking in at the source of M 2. So, therefore, you should expect that i n out 2 square should be equal sorry i n out 0 square should be equal to i n 0 square this is the second component of noise .

What about M 2? Noise from M 2, so M 2 remember is the common gate structure normally you do not expect additional noise from M 2 because as you might expect the noise from the cascode does not make its way to the output. Let us confirm that this is indeed true by doing the following. So, let us consider the noise from M 2. Now, we do not know how to analyze this really well. So, when then current source is connected across 2 loads of the circuit. So, we go back to the earlier at the trick that we have studied earlier we will now, split this into 2 correlated the current sources.

So, just to remind you I will now, show that if you have will now, point out that if you have current source i between 2 nodes 1 and 2 as far as the rest of the network is concerned this is exactly the same as putting 2 current sources in series because the rest of the network assumes that current i is pulled out of node 1 and pushed into node 2 and KCL is clearly valid even at the intermediate. And this is again not changed if I were to connect this to any convenient voltage because there will be no current through this particular branch and I will connected conveniently to ground.

So, now how does this affect us? I can now replace this with a pack of current sources. Let us just each of value i n 2 and I connect this conveniently do not know. So, now this makes that job much easier because now, I can consider these 2 current sources. The only thing I have to keep in mind are that these 2 currents are correlated noise current sources. So, therefore, I cannot work with mean square values I have to work with the root mean square values and keep in track of the keep track of the sign.

So, now let me use 2 different colors to distinguish between these 2 guys. So, let me use red and blue if you look at noise correct i n 2 I expect that to behave exactly the same as noise current of M 0 and M 1. I expect all of that current to go through M 2 into the output short circuit. And this should be clear because looking in at the source of M 2 I have a short circuit at the drain of M 2 and therefore, looking in impedance at the source of M 2 here would be 1 over g m in this case in the case of noise analysis and that is clearly much much smaller than r ds 0 and r ds 1. And so clearly noise of all of i n 2 in blue color will flow into the output short circuit. So, the component, i n out 2 I am still following the root mean square value will have a component being pulled out and I am going to call that i n 2 1 and that is being pulled out.

What about the red color current source? So, that current source has 2 paths to travel one as looking down looking up at the drain of M 2, the other has through the short circuit clearly this current is again going to flow through this and so maybe I can just use directly i n out 2 is going to be equal to minus i n 2 plus 2. These are the directions of the 2 current sources in blue and red.

As you can see these 2 current sources are equal and opposite and therefore, this current is going to be 0. As you can see there is clearly no noise generated from M 2 at the output and therefore, this we have seen before even for the regular cascode when we analyze the noise for the telescopic opamp. You do not expect noise from the common gate structure especially at low frequencies.

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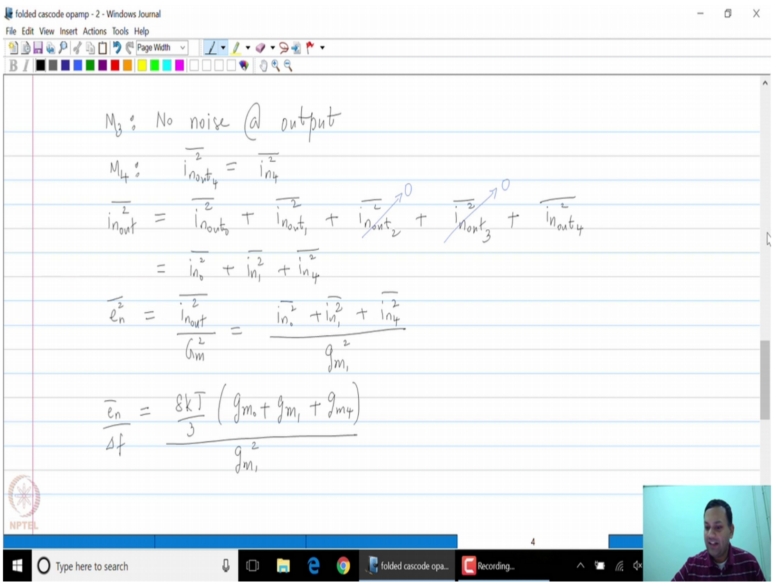

What about M 3? Transistor M 3 is again a common gate structure you do not expect any noise at the output you can follow the exact same procedure and show that the output noise generated by M 3 is equal.

And M 4 of course, will generate noise all of this noise will flow through the output. So, therefore, the total output short circuit noise which I will call by i n out square is going to be i n out 0 square plus i n out 1 square i n 2 square remember I have 5 noise sources I need to calculate the effect of short circuit current and the root mean squared value for all 5 of them. So, these are the 5 components. We have already established that noise from M 2 and M 3 0, so these two are 0 and therefore, for the cascode you have 3 sources of noise. So, this is i n once, i n 0 square plus i n 1 square plus i n, i n 4 square I put this. So, there are these sources of noise this is the short circuit noise the input referred noise voltage which I will now, represent as e n square is nothing, but the short circuit noise over the overall effect of trans conductance square. The effect of trans conductance of the circuit is of course, g m 1 I will write the down here that is the g m effect of trans conductance of the overall amplifier.

So, therefore, the input referred noise is going to be i n 0 square, i n 1 square plus i n 4 square over g one square and what is i n 0 that is clearly 8 kT by 3 g m 0 and let us say that I am interested in being that intensity and remember I am looking only at thermal noise I can always add the (Refer Time: 27:34) noise component of this as and when required.

So, this is clearly 8 kT by 3 into g m 0 as g m 1, g m 4 over g m 1 square. So, of course now, similar to the cascode you can see that you can look at the conditions that you would need to get a totally 2 noise solution you clearly need to maximize the value of g m 1 and minimize the relative values of g m 0 and g m 4. So, clearly the g m of transistor 1 should be maximized the g m's of this transistor and this transistor M 0 and M 4 should be minimized for you to achieve very low input referred noise.

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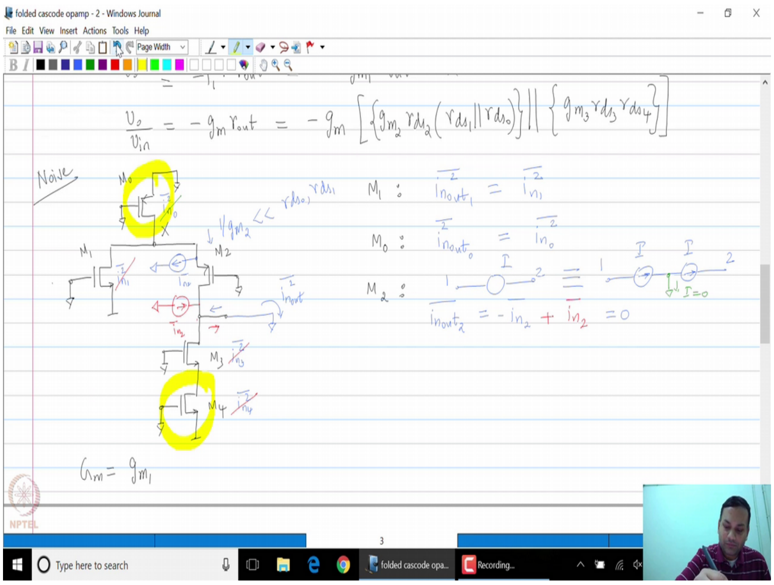

Now, we are in a position to built the folded, full folded cascode opamp and write down directly its noise, noise expressions and gain expressions and so on. That is what we will do in the next lecture.