Analog Integrated Circuits
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Lecture – 23
One-Stage Op Amp Example - I

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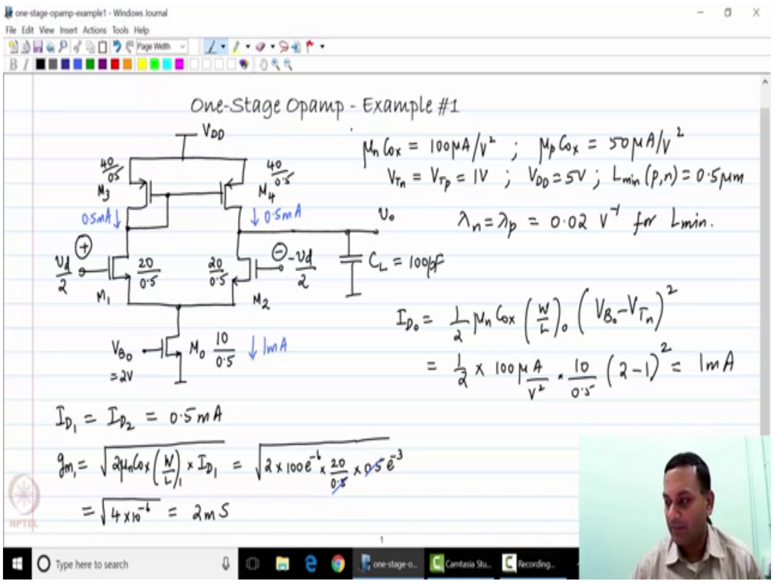

In this lecture, we look at a quick example to analyze the one-stage opamp that we have been looking at so far and we will try to put together as many of the datasheet components as possible, datasheet values as possible. So, to start off with this is the one-stage opamp, let us say that the opamp is driving a load capacitance of 100 picofarad. And let us also say that the device parameters are as follows mu n c ox is 100 microamps per volts square, mu p c ox is 50 microamp per volt square. Let us say that V T n is equal V T p is equal to 1 volt, and let us say that the supply voltage is 5 volts. And let us say that the minimum length possible for the PMOS and NMOS is 0.5 microns and lambda n and lambda p is equal to 0.02 volt inverse for l min. Let us start off with these numbers.

And let us say that the sizes of the transistors are as follows. So, m naught has a size of 10 over 0.5, all widths and lengths being in micrometers the width over length of M 1 is 20 over 0.5; M 3 and M 4 have a width over length of 40 over 0.5. And finally, let us say that V B naught was equal to 2 volts. So, the first thing we can do is write down the expression for the voltages and currents of every device that we can we can analyze

Now, the first thing we will do is to find out the value of the current through M 0 which is I D 0. So, the the current is as follows I D 0 is half mu and C ox W over L 0, I will do V B 0 minus V T n the whole squared. And this is clearly half into 100 micro amp per whole squared times 10 over 0.5 into 2 minus 1 the whole square. So, this current through M 0 is equal to 1. So, this current is milliampere. So, now, all the derived quantities will be placed in blue color. Now, of course, if that happens as long as both M 1 and M 2 are in saturation, you will find that each of them has a current, which is equal to half a milliampere.

So, I D 1 is equal to I D 2 is equal to 0.5 milliampere. So, you have a current of 0.5 milliamperes flowing through each of these half circuits. Based on this we can calculate the value of the g ms of the different transistors. So, let us calculate the value of g m 1, g m 1 is root of 2 mu n C ox W over L 1 into I D 1, this is 2 into 100 micro into 20 by 0.5 into 0.5 e minus 3. So, this is clearly if I have to make the actions, so 0.5 and this is root of 4 into 10 power minus 6 which is 2 millisiemens. So, g m 1 is equal to g m 2 is equal to 2 millisiemens.

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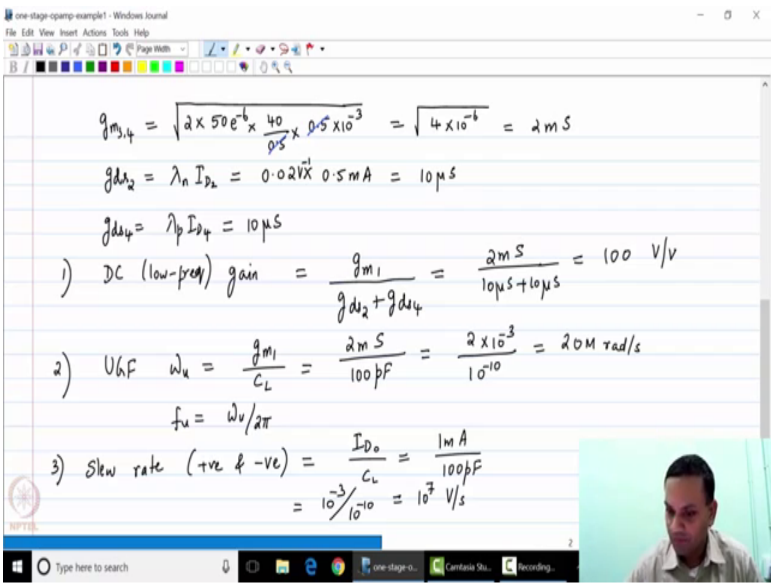

Let us now calculate what the value of g m 3 and g m 4 is; g m 3 or 4 is root of 2 into mu p C ox W over L, so which is 50 e minus 6 into the W over L of the PMOS transistors is 40 over 0.5 into 0.5 into 10 power minus 3. And this is clearly so 0.5 and 0.5 get cancelled and so this is root of 4 into 10 power minus 6, so this is also 2 millisiemens.

Once we know these two numbers, we know the transconductance of the devices. Now, we let us calculate the output conductance of the devices g d s 2 is lambda n I D 2. So, this is 0.02 into I D 2 which is 0.5 milliamperes, and this is 10 microsiemens. Similarly, g d s 4 is lambda p I D 4; this is also 10 microsiemens.

Now, we are in a position to start writing down the expressions for the various datasheet components of the opamp. So, the first component that we will write down is the DC also call the low frequency gain of the opamp this is nothing but g m 1 over g d s 2 plus g d s 4. 1 over g d s 2 plus g d s 4 is nothing but r d s 2 parallel r d s 4, so this is 2 millisiemens over 10 microsiemens plus 10 microsiemens. So, this is a gain of 100 volt per volt. So, this is the DC gain of the opamp.

The second component we will look at is the unity gain frequency of the opamp. So, omega u is nothing but g m 1 over C L this is 2 millisiemens over 100 picofarad. So, this is 2 into 10 power minus 3 over 10 power minus 10, so this is 20 mega radian per second. Of course, f u is omega u over 2 pi. The third component that we will write down, we will skip then dominant and non-dominant poles and zeros, because we do not know what the capacitance is at node x. Since, we are not given anything there we will assume that C L is the only capacitance of interest.

So, the next component that we can write down is the slew rate. So, the positive and negative slew rate are both equal for the one-stage opamp is nothing but I D 0 which is the maximum current that can flow in and out of the opamp over C L. So, this is 1 milliamp over 100 picofarad. This is it is 10 power minus 3 over, so this is 10 power minus 3 10 power minus 10 or 10 power 7 volts per second.

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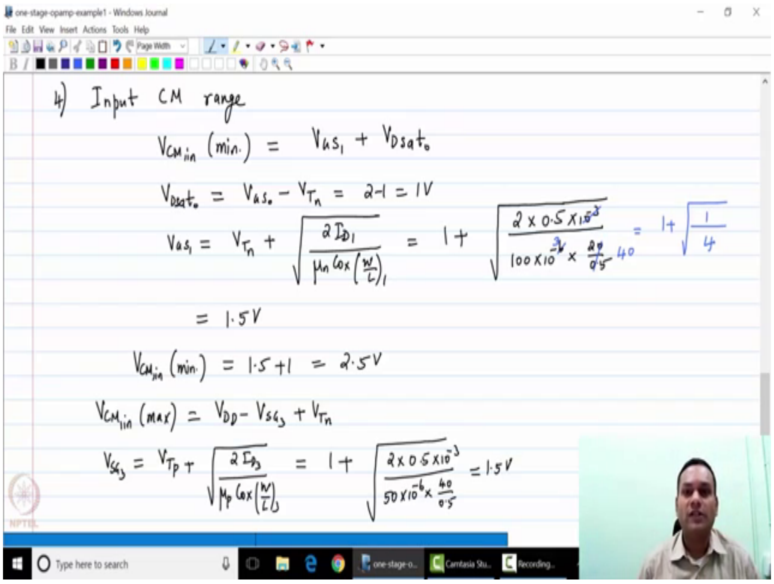

Next, we will write down the input common mode range. So, the minimum value of minimum is nothing but V GS 1. So, remember quick reminder, so when the input common mode is minimum, so as you keep decreasing the input common mode M 1 continues to have V GS 1 across its gate source, and the same with M 2, and the voltage at the common source node starts keeps falling with the decrease in common mode.

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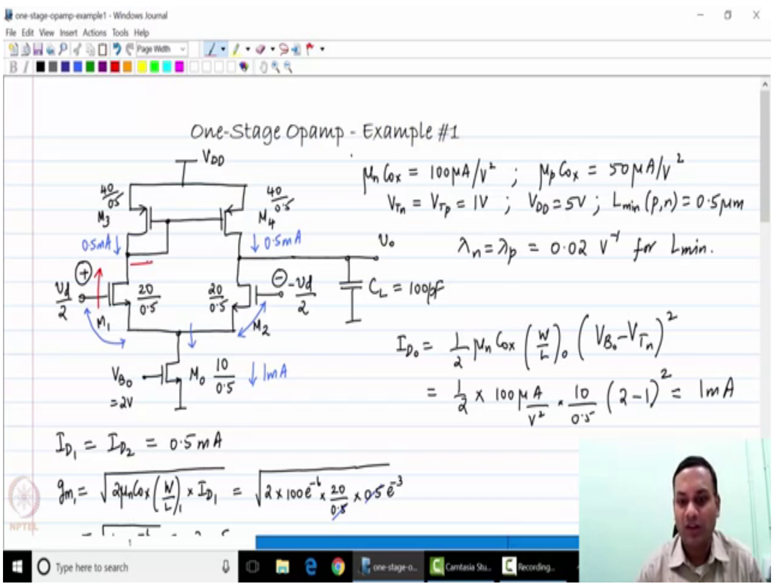

And finally, M 0 is at the edge of triode and therefore, the input common mode level at that point should be V GS 1 plus V D sat 0. Now, V D sat 0 is V GS 0 minus V T. So, this is 2 minus 1 which is 1 volt; and V GS 1 is given by V T, V T n plus root of 2 I D 1 mu C ox W over L 1. So, this is 1 plus square root of 2 into 0.5 into 10 power minus 3 over mu C ox is 100 into 10 power minus 6 into so the width to length ratio of M 1 and M 2 is 20 over 0.5. So, this is nothing but 1 plus square root of so this is 10 power minus 3, and this is 40 over 1. So, this is 1 over 4 or 1.5 volts. So, V GS 1 is 1.5 volts, and therefore, the input minimum common mode is 2.5 volts.

What about the maximum input common mode? As we have seen before as we start increasing the input common mode, the gate of M 1 increases, but the drain of M 1 stays constant at V DD minus V SG 3. And therefore, the limit is given by the point when M 1 just goes into triode region that happens at a voltage V DD minus V SG 3, this is the voltage at the drain, the gate can go one threshold voltage of the drain. Now, let us calculate what V SG 3 is so V SG 3 is V T p plus root of 2 I D 3 over mu p C ox W over L 3. So, this is 1 plus root of 2 into 0.5 into 10 power minus 3 over 50 into 10 power minus 6 into 40 over 0.5 or into 80, and as it turns out this is also equal to 1.5 volts.

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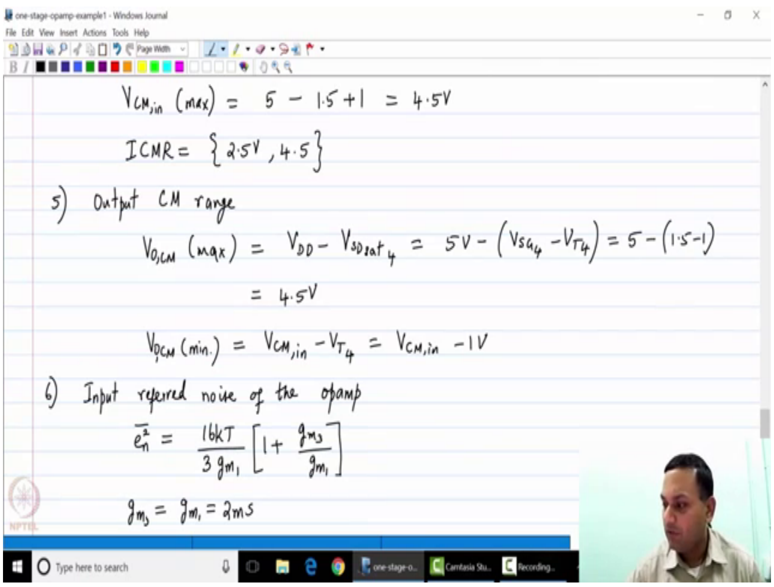

Therefore, the maximum input common mode is given by 5 minus 1.5 plus 1 or 2.5 volts. So, the input common mode can be anywhere between 2.5 volts and 4.5 volts. So, this is the input common mode range. What about the output common mode range? So, the output common mode range can be calculated as follows. So, the maximum output common mode is given by V DD minus V SD sat of 4. As we have seen V SG 3 is 1.5

volts, therefore which is the same as V SG 4; therefore, V SD sat 4 is V SG 4 minus V T 4, this is 5 minus 1.5 minus 1 or 4.5 volts.

Of course, the minimum output common mode depends on the value of the input common mode, so that would happen when as the output common mode decreases, eventually the transistor M 2 would go into triode region. And therefore, that will happen when the drain voltage goes one threshold voltage below the gate. So, this would happen V CM in minus V T 4, this is V CM in minus 1 volt.

Now, the next quantity that we will calculate is the input referred noise of the opamp. As we have seen before the input referred noise of the opamp so which we will represent as e n squared, this has two components. So, this is 16 K T by 3 g m 1 into 1 plus g m 3 by g m 1. The first quantity the first portion represents the noise of the input transistors referred back to the input of the opamp. The second quantity this quantity represents the noise of M 3 and M 4 referred back to the input. As you can see the noise of M 3 and M 4 depend on g m 3, but the overall trans-conductance of the opamp depends on g m 1 and therefore, the input referred component depends on both of these. As we have seen the since g m 3 is equal to g m 1 is equal to 2 milli Siemens.

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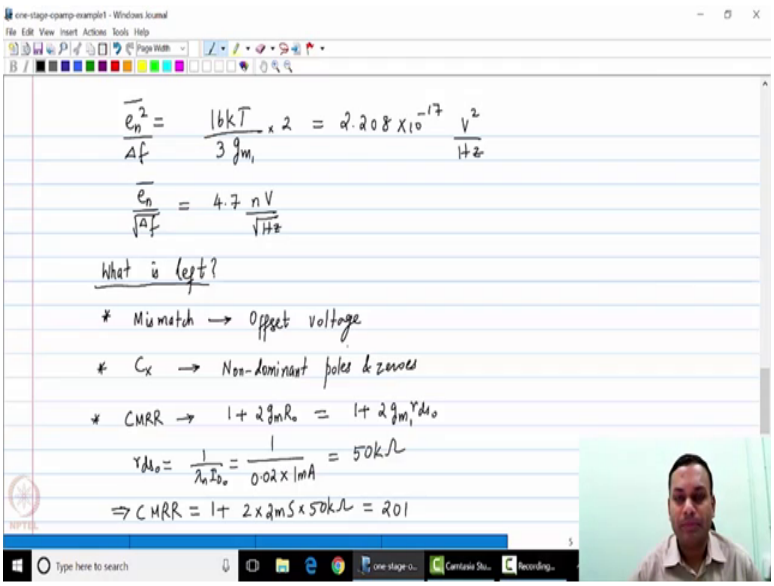

Therefore, e n squared is g m 1 into 2, and this happens to be equal to 2.208 into 10 power minus 17 volt square per hertz of course, we at always talking about the noise squared voltage density. So, I will make that explicit here. Finally, so the noise voltage density, which is e n over root delta f happens to be equal to 4.7 nano volt per volt hertz. So, this is the input referred noise density of the opamp. If you knew the mismatch characteristics, you could also calculate the mismatch characteristics. So, those there are two things that we have left uncharacterized. So, those are mismatch and calculation of offset voltage. Since, we did not specify a V T mismatch, we have not calculated the offset voltage. And of course, we had not specified the capacitance at node x, and this would allow us to calculate the non-dominant poles and zeroes of the system.

Finally, there are two more things to wrap up this analysis. So, the CMRR and common mode gain of the opamp, so let us directly write down the expression for the CMRR of the opamp. As we know the CMRR of the opamp purely depends on the g m of the input device and the output resistance of the current source transistor. So, to do that, so this is nothing but 1 plus 2 g m R naught, where R naught is the output resistance of the current source, so that is 1 plus 2 g m into R d I 0 and R d s naught is 1 over lambda n I D naught. Which is simply 1 over 0.02 times I D naught, which is as we can see from the original opamp, it is 1 million. And therefore, the output resistance of M 0 is 50 kilo ohms, this means that the CMRR of the opamp is equal to 1 plus 2 times 2 millisiemen times 50 kilo ohms and this is 201.

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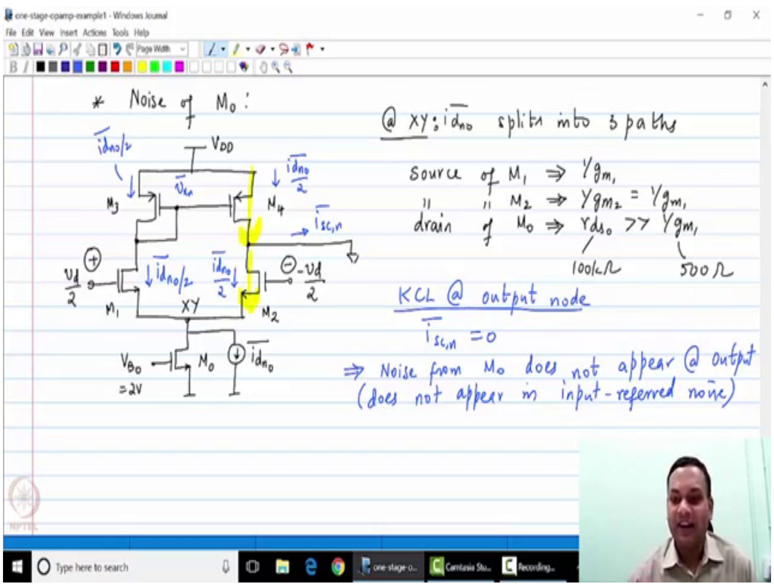

Last but not least, we need to look at what happens to the noise of M 0 because that has not been covered so far. So, let us briefly look at that. So, this is the noise of the current source transistor. So, in this particular case, let us assume that the output is short circuited to ground, so that you are trying to find out the short circuit current. Now, if the transistor M 0 has a current i d n 0, this current source now enters the node x y and at x y i d n 0 splits into three parts. So, the three parts are there is current flowing into the source of M 1, there is current flowing into source of M 2, and there is current flowing into drain of M 0.

The impedance looking up at the source of M 1 is approximately 1 over g m 1 which is a very low impedance node. The impedance looking up at the source of M 2 presents an identical impedance 1 over g m 2 which is equal to 1 over g m 1. And finally, looking down to the drain of M 0, it sees an impedance r d as 0, which is much much larger than 1 over g m 1. As you can see r d as 0 is 100 kilo ohms, and 1 over g m 1 is approximately is 500 ohms. So, as you can see all of the current flows up into the sources of M 1 and M 2, and half of the current flows through M 1 and half of the current flows through M 2. So, this current splits equally between these two paths these two currents are correlated. So, you cannot use i d n 0 squared you have to calculate the total current while using the linear quantities. So, there is a current i d n 0 by 2 flowing through M 1 and the same amount flowing through M 2.

Let us see what happens to the current flowing through M 1 that current flows through M 3 to create a small signal noise voltage which I will call V x n and that noise voltage causes a noise current to flow through M 4. Now, clearly, since M 3 and M 4 are identical, this noise is also i d n 0 by 2, which is the same as this noise.

Now, let us look at the total output short circuit noise current if you apply KCL at the output node you find that I s c in is equal to 0, because the current entering the node from M 4 is exactly equal to the current entering leaving the node into M 2. Therefore, there is no current flowing into the short circuit. This means that the noise from M 0 does not appear at the output. So, this is a very important result; and consequently it also does not appear in the input referred noise of the opamp. So, as you can see the noise of M 0 appears through the transistors M 1 and M 2, but does not affect the output at all.