Analog Integrated Circuits
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Lecture – 29
Telescopic OpAmp – 5

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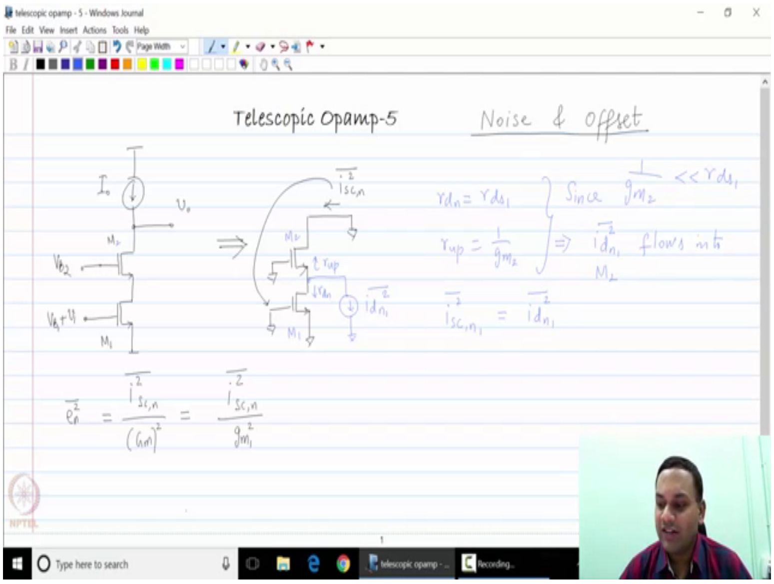

In this lecture we are going to look at the noise and offset of the telescopic opamp. Now before we do that it is a good idea to review the noise of a cascode amplifier of a simple cascode amplifier. So, the way we are going to do this is we are going to find out the effective input referred noise, because as we have studied before the input referred noise tells you how much noise is contributed by each particularly each set of components of these circuit.

So, to do this we are going to refer we are going to look at the short circuit noise of the circuit. So, since that is an easier way to do this I am going to redraw the small signal equivalent circuit with the output short circuited. So, we want to find out the short circuit noise, and in this particular case I will use this polarity for the very specific reason we will find out i squared S C n, and if I divide i square S c n by the square of the transconductance of the cascode amplifier, this will give me the input referred noise voltage squared which i shall call e n square.

So, to refer this back to the input of the amplifier I will divide by the square of the transconductance, and as we have seen the transconductance of the cascode amplifier is nothing, but g m 1. So, this is s square c n over g m square. Now let us take each the noise from each transistor and look at how much of it flows to the output. We will first start off with the noise from noise from M 1. So, now, the noise from everyone is my i d n 1 squared and this noise splits between transistors M 1 and M 2.

Now, if you look at the way it splits the current will split in the order of the impedances the impedance looking down which I call r down is nothing, but the r d s of M 1 the impedance looking up which I will call r up is nothing, but 1 over g M 2 because I have a short circuit at the drain of M 2. So, this means since so g m 2 is much larger than a g d s 2 1 over g M 2 is much smaller than r d s 1 and this means that almost all of i d n square flows into M 2.

The complete current flows for M 2 and flows into the a short circuit therefore, the first component of the noise I call that i S c n 1 square is equal to id n square. Now let us look any noise from M two.

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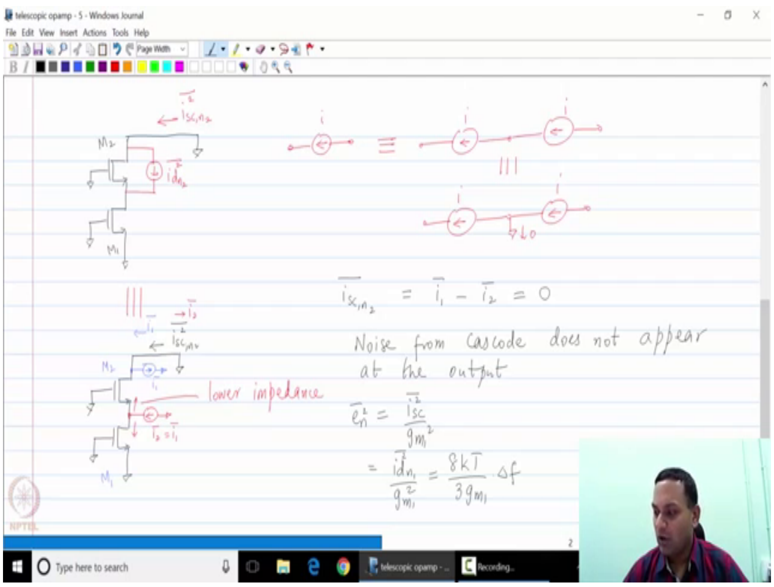

So, if you look at the noise from M 2, that can be represented by a current source across the drain source M 2 we do and we want to find out how much of this current flows through the short circuit. So, we want to find out the component flowing through the short circuit. So, to do this we will use a small trick that we have used before so, we know that a current source between 2 nodes can be represented by a series combination of the same currents also all that I can replace that with 2 correct sources i with no change in the circuit, and again this can be changed as 2 current sources i with a short circuit at the at the common mode point.

So, and there is no current through the short circuit therefore, the circuit does not change, it all we are going to do the same thing here. So, we are going to change this circuit to the following I am going to show that show the 2 current sources in red and blue. So, we are going to split this current source the only difference being these 2 sources red, and blue sources are going to be correlated my sources and I call that i 1 squared, and the red 1 sorry i 1, and the current in red is flowing into the source of M 2 and that will be called i 2.

And remember this is equal to and I am interested in finding the overall short circuit current. So, if you look at i 2 or rather if you look at i 1 let us look at i 1 first. So, i 1 has the option of flowing down into the drain of M 2 or up into the short circuit of course, i 1 will prefer to flow into the short circuit directly, because it is the path of least impedance. So, there is a current i 1 flowing in this direction through the circuit.

Now, what about i 2 if you look at i 2, i 2 also has the option of flowing through 2 paths in the circuit it either has the option of going upwards or flowing downwards as we have seen the impedance looking downwards is r d s 1 whereas, the impedance looking upwards is 1 over g m 2 which is much smaller and therefore, this current is much larger the impedance is much smaller. So, I just point out that this is a low impedance.

Therefore I have seen in red i 2 flows in this direction therefore, i S c n 2 is equal to i 1 minus i 2 is equal to 0. Since i 1 and i 2 have the same impedance, this means that the noise from the cascode does not appear at the appear at the inside the short circuit. So, the noise from even though the cascode produces noise, its noise does not appear at the short circuit node it keeps circulating inside the device. And eventually if you measure the input referred noise you will find that the cascade does not produce any noise at all.

So, therefore e n squared is nothing, but i d n 1 squared. So, i S c squared g 1 square this is nothing, but i d n 1 square over g m 1 square, and please remember that i d n 1 is 8 k T 3 8 k T by 3 into g m delta f. So, this is 8 k T by 3 g m 1 square f. So, the power spectral density is 8 k T by 3 g m as you can see the input referred noise of the cascode amplifier consists only of the noise of M 1, that even though you have added cascode the noise of the cascode does not affect the noise of the amplifiers. Now, we are going to use this to figure out the noise of the telescopic opamp.

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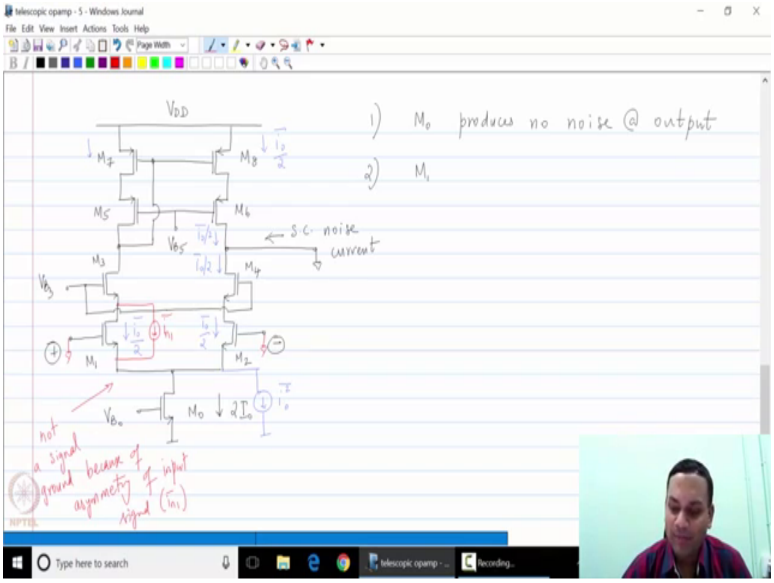

So, now, let us now take the telescopic opamp you can see, now that there are 9 sources of noise in the circuit we will go through these transistors 1 by 1 and figure out how much of this current flows into the output, to do that again we will short circuit the output node and figure out a short circuit noise current. And we can refer that back to the input to figure out what the input referred noise of the telescopic opamps.

As you might imagine the noise of M 0 is in parallel with which i call i 0 is it parallel with M 0 the impedance looking up through both sides is almost the same, because it is 1 over g m 1 versus 1 over g 2. So, I will see equal and opposite currents are almost equal and opposite currents i 0 by 2 and i 0 by 2, and this current gets mirrored as i 0 by 2 through M 8 M 6 and therefore, since the 2 these 2 currents are correlated there is no short circuit current noise at the output due to M 0.

So, there is a current i 0 by 2 entering this node, and that is a current i 0 by 2 leaving this node. So, M 0 produces no noise at the opamp, now what about M 1 and M 2 as far as noise of M 1 as concerned you will find that this current has 2 parts to split. So, we will now use the same method as we did for the cascode device, the reason we cannot use symmetry is because as far as noise is concerned this is not a virtual ground is not signal ground, because of asymmetry of input signal.

So, in this case the input signal of interest is what is I should call i n 1 we are going to ground the gates of M 1 and M 2, as you can see as far as the signal is concerned i which is i n 1. In this case the circuit is no longer no longer has a line of symmetry and therefore, you cannot consider the circuit to be symmetric on both sides. The way we shall approach this problem is to change is the same as before we will add 2 current sources in series and grout the ground the intermediate path, and we shall see how the signal travels through this circuit.

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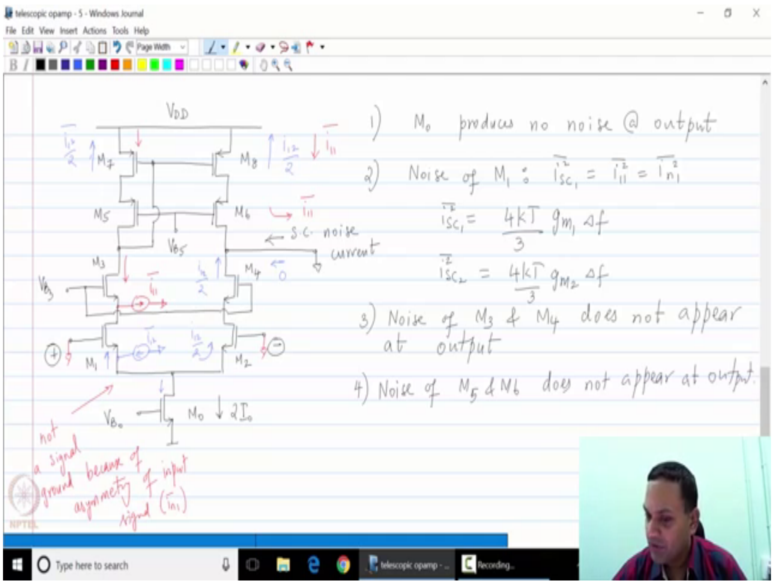

So, I will show that in red and blue as usual so, I recall that i 1 and a current source i 1 2 which are both correlated. If you look at i 1 2 seize the impedance of M 0 looking downwards which is extremely large, and the impedance looking up into the source of M 1 which is of the order of 1 over g m 1 and therefore, and the other surface by side which is 1 over g m 2.

So, these are the 3 parts of the circuit looks, and it turns out that the current i 1 2 is split equally between M 1 and M 2 these 2 paths are of course, a symmetric now. So, now, this current flows into M 7. So, this is i 1 to over 2 and therefore, there is a current i 1 2 over 2 flowing into the into M 8 what happens to the current flowing here, there is a current flowing in the M 2 of value i 1 2 over 2 and that current flows into this and therefore, this current is 0 because by applying case here at the output node. So, there is no current through the short circuit.

Now, what about the current source in the red, you will find that this current has 2 paths to flow at this node it can flow upwards looking up into the source of M 3, which happens to be a very low impedance versus flowing down where it has a very high impedance which is that looking down impedance at the drain off M 1 therefore, what happens is that most of this current flows from M 3, and this current flows down through M 7 and gets reflected to M 8.

So, this current is i 1 1 that is very little current flowing through M 1 M 0 M 2 and M 4, and this current flows through the short circuit therefore, if you look at the noise of M 1 the short circuit noise current is i 1 1 which is equal to i n 1 the plane thermal noise of M one. So, therefore, i S c 1 squared is this this is. So, i S c 1 is 4 k T by 3 g m 1 delta f. So, all of the noise of M 1 appears through the output short circuit.

You can do a similar analysis for M 2 and show that i S c 2 is also 4 k T by 3 into g m 2 delta f this is the squared noise at the output due to M 2. Now what about M 3 and M 4 you will find that noise of M 3 and M 4 does not appear at the output, this is because of the cascode action of M 3 and M 4, because M 3 and M 4 are cascade transistors that noise does not appear at the output.

Now, what about M 5 and M 6 it turns out that same is true for M 5 and M 6 noise of M 5 and M 6 does not appear finally, we need to look at the noise of M 7 and M 8.

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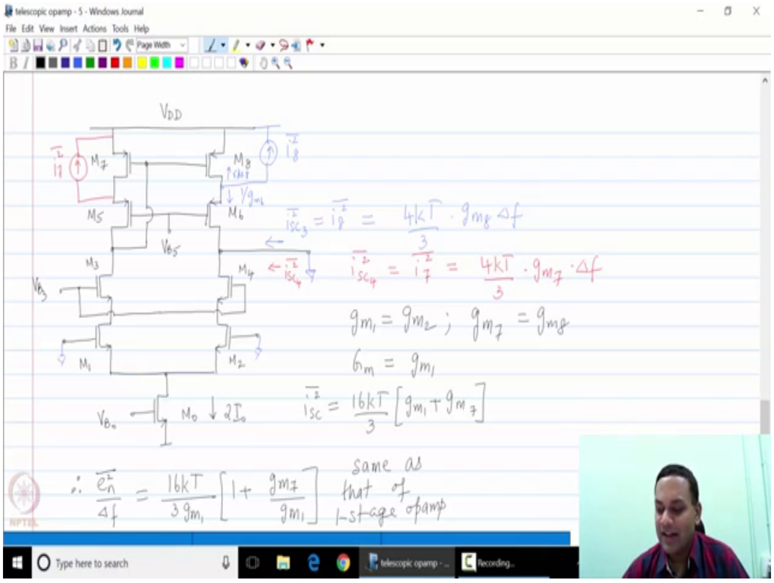

So, let us take the noise of M 8 itself we will show that in blue, the noise of M 8 is the current source which is i 8 squared in parallel with M 8, and as you can imagine i 8 squared has 2 parts to flow the impedance looking downwards as r d s 8, but as the impedance looking down this is 1 over g m 8.

So, most of i 8 tends to flow through M 6 and eventually through the output short circuit therefore, I will say that i S c 3 is equal to i S c 3 square is equal to i s square and this is nothing, but 4 k T by 3 into g m 8 delta f. Similarly you will find that noise of M 7 which is i 7 square also appears at the output, and if all that i S c 4 squared this is i 7 square this is 4 k T by 3 into g M 7 delta f.

Finally we will we know that g m 1 is equal to g m 2, g m 7 is equal to g m 8, and we also know that the overall transconductance of the opamp is nothing, but g m 1 therefore, you can say that e n square over delta f. This is the input referred squared voltage noise density this is nothing, but the total short circuit noise current divided by g m so, maybe firstly, we will write down the total short circuit noise current. The total short circuit noise current this 16 k T by 3 into g m 1 plus g m 7.

Therefore the total input referred noise quite voltage density is 16 k T by 3 g m 1 into 1 plus g m 7 over g m 1 please note that this is very similar to the noise of the input referred noise of the 1 stage opamp. So, even though the telescopic opamp has much larger d c gain it has very similar noise performance especially at low frequencies. Now, finally, we will write down the expression for the offset without deriving it directly I just point out that the behavior of an offset voltage or current is similar to that of noise.

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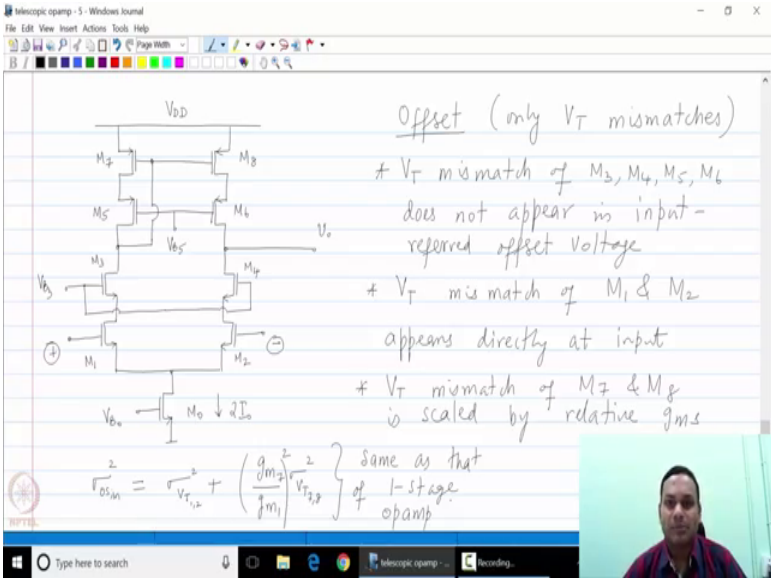

So, I just point out that as far as offset is concerned we are going to consider only V T mismatches, you will find that V T mismatch of M 3 and M 4 does not appear as an input referred offset, just as the noise was did not appear when referred back to their input the V T mismatch of M 3 and M 4, these also reduced and does not appear at the input of the at the input of the overall opamp and the same can be said for M 5 and M 6.

So, (Refer Time: 23:54) write in blue. So, you say that M 3 M 4 M 5 and M 6, this is similar to the that formulas now what about V T mismatch of M 1 and M 2 it turns out that V T mismatch of M 1 and M 2 appears directly at the input of the opamp. And finally, V T mismatch of M 7 and M 8 is scaled down scaled by the relative g m, then you refer back to the input. So, the input referred offset voltage which is ah represented by its standard deviation and say sigma squared over s in has 2 components, the first component is the V T mismatch of 1 and 2, and the p p mismatch of 7 and 8 a scale by the ratio of g m 7 to g m 1 whole square this is also same as that of 1 stage opamp. So, there are some parameters that are different for the telescopic opamp, and some that at the same when compared to the 1 stage opamp.