Analog Electronic Circuits
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Lecture - 87
Numerical Examples on Current Mirror and its Applications (Part-B)

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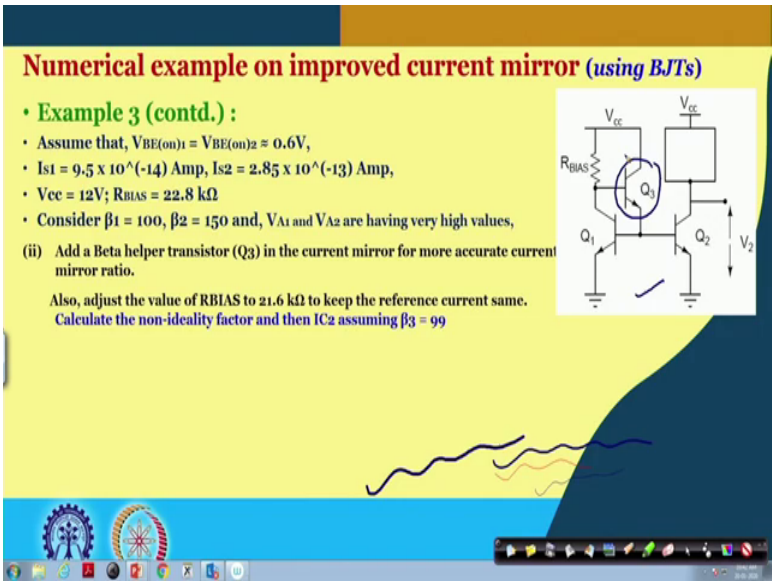

So dear students welcome back after the break. So, before the break we are talking about the numerical examples of the current mirror. As you can see here, and there we have used beta helper to improve the non-ideality factor coming due to the base current loss namely, this base current loss. So in the next example, what we will see that improvisation of the numeric current mirror circuit to take care of the non-ideality factor due to early voltage.

To be more precise, we like to place one cascode transistor here and that improves the output resistance of the current mirror.

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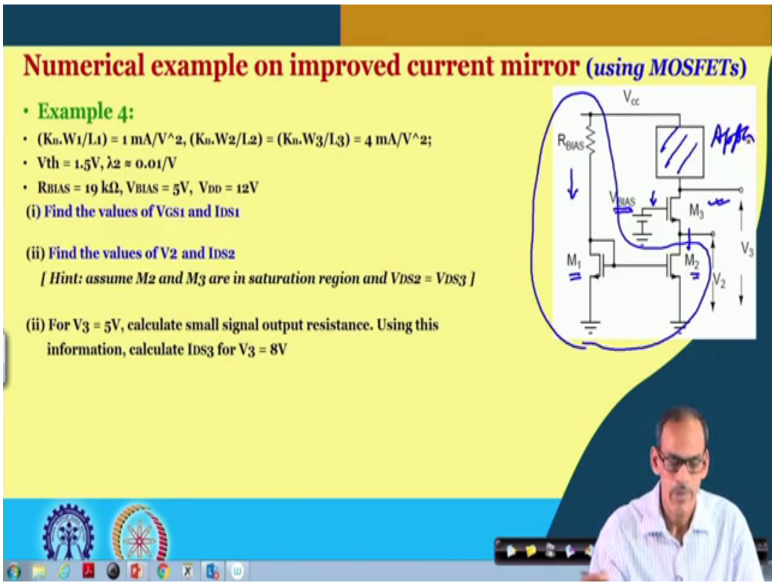

So in the next example, here we do have first, we are starting with MOSFET version and then after that we will go to the BJT version. And so, here transistor-3 it has been added on the main current mirror. So, the main current mirror it is constructed by M 1 and M 2 and whatever the reference current it is coming, it is mirroring here.

And then we do have this transistor M 3, to have meaningful operation of this circuit, we require its gate voltage V BIAS, denoted here. V BIAS it should be sufficiently high. So, that transistor-2 and maybe 3 also are in saturation region of operation. S, and of course, we do have the application circuit here.

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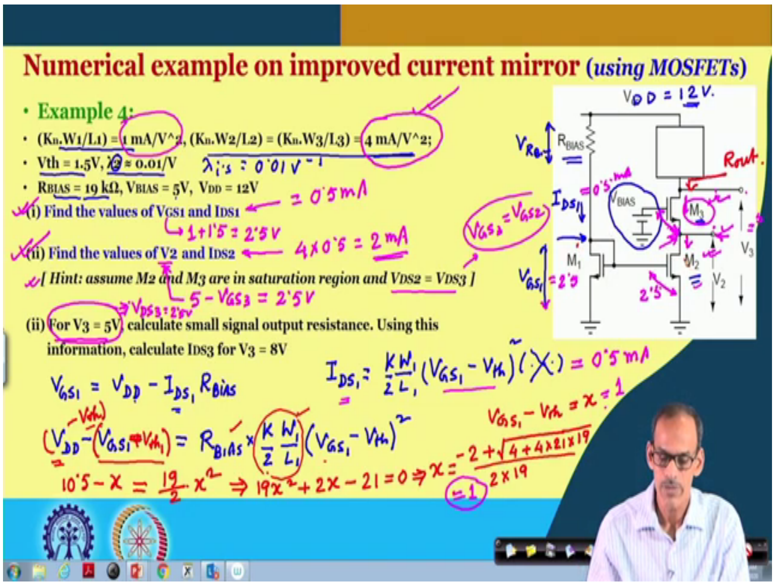

Now coming to the different sizes of different transistors given here, we do have for transistor-1, we do have the K into W by L, it is 1 milliampere per volt square. On the other hand for transistor-2 and transistor-3, we do have K into W by L, I equals to 4 milliampere per volt square. This is just for a change, we are using different values of the aspect ratio. Threshold voltage on the other hand, we are keeping it same for simplicity of the calculation and also the lambda of all the transistor it is not only for transistor-2, but for all transistors.

Let we consider this is equal to 0.01 per volt and then we do have the bias resistor which is 19 kiloohms and then V BIAS, it is 5 volt. Here, it is 5 volt and supply. This should be V DD. So, this is 12 volt. Now we need to find the value of this V GS1 and the current flowing here from whatever the voltage 12 volt it is given to us and then R BIAS, it is given there.

So to calculate that, in some of our previous examples we have done that this current which is I DS1, it is also creating a drop here and after subtracting this drop, say V R BIAS from 12 volt supply, it is giving us the V GS. So, we can say that V GS1 equals to V DD. So, V GS1 equals to V DD minus the I DS current multiplied by R BIAS. And on the other hand, we know that I DS expression of I DS equals to K W by L of transistor-1 by 2 and then V GS1 minus V th square.

Of course, by dropping the rest of the part, so if I drop this part and what we have we do have the expression of I DS here. So, we can put the expression of I DS here and then we can make probably we can take the V DD on the other side. So, we can say that V DD minus V GS1 equals to the R BIAS multiplied by I DS, an I DS expression it is given to us which is K W by L by 2 into V GS minus V th square.

Now, we do have V GS need also need to be find out. So, what we can do for simplicity, we let we consider we add V th1 here, so that we can write this is minus with V GS1, but then since we are adding it, we also have to subtract here the same V th. So, we do have V DD minus V th equals to this part and again, V GS minus V th is also appearing here, in the second order form.

So, if I consider V GS 1 minus V th equals to say x then, we can rewrite this V DD minus V th. So, this part it is 12 volt minus V th it is given to us 1.5. So, that is 10.5 minus x minus R BIAS it is 19 and this part it is 1 divided by 2 here. So, we can and also we do have kilo ohms here and this is in milli ampere.

So, again that is getting cancelled. So, we do have 19 here by 2 into x square. So, we can rearrange this equation, we can write in the form of 19 x square plus 2 x minus 21 equals to 0. In fact, that gives us solution of this x which is equal to minus 2. We have to consider only plus term because, we are considering V GS minus V th should be positive.

So, this then 4 plus 4 into 21 into 19 divided by 2 into 19. In fact, that gives us solution x is equal to 1. So that means, the so, this is equal to 1. So, that gives us V GS1 equals to V th plus 1. So, this is equal to 1 plus V th is 1.5. So, that is equal to 2.5. So, we got the voltage here it is 2.5 and the corresponding current if we put the value of this x is equal to 1 here, then we do get I DS 1 equals to 0.5 milliampere alright.

In fact, so, these 2. So, this is equal to 0.5 milliampere. Now we need to find what will be the value of V 2. V 2 is the voltage coming here and here we assume that both this transistor and this transistor, they do have K into W by L which is 4 times than this one. Which means that the current flow here it is 4 times of this current which is 0.5 here. And so that gives us I DS2 equals to 4 into 0.5 that is 2 milliampere.

So, if we do have this 2 milliampere current is flowing and the same current is flowing here also and the V GS here it is same since dimensions of transistor-2 and transistor-3 they are equal and if I assume transistor-3 it is in saturation region then the corresponding V GS here it will be same as whatever the voltage you do have namely. 2.5.

So, if the V GS3 it is 2.5 then voltage coming here which is V 2. So that is equal to V BIAS that is 5 volt minus V GS3. So, that is equal to 2.5. So, we do have DC voltage here it is 2.5. In fact, this the hint it is given that we can consider both the transistors are in saturation and if we assume that V DS of the 2 transistors that ensures that V GS3 equals to V GS2 because we do have same transconductance of the 2 transistors.

Now so now we obtain, we have solved this part. Next thing is that for V 3, if it is say 5 volt then what do you do expect? Here we do have 2.5 So, V DS3 So, V 3 equals to 5 volt that makes V DS3 it is also 2.5 right. And with this voltage, we can try to find what will be the corresponding value of the output resistance R out small signal R output resistance.

So, I am going to erase this board to create some space for next calculation, but you please keep in mind that the current flow in this branch it is 0.2 current flow here it is 4 times of that 2 milliampere.

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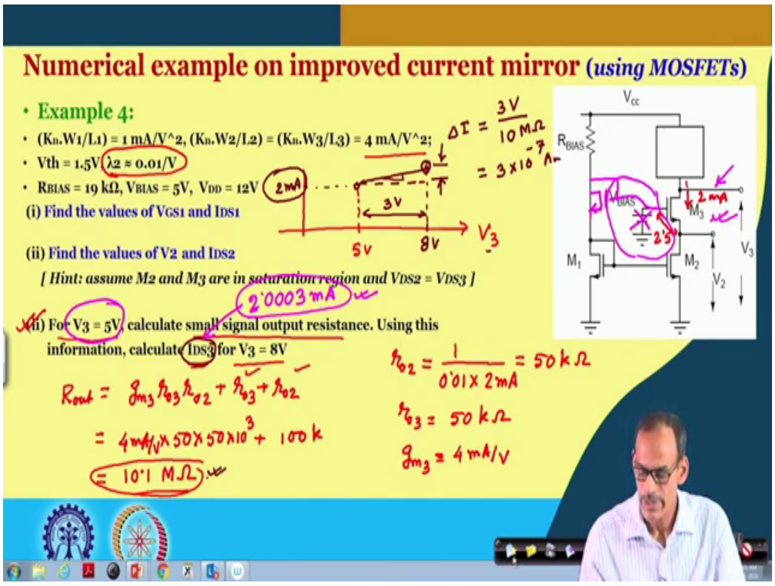

So, we need to find what will be the small signal output resistance. And R out is g m3 multiplied by r o3 or r ds3 multiplied by r ds2 plus r o3 plus r o2. Note that r o and r ds we are considering they are synonymous. Now r o2 in fact, all the transistors we assume that lambda is equal to 0.01. So, r o2 it is 1 by lambda 0.01 multiplied by its current which is 2 milliampere. And that gives us the resistance equals to 50 kiloohm. So same thing, r o3 equals to 50 kiloohm.

And on the other hand, g m3 and as I said that the current flow here it is 2 milliampere and the V GS DC voltage here it is 2.5 or V GS minus V th is 1 volt. So, that gives us the g m3 which is by utilizing say, K value here K into W by L of 4. So, we can say 4 milliampere per volt. And hence the R out we are getting here it is 4 milli multiplied by 50 K here into 50 K, and then we do have 50 and 50 here so that gives us 100 K.

In fact, this is becoming 10.1 mega ohm resistance ok. So, that is the small signal output resistance. Now utilizing this information, can we calculate what will be the current flow in this branch I DS3 or you may call I DS2 also for V 3 equal to 8 volt? So, how do you calculate? We can use this information we can use the information of the current at 5 volt.

So we know that if V 3 it is equal to 5 volt, the corresponding current it was the corresponding current here it was 2 milliampere and then if we increase this V 3 from 5 volt to 8 volt due to output resistance, it is having some slope here and we know that inverse of this slope which is the output resistance it is given here.

So, using that slope and this voltage change which is 3 volt we can find what is the additional current here. So, you may call this is delta of this current. So, delta of this current it will be 3 volt divided by whatever, 10 mega ohms ok. So, we do have. So, this is equal to 3 into 10 to the power minus 7 right so this much of ampere.

So, the corresponding current here at this point it is 2 milliampere plus this one. So, we can say that this current this current equals to 2. So, 0.0003 milliampere ok, now how do you get this voltage? Or so, this is this circuit it is fine, we are getting very small change of this current because of this cascode transistor. So, even though the voltage at this point V 3 it is going from 5 volt to 8 volt.

Still we can see that the variation here the current variation it is very small and hence, it is meaningful to add this cascode transistor. But then it is little inconvenient to get this voltage and to overcome this problem, what we can do we can put a transistor here which is also diode connected and that produces a voltage and that is normally that is what it is getting applied.

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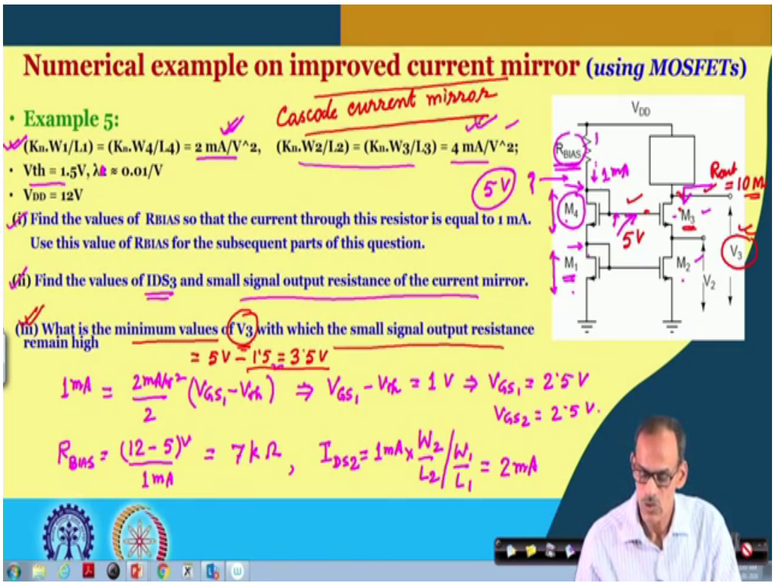

So in the next slide, we do have that example. So, we are adding here transistor 4 to generate this bias here ok. But of course, the voltage coming here it is now different from whatever the voltage you do have. So for the same condition here namely, sizes of transistor-1, now I have probably I have changed, yes. I have change here just for a change, we consider K divided K into W by L of transistor-1 and K into W by L of transistor-4 they are equal to 2 milliampere per volt square.

On the other hand, for transistor-2 and transistor-3, we are retaining this to be 4 milliampere. V th we are keeping it as same and all the lambdas are 0.01 per volt supply voltage it is 12 volt. So, we can try to calculate what may be this bias resistor so that the current flow here it is 1 milliampere.

So, how do you find that? If I know this current is 1 milliampere, probably from this dimension, we can find what is the corresponding V GS required and the V GS required. And then from that you can find what will be the voltage here and then we can see what is the drop here and from that we can calculate R BIAS.

So, 1 milliampere of I DS I DS1 equals to its corresponding K which is 2 milliampere per volt square divided by 2 into V GS minus V th square. Again we are dropping 1 plus lambda V DS part. So, this is giving us V GS 1 minus V th equals to 1 volt. And hence, V GS1 equals to 1 plus 1.5 that is 2.5 volt, and this is also giving us V GS2 equals to 2.5 volt.

So, that gives us the voltage here it is 2.5 and 2.5, so that is 5 volt. In fact this 5 volt, it is nicely getting generated for making a suitable bias for transistor-3 and R BIAS then R BIAS equals to we do have 12 volt here minus 5 volt divided by 1 milliampere current, right. So, that is giving us 7 kiloohm.

So that is how we can set this resistor. So that the current here in the left branch it is 1 milliampere. Now, we can try to find the value of this I DS3 in same way and here now the ratio aspect ratio of transistor-3 channel and transistor-1 channel it is 2. So, the I DS2 equals to the reference current 1 milliampere multiplied by W by L of transistor-2 divided by W by L of transistor-1.

So, that is 2. So that is giving us 2 milliampere. So now we obtain this part and this part we can calculate the small signal output resistance similar to whatever the way we have done. So, output resistance here it will be in fact, since the current here it is remaining same and this is also remaining same. So, we are expecting that output resistance R out.

So, here also it will be 10.1 mega ohms. So, next question is that what is the minimum value of this voltage here voltage here, so that we can enjoy this high output resistance. In other words, what should be the minimum value of this voltage so, that transistor-3 it is remaining in saturation region of operation?

So, we know that the voltage here it is 5 volt. So, the minimum voltage here we required it is 5 volt minus V th. So, the minimum voltage here it will be, 5 volt is the gate voltage here, minus V th 1.5. So, that is equal to 3.5 volt. So, as long as this voltage it is higher than 3.5 volt then we do get output resistance, it is very high.

So that is how we can make the output current very less sensitive to the voltage for improved current mirror or which is referred as cascode commonly known as cascode current mirror. And similar thing it can be done for BJT also. So in the next slide, in the next example 6, we will see that.

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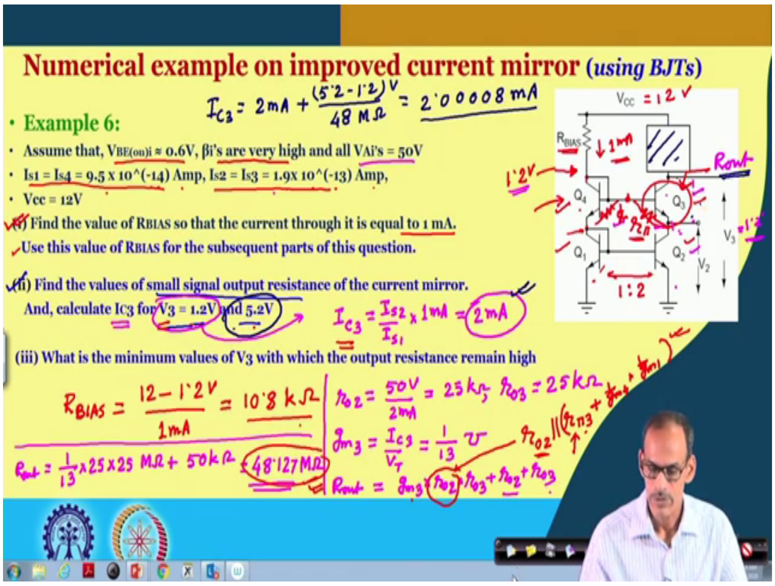

So here as we have done before, we have added transistor, transistor Q 3 to get higher resistance here and making this current insensitive to the output voltage variation. And instead of giving a bias here, independent bias here, similar to the previous circuit example, in

MOSFET, we have added transistor-4 in diode connected form so that we can internally generate a voltage here, suitable voltage here. Now here the dimensions, the information of different transistors are given; namely, we consider these 2 transistors are identical having reverse saturation current of 9.5 into 10 to the power minus 14 ampere.

On the other hand transistor-2 and transistor-3, they are identical having the reverse saturation current which is 109 into 10 to the power minus 13 ampere which is just 2 times of this current. So, we can say that the reverse saturation current ratio here it is 1 is to 2. Supply voltage it is 12 volt. So, the first part we need to find what will be the bias resistor. So, that the current here it is 1 milliampere.

Now, here for BJT getting the voltage here it is much simpler, we can always approximate that V BE on is very close to 0.6. So if this is 0.6 and then we do have one more 0.6. So the voltage here it is 1.2 volt. So, that gives us the R BIAS. So, the R BIAS equals to 12 volt minus 1.2 volt divided by 1 milliampere.

So this is equal to 10.8 kilo ohms. So, for the subsequent part we can use the same R BIAS to maintain this current 1 milliampere. Next thing is that we need to find what will be the; what will be the small signal output resistance and then we can calculate what will be the corresponding current here for V 3 is equal to 1.2 volt and 5.2 volt.

So for if I consider say, V 3 is equal to 1.2 volt, this is also 1.2 volt. So that makes V CE here and V CE here, they are similar. So what we can see that both transistor-3 and transistor-2 they are in active region of operation and that makes the corresponding current particularly, whenever this is 1.2 volt and the voltage here and voltage here making the 2 V CE voltage equal.

So, that gives us I C3 particularly for this case equals to just I S ratio I S2 divided by I S1 into the reference current is 1 milli ampere. And hence this is since the I S ratio it is 2. So, we can see it is equal to 2 milliampere. Now once we have 2 milliampere of current, probably we can get the value of the R out and the corresponding particularly r o and then g m and then we can find what is the corresponding output resistance of the current mirror.

So, to calculate let we consider r o2. So, this is equals to we do have the early voltage 50 divided by 2 milliampere. So, that gives us 25 k. In fact, this is true for r o3 also. So that is equal to 25 k. On the other hand, g m of transistor-3. So, this is equal to I C by V T I C by V T, thermal equivalent voltage we can consider this is 26 milli volt V T.

So, we can say this is equal to 1 by 13 mho. In fact, that gives us the output resistance R out equals to g m3 into r o2 multiplied by r o3 plus r o2 plus r o3. In fact, what we can get here it is ok, let me use this space here. So, g m3 it is 1 by 13 and then we do have 25 k into 25 k. So, this is this much of mega ohms plus we do have summation of this 2, 25 k's. So, that is 50 k probably that you can ignore.

In fact, you may calculate this one, but I think I do have some calculated value for you. So, this is becoming 48.127 mega ohms. Note that here I have ignored the r pi here, otherwise, I should have to consider instead of only this one. I should have to consider r o2 in parallel with r pi 2, but this node it is not ground. In fact from here to here I do have 1 by g m and also we do have 1 by g m.

So, I should have considered r pi 3 in series with 1 by g m4 plus 1 by g m1, instead of this one. But since we have considered beta is very high, we may say that this is infinite and as a result, I have dropped this part and that gives us much higher of resistance. Practically, you have to consider this r pi, and its value it may be much lower than this resistance. It may be in the range of say 1 k to 2 k.

In fact, if I multiply this r pi 3 with gm three so that gives us the beta of the transistor and the corresponding resistance it may vary, but even then this resistance it may be in the order of few megaohms. So anyway, for this numerical example since the output resistance it is here, using this output resistance information, we can calculate the variation of this current. If we vary this V 3 from 1.2 volt to 5.2 volt; that means, a voltage variation of 4 volt.

So for this voltage, for this voltage of V 3 we can calculate the corresponding I c 3 equals to 2 milliampere plus delta V which is 4 volt. So, 5.2 minus 1.2 and divided by 48 mega ohms. And in fact, again I have done the calculation for you and this is coming 2.00008 milliampere. That is again very close to whatever you do have.

So, that indicates that by adding this cascode transistor since the output resistance is very high, the variation here it is very small. So, this is again it is called the cascode current mirror and by adding this transistor, we are getting the advantage. Now coming to other kind of example instead of considering only the current mirror, if we consider some circuit where we have used the current mirror namely, in common source amplifier as well as in common emitter amplifier where we have use the current mirror to create the active load.

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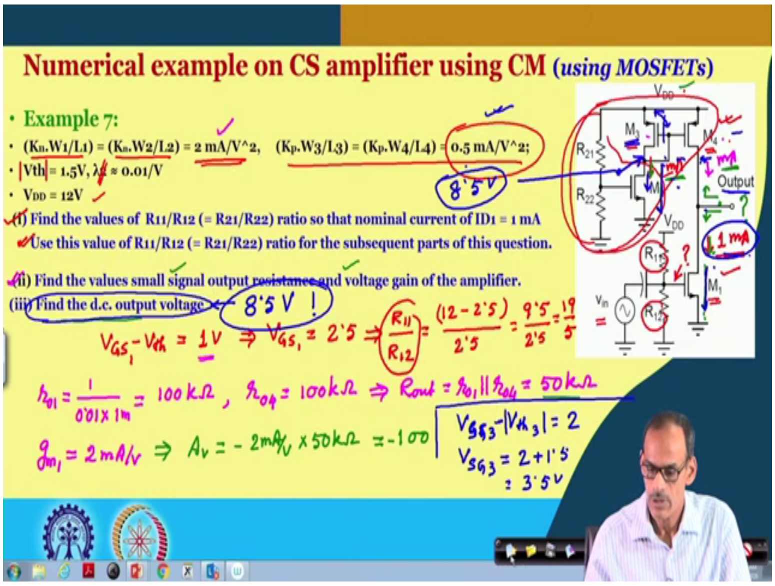

So in the next example, we do have common source amplifier I guess, yes we do have common source amplifier where we have the load part it is active load here, input we are feeding to transistor-1. So, transistor-1 it is working as the main amplifier and then transistor-4 it is working as a active load. But then this active load it is getting biased from or through this current mirror.

And our calculation of this numerical example is to find that how do you set the different meaningful value of these resistors and then current mirror. So, to start with, we do have the value of K into W by L of different transistors namely, transistor-1 and transistor-2. So we do have transistor-1 and transistor-2, we are assuming they are identical. And on the other hand, transistor-3 and transistor-4, they are PMOS transistors.

They do have different value of this transconductance factor, but they are same, they are this transistor-3 and transistor-4, both of them are having this factor equal to 0.5 milliampere per volt square.

Let we consider V th for all the transistors. So whether it is NMOS or PMOS, it is 1.5 and lambda for all the transistors lambda for all the transistors equals to 0.01 supply voltage it is to 12 volt. So, the first part we need to find what is the ratio this potential divider so, that it creates a voltage here, such that the current flow here it is 1 milliampere. So, how do you find? We need to calculate what is the V GS required here to get 1 milli ampere of current flow.

So again, if you use this information and the 1 milliampere of current requirement, you can find that V GS equals V GS minus V th equals to 1 volt and that gives us V GS1 equals to 2.5 and that gives us the ratio of R 11 by R 12 equals to V DD is 12 volt minus 2.5 divided by 2.5. In fact, this is equal to 89.5 by 2.5 or we can say this is 19 by 5.

So, if we use this ratio for this part also, and that also sets this current equals to 1 milliampere ok. So, we are using the same value of this ratio and for the subsequent part, let we consider this ratio. Now we need to find next step it is we need to find the small signal output resistance and the voltage gain. So, we are expecting this will be setting the current here right, which is 1 milliampere keeping both transistor-1 and transistor-4 in saturation region of operation.

So, the r o of transistor-1 which is equal to 1 by lambda which is 0.01 multiplied by 1 milliampere of current. So, that is equal to 100 kiloohm. Likewise, r o 4 it is also 100 kiloohm and that gives us the output resistance of the amplifier equals to r o1 in parallel with r o 4 equals to 50 kiloohm.

Now to get the voltage gain, we need to calculate g m of transistor-1 and again, by utilizing this information and V GS we do get this is equal to 2 milliampere per volt and that gives us the voltage gain A V equals to minus 2 milli per volt multiplied by this R out which is 50 k and that gives us a gain of 100. So, we got the voltage gain, we got the output resistance.

Next thing is that what is the DC voltage? We know that these 2 currents, they are equal. But both of them are having very high resistance, but we need to know what may be the precise value of this voltage. Will it be 6 volt? Which is half of this voltage or something else? We can keep that in mind that the current flow here it is 1 milli ampere. There we have ignored 1 plus lambda V DS part and to define this voltage, we need to consider this 1 plus lambda V DS part to get the precise voltage.

In fact if you see it carefully, the current flow through this transistor and this transistor they will be equal if their corresponding V DS they are equal, right. But then V DS of these 2 transistors if we see, V DS of this one output node voltage since it is very sensitive and its output resistance is very high. It may be difficult to get, but then voltage getting at this point is not so difficult because this transistor-3, it is diode connected.

In fact, if you calculate what may be the V SG of this transistor by considering its size here and the corresponding current here, you can find that V SG of transistor-3 minus V th of transistor-3 since it is PMOS we should consider magnitude. In fact, this is equal to since the current is 1 milliampere, but then K into W by L it is 0.5 V GS minus V th square it is equal to 4 and V GS minus V th, is becoming 2.

So that gives us I should say V SG because it is PMOS. So, V SG3 equals to 2 plus the threshold voltage 1.5. So, that gives us 3.5 volt. So that sets this voltage here, 12 minus 3.5 and this voltage it is 8.5 volt. In fact, if this voltage it is 8.5 and this is also 8.5, then only this 2 current they will be equal.

In other words, this current flow of this transistor and current of this transistor they are matched whenever these 2 voltages they are 8.5 and transistor-3 and transistor-4 they are also nicely supporting this conclusion that output voltage if it is 8.5 then the currents are equal.

So, from that argument we can say that DC voltage, output DC voltage instead of 6 volt it is rather 8.5 volt. It is not 6 point right. So, similar kind of exercise we can do for the common emitter amplifier.

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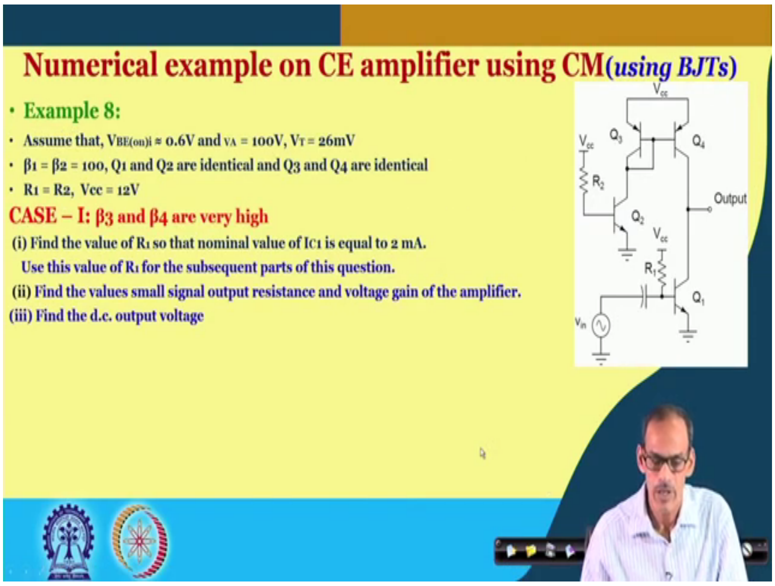

So in the next slide we will be having this common emitter amplifier, but then again, we need to take a break. So, after the break we will come back.

Thank you.