Analog Electronic Circuits
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Lecture - 86
Numerical Examples on Current Mirror and its Applications (Part-A)

So dear students, so, welcome back to our online certification course on Analog Electronic Circuits. Myself, Pradip Mandal from E and EC Department of IIT, Kharagpur. Today's topic of discussion it is Numerical Examples on Current Mirror and some Application Circuits, where we are using current mirror. So, primarily we will be talking about numerical examples, to complement whatever the theory you have learnt on current mirror and its application circuit.

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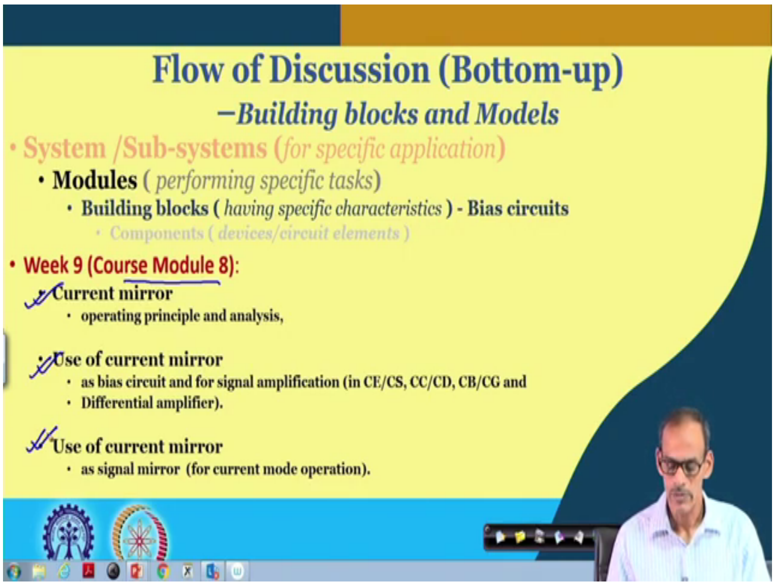

Now according to our plan, we are in week 9 and in fact, that is the course module 8 and we have discussed about the theoretical aspect of current mirror and different application circuits. And as I said that today we will be covering numerical examples extensively, on current mirror and different types of current mirrors including simple one and then advanced one.

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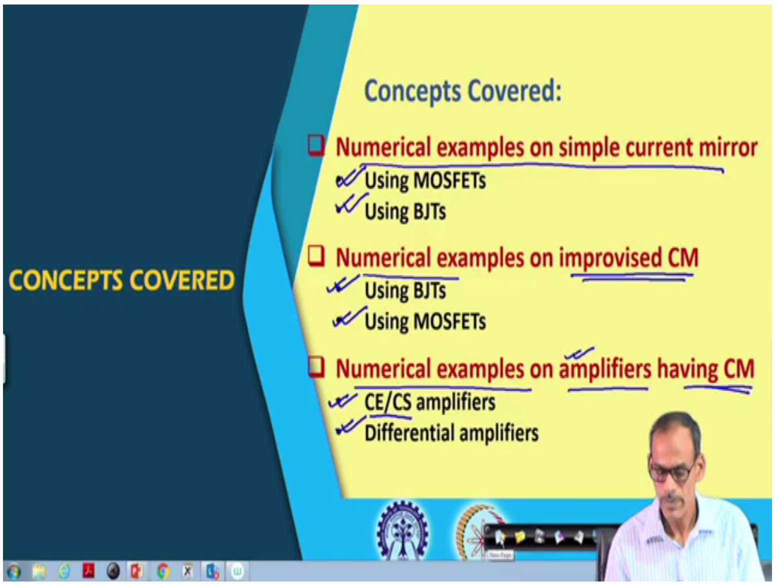

So, the coverage of today's presentation is enlisted here. So, we shall start with numerical examples of simple current mirror. We may start with current mirror having MOSFET transistor and then we can go for current mirror using BJT and then we will be moving to numerical examples on improvised current mirror or more precision current mirror.

And there also we will be having 2 types of circuits: namely one using BJT's and then other one is MOSFET. And subsequently, we will be talking about numerical examples on amplifiers which are using current mirror. So, our main focus is on the current mirror.

So, we may not be going into the aspect of the amplifiers, but primarily what are the advantages we can get using current mirror and what is the corresponding calculation we do? That will be highlighted by considering 2 specific types of examples, one is single-ended amplifier namely, common emitter and common source amplifier and then differential amplifier. Now, coming to a current mirror, simple current mirror constructed by MOSFET, here we do have the example.

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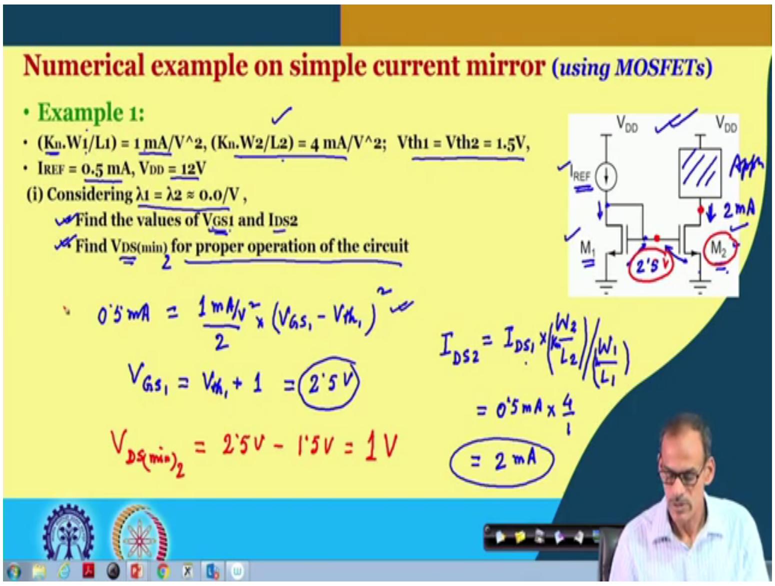

So, here we do have the example circuit where M 1 and M 2 are forming current mirror. We do have a reference current here and then we do have the application circuit here. So in this example, the W by L of transistor-1 and transistor-2 along with the K factor, it is given. For transistor-1, we do have 1 milliampere per volt square. For transistor-2, we do have 4 milliampere per volt square.

And let me assume that both the transistors are having equal threshold voltage of 1.5 and then we do have the reference current equals to half milliampere, and then supply voltage it is 12 volt. To start with, let we go simpler version, ignoring lambda effect considering both the lambdas are very small and let we try to find the values of V GS1 and I DS2.

Of course, I DS1 it is same as I reference current namely, half milliampere. But then, V GS1, it is setting V GS2 and since the W by L or K into W by L of the 2 transistors, they are different, we are expecting the current here to be different. So, let me start with the calculation of V GS1 or for I reference equals to 0.5, so 0.5 milliampere so, that is the I DS that is equal to its corresponding K W by L, which is 1 milliampere per volt square by 2 into V GS1 minus V th square.

So note that for this calculation, we are ignoring 1 plus lambda V DS. Even if the lambda is given, we normally ignore that. And if you see here, this equation it is giving us V GS1 equals to V th1 plus 1. So, that is equal to 2.5 volt. So, this 2.5 volt it is coming to the V GS of transistor-2 and the corresponding current here, it is either we can use this information of 2.5 V GS and then again, you can use the similar kind of equation. Or directly, we can use the expression of you know this I DS2 current.

In terms of I DS1 multiplied by W by L ratio of transistor-2 divided by W by L ratio of transistor-1. So, from this we can say that the I DS1 it is 1.5 milliampere and if you take the ratio of K into W by L, and K into W by L here. In fact, we do have K in here and K in here. So, they are getting cancelled and then W by L ratios are coming 4 by 1. So, that gives us I DS2 equals to 2 milliampere. So, current flow here it is 2 milliampere.

Now we can find next part it is that we need to find what is the minimum value of this V DS of transistor-2, particularly for transistor-2 for proper operation of the circuit. Namely, the current mirror current output current can be well defined by this equation only when transistor-2 also in saturation.

So to keep this transistor in saturation, we know that the drain voltage it should be higher than the gate voltage minus V th and gate voltage we know, it is 2.5 volt. So, the V DS min V DS min equals to V DS min of transistor-2, it is equal to 2.5 volt, is the gate voltage minus V th which is 1.5 volt. So, that gives us minimum requirement of this voltage it is 1 volt.

Now, let us consider the next part of the same question in the next slide. So, that will be continuation of this problem. But probably, we can consider some finite value of from this lambdas.

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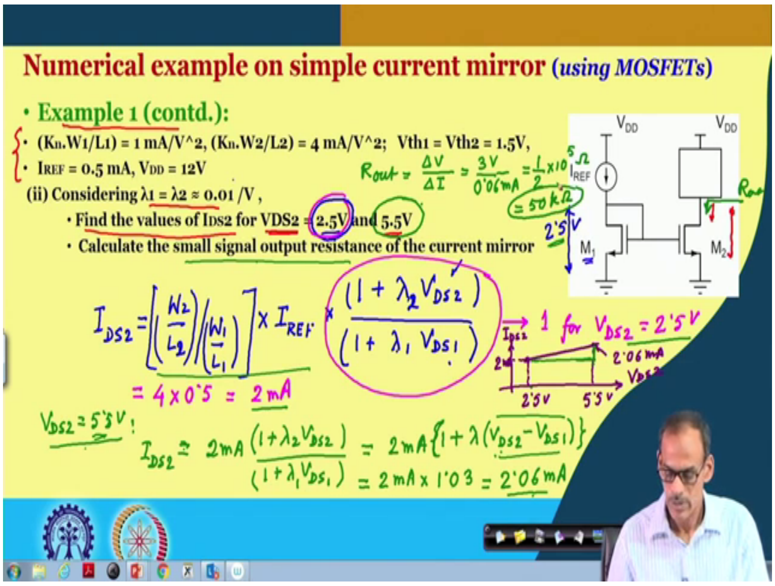

So, in the next slide we do have, so, what we have here it is all the other parameters remaining same. In fact, it is continuation of the same example, but we are considering lambda is equal to 0.01 per volt. And then again, we can try to find what is the corresponding value of this current. And particularly for 2 cases, if V DS2 here that is 2.5 and 5.5.

Now, you may recall from our previous calculation, the voltage here it is 2.5 V GS, we already have calculated is equal to 2.5 and so that is also V DS of transistor-1.

And then for the first case if V DS equals to 2.5 and if you consider this lambda, then you can get the current of I DS2 which is having this equation W by L of transistor-2 divided by W by L of transistor-1 multiplied by I reference. And then we do have 1 plus lambda 1 into sorry lambda 2 into V DS2 divided by 1 plus lambda 1 into V DS1.

Now for this case, V DS2 equals to 2.5, both this V DS and this V DS they are same. So, and also the lambdas are equal. So, we can say that this part of this equation it is becoming 1 for 2.5. As a result, the corresponding current here it is coming. So, this ratio it is 4 and I reference as I said it is 0.5. So, that gives us 2 milliampere. And this is for V DS2 equals to 2.5 volt. And let us try to calculate the I DS2 for the other value namely the V DS is equal to 5.5.

So for that, if I say V DS2 equals to 5.5, for this, I DS 2 it is equal to so, this part it is remaining same. So, we can directly write that part which is 2 milliampere multiplied by this non-ideality factor, 1 plus lambda 2 V DS2 divided by 1 plus lambda 1 V DS1. In fact, this part you can approximate well, approximate by considering this denominator factor into the numerator factor. And then if we ignore lambda square term, and since both the lambdas are equal, so, we can say that this is 1 plus lambda into V DS of transistor-2 minus V DS of transistor-1.

So, what we are getting here it is 2 milliampere multiplied by so, V DS2 minus V DS1. So, V DS2 it is 5.5 and V DS1 it is 2.5. So, this part it becomes so, this part it becomes 3 and lambda is 0.01, so that gives us 1.03 is the non-ideality factor. And that gives us the current equals to 2.06 milliampere. So, we can say that for these 2 different V DS values we do have different current; one is 2 milliampere here, another is 2.06.

So pictorially, we may say that if we vary the V DS of transistor-2, the current here it is having a finite slope. So, this is I DS2 and we do have one value here 2 for 2.5 volt the corresponding current is 2 milliampere. On the other hand, for 5.5 we do have so, this current is 2.06 milliampere. And from the slope of this line from the slope of this line, we can calculate the output resistance or we can strictly speaking, it is small signal output resistance.

So, to calculate the small signal output resistance what we can see here it is we can get the calculate the slope of this line and reciprocal of that is the small signal output resistance. So, small signal output resistance at the output of the current mirror R out. So, that is the voltage difference del V divided by del I and we know that del V it is 3 volt and the corresponding variation of this del del I it is 0.06 milliampere.

And so, this is giving us how much? 1 by 2 into 10 to the power 5 ohms, right. Or you can say this is 0.5, 0.5 and then in fact, 50 kiloohms. So that is the small signal output resistance of 50 kiloohms, right. So, now, if we continue this exercise for say, other condition. So, let we see in the next slide the third part of this, no now we are going to BJT. So, we have considered this simple current mirror. So, similar kind of circuit can be constructed by BJT.

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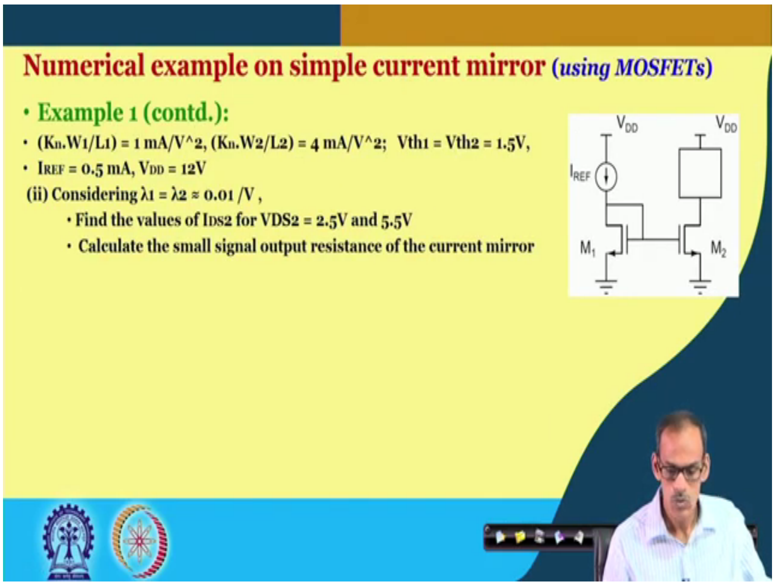

So, in the next slide will be going for simple current mirror constructed by BJT's and it will be having similar kind of exercise. But of course, the corresponding parameter of the BJT's are different. So, let us see in the next example how we calculate for current mirror circuit constructed by BJT.

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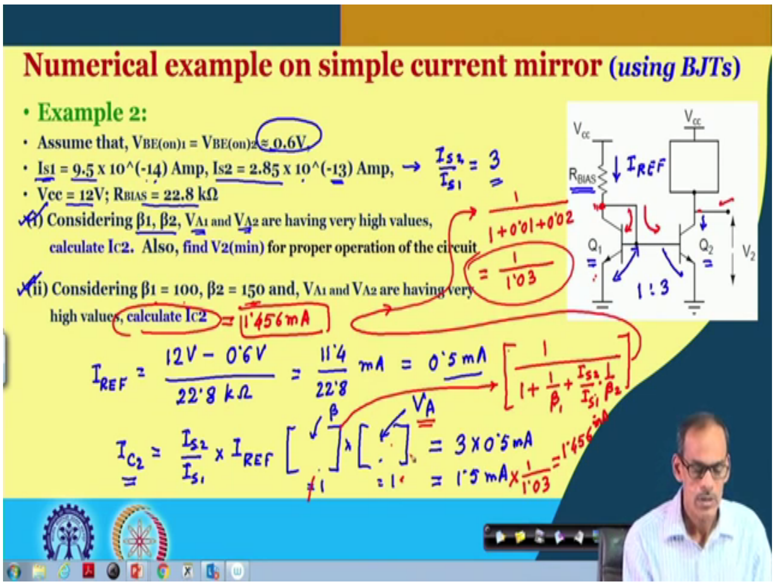

Now, in this example we do have Q 1 and Q 2. Now it is forming the current mirror and in this case, just for a change, instead of giving a reference current, we are giving a resistor here, supply voltage it is given to us 12 volt. This R BIAS register in resistance it is 22.8 kiloohm and then we can assume that V BE on voltage for both the transistors are approximately 0.6 volt. In addition to that, we also have the information about reverse saturation current of the 2 transistors.

So, Q 1 it is having reverse saturation current of 9.5 into 10 to the power minus 14 ampere. On the other hand, for Q 2 we do have reverse saturation current which is 2.85 into 10 to the power minus 13 ampere. In fact, if you see carefully, this is I S2 by I S1 is equal to 3. So, that is how I have picked up the number here.

So with this, what we can probably we can see the mirroring ratio it will be 1 is to 3 if it is, if we approximate that early voltage and then beta loss or the base current loss it is ignorable, then we can say this current mirror is essentially 1 is to 3 ratio current mirror. But before that we need to find what is the reference current itself I reference.

To get thus this I reference current, so we need to find what will be the I reference? I reference is equal to 12 volt V CC minus V BE on or 0.6 volt divided by 22.8 kiloohms. So, we do have 11.4 divided by 22.8 k. So that much of milliampere which is 0.5 milliampere. Now, if I consider a simple situation considering this both the beta's are very high, early voltages they are also very high which means that non-ideality factor we can we are approximating equal to 1.

So, the current flow here I C2 is given by I S2 divided by I S1 multiplied by this I reference current. And then we do have the 2 non-ideality factors. One may be due to early voltage another one may be due to the base current loss or due to finite beta. And for this part, both these non-ideality factors are equal to 1. So, this is equal to 1 this is also equal to 1.

So, that gives us the current I C2 equals to I S2 by I S1 which is 3 and then I reference current we have calculated is 0.5. So, that gives us the output current equals to 1.5 milliampere.

Now, let we consider the effect of beta namely, the current loss due to whatever the currents are flowing here. So that means, this is no more equal to 1 and to get this non-ideality factor you may recall that this part is equal to 1 by 1 plus 1 by beta 1 plus I S2 divided by I S1 into 1 by beta 2. So, this is the non-ideality factor and the values of beta 1 and beta two's are given. This is also the I S2 by I S1, it is also known that is why this is 3.

So, we can see that let me use this space. So, this non-ideality factor it becomes 1 divided by 1 plus 0.01. Then we do have 3 here and then 150 in the denominator. So, that gives us 1 by 50 so, that is equal to 0.02. So, that gives us 1 divided by 1.03, ok.

So with this factor, for this case, to calculate this current we need to multiply by this non-ideality factor of 1.03. In fact, if you calculate it what we are getting here it is 1.5 divided by 1.03 so, that is equal to 1.456 milliampere. So, this part it is coming 1.456 milliampere.

So if I consider beta, finite beta of course, this current is getting smaller because this non-ideality factor it is less than 1. On the other hand, if I consider say early voltage if this voltage and this voltage they are not equal, then again we will be getting non-ideal adding the second non-ideality factor. So, if this voltage it is higher than the V CE of transistor-1 or , so, in that case this non ideal non second non-ideality factor it may be higher than 1. So, to consider that let we go for the third part of this example.

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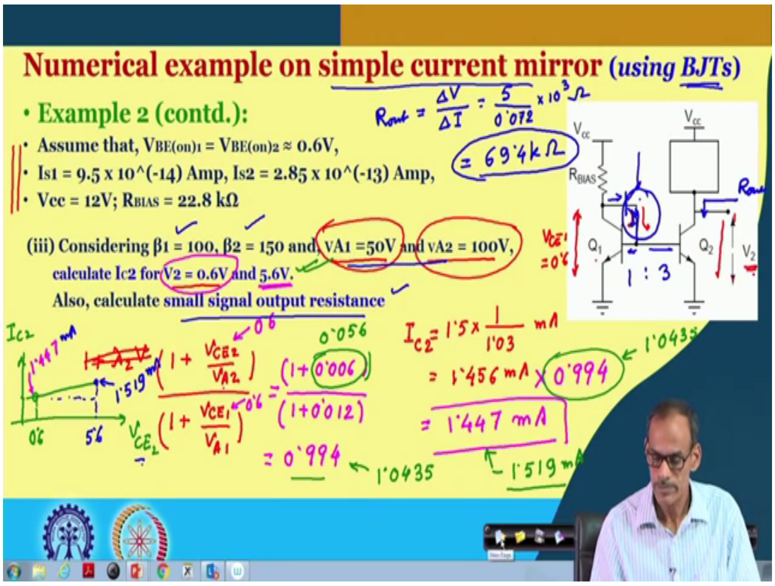

So, in the next slide it is continuation of the same numerical problem. So as you can see here, we do have all the parameters we are keeping same. Except, we do have early voltage of the 2 transistors are given here and intentionally, we are using different values of early voltage. And we already have obtained the effect of beta, right.

So, we already got I C2 equals to 1.5 multiplied by 1 by 1.03 which in fact so, this is equal to 1.456 milliampere, without considering this early voltage. Now, if we consider this early voltage and if you observe the V CE voltage difference, then we have we can calculate the that factor.

So, let me consider V 2, this V 2 it is equal to 0.6 volt and we know that this is V CE1, V CE1 equals 0.6 volt. So, if I consider this V B or V 2 equals to 0.6 then that non- ideality factor, which is 1 plus lambda 2 multiplied, sorry, I am going to (Refer Time: 27:29) 1 plus V CE2 divided by V A2 divided by 1 plus V CE1 divided by V A1. And for this case, both this part is 0.6 and also this part is 0.6.

However, this early voltage we are keeping it is same. So, it is not getting cancelled, it is rather we do have 1 plus 0.006 in the numerator and in the denominator, we do have 1 plus 0.006 divided by 50. So, that is equal to 0 1 2, ok.

So, this non-ideality factor it is 1.006 divided by one point sorry 1.006 divided by 1.012. So, this is 0.994. So, we need to consider this factor of 0.994 and so that gives us the current equals to 1.447 milliampere. This is the case with B 2 is equal to 0.6. Now if I consider say B 2 is equal to 5.6 so, in that case what are the changes do we expect? This part this part it will be different, namely, and that part it will be 5.6 divided by 100.

So, that it becomes 0.056. In fact, this factor then it will be 1.056 divided by 1.012. So, that is equal to 1.0435. So, instead of 0.994, we need to replace this by 1.0435, and the corresponding current here instead of 1.447, we do have 1.456 multiplied by this factor. So, that is equal to 1.519 so, this much of milliampere. So, for this voltage we do have 1.59 milliampere.

Again to you can use this to data point to calculate the slope of the I C versus V CE. So, at this point of 0.6 volt V CE2, we do have the current that current it was this was point 1.447.

On the other hand, at this point we do have current which is for 5.6 volt V CE2 and this voltage this current it is 1.519 milliampere. So again, by considering reciprocal of this slope we can calculate the output resistance offered by this current mirror at its output.

So, R out so, that is equal to del V voltage change divided by the corresponding current change. And voltage change it is 5 volt; 5.6 minus 0.6 so, that is 5 volt divided by this current difference. So, that is equal to 1.519 minus 1.447. So, that is 0.072 milli. So that means, it is 10 to the power 3 ohms or you can say that this is equal to 69.4 kiloohm.

So, the small signal output resistance it is 59.4 kiloohm. So now, here we have considered, so far we have considered simple current mirror. Now we can go for more precision current mirror and as we can see here, if I consider finite values of beta's and then early voltage, the ratio instead of 1 is to 3, it is becoming different, slightly different though. There may be some precision cases, precision applications where this much of difference may not be still acceptable.

And then we can go for betterment of the circuit. So, for current mirror constructed by BJT's we do have 2 types of improvement one is to take care of the non-ideality due to the early voltage another one it is to take care of the non-idealities factor due to the base current loss. So to take care of the base current loss, as we have said that we can have a beta-helper circuit here, so that the current loss to the base of this third transistor which is much smaller than whatever the base current is going to Q 1and Q 2 which is referred as beta-helper.

So, continuation of this new this numerical example, to go for that beta-helper, let we go to a next slide.

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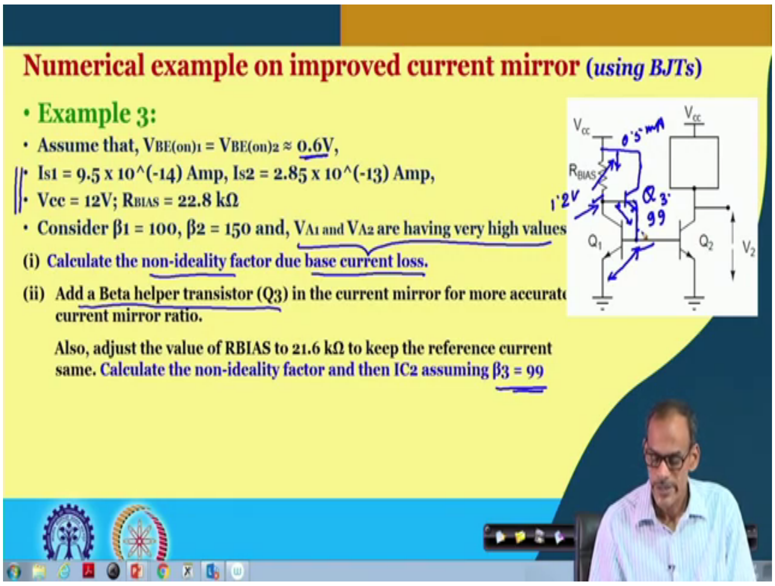

So it is, I should say it is more like a continuation of the previous problem. Namely, we are retaining the parameters here. So, the current flow here it is 0.5 milliampere and we have we have calculated the base current the non-ideality factor due to the base current loss. Now we can improvise the circuit by using beta-helper here.

So, let you call this is transistor-3. So, we are adding this beta-helper and this beta-helper its beta it is 99 and then once we add this transistor, we need to readjust this register because once you add this transistor, since the collector and base voltage they are not same, in fact, if you observe carefully, this is one V BE this is another V BE.

So, if I approximate that this V BE it is also 0.6, then the DC voltage coming here it is 1.2 volt, ok. Now since you are trying to keep the focus only on the non-ideality factor coming due to the base current loss, we are suppressing the other information namely, in this example, we are considering early voltage it is a very high. And we are primarily focusing on this base current loss. So, in the next slide we do have the beta-helper circuit.

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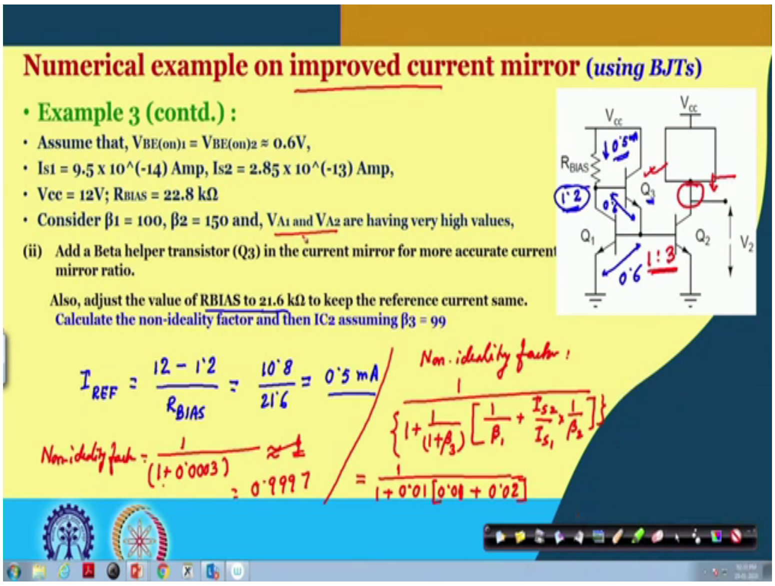

So, here we do have the beta-helper circuit drawn for you. We do have Q 3 here and as I said there this is approximately 0.6 and here also, it is approximately 0.6. So, we do have 1.2 volt. So what we are doing here, to retain this current of 0.5 milliampere in this numerical example, we are readjusting this R BIAS to 21.6 kiloohm And that gives us the I reference current, it is same as 0.5.

So, let us see that our I reference equals to 12 volt minus 1.2 volt here divided by this R BIAS and so, this is equal to 10.8, 10.8 divided by 21.6. So, that gives us 0.5 milliampere. So for our comparison, better comparison we are keeping this reference current same as the previous case. And then we can calculate the corresponding non-ideality factor.

So, you may recall the non-ideality factor in presence of the beta the beta-helper is. So, non-ideality factor it becomes 1 divided by 1 plus 1 by 1 plus beta 3 multiplied by 1 by beta 1 plus I S2 divided by I S1 multiplied by 1 by beta 2. And earlier, we have calculated in absence of this one. Now, we do have 1 plus so, this part 99 plus 1. So, this is 100.

So, that gives us a factor here 0.01 getting multiplied with beta 1 it is 100. So, 1 by beta 1 it 0.00 sorry 01 plus this one it is 150. So, that is equal to 0.02, right. And so this is how much? This 0.03. So, that is equal to non-ideality factor. So, it becomes 1 divided by 1 plus 0.0003 and this is very very small compared to 1.

So, we can approximate that this is equal to 1. In fact, how much is it coming? This is 1.0003 reciprocal so, that is equal to in fact, 0.9997. So, that is how this beta-helper is helping us to maintain this ratio here, it is very close to 1 is to 3. So, similar to so, this circuit as I said that it is improvised current mirror. Similar to this improvisation, we do have different improvisation by adding something called cascode transistor to make the non-ideality factor due to early voltage it will be very small.

So, we will be discussing that circuit, but before that let we take a break and we will come back.

Thank you.