Analog Electronic Circuits
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Lecture – 79
Differential Amplifier: Analysis and Numerical Examples (Contd.)

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So dear students, welcome back to our NPTEL 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 continuation of Differential Amplifier.

In the previous lecture, we have completed analysis and today we will be talking about numerical examples. So, the concepts we are planning to cover it is the following.

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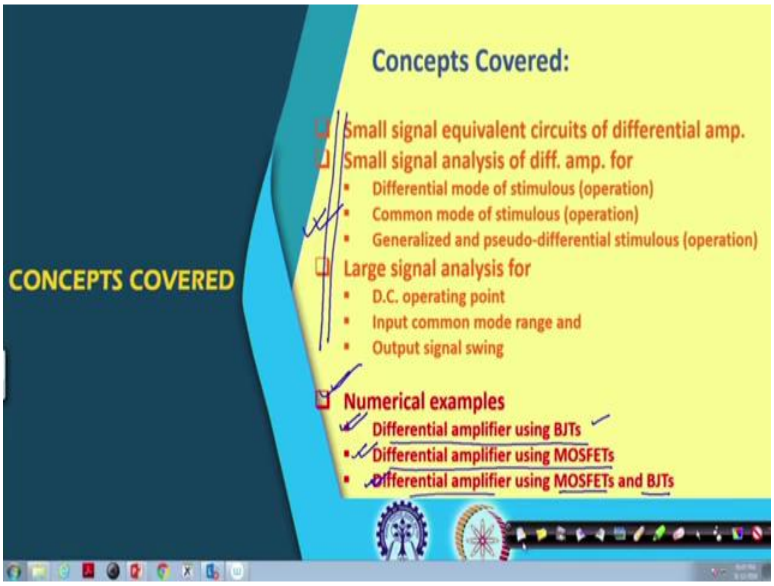

As I said that, the analysis part it is done in the previous 2 lectures, and we are going to talk about numerical examples, and we do have primarily differential amplifier using BJT then we do have differential amplifier using MOSFET and then also we do have another example where we do have the differential amplifier, we do have both types of transistor MOSFET as well as BJT.

So, this differential amplifier having BJT's it will be having different perspective; namely, the DC operating point and then small signal parameters, then differential mode gain, common mode gain and then going to the input range and output swing.

So, almost every aspect it will be covered with this example. Similarly, here also, we will be covering most of the aspects and then in the third example, we shall try to see that how the performance can be enhanced by replacing one of the passive element namely, the tail resistor by active device to enhance the performance ok.

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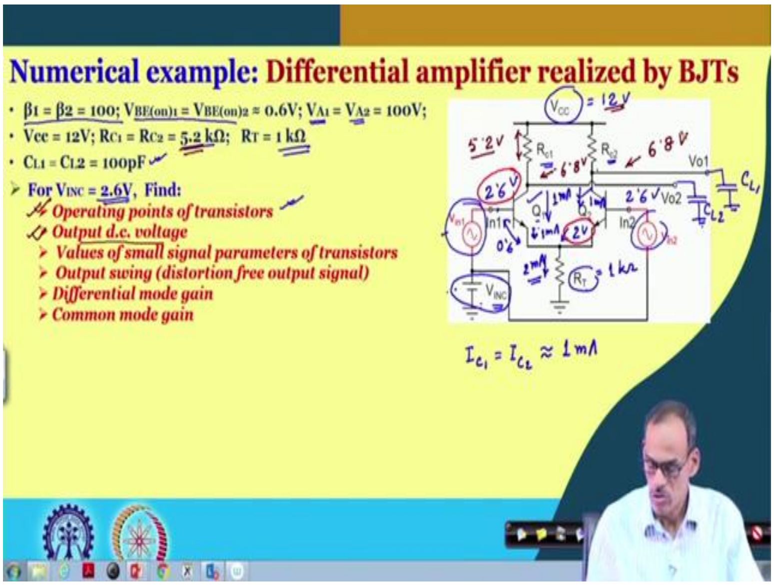

So, we do have differential amplifier realized by BJT. So, this is the circuit we have discussed before and you may recall that in our most of our analysis we used to split this resistor R_T into two identical elements in parallel. And the intention of that was to get more insight of the circuits particularly, to see how the differential signal and common mode signal they are getting propagated from primary input port to the primary output port.

Now, but then actual circuit of course, we do have only one tail resistor. So, the analysis we have done there where this R_T it was split into 2 identical part and then if you connect the emitter of the 2 transistors together, then this circuit and that circuit they are essentially same.

So in our discussion now, most of the time we will be using this tail resistor it is connected together. So, here how we do have the different device parameters namely, for BJT's we do have β. In this case, this β may not be having much of use, but for the sake of completeness we are keeping the parameter.

And then we do have the $V_{BE(on)}$ of both the transistors 0.6. In fact, we are considering Q_1 and Q_2, they are identical and then we also have the early voltage of the 2 transistors = 100 V. And then we do have the supply voltage = 12 V and then the loads R_{C1} and R_{C2}, both are equal; and they = 5.2 kΩ and the tail resistor it is 1 kΩ.

Then, load capacitance for this example it is not mandatory, but just to say that we may consider high frequency signal also and then we can consider that the load is also balanced namely the load here C_{L1} and C_{L2} they are in this case they are both are equal to 100 pF.

Now to start with, we do have this DC voltage given to us which is 2.6. In fact, this DC voltage should be sufficiently high, so that Q_1 and Q_2 should be in active region. And on the other hand this DC voltage should not be too high otherwise, Q_1 and Q_2 may enter into saturation region.

So, here we have picked up the value of this DC voltage well within its range, allowable range. So, with this 2.6 of V_{INC}, let us try to find the operating point of the transistors. And of course, we have considered Q_1 and Q_2, they are identical. So, how do you proceed? First of all, for DC analysis we can ignore the AC signal part and then we may say that we do have 2.6 V here and also 2.6 V here at both the base terminal of Q_1 and Q_2.

Now, if I consider $V_{BE(on)}$ drop of 0.6, then we do have the emitter voltage DC wise it is 2 V. Now R_T = 1 kΩ. So, the current flow here it is $\frac{2}{1\text{ k}}$, so that is 2 mA. And under quotient condition, in absence of the small signal, this 2 mA current it is equally getting divided into 2 halves, one for the left branch and another one is for the right branch. So, 1 mA current it is flowing through Q_1 likewise, for the Q_2.

Now, we assume that of course, this is the emitter current 1 mA. So, we assume that the base current is very small. So, we can say that the collector current of transistor 1 as well as transistor 2 both of them we can well approximate by 1 mA. Now we do have 6 V here sorry, we do have 2.6 V here we do have 2 V here, and now we do have 1 mA current is flowing through this resistor which is having a value up to 5.2 kΩ.

So, the drop across this resistor it is 5.2 V. So, the voltage at the collector DC voltage at the collector it is 12 V – 5.2. So, that = 6.8. So, we can say that now we obtain the operating point and then also we obtain the DC voltage. DC voltage it is same here also 6.8 V ok.

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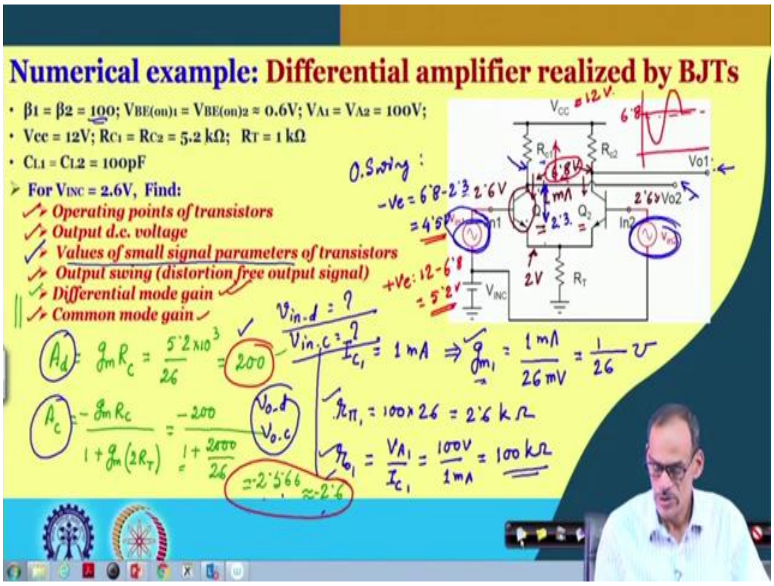

So, to summarize the DC operating point, we do have 2.6 V is the base voltage and then at the emitter. So here also, it is 2.6 V and at the emitter we do have 2 V. Then, voltage here it is 6.8 V and here also it is 6.8 V and the collector current in both the transistors they are equal and they are 1 mA right.

So, that gives us the operating point of both the devices. In fact, you can calculate what is the V_{CE} and ensure that Q_1 and Q_2 both are in active region of operation. In fact, we do have sufficient headroom.

So, in case if you have say V_{CE} is at is 0.3 V. So, this voltage it can come down as low as 2 point; so, this voltage it can go as low as 2.3. So likewise, so we do have a swing here with respect to DC voltage it is 6.8 – 2.3. So, that = 4.5. So, the –ve side swing it is 4.5.

So, the output showing; so, –ve side it is 6.8 – 2.3 V, alright. So, that is considering V_{CE} voltage = 0.3 and that = 4.5 V. So, likewise for +ve side for +ve side the voltage here it can go towards the supply voltage. So, here we do have 12 V DC and then the DC voltage at the output it is 6.8.

So, the +ve side on the other hand it is 12 – 6.8. So, that = 5.2 V. So, we do have fairly good swing. So, which means that whatever the DC voltage we do have, over that DC voltage we can have very nice signal swing. So, the circuit operating point it is very good. So, 6.8 V is the DC level.

So, now we obtain the output swing. So, we obtain operating point, we obtain the DC voltage; now, next thing is the small signal parameter of transistors. So, we do have the collector current I_C = 1 mA, and that gives us $g_m = \frac{1\text{ mA}}{26\text{ mV}}$, if I consider thermal equivalent voltage, it is 26 mV.

So, that = $\frac{1}{26}$ ℧ and then $r_\pi = \frac{\beta}{g_{m1}}$. So, that is 100 × 26; so, that = 2.6 kΩ. And then output resistance r_o, so, that = $\frac{\text{early voltage}}{I_C}$. So, this = $\frac{100}{1\text{ m}}$. So, that is giving us 100 kΩ.

So, we assume that this 100 kΩ it is much higher than this passive load R_{C1} and R_{C2}. So, that gives us the small signal parameter. In fact, for the other transistor parameters are also same corresponding to whatever the parameter we obtain for Q_1. So, now we obtain the small signal parameters of both the transistors. Next thing is we need to find the small signal gain namely, a differential mode gain and common mode gain.

So, the differential mode gain $A_d = g_m R_C$ and this is equal to R_C it is 5.2 and $g_m = \frac{1}{26}$ and this is of course, it is kΩ. So into 10^3 so, that is equal to 200 and the common mode gain on the other hand it is $\frac{g_m R_c}{1+ g_m(2R_T)}$ alright .

And so, in the numerator we do have 200, just now we have calculated and then we do have a 1 + $\frac{2000}{26}$. So, this is equal to how much? $\frac{2000}{26}$; I do have calculator for me. So, $\frac{2000}{26}$ = 77; + 1 and the denominator and so that, reciprocal of that, multiplied by 200 is giving me 2.566 and so and so.

In fact, if you ignore this 1, you will be getting this = 2.6. Of course, it is having a – sign, alright. So, we do have the differential mode gain of 200 and then we do have the common mode gain; common mode gain is basically approximately it is – 2.6.

So, now next thing is that once we feed the signal, once we feed the small signal namely, v_{in1} and then v_{in2} based on this differential mode gain and common mode gain, we will be getting the signal at this point namely, at v_{o2} and then v_{o1}. And to get the individual signal first of all, based on this A_d and A_c as you have done for the macro model based numerical example.

To get the individual signal first thing is that, we need to see what is the differential input, and then what is the common mode input, and then we multiply this differential and common mode component of the input by their respective gain to get the v_{o_d} and v_{o_c}, and from that we can find what will be the individual signal. So, keeping the operating point same, let we find what will be the corresponding output for a given set of v_{in1} and v_{in2}.

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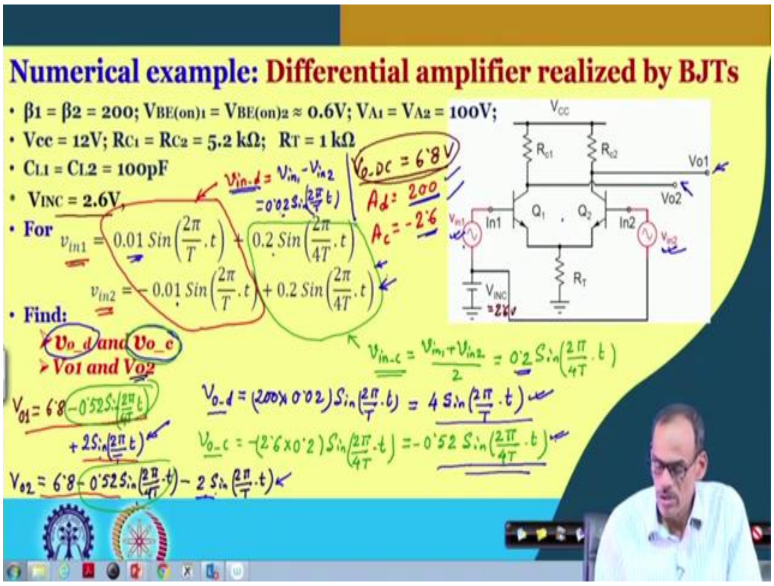

So, in the next slide what we have it is, so, we are keeping the operating point same. Namely, we do have V_{INC} = 2.6 V and that gives the whatever the operating point we obtain and we know that DC voltage wise V_{O_DC} = 12 – 5.2, so, that is 6.8, right.

And also, we have calculated the A_d = 200 and A_c on the other hand, it is – 2.6 now here we do have the v_{in1} and v_{in2} and if you see here, the this part similar to our numerical examples associated with the macro model v_{in}.

So, this 2 if I consider, so, this is giving us $v_{in\_d} = v_{in1} - v_{in2} = 0.02 \sin\left(\frac{2\pi}{T}\cdot t\right)$. On the other hand, if I consider the common part namely, if I take the average of the 2 inputs; so that gives us the common mode input $v_{in\_c} = \frac{v_{in1} + v_{in2}}{2} = 0.2 \sin\left(\frac{2\pi}{4T}\cdot t\right)$.

So, we do have the common mode component and we do have the differential mode component here and we do have the differential mode gain and common mode gain. So, from that we can get v_{o_d} = 200 × 0.02. So, that gives us 200 × 0.02 $\sin\left(\frac{2\pi}{T}\cdot t\right)$ = 4 $\sin\left(\frac{2\pi}{T}\cdot t\right)$. So, that is the differential output.

So likewise, we can calculate the common mode common mode output v_{o_c} = – 2.6 × this common mode part 0.2 $\sin\left(\frac{2\pi}{4T}\cdot t\right)$, it is having different frequency. So, this is equal to how much? This is 0.52 $\sin\left(\frac{2\pi}{4T}\cdot t\right)$ of course, with a – sign.

So, now we have obtained the differential and common mode component. So, the individual signal now, we can say that say V_{o1}, it is having the DC part 6.8 V, DC and then, we do have the common mode part. So, that is – 0.52 $\sin\left(\frac{2\pi}{4T}\cdot t\right)$ and then it is also having half of the differential part. So, that = +2 $\sin\left(\frac{2\pi}{T}\cdot t\right)$.

So likewise, if you see the other output V_{o2}; so, that is also having DC of 6.8 and then the common mode part – 0.52 $\sin\left(\frac{2\pi}{4T}\cdot t\right)$ and then – 2 $\sin\left(\frac{2\pi}{T}\cdot t\right)$. So, that gives us the complete output. So, we can see here; this is the common mode part. So, this part and this part they are common mode and then we do have the differential part, here and here.

And if you compare if you compare the common mode part and differential part, it is almost that differential part if I see, individual signal-wise and if you take the particularly the differential output, at differential part it is quite large. In fact, almost 8 times higher. So, this part it is almost 8 times higher than the common mode part.

However, if you see at the input if you compare the differential part which is 0.2 and then common 0.02 rather and common mode part it is 0.2. So, here on the other hand, the common mode part it was 10 times higher.

Which indicates that the whatever the signal we are receiving here, that may be getting affected by significantly I should say affected by unwanted signal having an amplitude which is 10 times higher than the desired signal, differential signal.

And through this differential amplifier which is having differential mode gain, it is much higher than the common mode gain and that is why at the output we are getting the desired signal almost having 8 times higher amplitude than the unwanted component unwanted component is this common mode component, right. So, that is the basic motivation.

Now, next thing is that how do we see the signal? Particularly, if I consider how the common mode and differential mode signal it is getting propagated.

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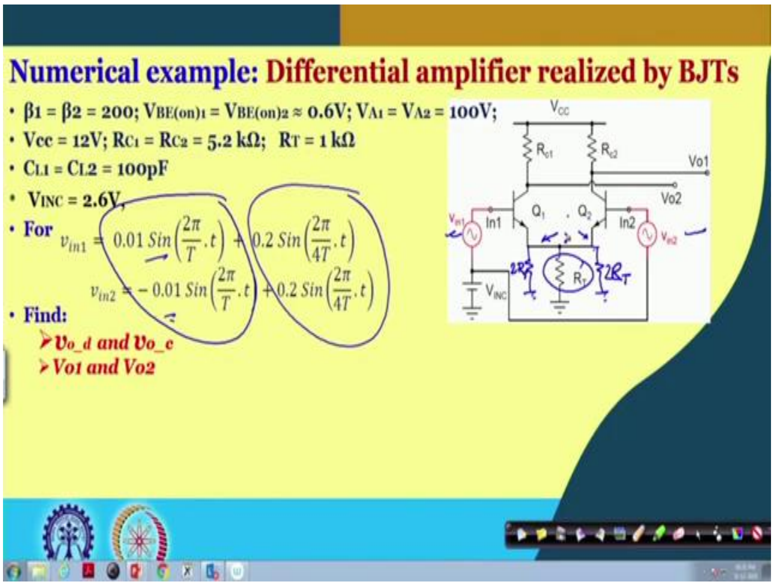

Particularly, you may recall in the analysis we used to split this resistor into 2 parts, and we use to claim that this 2 R_T and this 2 R_T we used to split them and then we used to see that the signal here and signal here it was propagating differently for common mode part and differential part.

And now here, at the input the stimulus it is having both differential as well as the common mode part.

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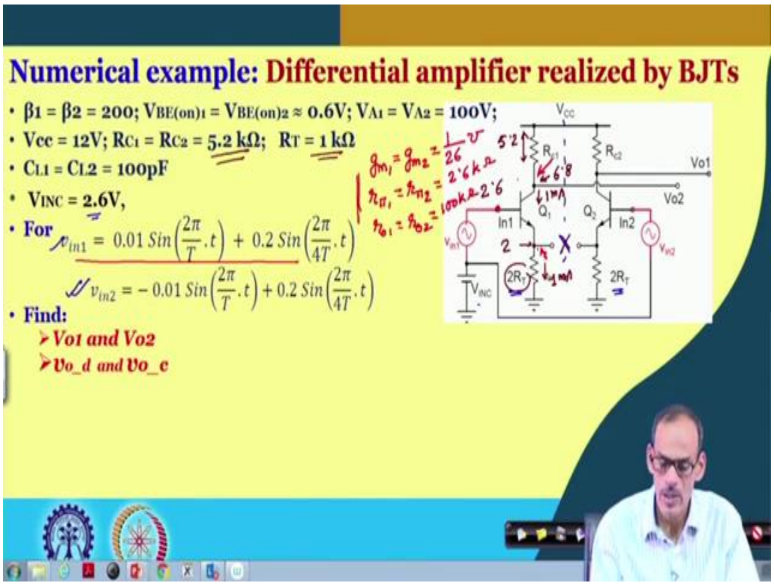

So, in case if you in this actual circuit if you split these 2 resistors and we like to see what other things are happening, namely, with this kind of signal what is the signal amplitude you are getting at the emitter and the output. So again, we are keeping the same operating point, only thing is that the R_T it has been split into 2 parts, identical parts 2 R_T and also here we have opened it, here we have opened it.

Now in this case, if we open it and if we are keeping the same stimulus namely, v_{in1} and v_{in2} then what happens? First of all, if you see once you do have a split here, identical split here and then even though we are applying the same 2.6 V here, the operating point it is remaining same, but left and right half they are completely isolated.

So here again, if you see the operating point here, the DC voltage it 2.6 and the voltage coming here it is 2 V and now $2R_T$ having R_T = 1 k, this current it is 1 mA. So, that gives us the emitter current 1 mA and then the collector current is also very close to 1 mA.

So, we can say that 1 mA it is flowing through R_{C1} creating a drop of 5.2 V since its value it is 5.2 k. So, the voltage here again it is 6.8. So, with this spilt of course, the as expected the operating point is not getting changed.

So, the corresponding small signal parameter namely g_{m1} and g_{m2}, they remain same and both of them are equal to $\frac{1}{26}$ ℧ and r_π of the 2 resistors transistors they are remaining 2.6 k and then r_{o1} = r_{o2} they = 100 k.

Now, if I am having this parameter and then I do have a signal v in1 coming here. So, what do you expect? That the left half it is completely isolated. So, just by analyzing this left part we can calculate what may be the signal coming here and the signal coming here, ok. So, let me clear the board and then let me write those signals expression.

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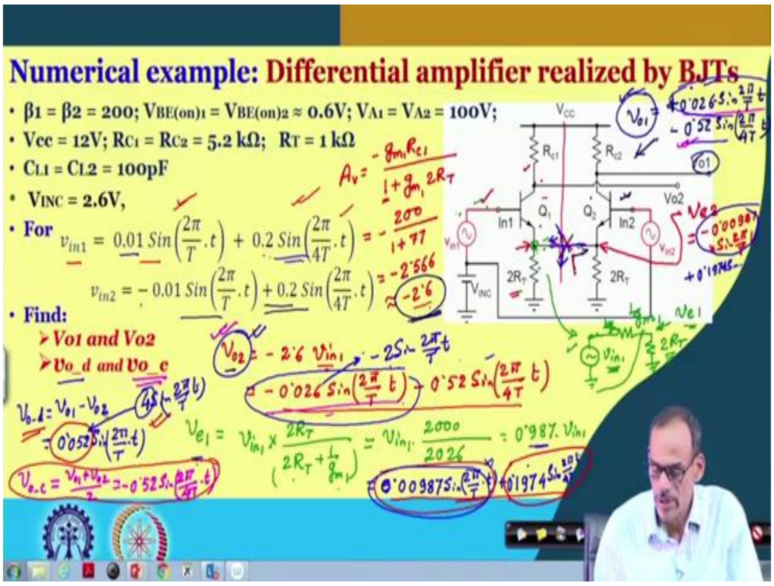

So, the gain of this transistor Q_1 and its corresponding associated bias we can say that its voltage gain = $\frac{g_{m1}R_{C1}}{1+ g_{m1}(2R_T)}$ of course, with a – sign. So, what is the value? Here, we have calculated this = 200 and this is 1 + close to 77 and this = – 2.56 or I should say, ≈ – 2.6. So, if I ignore this 1, then you then $\frac{R_{C1}}{2R_T}$ that gives us 2.6.

So, that is the gain from this point to this point. This means that for this input, the output signal we are getting namely, vo2 what we are expecting here it is – 2.6 × vin1, alright. And then we do have 2 components and if you see here so, the first component it is – 0.026 sin $\left(\frac{2\pi}{T}\cdot t\right)$ and then we also have to multiply this 0.2 and 2.6 for this component.

So, that is equal to – 0.52 sin $\left(\frac{2\pi}{4T}\cdot t\right)$. You might have observed that since this circuit, left part it is completely isolated from the right part. So, this circuit of course, it is working as common emitter amplifier having a degenerator of $2R_T$.

So, this circuit of course, it cannot distinguish which is common mode part and the differential part. So, the differential part as well as the common mode part it will amplify and whatever the signal it is coming here it is given here.

And also, if you see the signal at this point and so, if I call that signal it is v_{e1}. So, what kind of signal do I get? Before we can consider this R_T, we are getting almost the v_{in} here and then we do have the output impedance which is $\frac{1}{g_{m1}}$.

And then we are connecting 2 R_T. Note that this v_{in1} it is not this v_{in1}, it is the signal coming at this point which is very close to this signal, alright. And so, before we consider this resistance the signal here, if I consider it is having say infinite resistance then at this point the signal it will be same as whatever the signal we are applying here.

So, that is why you are calling it is voltage it is getting translated to emitter or emitter is following the base terminal. And then we do have this resistance which is $\frac{1}{g_{m1}}$. So, once this Thevenin equivalent voltage source it is getting loaded by 2 R_T then, whatever the voltage we do get here it is nothing, but this R_{E1}.

So, this voltage it is v_{in1}, the reflected signal coming to the emitter multiplied by 2 R_T that is because, divided by $2R_T + \frac{1}{g_{m1}}$. That is because, this signal it is getting divided across this $\frac{1}{g_{m1}}$ and $2R_T$ to create this voltage called v_{e1}.

So, this is the; this is the signal we are getting at this point before connecting the load, it was like this and then once we connect this 2 R_T then, whatever the voltage we are getting here. So, if I calculate this one, it is coming v_{in1} multiplied by this is 2 k. So, 2000 and this is 2000, this is $\frac{1}{g_{m1}}$ that is 26 so, 2026. In fact, this part it becomes very close to 1 this = 0.987, I think that was my calculation 0.987 multiplied by this v_{in1}.

Which means that, I do have this signal = – so, no I do not have the – sign here, I do have the signal coming in phase. So, I do have 0.01 × 0.987; so, I do have 0.00987 $\sin\left(\frac{2\pi}{T}\cdot t\right)$.

And then we do have this part that is also getting multiplied by this one so, that = + we do have 0.1974 $\sin\left(\frac{2\pi}{4T}\cdot t\right)$. So, that is corresponding to this part. So, this is the signal coming at emitter here.

In fact, similar kind of things you will be getting at the other side namely, at this point and likewise, here also we will be getting the signal. So, the signal coming here it will be similar to whatever we obtained namely, the gain of this transistor along with its bias arrangement it will be having the same gain of – 2.6.

So, we can say that v_{o1}, this v_{o1} signal wise, it = this is having – gain is – 2.6 and this signal it is –. So, I do have + 0.026 sin $\left(\frac{2\,\pi}{T}\cdot t\right)$ and then we do have this part. So, it is having a – and then we do have 0.52 sin $\left(\frac{2\,\pi}{4T}\cdot t\right)$.

So, we do have the 2 frequencies again, this amplifier it does not really understand the common mode part and differential part. So, both of these parts are getting amplified by the same gain. So, if I see individual signal, if I see the see individual signal this and this of course, it is having both the frequency component and if you are keeping this node still open and if you consider the differential output say v_{o_d} is $v_{o1} - v_{o2}$ by definition.

And, so if I take the difference of this signal and this signal then, obviously, this part it is getting removed, leaving behind this part and this part multiplied by 2; because they do have opposite sign. So, what we are getting there, it is 0.052 sin $\left(\frac{2\,\pi}{T}\cdot t\right)$, and this part as I said, that they are getting removed.

On the other hand, if I take the average of the 2 signals; so, if I take average of this signal and this signal that gives us the output common mode. And so, if I take average of v_{o1} and v_{o2}, in fact, in that case this part and this part they are getting cancelled leaving behind this part and this part.

So, that = – 0.52 sin $\left(\frac{2\,\pi}{4T}\cdot t\right)$. So now if you see, that this part even if you are keeping this is open, the common mode part common mode part it is same as the case when we have connected it or in the previous circuit.

But then, the differential part if you see it is quite small. In fact, if you connect it to get the original circuit, then what we have obtained it is that corresponding differential output; it was having an amplitude it was 4 V if you recall right, and so, now if I make a connection, what we are expecting that the emitter voltage at this at the emitter of transistor-2 it is also having similar kind of signal as you can see here similar kind.

So, what will be the difference? This part it will be same, but this part it will be having opposite sign. So, if I observe the voltage at this point, before we make the connection and we call this is say v_{e2}. So, that is equal to this part and the first part it is having a – sign, – 0.00987 then whatever, × $\sin\left(\frac{2\pi}{T}\cdot t\right)$.

And then this part on the other hand, it will be having + sign, + exactly this one 0.1974 then whatever it is. So, the moment we make this connection, this part and this part they are getting cancelled out, and also at the output this part and this part they got amplified and both of them this part it was it is getting converted into – 2 $\sin\left(\frac{2\pi}{T}\cdot t\right)$ with this connection, if you make this connection.

Same thing this part is also getting increased to + 2 $\sin\left(\frac{2\pi}{T}\cdot t\right)$ and naturally, the amplitude of the differential part it got changed to 4 $\sin\left(\frac{2\pi}{T}\cdot t\right)$. So, this got changed to 2 and this is also 2. So, that gives us the amplitude of 4, alright.

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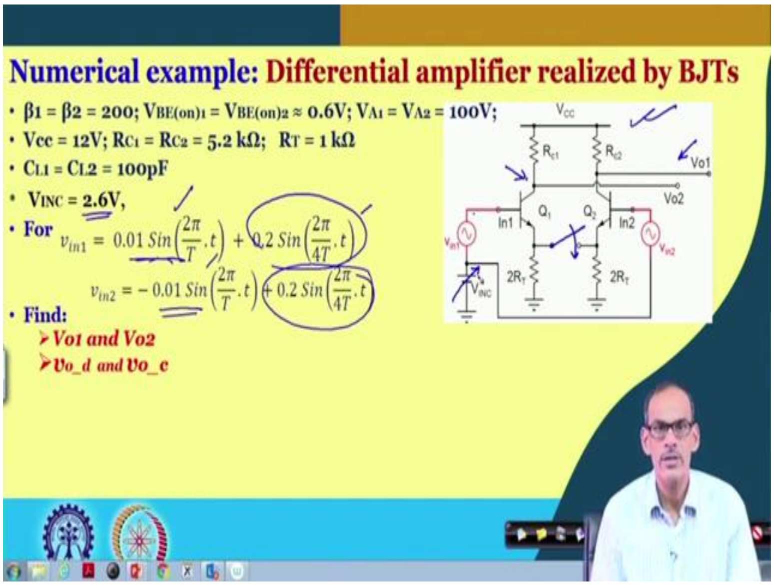

So in fact, in hardware you can make this experiment namely, you can construct this circuit and then if you keep it open and then if you observe the signal here and here, what you will be seeing here, mostly the common mode signal it will be dominating hardly you will be seeing the information out of the differential part because, at the input the strength of the differential signal is very small.

And then, the moment you make this connection all of a sudden, then you will see that the differential part it will be appreciated and then common mode component; however, it will be remaining same.

So in fact, you can do this experiment in the lab, lab setup and you can get a feel of it alright. So next thing is that we will see what will be the suitable range of this input common mode voltage? And so, we have taken a meaningful voltage here, but we like to see what may be its meaningful range namely, lower limit and upper limit. But then let me take a short break and then we will come back.