Analog Electronic Circuits
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Lecture – 76
Differential Amplifier: Basic Structure and Principle of Operation (Contd.)

Yeah, welcome back after the short break.

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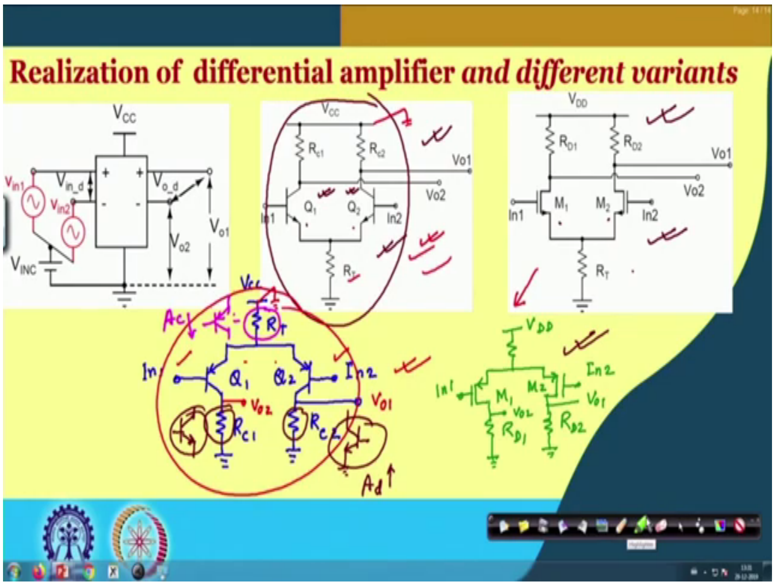

So, what we are talking about different realizations and different variants of Differential Amplifier and primarily in our next discussion, we will be talking about this circuit and this circuit as representing basic structure. Now, if you want to see the basic working principle of this circuit particularly, this circuit or this circuit, we need to convert this circuit into one of its equivalent.

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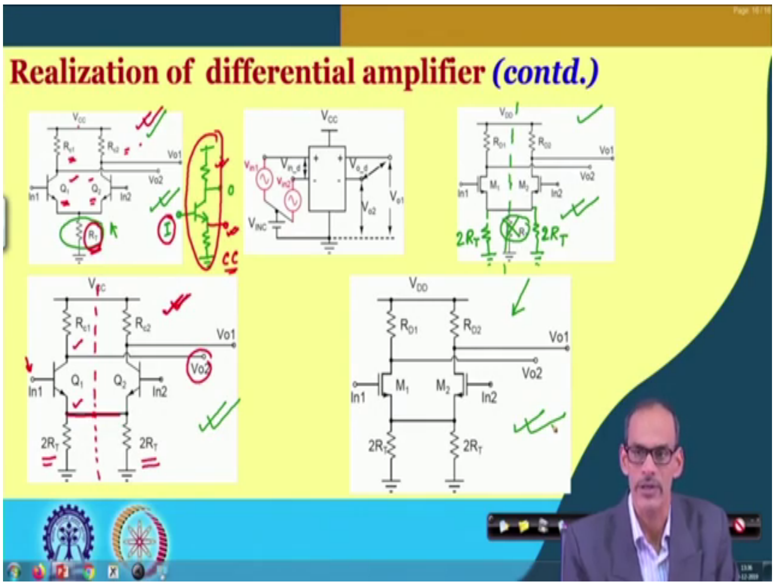

So, let us see in the next slide, what equivalent circuit we are talking about. So, here this is the basic differential amplifier using BJT and here we do have tail resistor called RT. So, this kind of circuit so far we have not analyzed, but at least to we have analyze something similar particularly, if I consider only half of this circuit something like this and if we feed a signal at the base and if you observe the corresponding output at the collector, we know that this is CE kind of circuit.

So, we also have seen resistor the emitter node need not be connected to ground, even if it is connected through a resistor still we call this is CE amplifier considering this is input and this is the output right. So, since we know the analysis of this circuit, I think it is better we you know go inside this circuit rather convert this circuit in this kind of form and then try to analyze the circuit.

In fact, in case if we are observing the output at this node and if it is remaining as input even though, we do have say resistor connected here and if I call it this is our new output then we call this is a common collector circuit.

So, even in this case also it is better, we convert the differential amplifier in terms of this kind of structure. Now in this original structure this RT it is connected to Q 1 and Q 2 together, but we also know that Q 1 and Q 2 and then Rc 1 and Rc 2 they are respectively identical. So, if we split this circuit, if we modify this circuit in some way so that we can have two identical halves probably then our analysis it will be simpler. So, instead of using only one RT let me consider that 2 RTs are parallelly connected to realize this RT. So, we are keeping this node connected.

So, this circuit as long as this is connected this circuit and this circuit they are same. So, in our subsequent analysis instead of really going into this circuit, we will be talking about the analysis of this circuit for simplicity. Namely, if I split the circuit into two identical half then probably if we feed a signal at the base then, we can see what kind of signal we do expect at this terminal and this terminal. So, same thing for the MOSFET version instead of analyzing this circuit directly, let we split this resistor into two identical parts each one of them is 2 RT.

So, that we can prepare this circuit such that, whenever it requires we can split the circuit into two identical halves and that is the corresponding circuit. So, in our next analysis instead of using this circuit and this circuit rather, we will be considering this modified circuit. I should not say modified, but it is a structurally it is different, but they are actually same circuit. So, in the next item what we have is analysis of this circuit rather this circuit and try to see its operation basic operation.

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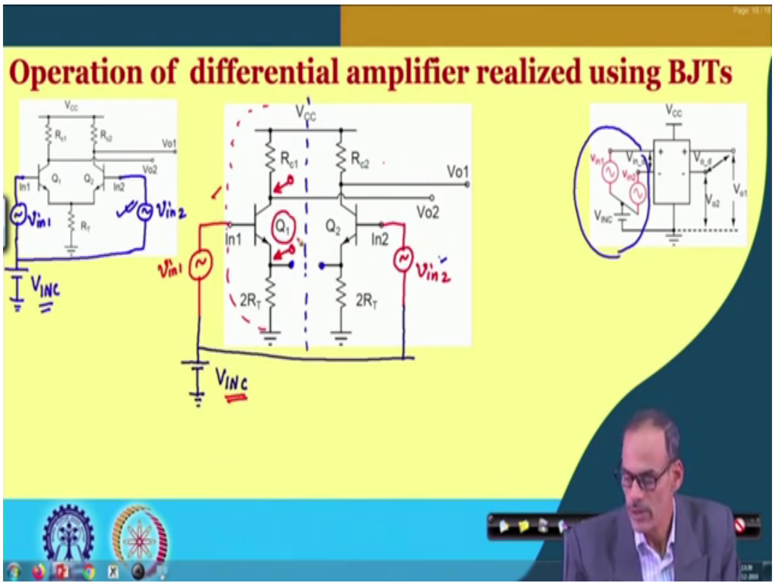

So, here is the circuit. Before, we really go into the analysis what we have done here it is, we have simply disconnected this two terminal then naturally this circuit and this circuit they are not same.

So, of course, this is different, but then depending on the situation probably, we can makes the left half and right half separate. Now while we will be applying the signal at the input like this namely at this point we do have one signal called V in 1 which is riding on a DC voltage called V IN C in capital; that means, DC and then the signal we are feeding here it is V in 2 which is also on the same DC voltage V IN C. So, same thing in the modified circuit here also, we consider that we are applying signal here V in 1 and V in 2 and both of them are they are on the same DC voltage called V IN C in capital right.

So, by doing this what we can see that, whenever we are applying a signal here and here probably since we are familiar with this circuit and of course, this circuit then, we can see what kind of signal we are getting at this point and this point and also we can analyze the circuit to really understand that what kind of DC voltage you require here for proper operation of this transistor and the circuit. So, let we consider this half. So, one of this half and try to understand that what kind of signal we do get. In fact, we already have seen this kind of circuit before, but it is more like a recapitulating whatever we already know it ok.

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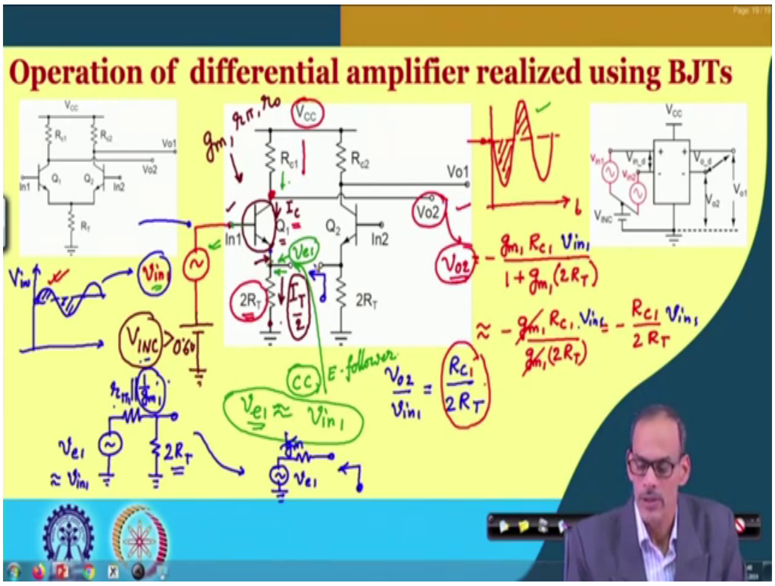

So, let me redraw again clear and redraw the circuit, let you consider we are applying a signal here on a meaningful DC voltage and when we say meaningful DC voltage this DC voltage should be sufficiently high. So, that transistor 1 it is remaining in active region of operation. Now for a meaningful collected current, we need this voltage DC voltage should be at least 0.6 with respect to this ground. So, we are assuming that this V IN C it is higher than Vb on say 0.6 volt. And then based on that based on how much this voltage it is higher the corresponding emitter voltage it will be higher than the ground and then it will be having a current flow. And let we call this current flow it is I T by 2 ok.

Later I will discuss about why we consider I T by 2, but let you consider this is whatever the current is flowing this is I T by 2 that is also setting the corresponding collector current. We can approximate that this IC collector current is equal to I T by 2. So, that sets the proper region of operation of transistor 1 and hence, we can probably calculate its corresponding gm and then r pi and then r naught based on whatever the condition you are putting. Now if you see this circuit and if I feed the signal at the base, then at the collector what you are observing this Vo 2.

And since this emitter node it is degenerated by this resistor, we know that the signal will be getting here say Vo 2 equals to if I call this is V in 1. So, Vo 2 it will be minus gm of this transistor called gm 1 multiplied by Rc 1 divided by 1 plus gm 1 into 2 times R T. In fact, this expression we obtained by considering something called common emitter amplifier, where emitter it is getting degenerated by 2 RT right. And you may approximate that this is equal to minus gm 1 R c 1 divided by gm 1 2 times RT or further to that you simply remove this gm.

So, we do have the essentially minus Rc1 divided by 2 RT. So, that is the that is the signal that kind of signal, we are expecting sorry I forgot to write the signal part this is multiplied by V in 1 multiplied by V in 1. So, we can say that V o 2 divided by V in 1 equals to Rc divided by two RT ok. So, depending on this ratio, we are expecting some signal here. So, if I observed the signal here see it is having a DC voltage defined by V in c and this is a corresponding signal. So, this is capital V small in 1 and this part is the signal here.

So, the corresponding output, what do you get here it is, it is having its own DC level. Now, of course, this DC level it can be obtained by considering Vcc minus this ir drop across this resistance due to this quiescent current IC flowing through it. So, this voltage we know how to get it and on top of this one, we do have this signal just now we have derived is its expression it is having a minus sign and probably it is having some amplified version. And this amplification with respect to this input it depends on this ratio right.

So, it may be amplification or attenuation of course, it depends on the relative value of Rc 1 and then two times of RT. Now, if I consider the other node at this node and if I call this the emitter signal at transistor 1 called say V e 1. So, now, the circuit it is basically it is working as common collector circuit or something called emitter follower emitter follower. What does it mean is that the signal we are expecting here it will be almost same as whatever the signal you do have.

So, you may approximate this is equal to V in 1 and it is in the same phase. In fact, it is its supposed to be slightly less than V in 1 because we do have some signal between base to emitter and that how we are getting the current here it is having signal and hence we obtain the signal, but the signal here at the emitter node at this node V 1 it is very close to this signal and they are in phase. Now, if you also look into the emitter terminal we can find its corresponding resistance. In fact, if you look into its emitter terminal, what we do expect that it is having a signal.

And this signal it is Ve 1 which we claim that it is very close to V in 1 and then it is having its own Thevenin equivalent resistance and that Thevenin equivalent resistance we know this is common collector stage. So, that is r pi in parallel with 1 by gm 1 and then it is connected to 2 RT. So, that is what we see here at this point and you can probably approximate that this 1 by gm it is much smaller than r pi 1. So, you may consider approximately this resistance is equal to 1 by gm 1 and then this resistance is typically a it is much higher than 1 by gm.

So, we can further approximate that this is equal to V e 1 and this resistance it is 1 by gm 1. So, I should say this kind of Thevenin equivalent signal source, we can see here right. Now.

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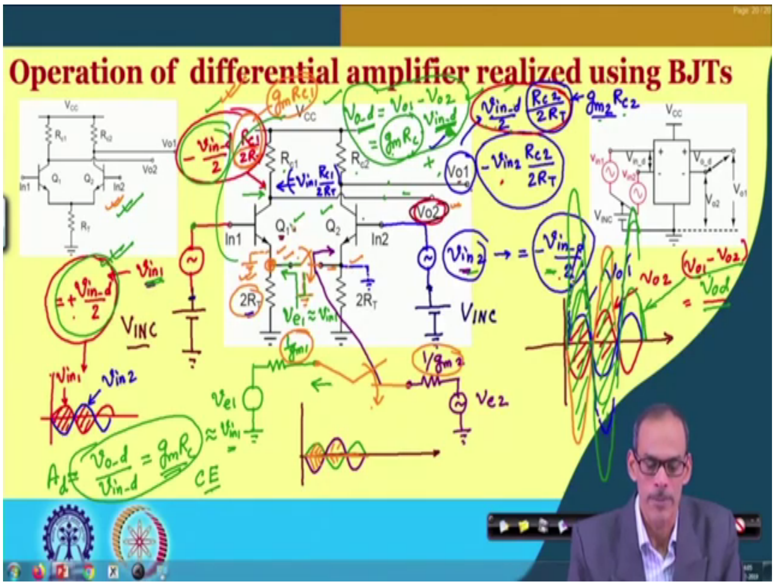

So, now let me let me again summarize what we said here, it is that if we feed a signal at this point called V in 1 on top of a meaningful DC voltage. Let we call V IN C. So, that this meaningful voltage it is ensuring that this transistor it is in active reason of operation. Then the signal we observe at the output terminal, it is V in 1 multiplied by Rc 1 divided by 2 times of R T.

That is because of the circuit it is working as common emitter with emitter de generator of course, we do have a minus sign here there will be phase shift. On the other hand, if you if you look at the emitter terminal what we can get that if I call this V e 1 this is the signal of course, it is having a DC voltage, but signal wise V 1 it is approximately equal to V in 1 without any phase shift and also its resistance Thevenin equivalent resistance it is very close to 1 by gm 1.

So, looking into the emitter node of transistor 1 what we can see here it is a voltage signal source having a strength of Ve 1 which is very close to V in 1 and then the corresponding resistance of gm 1. Now, if I apply signal here call V in 2 on the same DC voltage level same DC voltage level ok. This is very important that V IN C it is also coming here. So, this voltage and this voltage they are same and then we do have the signal here. So, now, if I analyze the right half the signal will be getting at this point it is minus V in 2 R c 2 divided by 2 R T. And in the same way as we have discussed for the left half if I look into its emitter. So, here also you will be seeing that a signal source called V e 2 and having Thevenin equivalent resistance which is one by gm 2 ok. Now the moment we are keeping these two are disconnected then we do have the signal here.

Now, let us see what happens for two cases namely if I say that, the circuit it is stimulus in differential mode of operation namely V in 1 and V in 2 they are identical in terms of magnitude, but they do have opposite phase. So, then what happens? So, if I assume that this is equal to plus V in d by 2 and then this also this if I consider equals to minus V in d by 2 ok. So, this is one case. So, we consider that both the circuits are we are preparing in such a way. So, that the stimulus it is perfectly in differential form which means that this signal.

So, this part it is minus V in d by 2. So, as a result this part it becomes minus is getting plus. So, we do have V in d by 2 and then R c 2 divided by 2 RT. On the other hand the corresponding output here at this point, we do have a minus sign here we do have a plus sign here. So, so, here to here we do have minus. So, minus it is getting plus and a here, we do have plus and this is minus. So, this is a minus V in d by 2 into R c 1 divided by 2 RT. Now, if I assume that this Rc and this Rc they are same. So, we can say that the signal here and the signal here they are identical in terms of magnitude, but they do opposite phase.

Now still it is um. So, if I if I try to plot these two signals namely Vo 2 and Vo 1. So, what we are getting it is see Vo 1, if I plot Vo 1 in blue color something like this and. So, this is Vo 1 and then V o 2 in red color which is similar or I should say amplitude wise it is identical, but it is having opposite phase. So, this is Vo 2 and the difference of course, if I if I say that Vo 1 minus Vo 2. So, that is essentially coming as two times of this amplitude. So, this is I should say now Vo differential. On the other hand if you see the signal at the emitter at this point.

Let me sketch the two signals at the emitter, we do have signal at the emitter which is in phase in phase with the red color of course, I am considering a differential input it is in this form. So, this is the signal and of course, the signal here it is this signal it is in opposite phase. So, this signal it is V in 2 and this signal on the other hand it is V in 1. So, the differential signal we are applying here it is the shaded part and the corresponding output here we are getting which is the differential output. Now, what you are talking about the emitter signal at this point and if you see that this is almost equal to V in 1. So, we are expecting that V Ve 1 it will be like this.

And the V e 2 it is following V in 2 magnitude wise is it same. Now it is now it is very interesting thing it is going to happen is that to get this circuit same as this circuit I need to make a connection here. So, from here to here I need to connect. The moment you will be connecting these two you know nodes together which is having completely identical signal with opposite phase. So, this signal and this signal they cancels each other and it is making it 0. Primarily because, they are corresponding Thevenin equivalent resistance they are equal. So, the moment we make these two signals are getting shorted.

So, that makes the this node and this node as single node and making the corresponding output equals to 0. And hence we are expecting the signal at this point it will be 0. Now, all of a sudden if we do this operation all of a sudden what we are expecting that, the signal at this node it will get amplified. Why? That is because this node earlier it was having a signal because of this emitter degenerator of 2 RT, but because of the connection of the other half which is having identical signal, but the signal having in opposite phase making this voltage it is signal wise it is 0. So, I can say that after making this connection this node becomes AC ground or I should say this is virtual ground which means that this Re it is getting completely shunted by this AC ground.

So, then this 2 RT is not having any meaning. In fact, if this is if we are saying that by some means we are making it to ground either by a bypass capacitor or this kind of arrangement then this circuit it becomes simply CE amplifier without having any degenerator. So, as a result this gain instead of Rc 1 by 2 RT it becomes gm 1 into Rc 1 and of course, this is much higher than Rc 1 divided by 2 RT. So, the consequence of this modification, whenever we are making this connection the red signal the signal at Vo 2 it just gets amplified like this with a very big amplitude. In fact, same thing it is happening for this also because now, this node it is becoming AC ground.

So, the gain of this circuit it is instead of Rc 2 divided by 2 RT this gain it becomes gm 2 multiplied by Rc 2. So, the corresponding output it will be V in d by 2 multiplied by gm 2 into Rc 2. So, this blue color it got extended like this and it is also having very big amplitude. And the corresponding output the net output the differential output; obviously, which is the difference of this extended blue color and this your local golden color. So, the corresponding output it got amplified like this.

So, in summary I should say that in case if we are making this connection to get this actual signal actual circuit or equivalence of that actual circuit and if we stimulate this signal the circuit with perfectly differential kind of a signal namely, V in d by 2 with plus sign as V in 1 and minus V in d by 2 with at say the other terminal for V in 2. Then the signal coming at this point at this point it is minus V in d by 2 into gm into Rc 1 and the signal here it is a plus V in d by 2 multiplied by gm into Rc 2 and this node it is becoming grown. So, if I see the corresponding output here differential output

Now if I take difference of this and this, where if I take this as positive side and this has a negative side then the corresponding Vo d it becomes which is defined as Vo 1 minus Vo 2 it becomes a gm into R c assuming that this gm and this gm they are same. So, gm 1 equal to gm 2 is equal to gm, same thing Rc 1 and R c 2 they are equal and they are R c this multiplied by V in d by 2. So, this is what we do get as differential gain which means that if I take the sorry this 2 it is getting cancelled because, we do have half signal here and another half signal we do have. Now, if I take the ratio of the differential output divided by this V in d then the corresponding gain of the circuit it is gm into Rc.

So, what we are getting here it is V o d divided by V in d equals 2 gm into Rc. In fact, this gain it is same as common emitter amplifier gain of course, the minus sign is not here because, we have excess this terminal for Vo 1 on Vo 2 otherwise magnitude wise gain of CE amplifier and this circuit it is same. So, the I should say that differential mode gain A d is equal to same as a gain of a CE amplifier constructed by only one half of it right. Now next thing is that how this circuit works for a common mode right.

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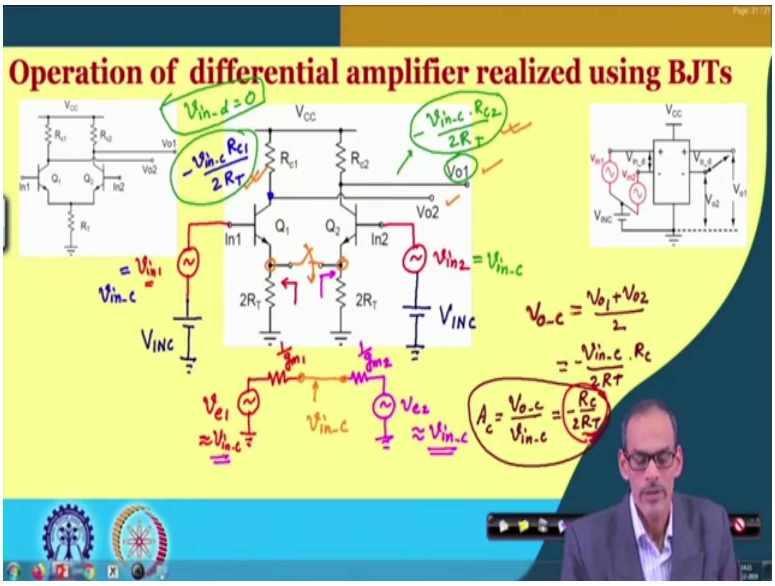

So, let us see for common mode operation. Again coming back to the same circuit, we are applying say V in 1 here and V in 2 here. So, V in one; however, of course, both of them with DC voltage V IN C in capital V IN C and; however, in this case we consider signal here equals to V IN C and also the signal here it is V IN C which means that it is a stimulus in perfectly in common mode operation in other words, we are assuming that a differential input V in d equals to 0.

So, with this operation before we make this connection again, we can analyze the circuit and then we can see that the signal coming at this node it is minus V IN C multiplied by R c 1 divided by 2 RT. So, likewise at this point at this point this signal it is minus V IN C into Rc 2 divided by 2 RT. Now, both this signal and this signal they are identical, but of course, they do have a different magnitude and the signal coming at the at this point. So, signal coming at this point it is same as the V in 1 and it is a impedance it is 1 by gm.

So, we can say that the signal will be getting at the emitter of q 1 call say Ve 1 which is equal to very close to V in c and it is having a Thevenin equivalent resistance of 1 by gm 1. On the other hand, if you consider the other side this side emitter node of transistor 2. So, here also you will be having the signal V e 2 that is very close to V in c and the Thevenin equivalent resistance it is 1 by gm 2. Now if I if I see here both this signal and this signal they are same. So, even if I now, if I make this connection if I make this connection then there will not be any change because both the signals are same.

So, even if I make this connection the signal coming here it will this or this whatever you say which is V in c. So, even after making this change or a making this connection there is no change of the signal here and here. As a result these two signals are also demeaning same. Now, if I say that a individual signal this signal and this signal they are identical. So, if I take the average called V o c.

Let me use different color it is not so, visible. So, Vo c equals to Vo 1 plus V o 2 by 2 which is same as a individual 1 namely minus V in c by 2 RT into Rc assuming Rc 1 and Rc 2 they are same and from this one we can say that vo c divided by V in c which is equal to minus Rc divided by 2 RT, but this is the definition of the common mode gain.

So, we can say that the common mode gain of the circuit it is it is primarily depends on Rc and RT all right. So, by making this two modes of operation we obtain these two parameters.

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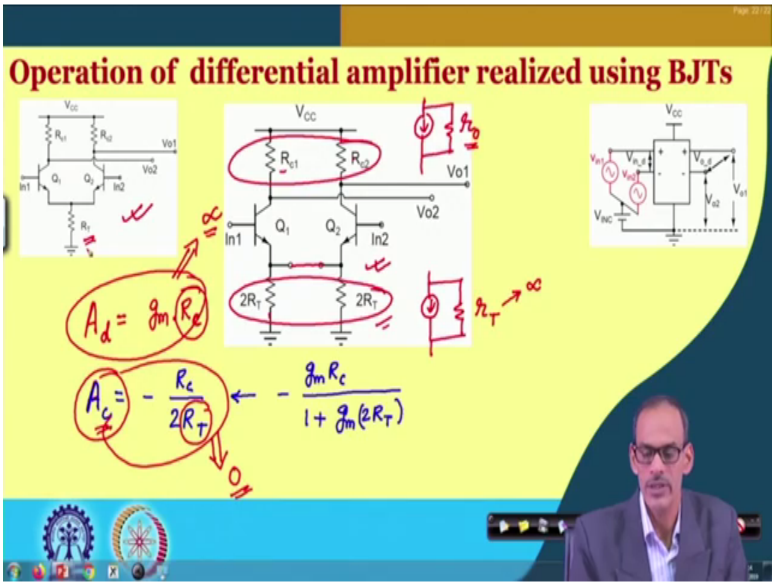

So, the summary of that what do you see, that once you make this connection this circuit and this circuit they are equal and by considering a differential mode of operation, we obtained the expression of Ad which is equal to gm whether it is gm 1 or gm 2 gm multiplied by Rc R c 1 and Rc 2 and the common mode gain on the other hand common mode gain equals to minus R c divided by 2 RT. In fact, to be more precise this expression it is minus gm into Rc divided by 1 plus gm into gm into 2 RT right.

So, the and now, we can we may recall that we want ideally this gain should be as high as possible and this common mode gain on the other hand this should be as low as possible. Now, you can see that what are the elements we supposed to be changing say for example, to increase this gain, we can replace these two resistors by active device which may be having equivalent circuit like this having very high resistance coming from the active device and that may that may replace this capital Rc by this r naught and hence that will increase the differential mode gain.

On the other hand if you replace this part by active device having a very small conductance or very high resistance, if I call say R T and by making this RT higher and higher we can make the corresponding common mode gain lower and lower.

So, that makes sense that if you replace these two resistor by active device and if you replace this till resistor by active device performance of the circuit it is getting enhanced.

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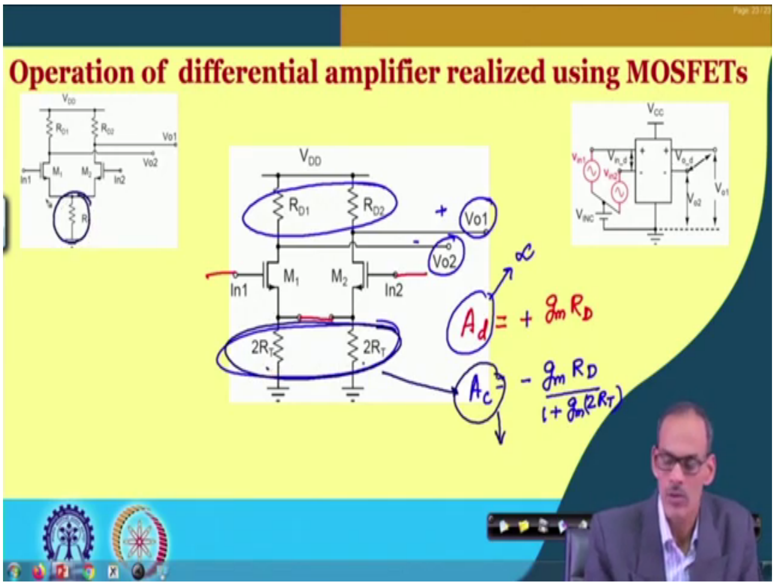

Similar kind of analysis it can be done for the MOSFET version and the circuit it is very similar. So, you can see the circuit is very similar. So, I am not going to repeat this part, but basically, what you can say that you consider two modes of operation differential mode of operation and common mode of operation and then you make the connection from that you can get here also the differential mode gain it is minus gm into Rd and then common mode gain Ac equals to sorry it is not minus based on the definition we are defining the differential mode `output.

So, this minus is not there, we are considering this is plus and this is minus. On the other hand the common mode gain it is having a minus sign gm into Rd divided by 1 plus gm into 2 RT right. And again to enhance the circuit performance, we like to replace these two resistors giving us higher differential mode gain and replacing on the other hand replacing the tail transistor or tail element by active device that makes this common mode gain going lower and lower. Now, for our analysis, we have splitted this resistor, but in actual circuit, we will be having only one element. I think most of the things we have covered what we planned.

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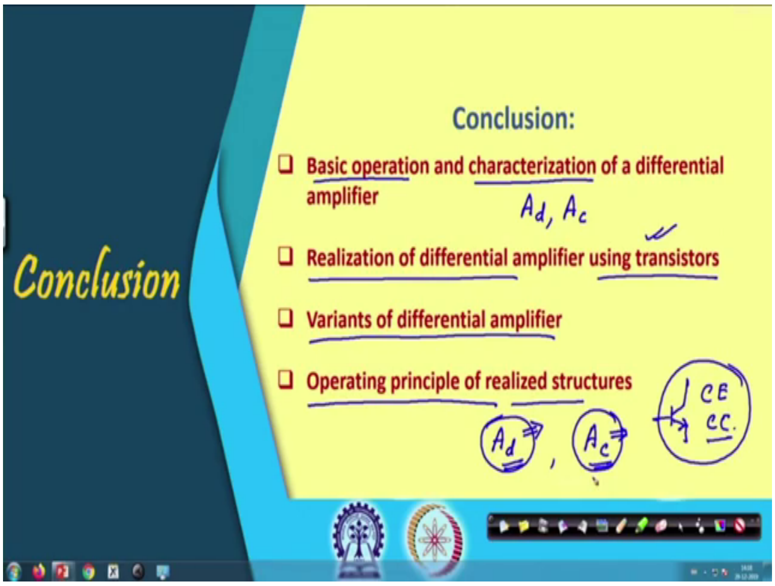

So, the conclusion wise, we can say that we started with basic operation; basic operation of the differential amplifier rather it we started with recapitulation of basic operation and also we said that how to characterize a differential amplifier and particularly how do you get the differential mode gain and common mode gain. And then we talked about realization of different differential amplifier using transistor, I should say transistor level realization of differential amplifier.

And though the circuit represented circuit it is I should say simple enough, but that represents most of the cases and that helps to understand the basic operation of differential amplifier. You also have given hint of how to get the different variants of different differential amplifier with respect to the basic structure we have discussed.

And then, we have discussed about the operating principle of the simple differential amplifier particularly with BGT we have gone in detail how we obtain the expression of differential mode gain intuitively and also the common mode gain by using the common emitter and common collector operation common emitter and common collector operation.

So, at least we understand that how the basic structure it works and in the, we also obtain the corresponding expression of the differential mode gain and common mode gain through this analysis and intuition. in the next class, we will be talking about small signal equivalent circuit and arriving at the same expression of the differential mode gain and common mode using the small signal equivalent circuit of the differential amplifier. I think that is all to cover.

Thank you for listening.