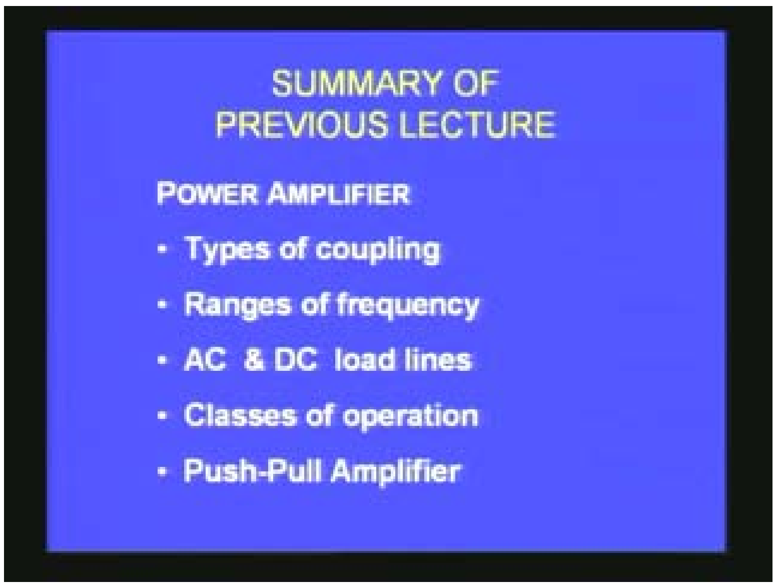
Basic electronics

Prof. T.S. Natarajan
Department of Physics
Indian Institute of Technology, Madras
Lecture- 19

Differential Amplifiers Ckt

Hello everybody! In our series of lectures on basic electronics we will move on to the next one. Before we do that as usual let us recapitulate what we learnt in the previous lecture.

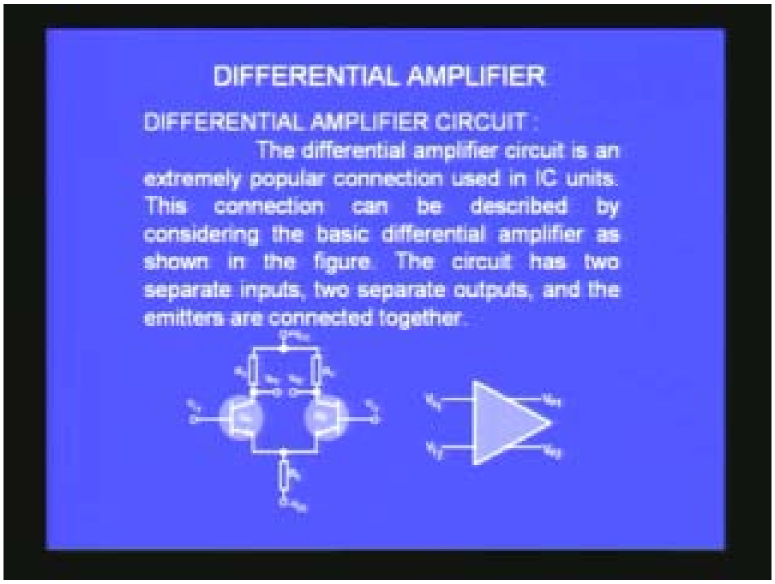
(Refer Slide Time: 1:36)



You might recall, in the previous lecture we discussed about power amplifiers using transistors basically. Under that we discussed several sub topics like different types of coupling that is employed; how amplifiers are named after the type of coupling, RC coupled amplifiers or transformer coupling and then we also looked at how amplifiers can be classified on the basis of the frequency of operation like low frequency amplifiers, high frequency amplifiers, RF amplifier, audio amplifier and when we wanted to look at the power amplifier characteristics we had a discussion on the ac and the dc load lines on the characteristics. We also saw the different classes of operations class A, class B, class C and class D operation of power amplifiers and then finally we also took some example of the push pull amplifier where we have two different transistors helping us to amplify half signals; the positive half and the negative half signals of the power amplifier.

Now let us move on to the next lecture which is basically another configuration which is a very important configuration for future application you would see in the later lectures. That is the differential amplifier. People call it differential amplifier. Some call it also difference amplifier. They mean the same. The amplifier amplifies the difference in signal between two inputs.

(Refer Slide Time: 3:22)

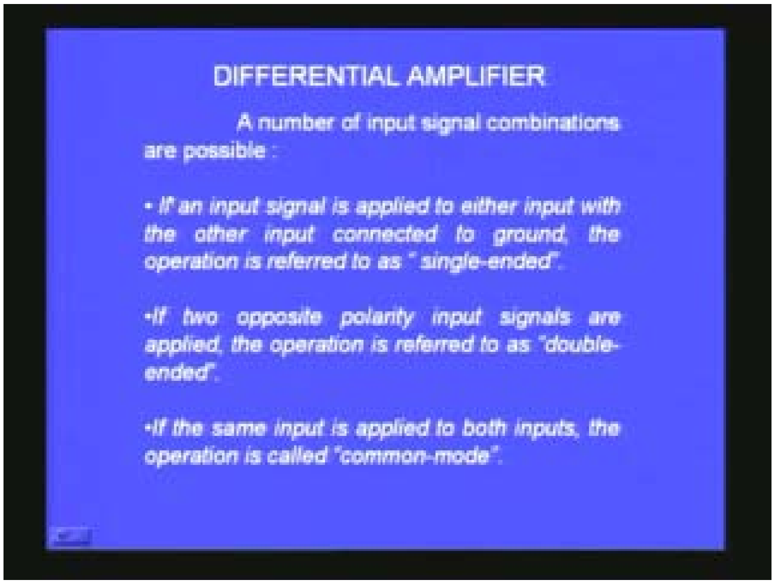


If you talk of difference you must have two different inputs. So the difference amplifier is an extremely popular amplifier and that is one of the reasons why it has also been made use of in many of the modern integrated circuit design. It can be looked at in a very simple way. As you can see on the screen the difference amplifier basic configuration has got two transistors Q_1 and Q_2 and they look very identical. If you draw a line at the center you find both sides are symmetrical. You have one transistor Q_1 on this side and Q_2 on the opposite side. You have two resistors RC_1 and RC_2 corresponding to the transistor Q_1 and Q_2, the collector resistors and you have one common emitter resistor. The emitter resistor R_e is common to both transistors. So both the emitters are connected together and you have one single resistor R_e connected here and this V_{EE} is a negative voltage source supply. You have to connect to a minus terminal this is to be connected to a plus terminal and you can also have a common terminal. Here we have a situation where we require not one single power supply, as we have seen earlier in some of our lectures. We require a dual supply because you require a plus voltage, minus voltage and a ground reference ground.

This dual supply comes out because you require the amplification of both the signals; the positive half cycle and the negative half cycle. That’s why you require a dual supply. It is a very simple configuration if you look at it. The corresponding circuit symbol is shown on the right side. You can see that it has got two inputs Vi_1 and Vi_2 which are basically the inputs into the base of the transistors Q_1 and Q_2 and you have two output terminals Vo_1 and Vo_2 shown on the right side which are actually taken from the collectors of the two transistors Q_1 and Q_2. The output from one terminal Q_1 is taken as Vo_1 and the other terminal from the collector of Q_2 is Vo_2. This is the two output terminals, two input terminals and you have a dual supply. This is a characteristic feature of a difference amplifier or differential amplifier.

There are different types of different combination possible in a transistor amplifier.

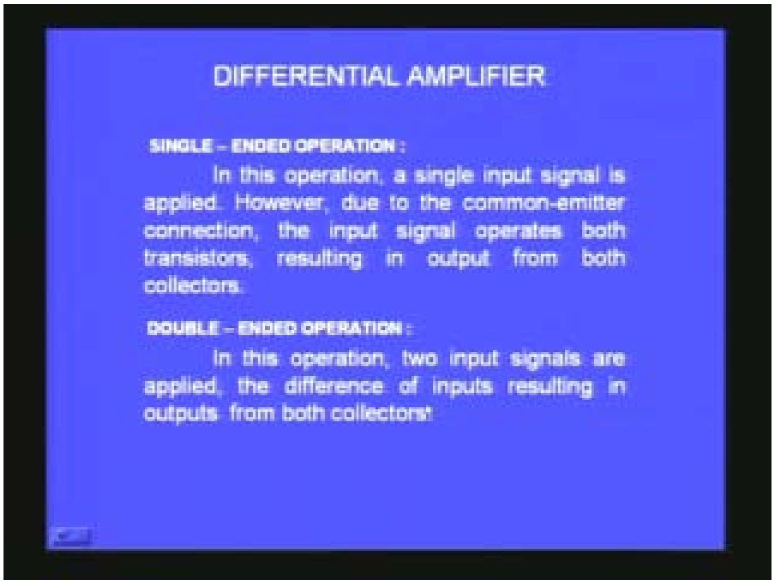
(Refer Slide Time: 6:02)



That is you can have the input signal applied to either input. That means one of the inputs only while the other input is connected to ground. When you use this type of an amplifier it is called a single ended amplifier, single ended input. If two opposite polarity input signals are applied the operation is referred to as double ended. You are applying voltages which are oppositely moving on the two input base terminals of the two transistors Q_1 and Q_2. Then it becomes double ended. Sometimes what will happen the same input will be applied to both the inputs. Both Vi_1 and Vi_2 will be connected to the same signal source. Then it becomes a common mode signal because the signal now is common to the both the transistors or both the input. Therefore that is called common mode input.

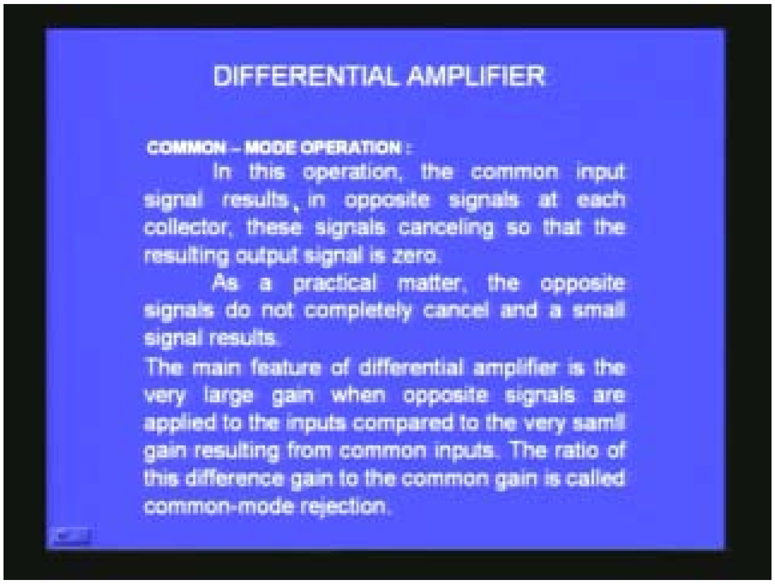
You can similarly have on the output side also. In a single ended operation a single input signal is applied. Because the two emitters are connected together this single input signal will modify the corresponding emitter currents and collector currents and this change in the emitter current of one transistor can also affect the emitter current and the collector current of the other transistor even though you don't apply any signal to the second transistor. I hope you understand what I am trying to say. You would always be able to get output voltages from both the collectors even though you are applying the input voltage to only one of the base of the transistors. You can still get the collector output from both the transistors. So it is a single ended input and double ended output. In the case of double ended operation the two input signals are applied to both the inputs, both the transistors and the difference of input is what you get at the output at the collectors.

(Refer Slide Time: 8:19)



So this is one of the very important configurations that we will be talking again and again. Then the third one is the common mode operation.

(Refer Slide Time: 8:29)

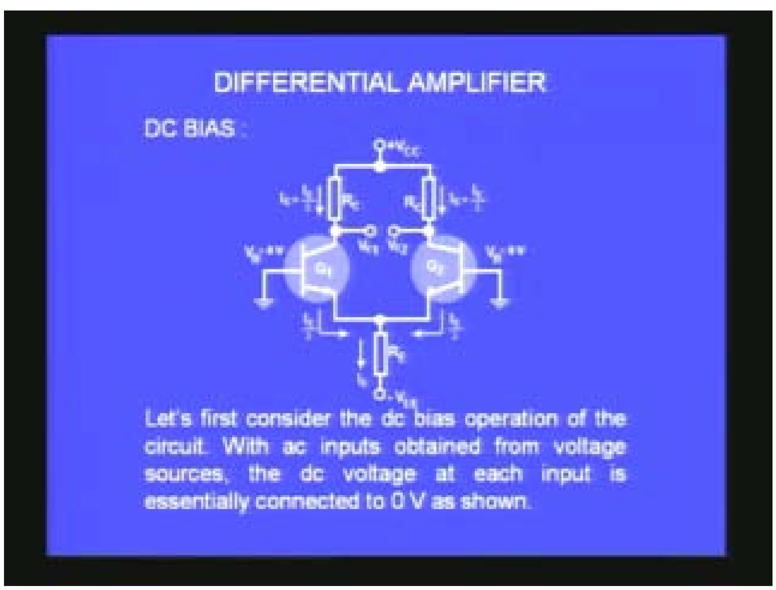


In this one single input from a signal source is applied to both the bases, both the input terminals and what will happen is you will get two different polarities at the two different collectors. I hope you can see that. I will try to explain this to you and if I apply the same signal to both the inputs and if I take the output from both the collectors you would expect there should be no signal. The signal should be zero because one signal is in phase. So if this input is increasing the output will also be increasing. The other output is out of phase. Therefore when the input is increasing that will be decreasing by the same amount and effectively the two will cancel each other and what you get at the output should in principle be zero. This is corresponding to the common mode operation. But in practical situations you would find the opposite signals do not completely cancel and a small signal ….. because there will always be some difference in the transistor, in the gain, in the h_{fe}, in the resistors and it is not possible for us to exactly match the two transistors and the two outputs and you will always get some residual voltage which will be coming at the output of the collectors.

But in principles the common mode gain that is the output voltage divided by the input voltage will generally be very small whereas the differential gain will be rather large by several magnitudes. For example 1 or 2 magnitude can even be 200 the difference gain; but the common mode can be number 1 or 2. This ratio of the differential gain, the gain for the differential input and the common mode gain is what is called, a very important parameter, figure of merit, and that is called common mode rejection ratio. We will again refer to this at later stage when we talk about operational amplifiers. We have to remember three different things with reference to differential amplifiers. One is the differential gain, the other is the common mode gain and the third one which is related to these two is the common mode rejection ratio which is just the ratio of the differential gain to the common mode gain.

Before I go further I will try to quickly explain to you how you get two different polarities.

(Refer Slide Time: 11:14)



For example if you refer to the picture that you see on the screen you can give an input signal. If I give an input signal due to which the base current is increased, in a common emitter amplifier the collector current also will increase. The emitter current will increase, the collector current will increase. If the collector current will increase there will be more drop from the V_{CC} given by the I_C R_C component here and when this base voltage increases the collector voltage decreases. This relationship we have already seen in the basic amplifier common emitter amplifier situation and there is a 180 degree phase difference between the input and the output when I give the input at the base and take the output from the collector of the same transistor.

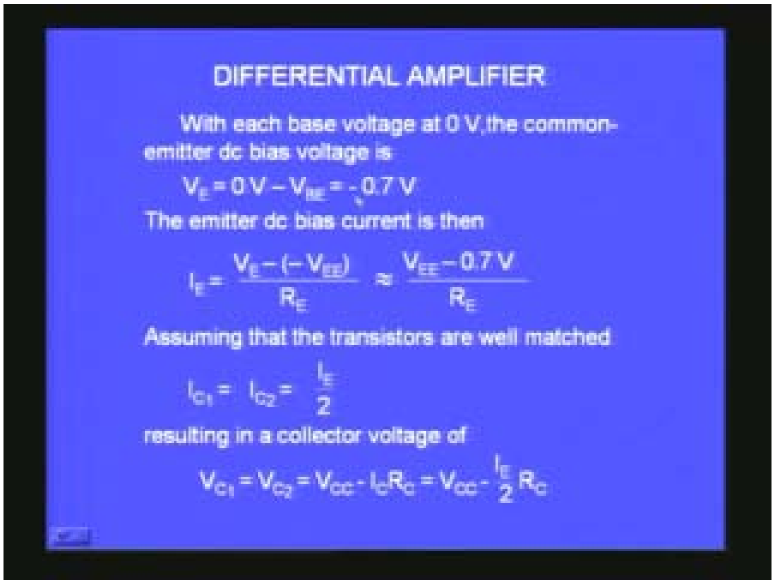
What happens when I take the output from the second amplifier? But the signal is given to the same base. I try to look at what happens to the voltage at the collector point of the second transistor. When I increase the voltage at the base you can realize the voltage at the collector will increase. But what will happen to the voltage at the emitter? When this increases you can realize the emitter voltage also will increase because they are differing only by the V_{BE} component here between the base and the emitter of the Q_1. When the voltage at the base increases the voltage at the emitter also increases. When the voltage at the emitter increases this is connected to the ground, the second base is connected to the ground for the second transistor. But this voltage increases. The difference which is responsible for the emitter current will actually decrease here between zero and this. This decrease will decrease the current and hence the collector current and less voltage will be dropped across the R_C from V_{CC} and this voltage tends to increase. I hope you are able to see that.

When the base voltage increases the emitter voltage also tends to increase and because this emitter voltage is also the emitter voltage at the other transistor the difference in voltage for the base bias, between the base and the emitter will decrease and there will be a decrease in the collector current in the second transistor that will correspond to an increase in the voltage at the output of the collector. When I give a signal source here this signal will be in phase and this signal will be out of phase from the second collector. When I take the output from both the inputs not with respect to ground but with reference to Vc_1 and Vc_2 terminals if they are perfectly matched I must get zero. They should cancel each other. One is increasing the other is decreasing by the same extent and the resultant should be zero. That is what I was telling. When you give input to one of the base and take the output differentially from the two collectors you will get almost zero voltage at the output.

Having understood that let us understand the dc bias condition first. We will first consider the dc conditions and later we will go into the ac condition by drawing the equivalent circuit in order to understand the working principle of the differential amplifier. I will again request you to look at the picture on the screen where you have the difference amplifier and you can see the current which is flowing through the emitter resistance R_e can be easily calculated. Because on this side it is ground and this is V_{BE} between the base and the emitter and you have $-V_{EE}$ here. So I can calculate the current that is flowing through I_e. For that initially we connect both the bases to ground. V_{B1} is 0, V_{B2} is also 0. Under this condition we will find out the DC currents and voltages at the collector emitter.

With each base voltage at the zero volts the common emitter DC bias I already mentioned to you V_e what is the voltage at the emitter V_e is zero volts, that is at the base, minus V_{be} and it is -0.7 volts.

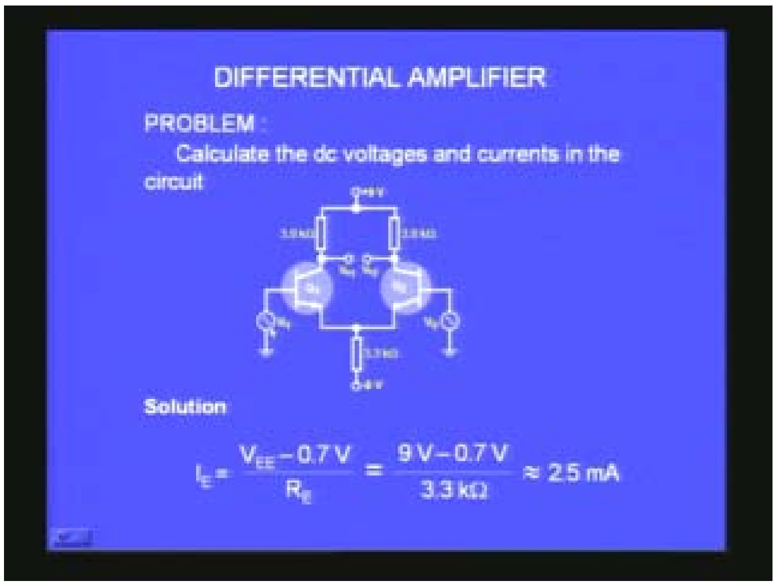
(Refer Slide Time: 15:52)



That is the emitter is if you go back to this the emitter is above the ground by only V_E and actually this is ground. The current is flowing in this direction. Therefore this should be negative. It is more negative. Emitter is more negative than the base and it is by the V_{BE} and that is why we say it is -0.7 because it is lower than the 0 volts, -0.7. The emitter DC bias current we can calculate is nothing but I_E the voltage across R_E at the two ends of the R_E divided by R_E. One end is at V_E the other end is at - V_{EE}. So V_E minus minus V_{EE} by R_E which is equal to V_{EE} minus V_E. But V_E we have assumed is -0.7. Therefore V_{EE} minus 0.7 divided by R_E is the current I_E and if you assume that the two transistors are well matched then you can see it is the ……. So the I_E is obtained by the two emitter currents. That is one common current coming from this transistor, the other emitter current coming from this transistor Q_2 and together they add and flow as I_E through R_E. So if you know I_E I know this and this will have to be half of that I_E by 2 and I_E by 2 because of symmetry. If the individual emitter currents of the transistors are I_E by 2 then the individual collector currents also should be almost be equal to I_E by 2 because I_C is almost equal to I_E. Therefore I_C is equal to I_E by 2, the two collector resistors for all current sources; so I_E by 2.

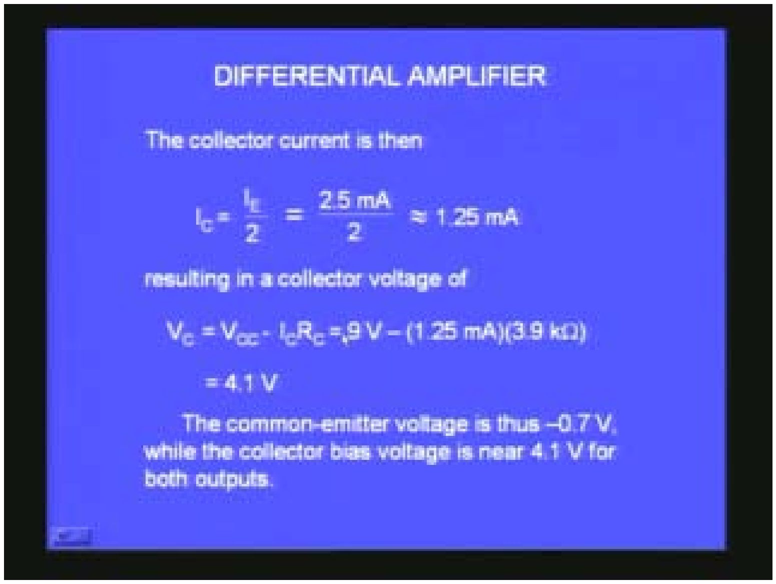
If you know the collector current in the two transistors the resulting collector voltage at the two transistors can be easily evaluated the Vc_1 the voltage at the collector of Q_1 is equal to voltage at the collector of transistor two Q_2 is Vc_2 and that is V_{CC} -minus $I_C R_C$ that we have seen. We have to subtract the voltage drop due to R_C from V_{CC} and that will be the voltage at the collector; so V_{CC} minus $I_C R_C$. In this case I_C is I_E by 2; therefore V_{CC} minus I_E by 2 into R_C. It is possible for us given a configuration to calculate the emitter current, the collector current and the voltage at the emitter as well as the collector. That is what is meant by DC bias condition. If you get the all the voltages and current here we are clear about the DC condition of the amplifier. Let us take a simple example. I have given a small illustration here to calculate the DC voltages and currents in terms of the numerical value. I have assumed that we have a 9 volts battery for the positive and 9 volts for the negative. It is a dual supply with + 9 and -9 with reference to ground and the two collector resistors are 3.9 kilo ohm each and the emitter resistance is also 3.3 kilo ohm as an example.

(Refer Slide Time: 19:06)



How do I understand the DC bias condition of this circuit? We can calculate I_E as V_{EE} - 0.7 by R_E. V_{EE} minus the voltage drop V_E across this divided by the resistor gives me the current; V_{EE} minus 0.7 by R_E. V_{EE} is 9 volts; 9 volts – 0.7 by R_E is 3.3 kilo ohms. If I substitute this value I find the current I_E is approximately 2.5 milli ampere. So I know I_E. If I know I_E I know the individual emitter currents. They are half of that. So I_C is also half of that. So I_C is equal to I_E by 2 which is 2.5 milli ampere by 2 and therefore 1.25 milli ampere. If you know I_C then you can also calculate the V_C. The collector voltage V_C is nothing but V_{CC} minus $I_C R_C$.

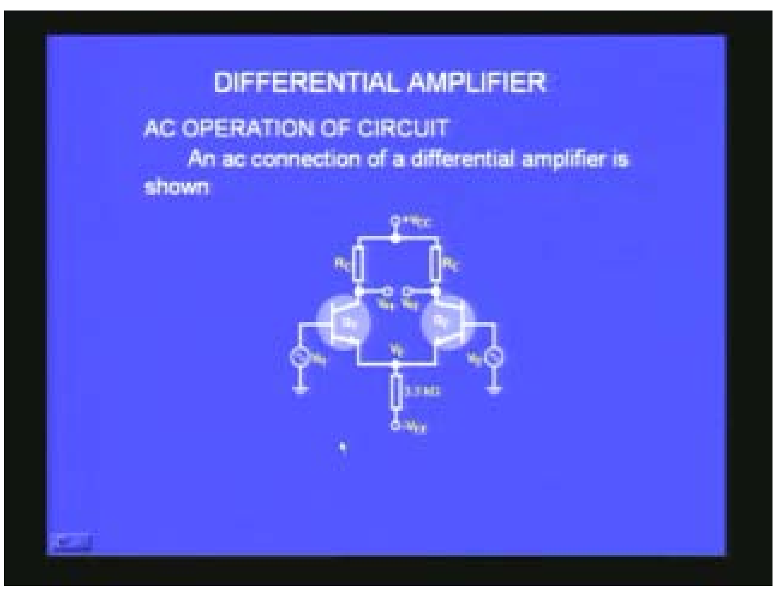
(Refer Slide Time: 20:06)



That is 9 volts – 1.25 milli ampere is the collector current multiplied by 3.9 kilo ohm. That corresponds to about 4.1 volts. So we know the V_C, we know the I_C, we know the I_E. We know all about that DC conditions of the amplifier. It is possible for us to understand the DC conditions.

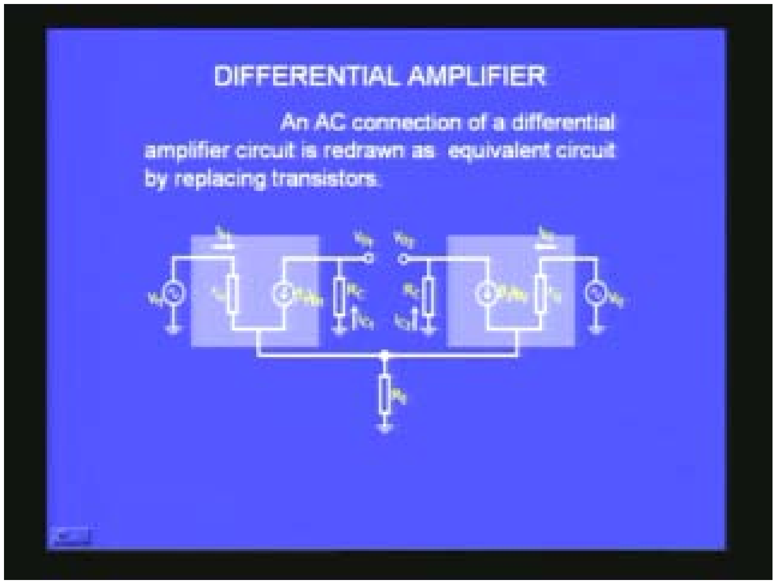
Now let us move on to the ac operations.

(Refer Slide Time: 20:29)



When I want to look at the ac operation the power supply will have to be shorted. That means the $+V_{CC}$ and $-V_{EE}$ they will all be grounded and so what we will get will be a modified equivalent circuit replacing the transistor with its equivalent model. We have taken the very simple model where you have the emitter resistance R_{E1} and you have got the current source beta times I_{B1}.

(Refer Slide Time: 20:59)

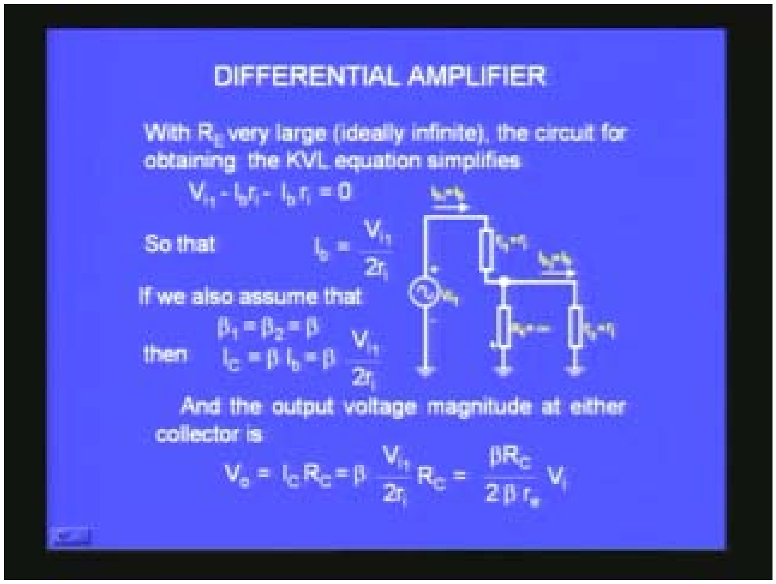


The rest of the things we have assumed to be very, very small and the modified equivalent circuit is shown in the screen. You have the Vi_1 Vi_2 here. I_{B1} and I_{B2} are flowing into the base. This Ri_1 and Ri_2 are the internal resistance of the base emitter junction and you have the current sources beta I_{B1} and beta I_{B2} in the two collectors and you have the R_C coming in parallel with that. So you have the common emitters connected and you have a R_E here at the end of the R_E the power supply is ground so you have connected to the ground. This is the ac equivalent circuit we have seen. Similar discussions we had when we discussed about RC coupled amplifiers and H parameters and other ac equivalent models. I hope you can recollect that. This becomes a very simple circuit then we will be able to obtain the various parameters and also try to look at what is the amplification gain of this difference amplifier, differential gain we can calculate.

To calculate the single ended ac voltage gain we connect the second transistor to ground. The first transistor has got Vi_1. We also see that we are not taking the output from both the collectors but from only one of the collectors Vo_1 alone we monitor; so single ended input and single ended output that's what we are doing. V output by Vi will be the gain for this difference amplifier. Let us see how it comes. We apply the voltage loss for the input and then you can see I_{B1} is equal to I_{B2} is equal to I_B because they are very symmetrical the base current should be same. ri_1 should be equal to ri_2 should be equal to ri let us say in the two cases and since R_E is very large the input circuit is modified now. You have the voltage source, you have the input resistance of the first transistor. This is R_E connected to ground and it is also connected to the ground through the second resistor, base emitter resistor. What you have is a simple source and two resistors in series if you ignore because R_E is very large we can ignore the contribution compared to the small r.

Small r will be few ohms 25 milli volts by I_E that will be very, very small whereas R_E can be in several tens of kilo ohms and this is very large compared to this. Therefore we can ignore.

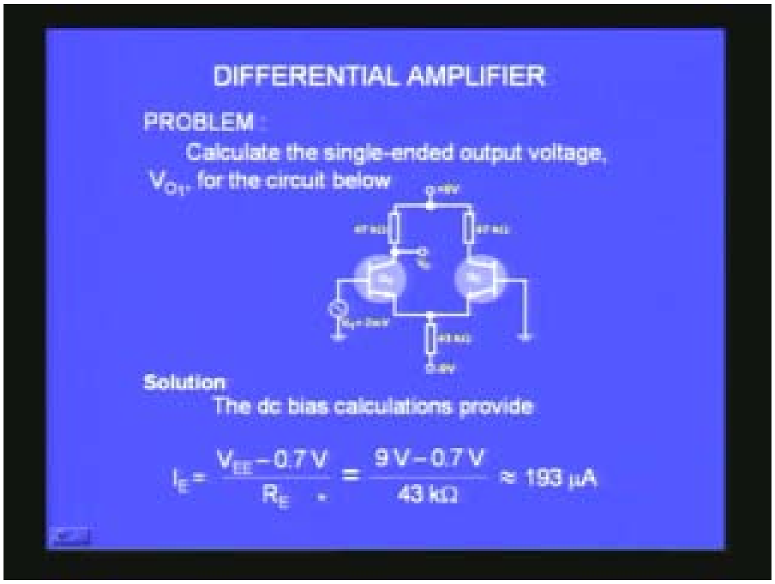
(Refer Slide Time: 23:46)



When you do that you can see that Vi_1 minus $I_b r_1$ minus $I_b r_i$ due to the second transistor should be equal to zero by KVL, Kirchhoffs law the loop equation. From this we can find out I_B should be Vi_1 by $2r_i$ from this equation with the simple algebra you can find out. You can also reasonably assume that the two transistors are close or almost matched. Beta one the current gain of Q_1 is equal to beta two the current gain of the second transistor and that I can call as beta the common amplifier the current gain. I_C will beta times I_b and that will be beta times instead of I_b I can write Vi_1 by $2r_i$ from the earlier discussion. What is the output voltage? The output voltage is $I_C R_C$ the voltage across the R_C due to the ac current and that will be beta times I_b R_C. Beta times I_b is beta time Vi_1 by $2r_i$ into R_C. We all know what is r_i? The small r_i is nothing but beta times r_e where r_e is the emitter resistance emitter base resistance. So beta times R_C divided by 2 beta times r_e times V_i and the beta will cancel leaving you with V output by V_i the gain to be R_C by $2r_e$. This is an important relationship. So in the case of a difference amplifier with voltage applied to one end and output taken from one collector the gain of the difference amplifier A_v is equal to V output by Vi_1 that is equal to R_C by $2r_e$ where R_C is the collector resistance connected to the two transistors and small r_e is the base resistance two times small r_e. This ratio is what we get as the current here.

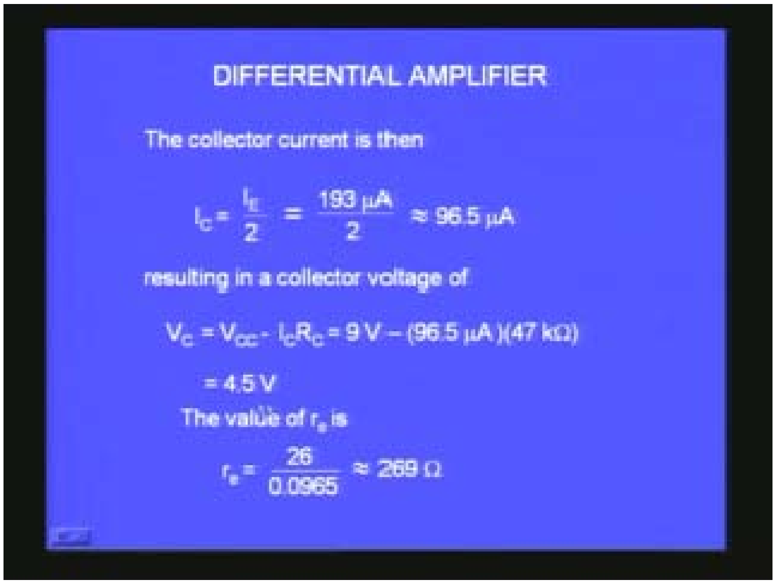
Let us take a simple numerical example. Again you have a +9 volts, -9 volts; you have 47 kilo ohms at the two collectors and 43 kilo ohms for example at the emitter R_E and I impinch a small ac signal with a rms value of 2 milli volts. Let us now first calculate the DC bias calculations and then you will try to calculate the ac gain.

(Refer Slide Time: 26:24)



So for DC bias condition I_E is equal to V_{EE} minus 0.7 by R_E that is 9 volts minus 0.7 by 43 kilo ohms in this case and that is around 193 micro amperes. The I_E is 193. The two emitter currents will have to be half of them I_E by 2. That is 193 by 2 that is 96.5 micro amperes and that will be the same as the collector current within approximation resulting in the collector voltage V_{CC} is equal to V_{CC} minus $I_C R_C$ that is 9 volts minus 96.5 into 47 K and what you get will be around 4.5 volts.

(Refer Slide Time: 27:08)

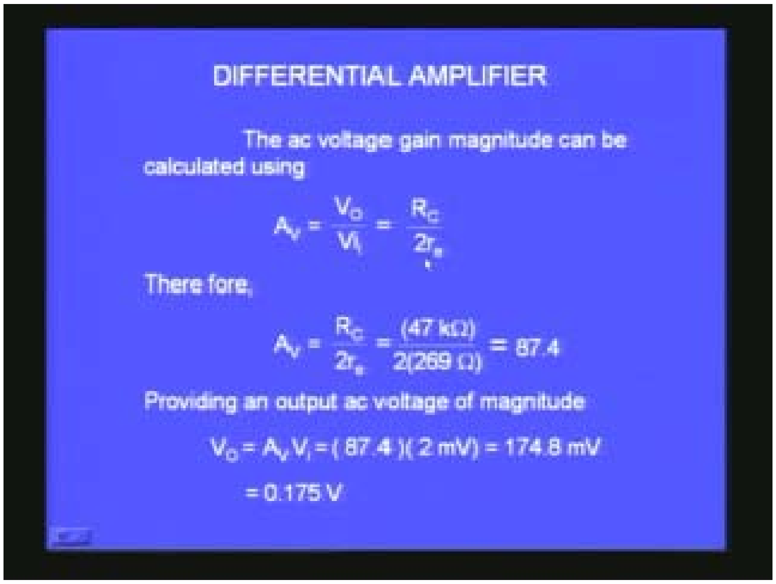


So the collector voltage is at 4.5 volts when the emitter is with the zero bias. This is the DC bias condition. What is the value of small r_e? The r_e is 26 milli volts divided by

0.965. There should be milli volts here. That corresponds to 269 ohms. We saw that r_e is usually very, very small. That is 269 ohms.

What is the voltage gain? The voltage gain for ac can be calculated by Vo by Vi_1. That is R_C by $2r_e$.

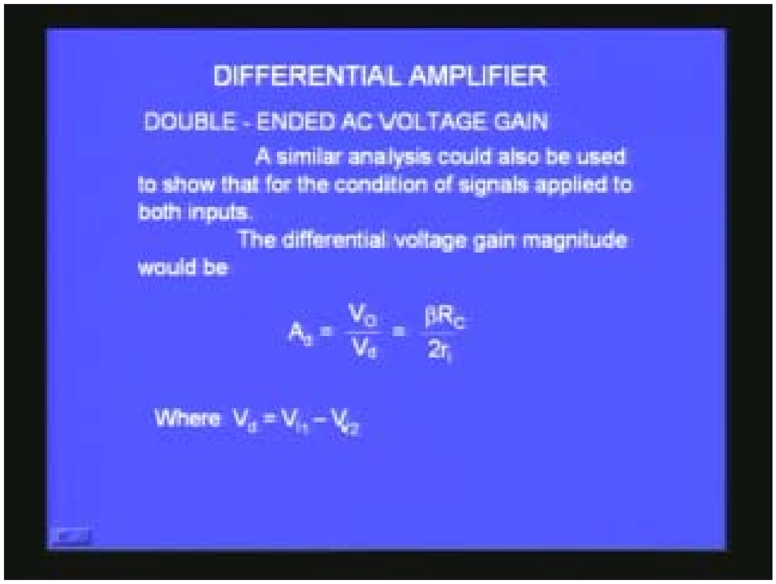
(Refer Slide Time: 27:42)



R_C is 47 kilo ohm. 2 into r_e is 2 into 269 ohms. That will be around 87. So this is the voltage gain of the difference amplifier. If I tell you that the input voltage is 2 milli volts then the output voltage can be easily calculated as 2 milli volts multiplied by the gain that is 87 multiplied by 2 milli volts it is around 174.8 milli volts. So around 175 milli volts is what you get as the output voltage. In principle it is possible for us to calculate the gain and the output voltage.

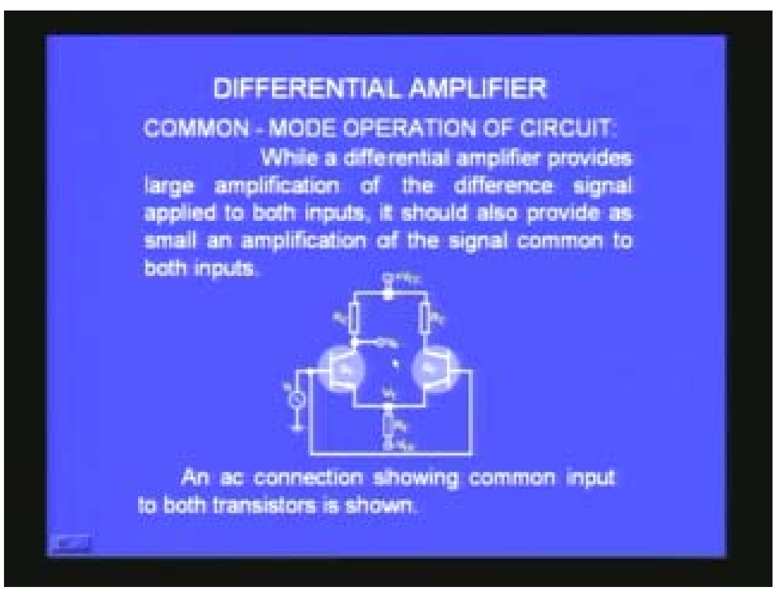
Let us look at the differential that is the double ended voltage gain. If I apply signals to both the inputs what will happen? The differential voltage gain magnitude will be beta times R_C by $2r_i$ again. It will not be very different. You can try as a small exercise and both the collectors will give this voltage. When I want the differential gain it is the difference in the two input voltages that I should take care and V differential is Vi_1 minus Vi_2.

(Refer Slide Time: 29:03)



I will calculate what is Vi_1 using R_C by $2r_i$ and Vi_2 and then I find the difference. That will be the differential voltage and that should be multiplied by the gain factor to get the output voltage here. I also mentioned to you that there is a third configuration which is corresponding to common mode signals. You can have both the signals applied common to the two inputs. Single signal is applied to both the transistor inputs. Then what will happen? What will be the gain of a common mode signal? That is what we are interested in.

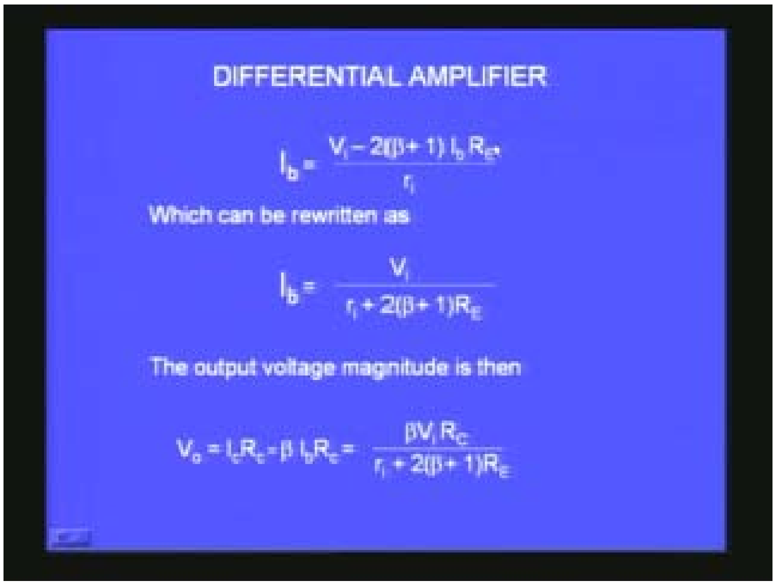
(Refer Slide Time: 29:43)



We can see in the picture the two bases are connected together by a single wire and the signal is connected to one of the base. The same signal in effect this connected to both the bases and you take the output from one of the collectors; single ended output. Let us see what happens?

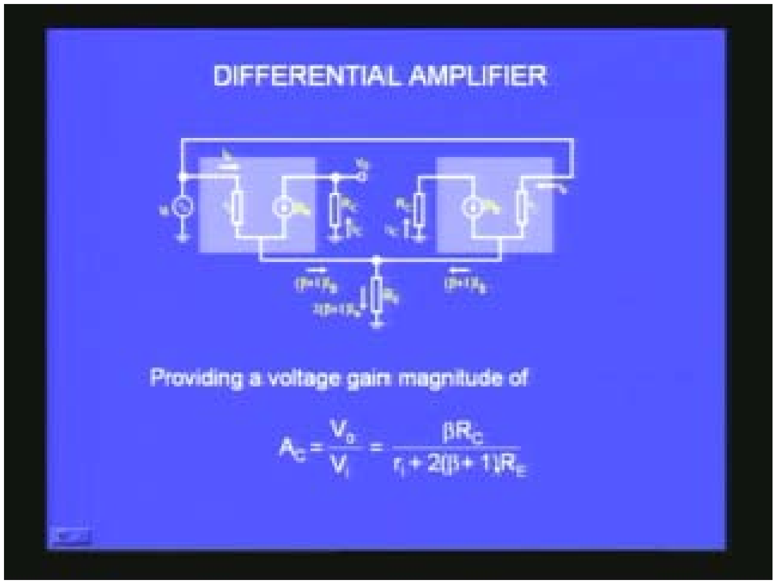
What is the I_b? I_b is whatever voltage you give V_i minus the voltage drop across the r_i and r_e combination. Because r_e is very small we are only taking a drop due to capital R_E. So V_i minus 2 beta plus 1 I_b into R_E.

(Refer Slide Time: 30:38)



Why two beta plus 1 I_b? Beta plus 1 I_b is the emitter current I_E. Two times I_E because this current will only be corresponding to one of the emitter and you have to multiply by a factor 2 if you want to calculate the current across the R_E. Therefore 2 times beta plus 1 into I_b multiplied by R_E gives me the voltage drop across the R_E. So V_i minus this voltage divided by r_i gives me the base current. I hope you are able to see. There is a voltage here. This input voltage minus this input voltage (Refer Slide Time: 31:21) gives me the voltage between the base emitter and that actually is the voltage generated by the internal resistance r_i of the transistor. I_b is equal to V_i. There is also I_b here on this side; right side as well as left side. If I group them together and rearrange you would find I_b is equal to V_i divided by r_i plus 2 times beta plus 1 R_E as you see on the screen and what about the output voltage magnitude? The output voltage magnitude V output is equal to I_cR_c and that will be beta times I_b R_C. I_b is given by this expression. I will substitute that and multiply by R_C so beta times V_iR_C divided by the denominator; the small r_i plus 2 times beta plus 1 R_E. This is what the output voltage is going to be for a common mode signal. What will be the voltage gain? The voltage gain for the common mode I represent as Ac is equal to V output by V_i. That will be beta times R_C divided by r_i plus 2 times beta plus 1 R_E. This is the expression that I get for the common mode signal.

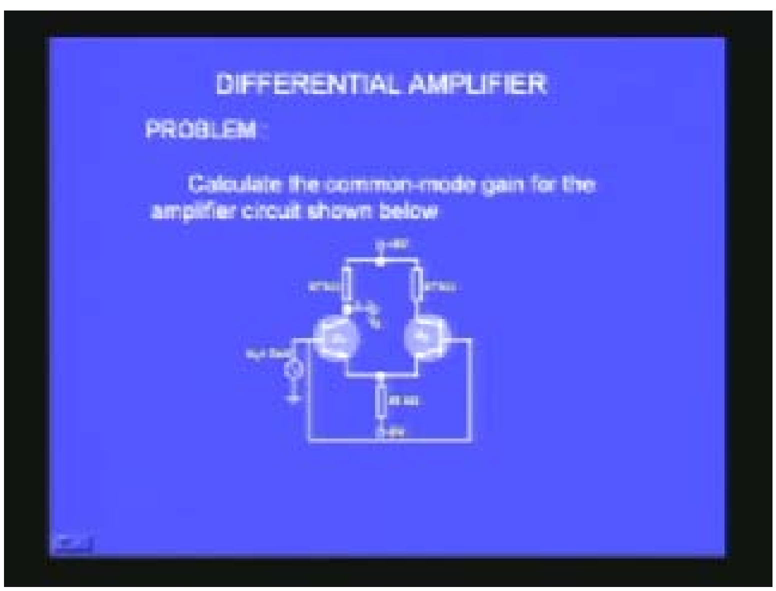
(Refer Slide Time: 32:35)



R_E is very large. Previously we got R_C by 2 r_e; small r_e. Now we are getting beta times R_C divided by the whole expression. Because R_E is very large you will find this number could be very large compared to 1 and the overall gain, common mode gain will be very, very small.

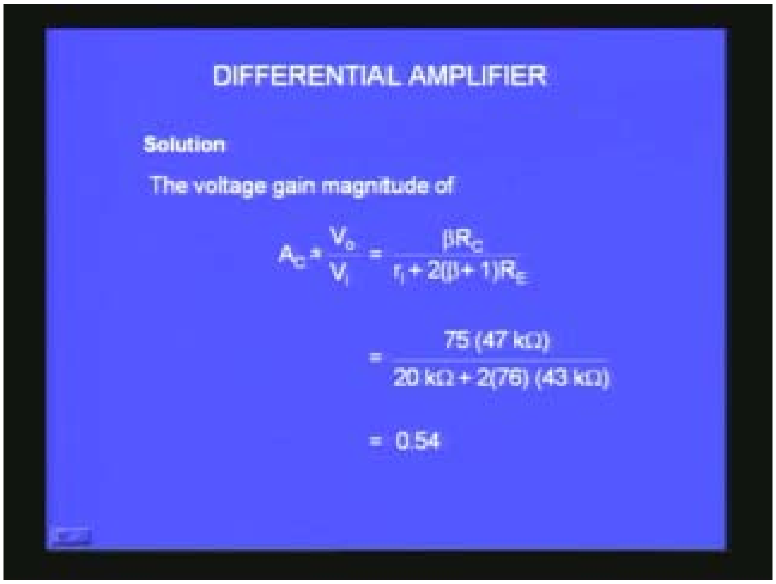
We will try to do a very simple numerical example. Again we have taken the same circuit as before.

(Refer Slide Time: 33:05)



You have the +9 volts and -9 volts and R_C value is 47K and R_E value is 43K and you ….. again 2 milli volts now but connected to both the inputs common mode signal. The voltage gain magnitude we have already calculated.

(Refer Slide Time: 33:22)



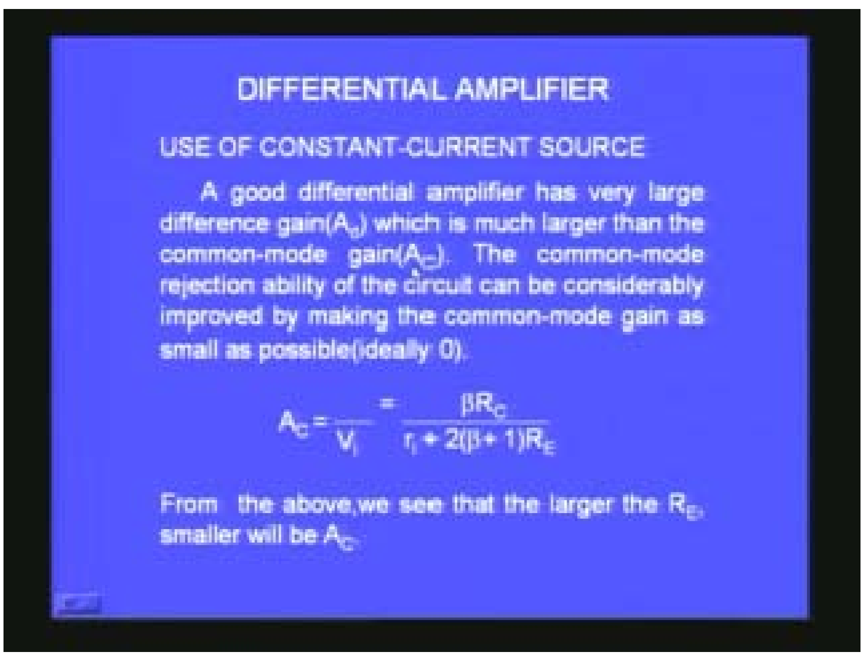
Ac is given by beta R_C divided by small r_i plus 2 times beta plus 1 times R_E and if I substitute beta which is 75 given in the problem, 47 kilo ohm as the R_C, r_i is 20 kilo ohm and 2 times beta plus 1 is 2 times 76 into 43K and if you calculate this comes out to be 0.54. That means what? It is less than 1. That means nearly half. What is going to happen? If I give an input which is common to both the transistors then the output will be half of that. There is going to be attenuation not amplification. That is why I said common mode gain will normally be small compared to differential gain. In principle you would like to have a common mode gain which is very, very small compared to the differential gain so that the ratio which I referred to earlier as the common mode rejection ratio should be a very large number. Because it is called a difference amplifier the amplifier should amplify different signals better than common signals. That is shown by the factor cmr.

In a simpler way if I apply for example 100 milli volts to both the inputs I will get one output because that 100 milli volts becomes the common mode signal. Let me take this example. I apply 100 milli volts to one of the base and 0 milli volts to the other base. I understand we have calculated also the gain of the difference amplifier let us say is around 100. We got about 87 in our example. Let us take 100 as a very simple number. So I give 100 milli volts. The gain of the amplifier is 100 therefore I will take 10,000 milli volts that is 10 volts at the output. With this condition I will get 10 volts. I apply 1 volt as a common volt for both the inputs. That is to one input I am applying 1.1 volt. 1.1 volt is 1 volt plus 100 milli volts. To the other transistor I apply only 1 volt. What is the difference between the two inputs? What is the differential input that I have given? It is the same as the previous case just a 100 milli volt. This is 1.1 that is 1. The difference is

0.1. 0.1 volt is nothing but 100 milli volt. So I have not changed the input at all; the differential input at all. So what should be the output? Output should again be multiplied by 100; differential gain. So 100 into 100 again it will be 10 volts. If this happens in any difference amplifier then the cmrr is a very large number for this almost infinity. Ideally if you get the same number it is infinity. Cmrr is infinity. But usually it will not happen like that. The transistor will be also affected to some extent due to the common signal that you applied the 1 one volt and you will get a finite gain for the common signal and cmrr will not be very large? infinity. It will be a reasonably small number. It is not as high as infinity but it is not small also. It will be reasonably high. Because it is a very important characteristic of a difference amplifier we are interested in making the cmrr as large as possible.

If you want a very large cmrr the best way to do that is to have very good current source at the emitter. You must have a current source at the emitter but you know it is difficult to have constant current source. That is actually what we require is we require a very large resistance and a very large voltage source. If you have a very large resistance and a very voltage source connected together it can become a reasonably good current source. A good differential amplifier as you can see on the screen has a very large differential gain and very small, reasonably small common mode gain, Ac.

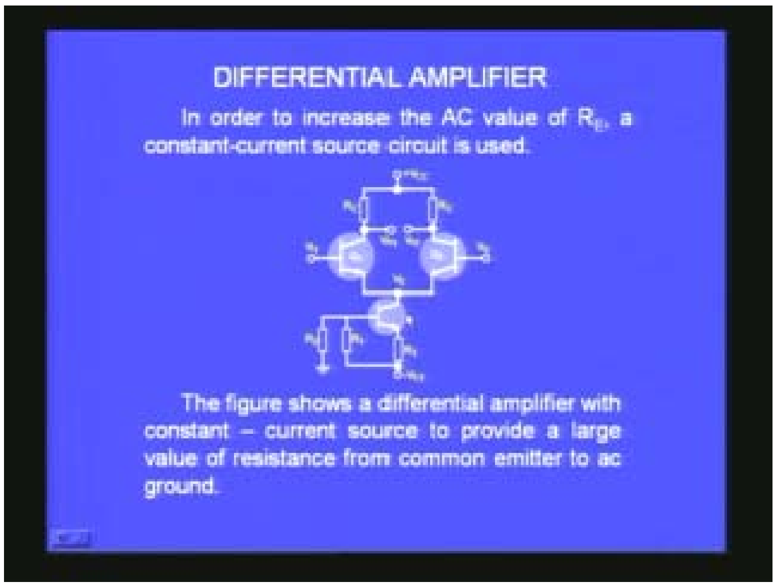
(Refer Slide Time: 37:55)



The common mode rejection ability of the circuit can be considerably improved if you use the common mode gain as small as possible ideally zero. That means A_c which is given as V output by V input is equal to beta times R_C by r_i plus 2 times beta plus 1 R_E what we obtained last time. We see that larger the R_E smaller will be A_c. If I put larger R_E the emitter current itself will decrease. So if you make R_E large you must also make V_{EE} large which is equivalent to saying I can replace the V_{EE} and R_E by a constant current source. A constant current source, I was mentioning to you, is nothing but something which is obtained by applying a large voltage across large resistance so that the current is almost decided by the internal resistance rather than by the resistance I connect outside.

In order to increase the differential gain and reduce the common mode gain we want to increase the A_c value of the R_E to a very large number. For that we use a constant current source circuit.

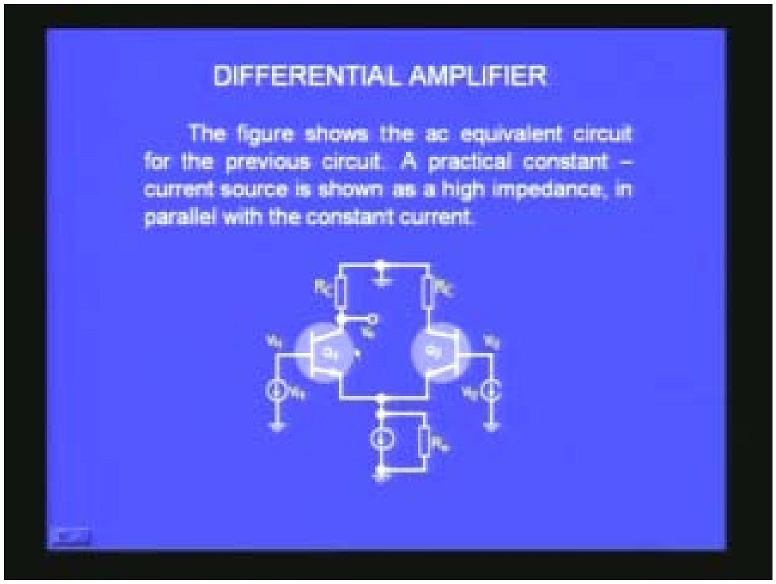
(Refer Slide Time: 39:20)



You can see in the picture we have removed the earlier R_E and the V_{EE} by a small transistor circuit. If you look carefully you can see it is nothing but a very simple transistor with an emitter resistance and you have a R_1 and R_2. This is a voltage divider bias and an emitter voltage and with reference to this end this is negative. The current is still flowing in the right direction. Depending upon the R_1 R_2 there is no base voltage applied in the ac condition. With reference to the voltage divider bias there is going to be some voltage here and there is also a voltage corresponding to V_E and this voltage will be decided by R_1 R_2 and the emitter current and this will be a constant like the mirror circuit that I mentioned to you earlier. The collector current here is going to be constant because it is decided by the R_E value and R_1 R_2 value of the transistor. If this is going to be constant the emitter current will also be constant and the collector current also will be constant and the difference amplifier will perform well and this constant current effectively is equivalent to a very large resistance connected in series with a very large voltage source and very large resistance means the common mode gain will still be reduced and automatically cmrr will be increased.

We have shown here on the screen the equivalent circuit of the same thing which we have drawn earlier for the ac condition.

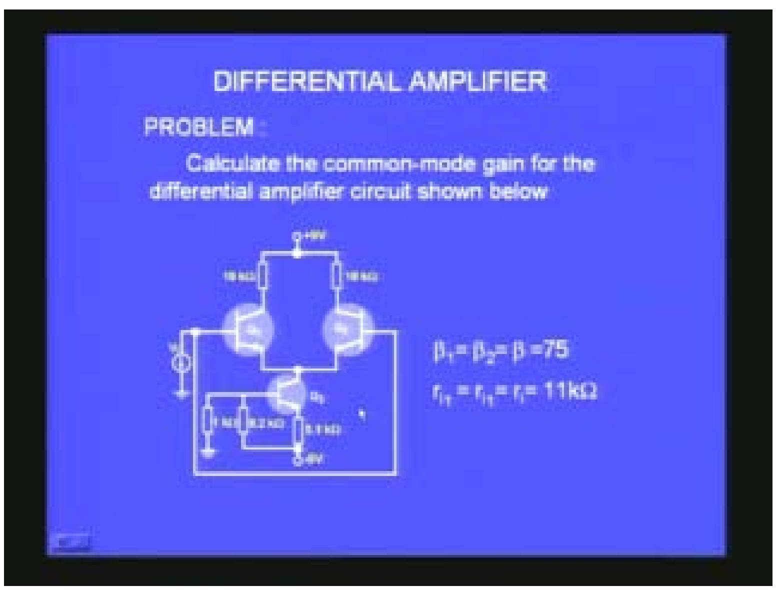
(Refer Slide Time: 41:20)



For the ac condition the power supply should be grounded. Here also the V_{EE} is grounded and you have the constant current source here along with the corresponding output source resistance internal source resistance. It is equivalent to high impedance in parallel with a constant current source.

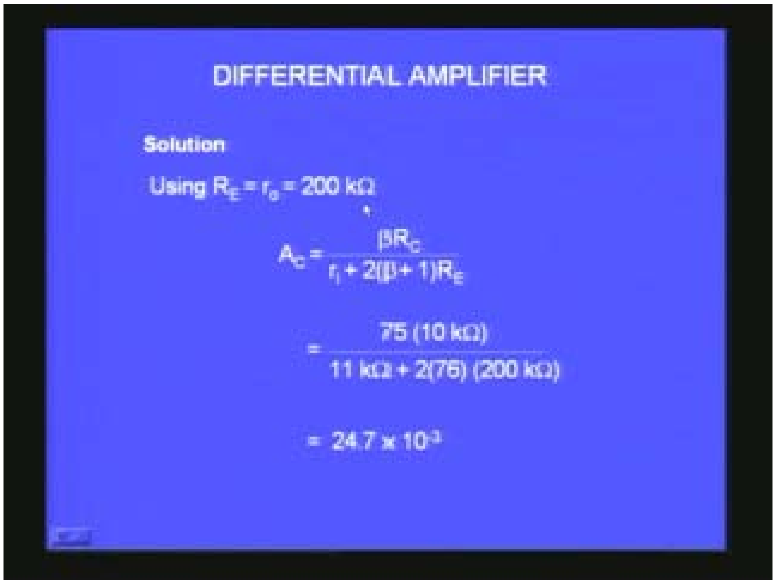
We will try to do a small numerical example of how a common mode gain gets reduced when I use a current source.

(Refer Slide Time: 41:52)



We assume the beta one beta two is about 75. They are equal to 75 and r_{i1} r_{i2} equal to 11 K for the two transistors Q_1 and Q_2. If you assume R_E is equal to r_0 the internal resistance of the current source it will be around 200 kilo ohm.

(Refer Slide Time: 42:14)



The common mode gain becomes beta R_C divided by r_i plus 2 times beta plus $1R_E$. We have seen already this beta is 75, R_C is 10 kilo ohms in the example given and small r_i is 11 kilo ohms and 2 beta plus 1 is 2 times 76 and R_E is 200 kilo ohm. We calculate it. It is coming to be about 24.7 into 10 to the power of -3. That means it is a very, very small value. A common mode gain when I use a constant current source is found to be very, very small. If I divide the differential gain by such a small number the 10 to the power -3 in the denominator will go to the numerator which will become 1000 times. Thereby you would find having a fractional or smaller than 1 current gain for the common mode scheme will certainly multiply the ratio of the differential gain to the common mode or the cmrr. So the cmrr will become a very, very large number.

Having discussed about the difference amplifier, now we should look at the applications of the difference amplifier. One of the very well known applications of the difference amplifier is in integrated circuit design especially in operational amplifier. Most of the linear IC's will have differential amplifier as the input stage. There is a very specific reason why it is done. What do you mean by integrated circuit? In an integrated circuit on a silicon chip you try to integrate the different electrical functions; functionalities like devices like transistors, diodes, resistors, capacitors all together and then you can form on the same silicon wafer the whole circuit. A circuit is made up of resistors, capacitors, diodes, transistors. So any one of these can also be made with silica. John or Jack? Kilby and Robert Noyce really thought independently why a whole circuit cannot be done on a silicon chip by isolating some area as resistance, some other area as a diode, transistor, capacitor, etc. Integrate all of them and only interconnect the components with some fine metallic wire like gold wire. Then what you have on the silicon is no more a single device like a transistor or a diode but a whole circuit.

It not only makes the device very, very compact, very, very small but it improves the performance enormously. How do I say that? Every transistor circuit, semiconductor device is very sensitive to temperature which is one of the examples I can tell you. When the temperature changes the performance of the circuit will also change. If I make all the transistors and resistors on the same silicon chip the circuit will be very, very small and the components will be only few micrometers apart from each other. Two transistors for example can be separated only by a few microns. Micron means one micro meter. If that happens if there is going to be a temperature change then the two transistors will have almost identical conditions when they are formed on the silicon chip and we will almost have identical characteristics.

When there is a temperature change both will be affected equally. Hence if I have a differential amplifier as the input stage whatever that is same or identical to the two transistors will be rejected by the factor which we already know as the cmrr, common mode rejection ratio. When I have differential amplifier as the input stage the common voltages like the noise signals, the pick up signals, etc will be completely rejected and if there is any change due to temperature that also will not affect too much because the two transistors at the input stage are almost identical and they will have similar characteristics and if one increases the other decreases exactly and when combined together you don't get anything at all. Zero volts will be the output because it is matched. This feature is one of the reasons why difference amplifiers are used in integrated circuit design.

There again is another important reason and that is in an integrated circuit design it is very difficult to make capacitors. How do you make resistors on a silicon chip? It is very simple. If I dope the silicon with a pentavalent or a trivalent impurity the resistance will decrease. It will either become p-type or a n-type semiconductor and a n-type or a p-type semiconductor has got finite conductivity at room temperature and they are basically something like resistors. By controlling the doping I will be able to get any magnitude of resistance on a silicon chip. I can always make a transistor or a diode on the silicon chip by selectively by making some area p-type and then making n-type over and above that or three layers means npn or pnp as the case may be you can generate on the silicon chip. You can get transistors easily within small regions, you can get diode within very small regions you can get resistance by just simply doping the semiconductor in some region and you can also get capacitance.

How do you get capacitance? Capacitance is obtained by using diode. Diode is a pn junction device and there is a depletion region at the junction and the p-type and the n-type because they are conducting they will act like metal plates and the depletion layer in between acts like an insulator or dielectric and so what you have here is a capacitance. We have seen that earlier. We also discussed about the different types of diodes like the varactor diode where this property of the capacitance of the junction is exploited in different applications. Now you have possibility on the silicon wafer to make every type of electrical component that you want. You can make resistors, you can make diodes, you can make transistors and you can make capacitance. But there is one other problem. When you prepare the device the doping will be controlled by the pressure and the flow and temperature of the process where you let in the phosphorous pentoxide for doping. The flow rate and the temperature will all be controlled and because silicon is a very small region 1 inch or 2 inch wafer for example, on that you can make thousands of transistors or capacitors or resistors. But if I take one single set the doping is the same whether I want to make a resistor or a capacitor or a diode. The doping will be only decided by the parameters like the temperature, the pressure, etc and that will be the same through out the wafer. Under the same conditions if I want smaller resistors that mean I want more conductivity I should dope more. But I cannot dope for longer period because the diode and the transistor will not perform well. They require a very specific level of doping and only way I can do that is by increasing the area for the resistance for the given flow rate and given pressure. I have to increase the area of the resistor, region of the resistor on the silicon chip and if I want smaller and smaller resistances then I have to use larger and larger area on the silicon chip.

Similarly if I want larger capacitance you have to have larger area for the capacitance and the problem on the silicon chip now has become a problem of real estate, something like the real estate. The area available is very small and you want to put different types of devices on that like resistors, capacitors, diodes and transistors. You have to allocate different regions for the different components and the values of resistors if they are small you will have larger resistance, larger areas for that; similarly for capacitors. Whereas for transistors and diodes you can do with a very small region and you would like to avoid making use of capacitances. If possible low value resistances because they occupy larger space and in that space you can as well make more number of transistors and diodes and in all integrated circuit the whole philosophy of the circuit design has now shifted from any components can be used for the transistors to you now say if possible design your circuit only with resistors, diodes and transistors with almost no capacitors and none inductances; not even one inductances can be allowed. So you want to avoid capacitances and you want to avoid inductances. You can only have in all your circuit diodes, transistors and high value resistors. These are all what is only possible. So the philosophy itself is changed.

But how do I make an amplifier without a capacitor? You can immediately see one good scheme of making an amplifier without capacitance is the differential amplifier. You saw that there were no capacitors used in the difference amplifier. So if I use the difference amplifier as the input stage and couple it to other later stages for higher gain I can do away with the need for large coupling capacitors to take very wide band width for the amplifier. In the case of op amps, operational amplifiers the input stage is a differential amplifier. Why do we use coupling capacitors in a normal amplifier? You want to only couple the ac signal and block the dc voltage. Again in the difference amplifier without any capacitor you are able to do that. Because the amplifier has response only to difference in the input signals I can use a difference amplifier and later couple to another stage of amplifier without worrying about using a capacitor to isolate the dc.

Because this amplifier itself is responding only to the difference between the two inputs and the only difference that you are going to have is only with reference to signal and all the dc will be equal and they will be eliminated. So input stage of an integrated circuit amplifier will have to be a difference amplifier because thereby we can avoid the necessity for large value coupling capacitors to be integrated in the circuit in the silicon wafer and that is the reason why difference amplifiers are very, very useful and that is why we discussed in this lecture about difference amplifiers. In the present lecture what I discussed today is I took an example of a difference amplifier which requires two transistors and one emitter resistance and two collector resistances and we discussed the dc bias condition. How to calculate the various currents and the voltages and we also saw by drawing the equivalent circuit how to obtain the ac gain for the common mode signal and for the differential signal. Finally we also saw how the common mode rejection ratio of the difference amplifier can be improved by introducing a current source in the emitter circuit instead of a voltage source V_{EE} and r_e. Next class onwards we will start looking at the integrated circuits, their advantages over the normal discrete circuit and how an operational amplifier can be used for different applications. Thank you very much.