**Electronics for Analog Signal Processing - I**
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**Lecture - 31**
**Cascading (Direct Coupling)**

In the last class we discussed something about cascading. We discussed capacitive coupling and also we discussed direct coupling, which can get rid of large values of capacitors required for capacitive coupling circuits. And it is highly suited for integrated circuit fabrication, where capacitor is not at all there, required. For this direct coupling, we said, if we couple, for example an N P N common emitter with an N P N common emitter, we have a problem. That problem, we are now illustrating by an example. What is it?

Here is a circuit. This analyze... this is analysis. Example is nothing but analysis of the circuit, complete analysis of the circuit.

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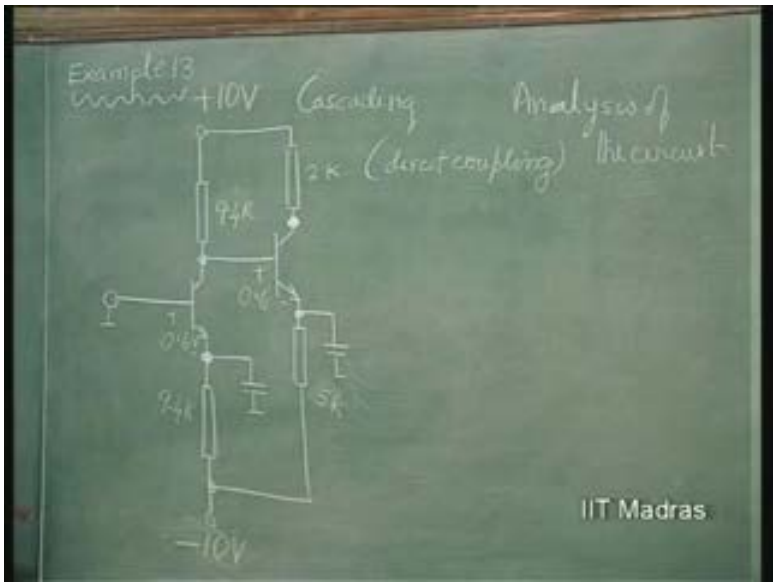


So, let us now see. This is using dual supply; and this resistance is fixing the current in the following fashion that, if we assume that the V B is point 6 volts, then I have chosen

this as minus 10 volts and this conveniently as 9 point 4 Kilo ohms, so that 9 point 4 volts drop across this resistance is caused by a current of 1 milliampere. So, 10 minus point 6 is 9 point 4 divided by 9 point 4. So, let us just put down that. 10 minus point 6, this is important; divided by 9 point 4 K is equal to 1 milliampere.

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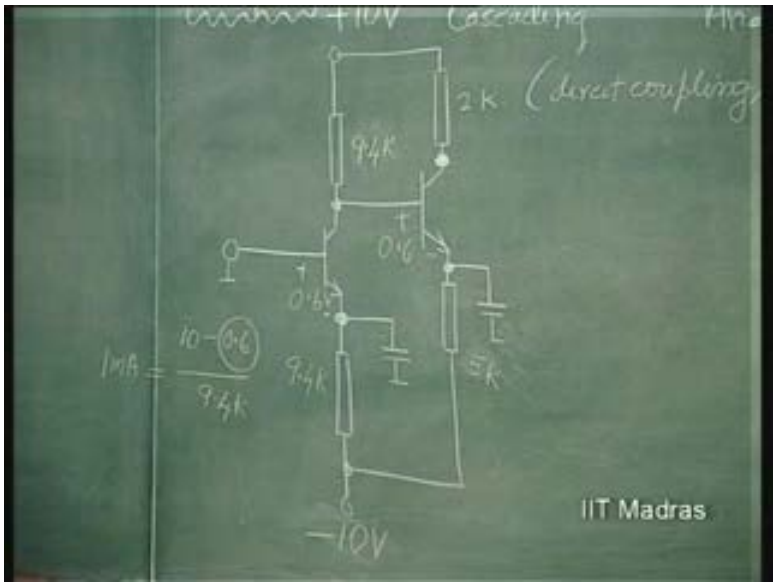


So, I am now illustrating this fact. We will highlight this later. So, this has a D C current of 1 milliampere, quiescent current; and therefore this drop in this is going to be approximately 9 point 4 volts. If Alpha is given, then we could say it is Alpha times that. If Alpha is not given, then we could say that it is approximately 9 point 4 volts. So, the voltage here is 10 minus 9 point 4 volts, which is about point 6 volts.

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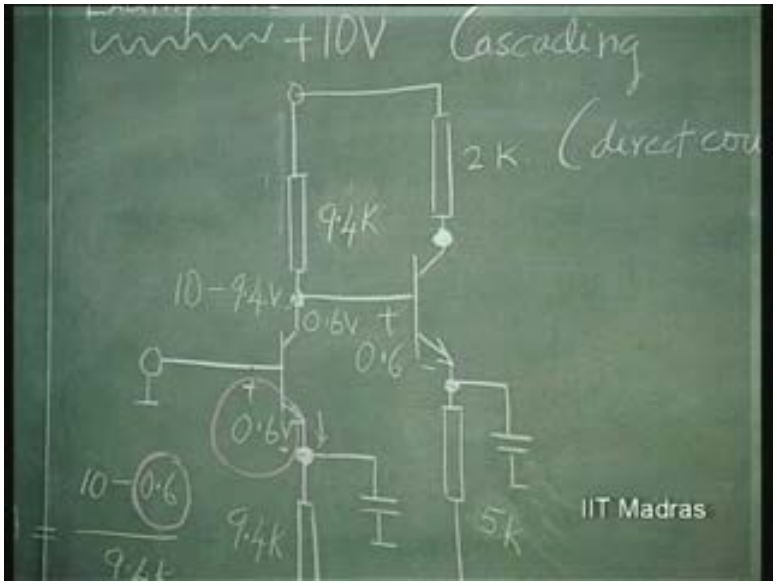


This is point 6, this is point 6; therefore, the voltage here is zero volts, quiescent. This is zero volts. This is minus 10 volts and I put a resistance of 5 Kilo ohms. This is already zero volts. This is minus 10 volts. So, across 5 K, we have a drop of 10 volts. So, the current in this is 2 milliamperes. So, the current in this was 1 milliampere. The current in this is 2 milliamperes. This is 2 milliamperes. This is 2 K. The drop across this is 4 volts. This is 4 volts drop; and therefore 10 minus 4 volts. That means the voltage at this point is 6 volts with respect to ground, quiescent.

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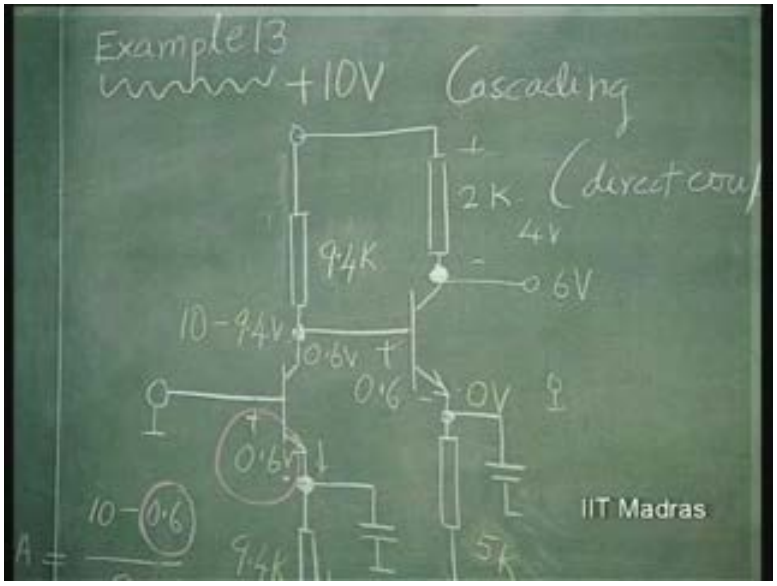


So, the entire circuit now has been analyzed for its quiescent condition. Let us investigate that. How much do we have as V C B for T 1 and T 2. So, T 1, T 2 - operating point.

So, what will be the V C B for this? V, base is at zero volts. This is at point 6 volts. So, V C B Q is point 6 volts which is good enough hopefully because it is the first stage of amplification. The voltage swing is not going to be much. This is a two stage amplifier. So, this point 6 volts should be good enough for it and V C B Q for this, this is at point 6. This is at 6. So, what is the V C B Q? 5 point 4 volts. 6 minus point 6. So, 5 point 4 volts. It is good enough for 5 point 4 volts, say, for that.

Now, the quiescent current I C Q for the first stage is 1 milliampere; for the second stage is 2 milliamperes. So, this gives complete details about the fact that this is conveniently biased. These two transistors are conveniently biased. This one can give you a swing of point 6 volts on one side before it goes to saturation. This can give a swing of 5 point 4 volts before it goes to saturation, appropriately designed. This current is going to swing from say, 1 milliamperes, all the way up to 2 milliamperes, it can go; and zero milliampere it can come. Similarly, this can go up to 4 milliamperes, that way.

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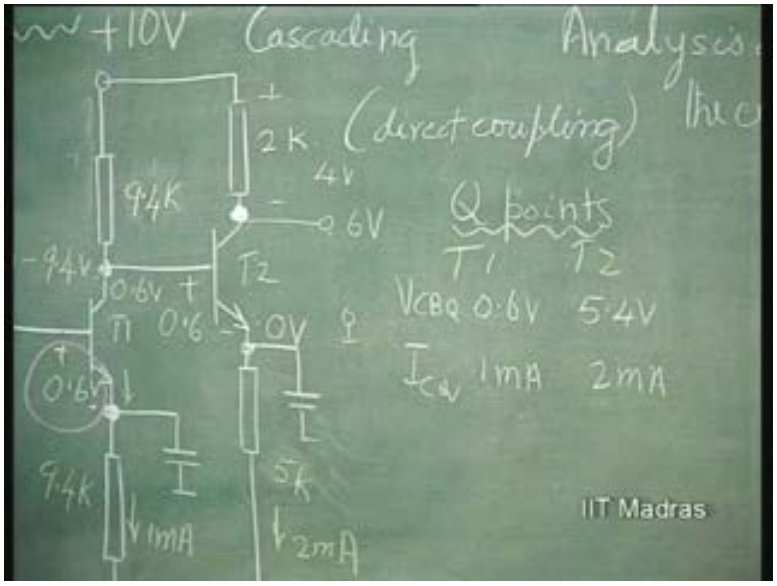


Now, the current swing into the load resistance will give you the voltage swing corresponding to that. So, if there is a 2 milliampere quiescent, the swing here is 2 milliamperes into 2 K, which is 4 volts. So, on one side, limitation due to cut-off can go up to 4 volts here because of this; and because of this, it is limited to 5 point 4 volts. So, limitation occurs due to transistor going to cut-off earlier, if you are talking of symmetric swing; then, the transistor is going to saturation.

So, the swing here due to this is 4 volts; this swing is of no consequence because this is too large a current. For this kind of current swing, this current swing permitted is pretty large. Same is the case with this. This we will realize presently. This is cascaded from... This is the input where the signal generated can be connected; and let us consider the first stage gain. The first stage gain...

Let us look at the first stage. We have established earlier that common emitter amplifier, the amplified gain is g m into r c. So, we would like to... minus g m into r c. So, minus g m into effective R C. R C effective, that is important. R C is 9 point 4 K. But it is shunted by the input resistance of the next stage. So, r c effective is to be computed; g m is to be computed.

g m is 1 over R E, Alpha over R E; Alpha is very close to 1. So, R E is, for 1 milliampere it is 25 ohms; 26 ohms really. We will take it as 25 ohms for convenience. So, it is 40 millisiemens, assuming that it is 25 ohms.

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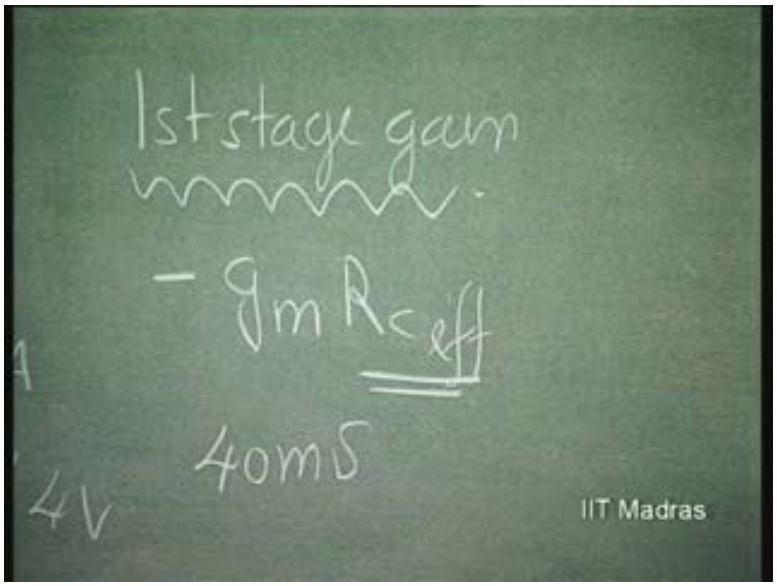


So, g m at 1 milliampere, approximately. So, we will call this g m 1, R C effective 1, corresponding to transistor 1.

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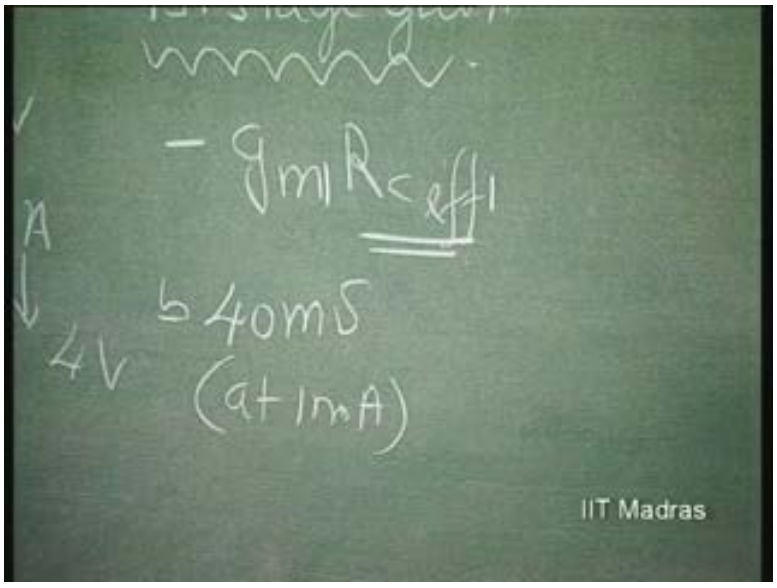

The second stage gain is minus g m 2 R C effective 2. g m 2, it is working at 2 milliamperes. If this is 40 millisiemens, that should be 80 millisiemens; double. So, this is 80 millisiemens, g m. R C effective is 2 K; nothing has been connected further. So, the second stage gain is easier to evaluate, always in cascading. Thus you always, therefore, start from the final stage and come towards the first stage because, you see, here, everything is straightaway known to us. So, what will be the gain equal to? Minus 160.

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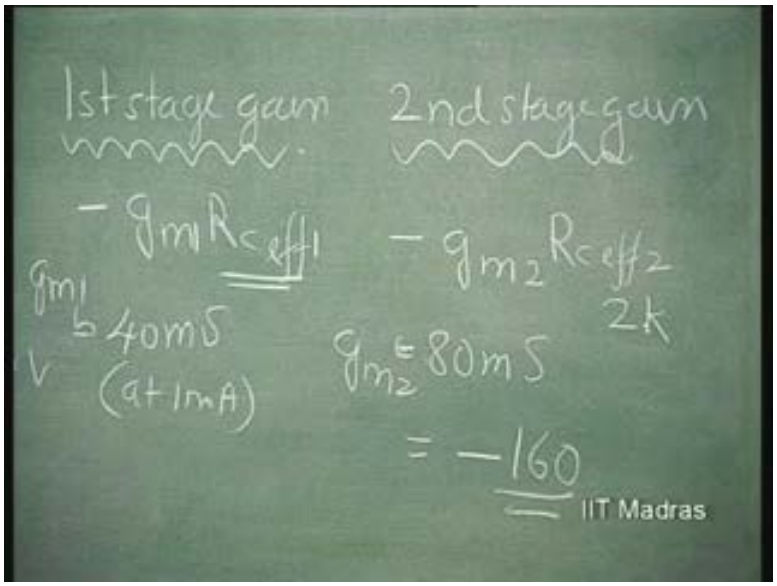


The first stage is loaded by the second stage input impedance. Therefore, let us take Alpha as point 99. Now, let Alpha be equal to... So, the second stage is loading the first stage. What is the load? This is r e into Beta plus 1. r e is for 1 milliampere, 25 ohms; for 2 milliamperes, 12 point 5 ohms. So, r e of this stage, r e 2 is 12 point 5 ohms.

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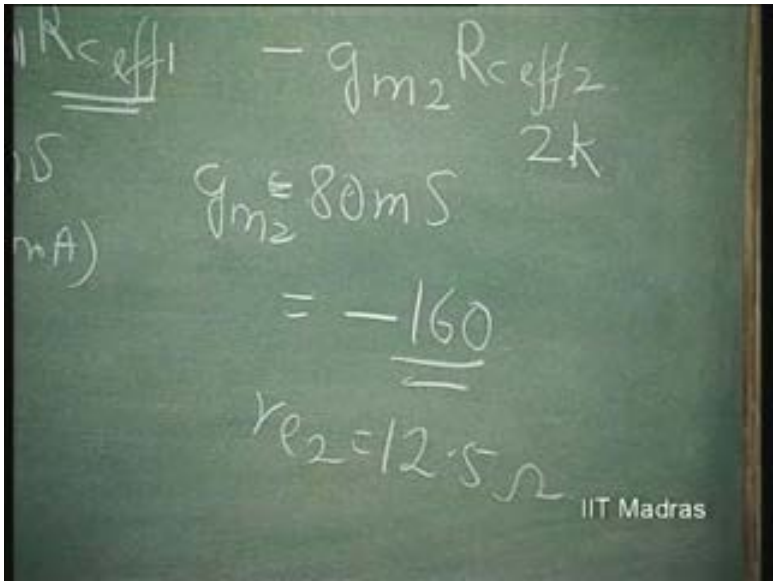


And Beta is 100. So, the load R i 2 is Beta plus 1; Beta plus 1 into r e 2.

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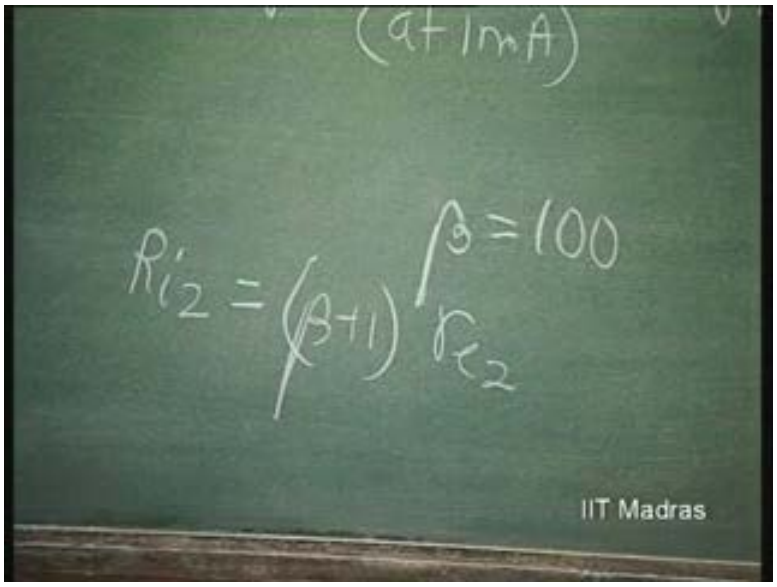


The current here and here are related by Beta plus 1. Whatever resistance is there in emitter is reflected as Beta plus 1, higher.

So, this is equal to 101 into 12 point 5, which is, how much is it? 12 125 100, pardon 1 1 point 2, 126 point 25, whatever it is. So, it is 12 point 625 K. So, is it 12 point? 1 point 26 K. So, it is 1 point 2625 K.

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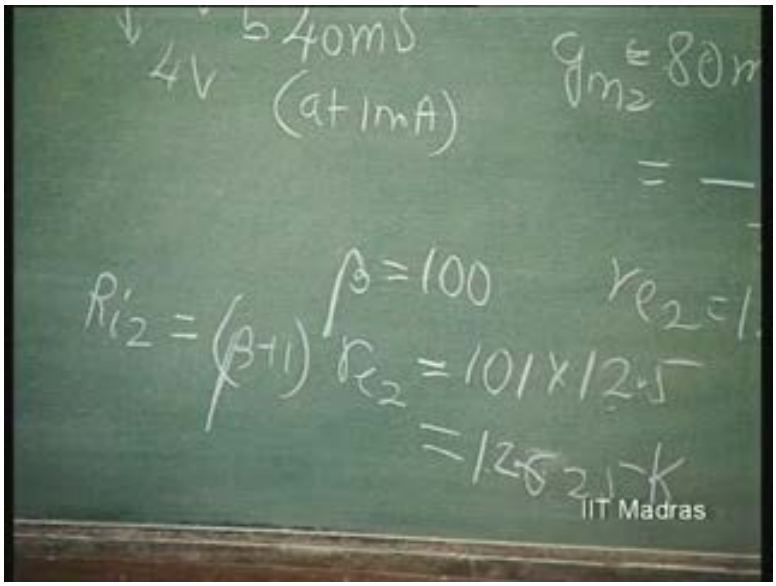


So, please see here that 9 point 4 K is the collector load here; but effective collector load is much less than that because of the input impedance of this. So, it is 1 point 2625 shunted by 9 point 4 K. So, R C 2 effective is 9 point 4 K parallel 1 point 2625 K. How much is this? R C 1, R C 1 effective. We are calling it R C effective 1. How much is it? This is going to be almost less than 1 point 1K or so. 9 point 4 into 1 point 2625 divided by 9 point 4 plus 1 point 2625. 1 point 11 K.

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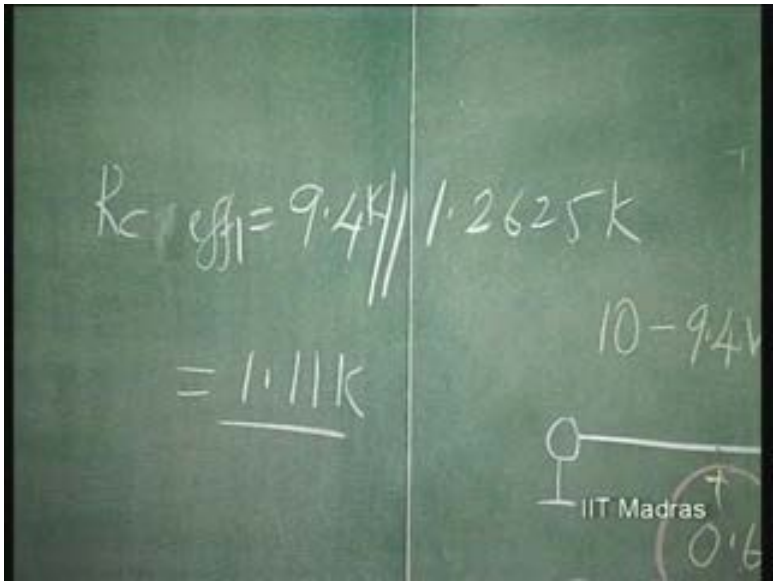


So, what will be the gain now for the first stage? See, gain for the first stage is therefore equal to, first stage gain, minus 1 point 11 into 40. That is, 44 point 4, minus.

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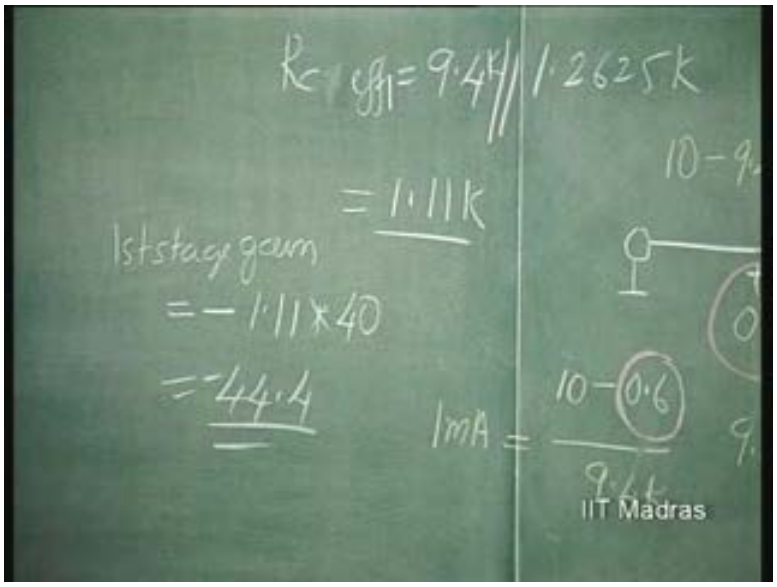


Overall gain is equal to plus; minus into minus will get, give you, plus. That means there is no phase shift. This is a non-inverting amplifier. So, 44 point 4 into 160 which is 7, 7 1 0 4. Yes, how much is it? 7 71...So, you can get a fairly high gain amplifier just by

cascading two stages. So, this is the basis of design of high gain amplifiers. Cascading two stages, we can get high gain amplifiers.

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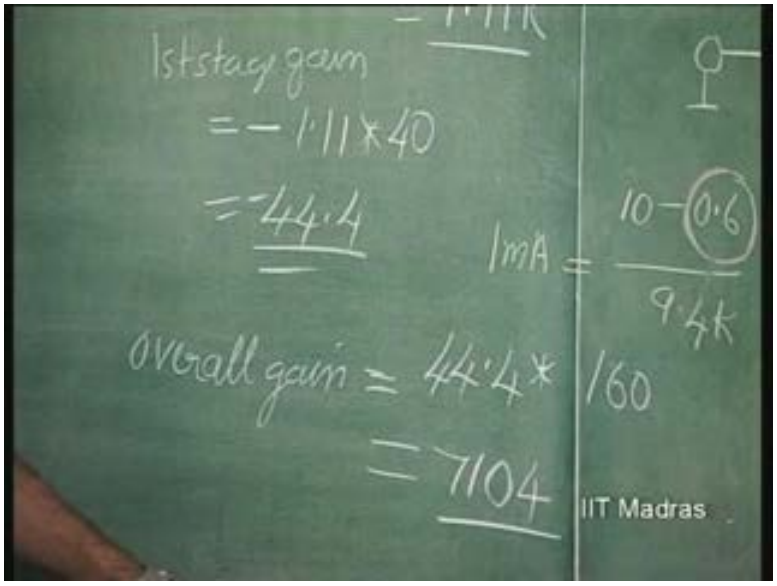


Now, let us see the implication of this. Gain is very high. That means even if I apply a very small signal like 1 millivolt at the input, if the gain is 7104, output will be 7 point 1 volts swing; for 1 millivolts swing at the input. But this is not capable of giving that much swing. We have seen that this can give maximum of 4 volts swing, symmetry.

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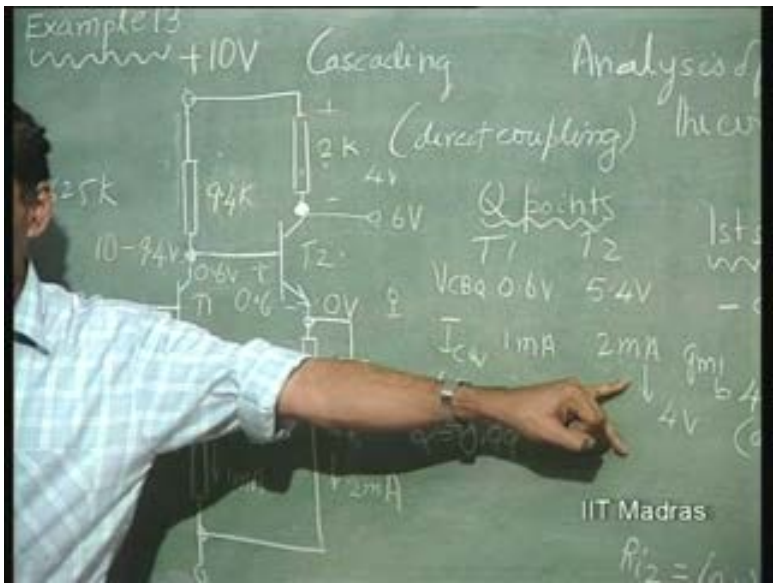


And therefore, this particular gain, you have to be very careful with, in the sense, even if there is a voltage which is of the order of micro volts, that is going to amplify. Now, let us see what the implication is. This diode drop is strictly not what? – constant with respect to temperature. We have discussed when we discussed the diode example. And Delta V Gamma by Delta T is typically, we remember we used this for temperature transducer. So, minus 2 point 5 millivolts per degree centigrade.

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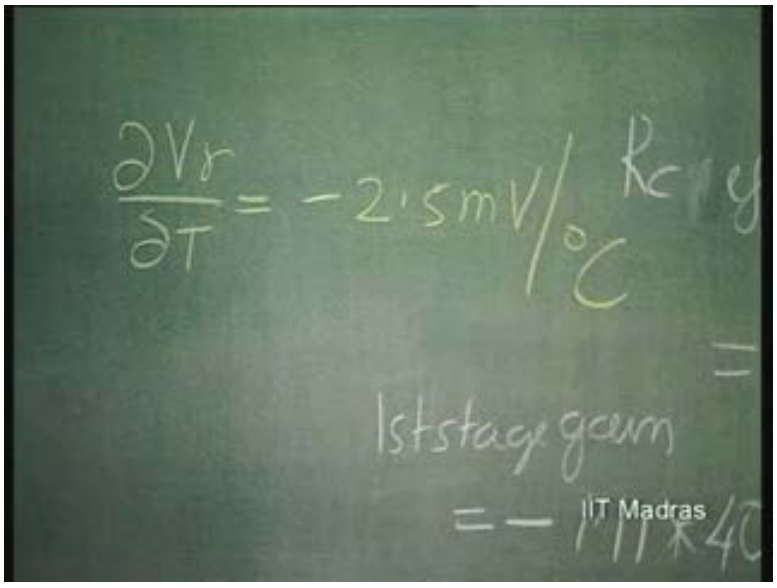

This is a typical number which we should remember all the time. For silicon diodes, the forward voltage drop at a specific current has a temperature coefficient which is very constant; and that is equal to minus 2 point 5 millivolts per degree centigrade. If that is the case, this point 6 volts is drifting with temperature; hence, with time. This V Gamma, point 6 volts, changes because of this temperature coefficient, with temperature.

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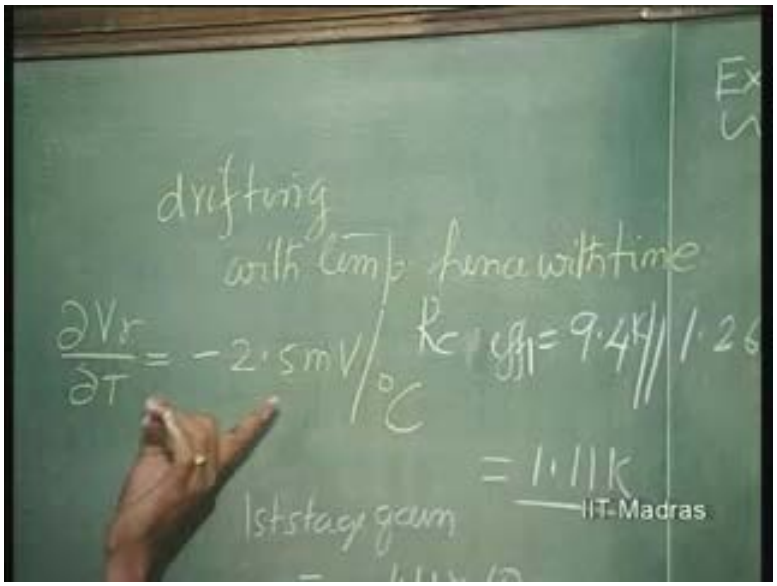


And because of that, the voltage here keeps fluctuating. What does it mean? You can therefore imagine that the voltage is point 6, but there is a signal applied which is changing with respect to current. Voltage is remaining constant at point 6. Only the change of this, we can treat it as D C signal. Fortunately for us, this capacitor is not really a short circuit for that drift frequency, because this temperature variation is going to occur very slowly. That means the voltage variation with respect to time is a very slow phenomena; that is almost equal to a D C signal.

So, if you have a good D C amplifier, then we have a problem. But, we do not have a good D C amplifier here because this capacitor is going to limit the performance of this amplifier to a certain low frequency, on the lower side. Therefore, this current is changing due to the signal changing here. But, that change is not bypassed. If it is

bypassed... Let us say, I have put such a huge capacitor here. Imagine that I have put such a huge capacitor here; that, even this small change, for this change in voltage with respect to temperature and hence with respect to time, this capacitor is a short circuit. Then, this, if there is 1 degree centigrade rise in temperature, this signal will just keep jumping by about 7 volts.

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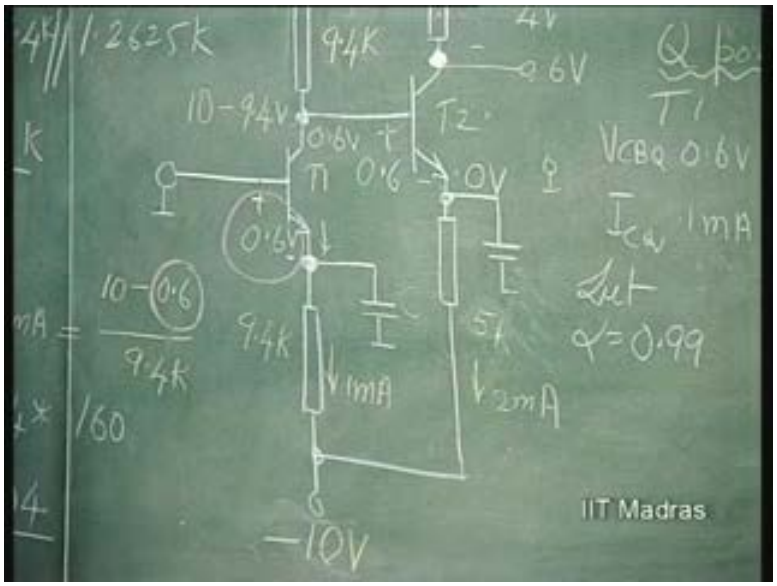


What that means is it will make this transistor go to cut-off or saturation and it will start limiting; just that temperature variation. This is an important nuisance factor in the case of what is called as D C amplifier, video amplifier. This D C amplifier is also called video amplifier.

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All these cases, this is definitely interfering with the signal because I would like to make my video amplifier or D C amplifier to operate up to the lowest signal of concern to me. That means I will put a huge value of capacitor here so that it is capable of amplifying by a large extent. So we, in design of these amplifiers, this used to be a major headache before the advent of integrated circuits. People were virtually spending hours in trying to compensate for this kind of drift.

So, this variation with respect to temperature here will cause a huge variation here. One of the greatest disadvantage of such coupling is that if there is a D C variation here, that will be amplified here if the capacitor is large; and that amplification is further amplified here.

If there is therefore decoupling, these will be contained in the local stages; and therefore, you can amplify without amplifying the drift component. But then, moment you put coupling capacitor, its lower frequency performance also is affected. If you put such huge coupling capacitors that it responds to drift, you have a gain problem. So, getting rid of this drift of offset caused due to this temperature variation is not a solution because, it is causing the lower frequency performance to become very poor.

So, this is the point where, what we call integrated circuit, came into picture. So, that is why, today we will discuss how we can get rid of capacitor and how by getting rid of this capacitor, bypass capacitor, we have also solved the problem of what? – drift. So, this lecture is an important introductory lecture to I C amplifiers or for that matter differential amplifiers or operational amplifiers, all these categories. These are I C amplifiers.

So, we will now see how to get rid of this capacitor, which is huge, if you want good, low frequency performance. And if you put such huge value of capacitor, we would like to get rid of drift. So, this is... in one shot therefore, we would like to solve both these problems.

Let us consider the common emitter amplifier; minus V E E it is connected. Let us now concentrate on this part. We would like to get rid of this capacitor.

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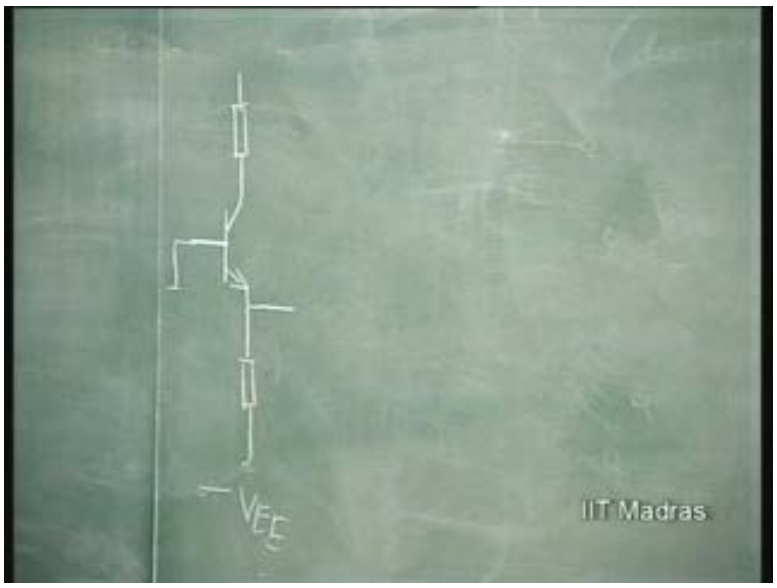


We would like to use, in space of this capacitor, components which are readily available in integrated circuits. That means transistors, diodes, resistors, in that order. If you can use... get rid of capacitor using transistors, diodes and resistors, you should do it. If you can get rid of resistor using transistors and diodes, you should do it.

So, this is the priority because in an integrated circuit, these components are available almost free; whereas, components like resistors, capacitors, are available only at a certain cost, because they take up huge amount of area. So, let us therefore see how to utilize active components in a configuration like this.

But, what was the purpose of putting this resistance? If you remember, we wanted the current to be fixed by the emitter resistance, so that the current in the circuit became equal to V E E minus V Gamma divided by R E; stable it became. This... This fixed up the emitter current and then the collector current was very nearly equal to that; so, the operating point was very stable. We do not want to affect the stability of operating point.

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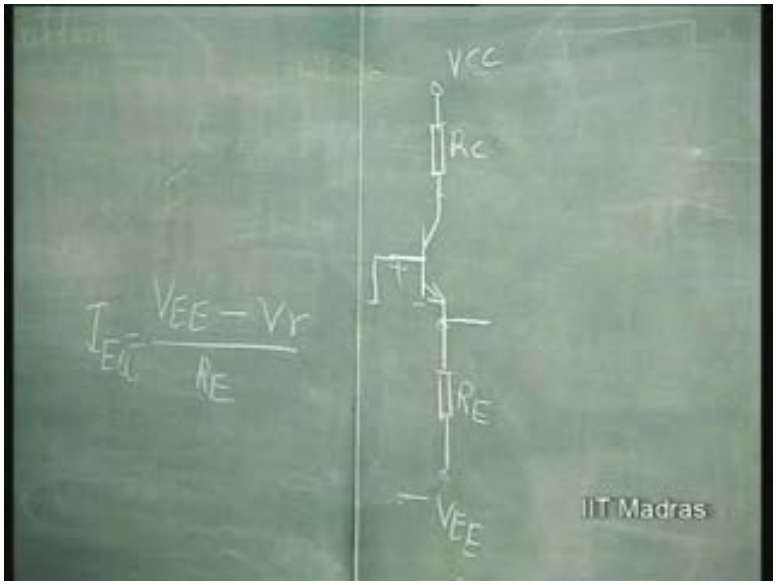


Now, I would like you to understand what is meant by stability in very plain terms. Stability of operating point, in this case, simply means that the operating point is fixed by you and not by the transistor. You decide that this shall be the collector current; and it becomes the collector current, without your knowing anything about the transistor. So, that is meant by stability of the operating point.

That means what you say gets fixed without much of a trouble; without knowing anything about the transistor parameters. If you say that you please give me the transistor parameter, then only I can give you the collector current; then, it is an unstable way of biasing. Now, this fact if you understand; now you will appreciate how it is going to be stable.

Instead of the capacitor, I would like to put a low valued resistor. Why did you put the capacitor? Because, as far as D C is concerned, the operating points should remain stable; should be predictable; but, as far as the A C is concerned, the resistance simulated by this, whatever it is, should be very low compared to this resistance R E. It is coming in series.

Now, I do not have anything that becomes very low compared to R E; but I can have a scheme which is equal to R E. What do I do? I put a diode which is forward biased in this direction. Because this is plus minus, if I ground this diode, that also will get simultaneously forward biased by the same extent as this diode. This is a diode; base to emitter junction is acting like a diode. So, I put a diode here; this will be grounded. This is grounded and this is at minus point 6. This is at minus point 6 for this diode also. So, this diode is as much forward biased as this diode.

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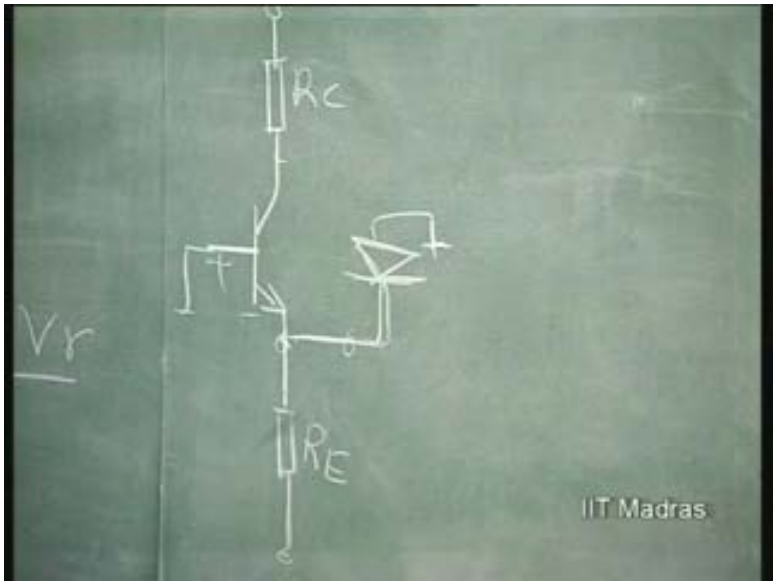


If I say that this diode in an integrated circuit is not going to be specially made for you, you are going to use the same transistor emitter base junction. So, if you are using the same emitter base junction, it is forward biased to the same extent, I E naughts of the two transistors, if they are same. Because, if they are made in the same shape, they are identical; then, this current and this current will be the same. This current, if it is I, this current also has to be I because they are identical. This is possible only in integrated circuits. If you try to put one transistor discrete, another discrete transistor belonging to the same type, this does not occur; because even if they are of same type they may not have the same I E naughts.

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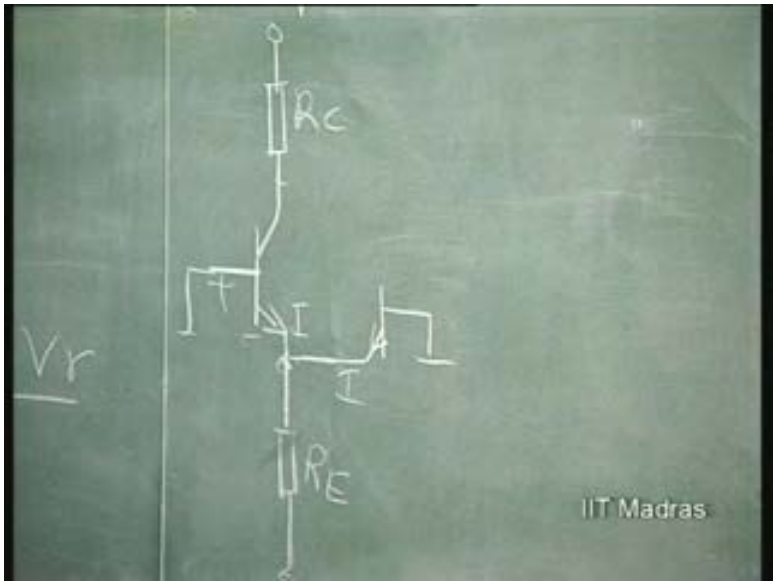


But it is highly likely that when they are made in the same wafers subjected to the same process conditions, I E naughts are likely to be fairly equal. If such is the case, these Is will be very close. If such is the case, then this current is going to be twice I because I, I, flowing here.

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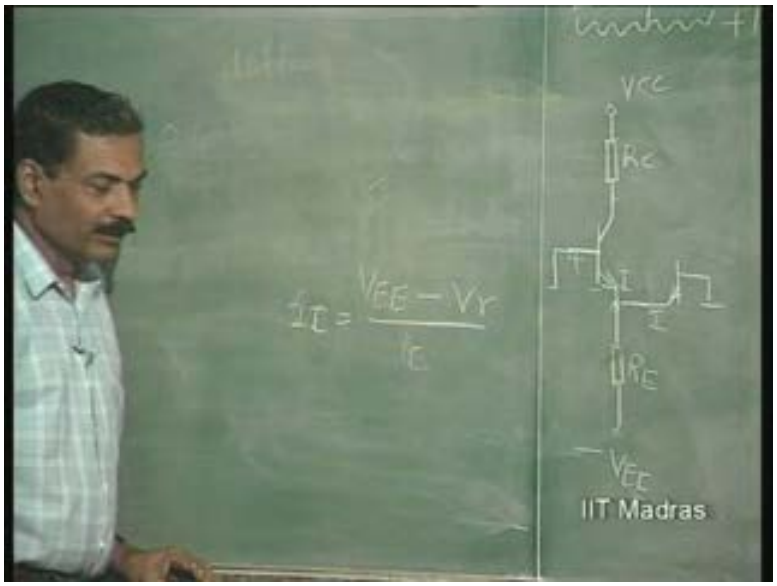

So I is going to be still predictable. It is V E E minus V Gamma by 2 R E.

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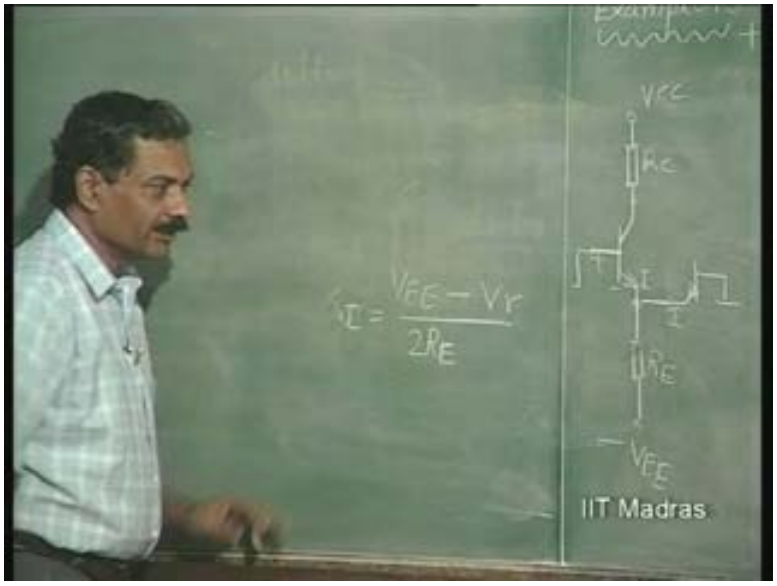


That means it is as stable as before. The reason that it has remained stable is primarily because these two transistors can be assumed to be having identical characteristics. This kind of design has become very popular in integrated circuit making use of, exploiting, identical characteristics for your design. So, these two are now operating at the same current; therefore, operating point is fixed.

Now, what is the effective resistance from here to ground? What is the resistance from here to ground? Earlier, with capacitor, we could have made it a short circuit compared to small r e. Now, it is not a short circuit. But remember, it is r e whether the frequency is high or zero, very nearly D C; that, the capacitor was never capable of being simulating. Capacitor was a short circuit only above a certain frequency; whereas this, by introducing this diode here which is simulating a low impedance to ground, we are extending the frequency range almost up to D C. That means this is suitable for video and D C application straight away; this arrangement of bypass.

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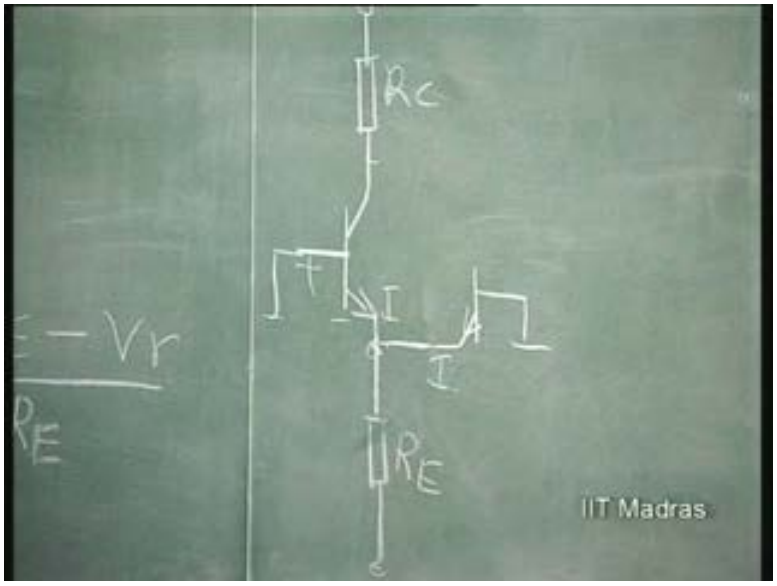


Now, let us see. Obviously, we want this current to be exactly identical at all times. If such is the case, we should treat this fellow with as much amount of respect as this fellow. What it means is that the collector voltage applied here is zero. I mean, collector is kept hanged here. This current is also, to a first order approximation, influenced by the collector base voltage. This is what is called as what? - Early effect, which we discussed.

The collector voltage also has some influence on increasing the emitter current. That is because of the reduction in base width and consequent increase in Alpha to closer value to 1. So, we would therefore connect this also with the same value of R C to the same D C, so that the voltage, reverse bias voltage, for both the transistors remain the same.
Now you can be, for sure, saying that these two currents will be exactly identical because this is nothing but a symmetric circuit.

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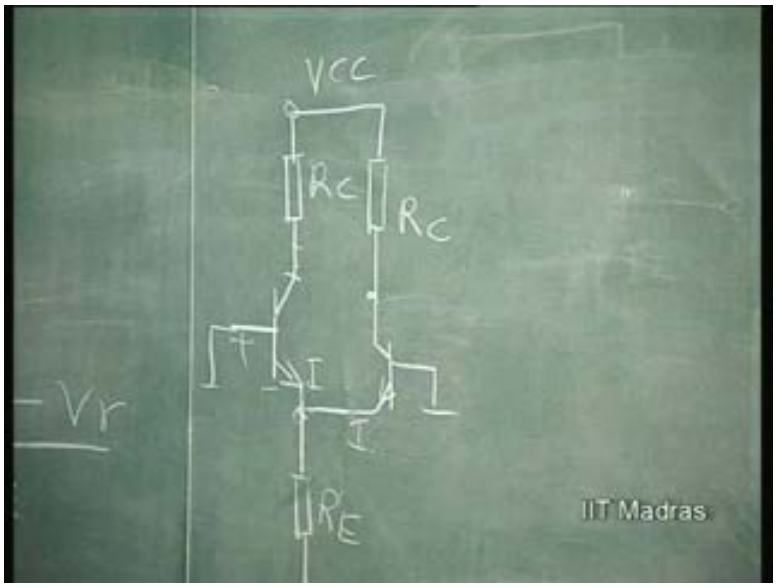


So, you can see, therefore, redraw the circuit. This is an absolutely symmetric circuit. The two transistors are identical and the two collector resistors are the same. This is called what? – the differential amplifier.

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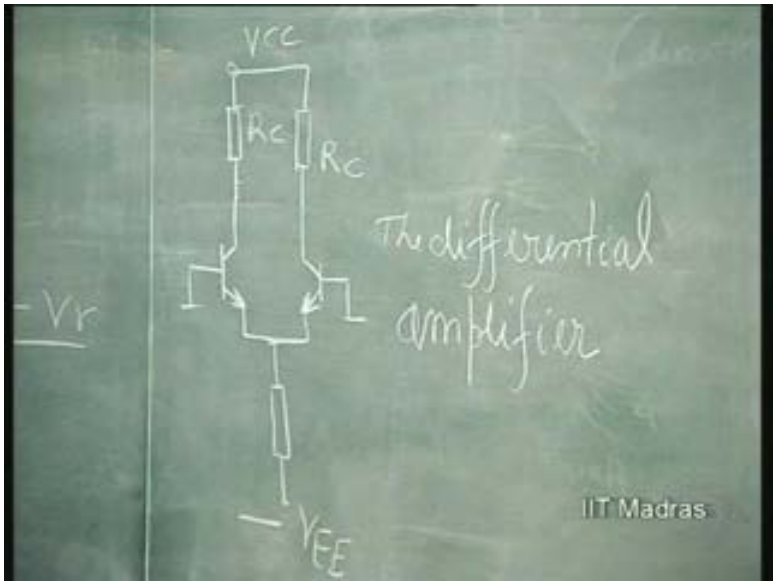


So, let us now again assert what we have understood earlier. I wanted to get rid of the bypass capacitor because the capacitor is the biggest sized element in the present day

microelectronics circuit. And this capacitor had to become bigger and bigger, the lower and lower, the lower cut-off frequency I demand. And therefore, if I use an active element here to simulate this effect, what is effect I have simulated? I have lost to a certain extent. It was not capable of making it an impedance of the order of R E by 10. It is making it R E. That means I am losing certain amount of gain.

How much? If this is R E and this is also R E, I am now reducing the gain by R. Earlier, gain was g m R C. Now, the gain is g m R C by 2; because this input voltage is shared between this and this. So, the earlier gain was g m R C, let us say this is. This gain I am talking of is with respect to collector to ground, single ended gain. So, this gain became, became g m R C by 2.

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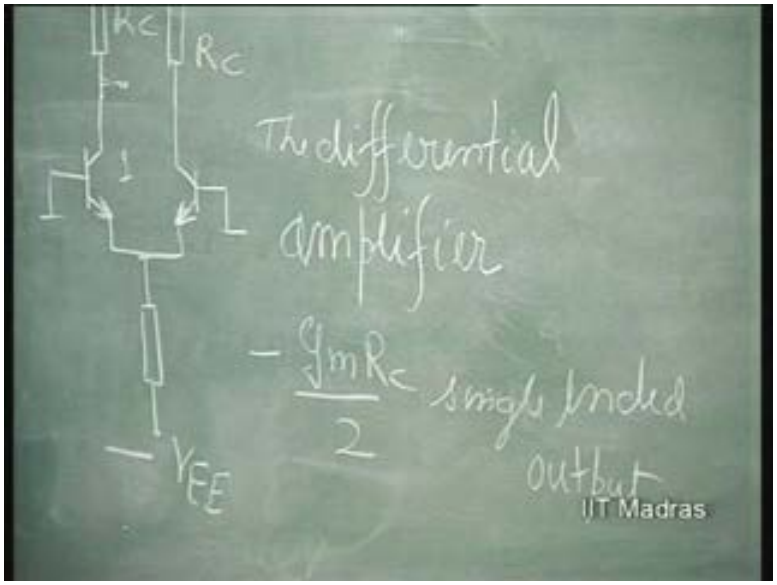


Once again, why did it become g m R C by 2? This input voltage was coming directly between base and emitter earlier because of the capacitor. Now it is shared equally between this base and emitter and this base and emitter. And, if the operating currents are same, I, I, the REs are the same; and therefore, this will be having half the input voltage. This will be having half.

So, in case I apply a voltage v i here, v i by 2 will come here, v i by 2 will come here. So, that is it. So, the gain of this is minus g m R C by 2. But, that is not of consequence. Let us see what happens. What exactly happens? When I apply v i, this voltage is going to go above the quiescent of this V B E Q R by some amount. This will go below the quiescent because this will add on to quiescent; this is plus minus this way. That means this will get subtracted from the quiescent. This current will increase by some amount; this current will decrease almost by the same amount.

So, if this voltage increases by some amount, this voltage will decrease by almost the same amount. So, instead of just forgetting about this, I can take the output from here also which will give me an output of g m R C by 2 into v i. This is g m R C by 2, but minus. Thus, therefore, this is giving me inverting input. This is giving me non-inverting output. Inverting, non-inverting. Therefore, if I take the differential output, how much do I get? I will get the same old stuff – g m into R C.

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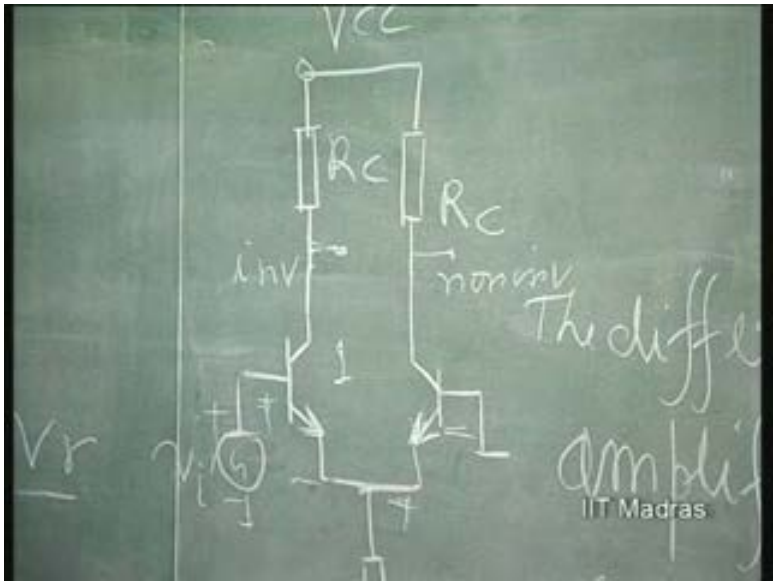


So, by using a differential configuration, I have solved a number of problems without losing anything at all in terms of gain. So, I got back my g m R C gain of the common emitter amplifier even in this. But, what I have gained is enormous. This is a D C

amplifier in the true sense. Now, if V B E of this transistor changes by minus 2 millivolts per degree centigrade, V B E of this also changes by same amount; and are effectively... there is no change in the input voltage because of temperature variation of V B E. That means there is no change in the output voltage because this is going to appear as what is called as common mode voltage to this.

If this voltage V changes by some amount, this voltage also will increase by the same amount; effectively, there is no differential voltage change as far as temperature change of V B E is concerned. And therefore, this voltage is not going to drift.

This is an important contribution in 1960s in terms of designing amplifiers which became drift free. This was such a headache earlier, prior to integrated circuits; that an amplifier used to cost the heavens. Because of this kind of drift, people had to design some engineer schemes to get rid of the drift. That means the op-amp, which is a high gain amplifier, used to cost a lot. But with this simple technique of the technology presented the possibility of fabrication of identical components; that made it possible to realize a differential amplifier which is drift free.

So now, we have solved two problems just by one solution. That is, using what? – a differential amplifier in place of common emitter amplifier. Therefore, there is no cause, no reason, for you to ever use a common emitter amplifier, when you have the differential amplifier, which is superior to common emitter amplifier, available at the same cost. Therefore, you should never use, in future electronics, common emitter amplifier. Every such single stage amplifier can always be converted to a differential amplifier by this means. Every such single stage amplifier which require capacitive bypass can always be converted to a differential amplifier which will not require bypass. That means you...if you want now to convert all your good old signal stage structures with bypass capacitors to I C versions or better versions, you can simply do it by converting it into differential amplifiers.

So, we will see what happens to a differential amplifier when we have different types of signal. Now, this structure is important. It is a symmetric structure. So, it acts, it behaves differently for different types of inputs.

What are these inputs I am talking of? Any two signals given to this, V i 1 and V i 2, can always be given as V i 1 equals equals V i 1 minus V i 2, which is called the differential signal component, divided by 2 plus V i 1, minus V i 1... So, let us see. This, we will call it as plus; this as... So, this is what is called V i 1, common mode signal, which is V i 1 plus V i 2 by 2. This is called common mode; what is common to both the signals. That is common mode.

This is, this V i 1 minus V i 2 is definitely V i d, we will call it. This is, we will call it V i c. This is called differential mode signal.

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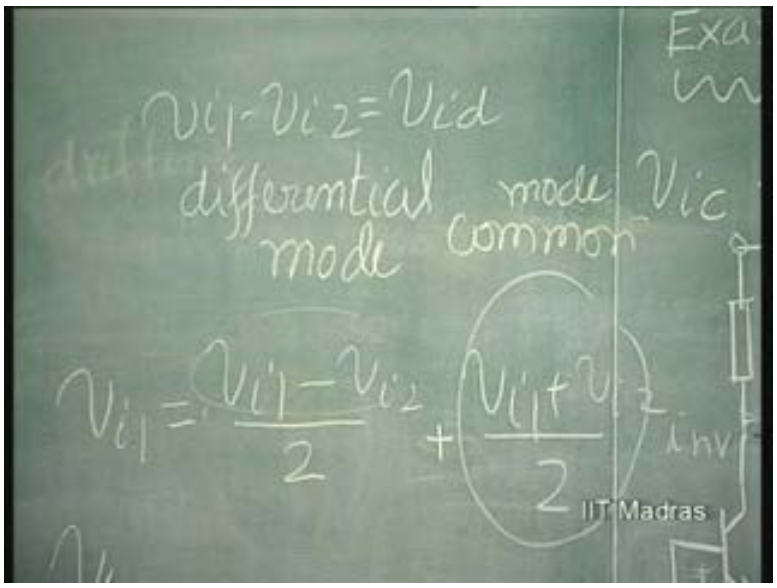


How will you write this then? This will be V i 2 minus V i 1 by 2 plus the same same component. This is something common.

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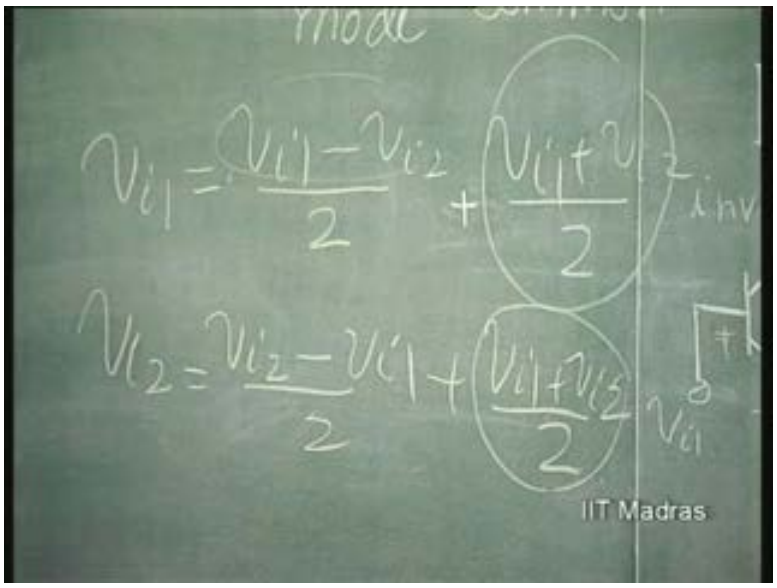


As an example, let us see. V i 1 equal to 1 volt. V i 2 equal to point 9 volts. The differential signal is V i d, which is point 1 volt. The common signal is 1 point 9 divided by 2 which is point 95. So, I can write therefore, V i 1 as equal to point 95 plus point 1 by 2. That is 1 volt. And V i 2 as point 95 minus point 1 by 2. So, this is a way of representing the signal.

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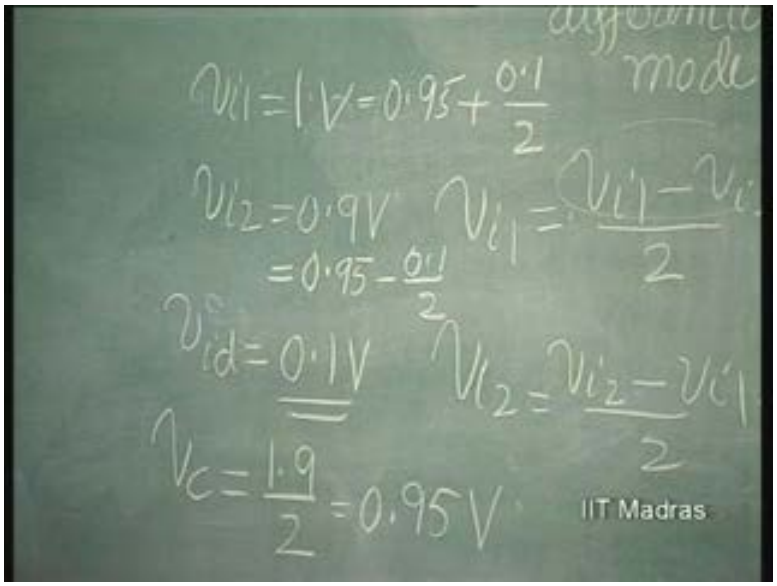

A differential amplifier should only respond to differential signal; it should not respond to common signal. A differential amplifier should respond only to what? – V i d. That means its differential mode gain should be as high as possible; but its common mode gain should be strictly zero.

Now, how to evaluate these two gains separately. This, therefore, is better than what? – common emitter; because common emitter had no such nice property of separating out the common mode from differential mode. Because of this symmetry, we will see that this analysis can be easily carried out by splitting this network into simpler networks for differential mode as well as common mode. Let us therefore do that.

This is a symmetric network. So, we will now apply not V i 1 because this is linear; we can apply superposition theorem. So, if I have V i 1 and V i 2, I can apply V i 1 first and make V i 2 zero; find out the output; make V i 1 zero; apply V i 2; and find out the output; and add the two outputs. Or, I can split V i 1 and V i 2 into separate components and use these components to excite. That is what I am going to do. V i 1 has been split into two components. V i 2 also. So, I will apply first, the common mode voltage; find out the output; and then apply differential mode voltage; and then find out the output; and then add.

So, this is V i c. This is V i c. Now, you see a perfectly symmetric structure here. R C, R C. V i c, V i c. R E. So, what does it mean? This particular potential, you can call it... Let us say, V whatever it is. It may be different from V i c, V.

And this current is going to be, let us say, v, minus V E E, minus minus V E E, v plus V E E divided by R E. Is this clear? V plus V E E divided by R E. What about the two currents here? They will be...because it is symmetric, this is V i c, this is V i c; this is single current component. They will be equally divided. That means the two currents here can be V plus V E E by 2 R E, V plus V E E by 2 R E.

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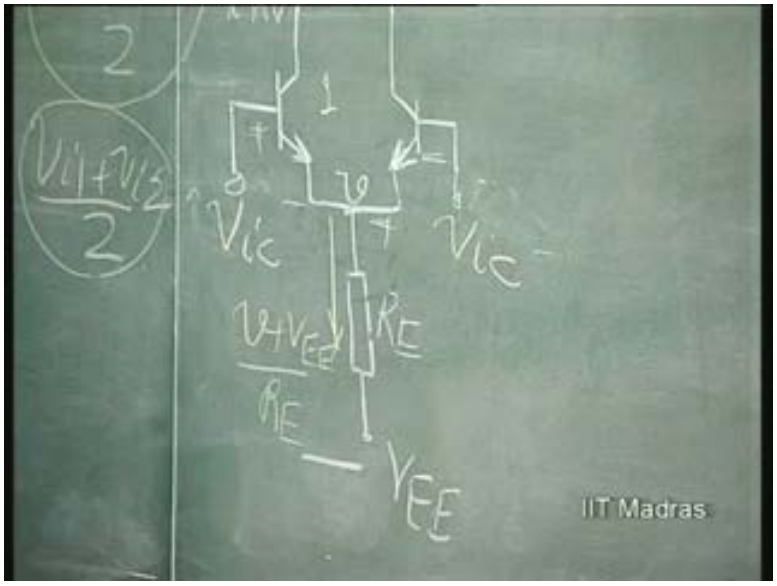


Is this clear or not? So, that means I will put down 2 R E, 2 R E; because 2 R E parallel 2 R E is the same over here. I have not done anything. So, the current in this is V plus V E E by 2 R E. This one is also V plus V E E by R E. What can I do with this short here? This is V plus V E E divided by 2 R E. This also is V plus V E E by 2 R E. This current, this current are the same.

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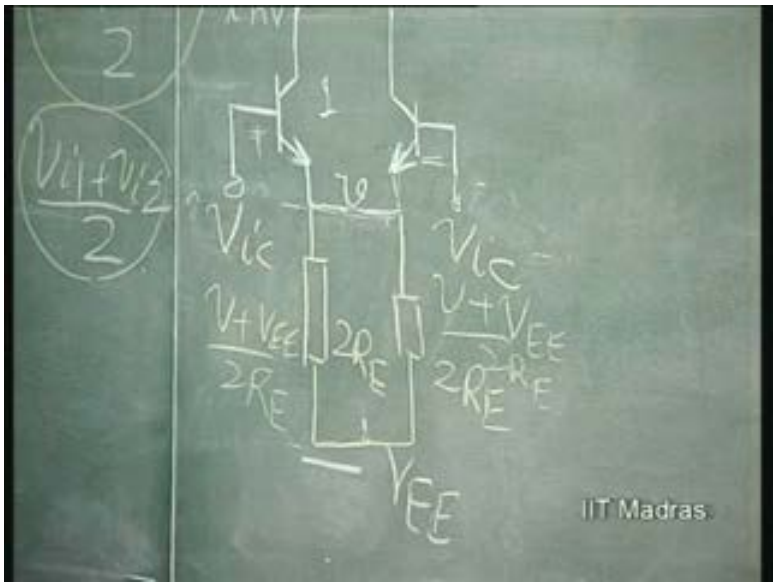

There is no current in this and this voltage across it is zero. So, I can keep it open or short. It does not make any difference. Kirchhoff's law is not violated. Have you understood this? Because the current in this is zero and the two potentials are same, I will therefore say this is V, this is V. Nothing has happened. I can say. Now therefore, they separate themselves into two identical circuits, which are circuits which we have analyzed earlier using single transistor. So, the differential transistor pair can be split into two single transistor circuits for common mode voltage in this following fashion. Only for common mode voltage, this is valid.

So, let us therefore see this circuit and this circuit. The only difference is, instead of R E which you should have taken for the common emitter, you should take R E plus 2 R E. Wherever small r e was there, replace it by r e plus 2 R E. Rest of analysis is same as that of what? - common emitter amplifier.

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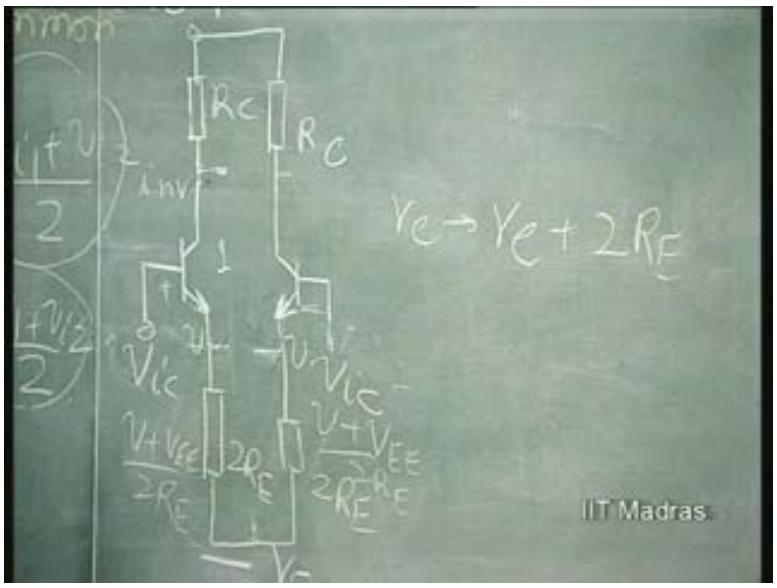


That means what is the g m of this structure, single structure? Earlier it was 1 over small r e. Now, it is 1 over small r e plus 2 times capital R E. That means g m is drastically reduced because capital R E is huge compared to small re; and therefore, g m of this stage is drastically reduced for common mode gain.

What will be the gain? This into...this is the g m. This into R C; g m into R C. So, R C divided by r e plus 2 R E is the gain. This is always called... You can forget this r e. This is always called the common mode gain.

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It is the same for both. If it increases here, it will increase here also by the same amount. Therefore, differential common mode voltage is always zero in a symmetric circuit. Differential common mode gain in a symmetrical circuit is always zero.

But in practice, these may not be so identical. Therefore, we should compare the individual gains. These themselves must be made to go towards zero; and then, if there is a mismatch, the differential things will still be closer to zero. So, a measure of common mode gain is always done for single ended output because differential output can always be made equal to zero, artificially also. By choosing R C different, you can make it equal to zero.

So, that is not a meaningful solution. Meaningful solution is, without making any adjustment, it should be very low. Adjustment means personal attention. It means cost in integrated circuits. So, without making any adjustment, it should have excellent

performance; and therefore, this has to be made very low; which means R E has to be very large, capital R E has to be very large.

So, this is the basis of evaluating common mode gain. In the next class, we will learn how same, similar trick can be adopted to analyze the circuit for differential mode signal.