Analog Electronic Circuits
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Lecture – 61
Multi-Transistor Amplifiers: Cascode Amplifier (Part A)

Dear, students welcome back to our NPTEL online certification course on Analog Electronic Circuits, myself Pradip Mandal from E and ECE department of IIT Kharagpur. And today's topic of discussion, it is Multi - Transistor Amplifiers in fact, this is continuation of our previous discussion.

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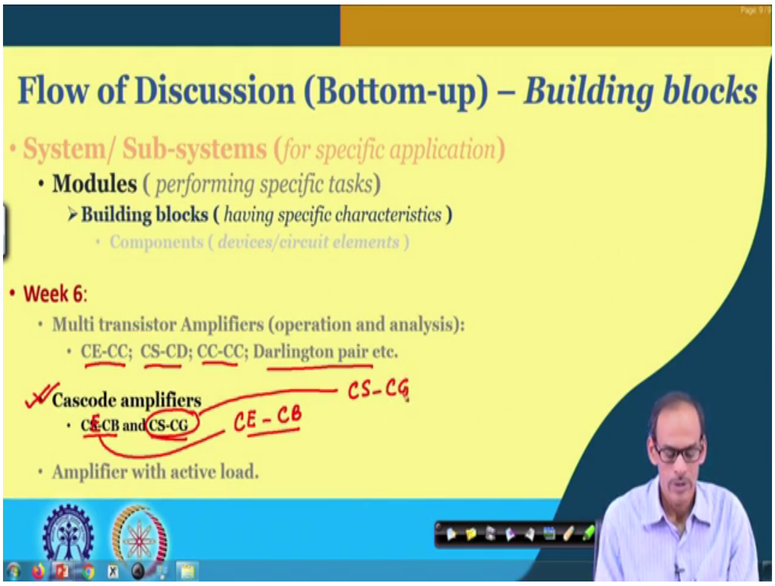

Now the plan overall plan if you see according to our weekly plan so far we have covered CE – CC; CS - CD and CC; CC; Darlington pair etcetera both theory as well as numerical examples. And we are going to discuss about Cascode Amplifiers which are essentially I should say CE this should be CE, CE followed by CB and CS followed by CG.

So, I should say this is combination of common emitter amplifier with common base. So, this is BJT version and this one is a MOS version common source followed by common gate.

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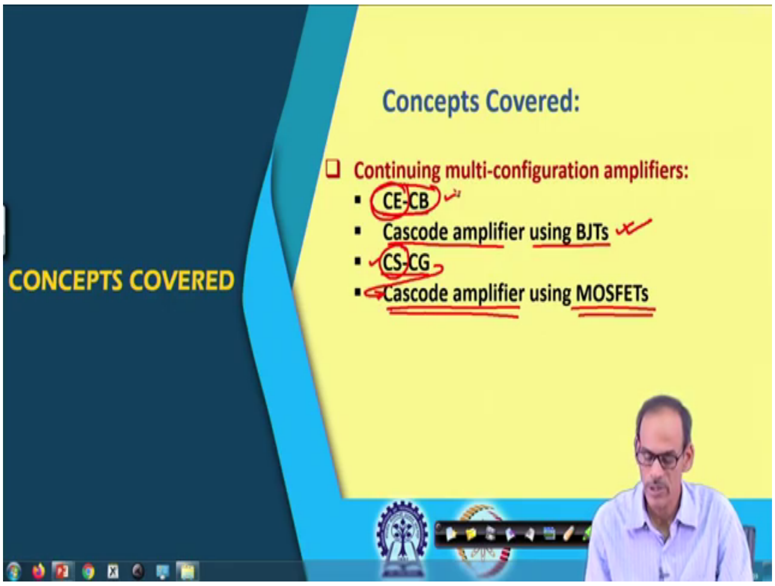

So, the concepts we will be covering in this lecture is the following. So, we shall start with CE followed by CB and in fact, with appropriate modification. It gives us a relatively simple circuit configuration which is commonly known as cascode amplifier so, that amplifier we will be discussing in depth. And then this is a course with using BJT. So, likewise we do have cascode amplifier using MOSFET transistor and, but prior to that since it is essentially coming from a common source followed by common gate.

So, we shall start with common source followed by common gate configuration and then we will simplify to conclude to cascode amplifier using MOSFET. I like to say that you might have observed that if we consider simply common emitter amplifier, its gain is typically quite high more than 100. On the other hand if I consider common source amplifier it is gain it is not so high. So, we must be having some alternative for particularly for MOSFET version otherwise that circuit may not be really much of an use. And this cascode amplifier is one of the configuration in a MOSFET amplifiers which is essentially helping to get the higher gain.

So, may not be the cascode amplifier may not be very popular in in the in the domain of BJTs amplifiers, but it is quite popular in the community of MOSFET. So, anyway both the circuits we will be discussing. So, let us see first the CE and CE followed by CB and then cascode using BJT.

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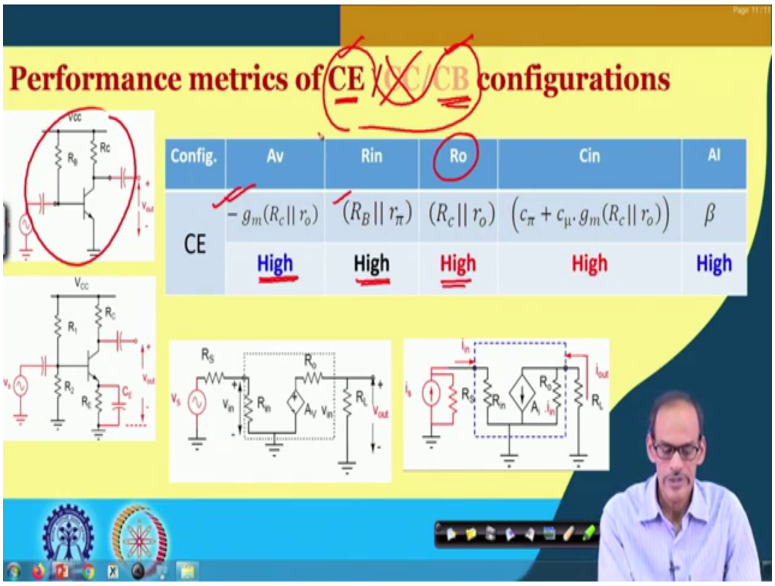

So, to start with you may recall we made a summary that a different performance matrices of CE amplifier. So this is the basic CE amplifier configuration and then we also have a different performance matrices and their expressions and qualitatively we said that some of them are high, some of them are not so high or whatever it is and in fact, even though R o it is high it is not good for voltage amplifier. So, those kind of discussion we already made. So, likewise we also have discussion related to a common base, common collector, this part we already have discussed so we will not be covering now.

So, we need to basically revisit this important property of CE and CB to motivate ourselves that combining CE and CB it is giving us a better performance. So, this is what the performance summary of CE amplifier, likewise we do have the performance summary of a common base amplifier.

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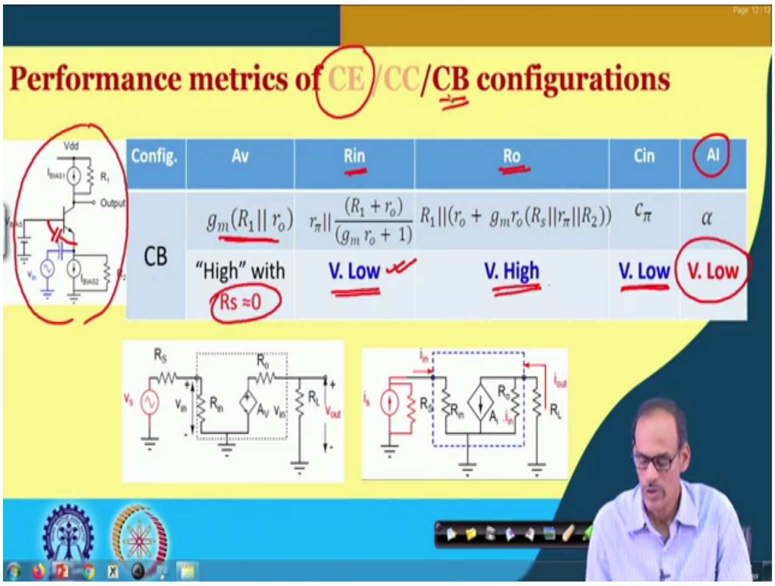

So, this is the corresponding circuit configuration common base circuit configuration and you may recall that it is voltage gain it is quite good, but we assume that the signal source resistance is 0 and then its main property here it is that input resistance it is low, as a result it is input port it is not really good for voltage feeding. So, we will see that, but then of course, this property it is helping to make the port suitable for current signal feeding. On the other hand the output resistance of the amplifier it is very high so, that also makes the circuit suitable for current mode signal at the output port.

So, then also it is input capacitance its a low namely only the [vocalized- noise] the C pi and the current gain on the other hand it is not good. In fact, it is theoretically it is less than 1 though it is very close to 1. So, now, if we put say performances of CE and CB together to construct a new configuration called CE CB, then let us see what kind of performance we do expect yeah.

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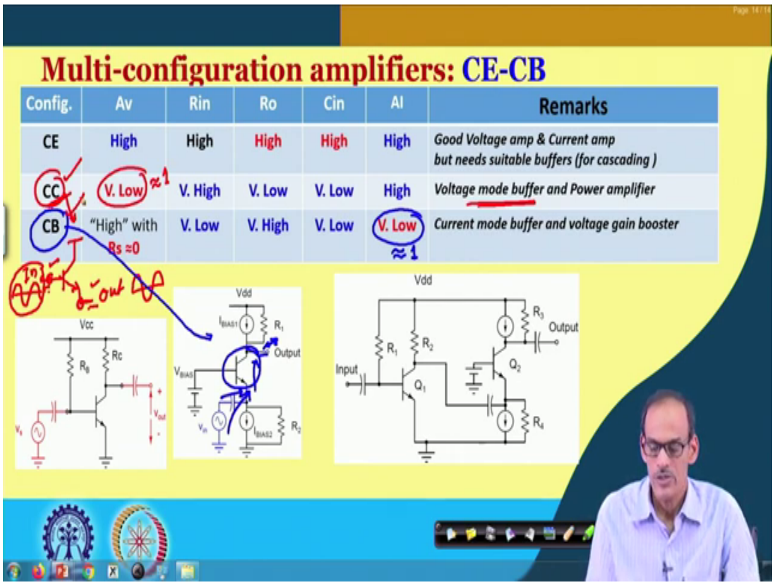

So, this is the [vocalized- noise] summary and as I said that at present we are interested to focus on CE and CB, this we may not be concentrating. And our main purpose here is of course, CB can be utilized for current buffer, but today we are going to discuss more like application to boost the voltage gain. Before I go into that I must say one important point I missed it whenever we have discussed about the CC amplifier we have seen that its voltage gain it is slow in fact, it is very close to 1.

And whenever in CC stage whenever we have given the input at the base and we are observing the output here and we have seen that the gain it is close to 1 and the phase also it is a phase shift is also 0 degree. So whatever the input signal you are giving at the base in fact, almost to the same signal it was coming to the emitter. So, that is why this CC it is having other name which is also quite popular it is referred as emitter follower. So, which means that emitter node it is following the base node.

So, the CC stage whenever we are using as a voltage buffer it may be referred as emitter follower. So, likewise when you talk about say common base configuration and their the current gain it is approximately 1. So, whatever the input current we give so, we do have the CB stage here, whatever the input current we give here almost the same current we do get at the output.

So, this circuit CB circuit it is the other name of CB circuit it is something called current conveyor. So, it coveys this current from emitter node to collector node almost with the same magnitude but the base basic purpose here it is that impedance at this port at the emitter port it is quite low whereas, impedance at the collector port it is high. So, this current conveyor basic purpose of the current conveyor, it is taking the or rather taking the receiving the current at the low impedance port and it is delivering the current at the high impedance port.

On the other hand the complimentary things are happening for voltage follower or I should not say voltage follower emitter follower, the input voltage it is getting conveyed from the base terminal to the emitter terminal. And so, here it is while it is conveying it is input port resistance it is high and then it is delivering the signal at the emitter where the output port resistance it is quite low. So, these two configurations [vocalized- noise] common collector and common base they do have their dual property and they are essentially used as voltage mode and current mode buffer respectively ok.

So, now coming back to whatever we are about to say the application of the common base to enhance the circuit gain. So, we will be seeing that how this this will be enhancing the gain.

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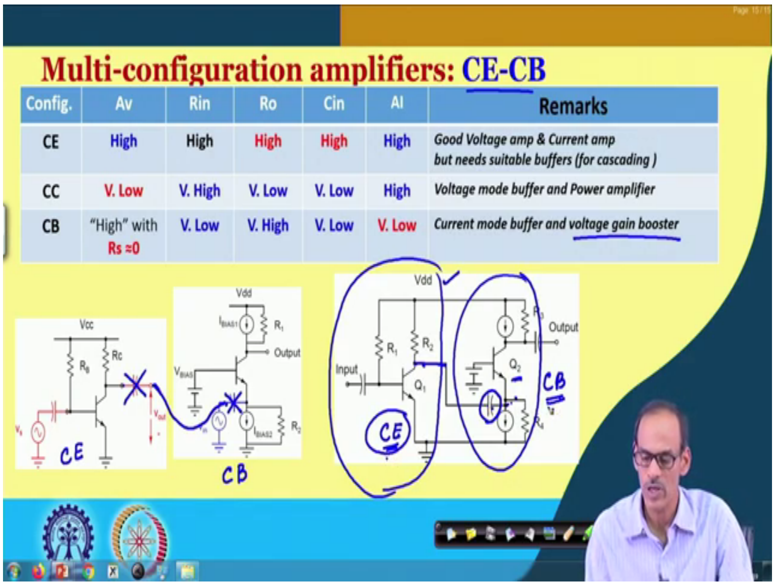

So, we do have the CE stage here and then we do have the CB stage as the name suggests that the output of the CE stage we like to feed it here and if we are feeding the voltage here and there may be a different possibilities, we may remove the capacitors or at least we can say that we can keep only one capacitor. So, if I am putting one capacitor here, then the corresponding configuration becomes like this.

So the output of the CE stage namely collector or Q 1 it is and getting connected to the emitter of Q 2 through a DC blocking capacitor. So, that the operating point of the second stage it is it should not get affected by this circuit so that is the purpose. Now we will see that in fact, the condition of the [vocalized- noise] of the DC operating point of CE and the CB stage is in this connection they are remaining isolated, but then of course, the signal it is going from the first stage to the to the second stage at its input.

Now we can modify this this connection without really putting this capacitor here, but then of course, we should be having a meaningful connection. And in the next slide, we will be discussing about how we can cleverly directly couple these CE and CB together and that gives us the new configuration called cascode configuration.

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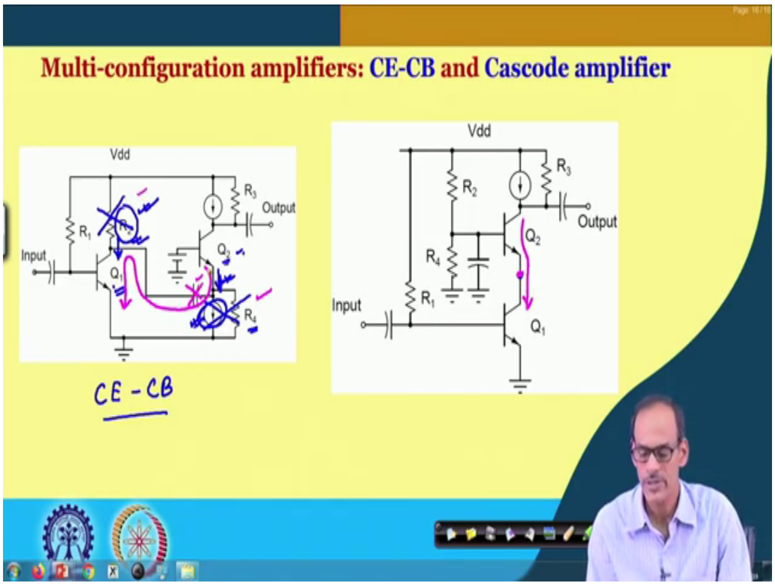

So, I should say that cascode circuit, it is essentially CE-CB, but I should say it is simplified or modified version. So, here we do have the [vocalized- noise] CE-CB amplifier whereas, if you see here this Q 1 in fact, whatever the DC voltage you do have here that may be useful, I should not say DC voltage rather I should say the current. So, if you see the Q 1, it requires it is collector current and that current it is getting supplied by this R 2 and on the other hand the emitter current, DC current of Q 2 need to be consumed by this circuit.

So, we can say that basic purpose of having this R 2 and this I whatever the I bias here maybe along with this R 4, it is essentially to bias Q 1 and Q 2 respectively. Q 1 it demand some current to become entering to it is collector and Q 2 it is expecting it is emitter current need to be consumed by somebody else.

So, what you are doing here it is, if we remove say this part and if you remove this part and then if you remove the DC blocking capacitor also. Then what you can say that the emitter current of Q 2 can enter into Q 1 and; that means, support this bias requirement of Q 1 and that is what exactly it is happening here. So, the emitter current of Q 2 it is entering into Q 1 as its collector current. So if here at this node in fact, instead of blocking their DC current and [vocalized- noise] DC voltage we are directly rather utilizing the opportunity here. So, that we can get rid off the bias circuits here we can we can get rid of the capacitor, but then of course, you have to see whether everything is falling in place or not.

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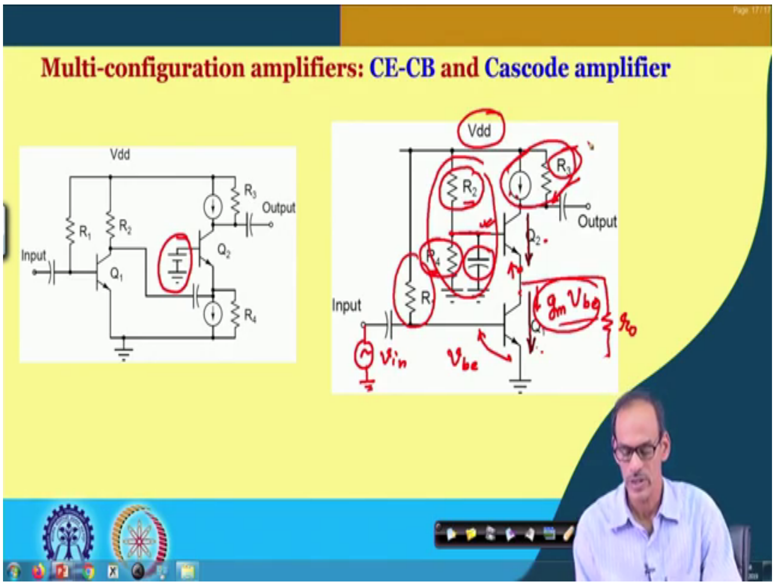

So, what we said here it is DC current of Q 2 it is supplying require DC current of Q 1, on the other hand we are feeding the signal at the base of Q 1 and we are expecting that this V in signal it will be producing V be signal V be that supposed to be producing a current here signal current and that is gm into that V be. So, along with the DC current here of course, we do have the signal and this this signal should be successfully reaching to the collector or transistor to which we call it is the primary output port.

So this current this current source of course, it is having it is own conductance called r o and then this current supposed to be successfully entering into this circuit. So, we will be going through detailed analysis for that, but then just I like to say that instead of having this ideal bias here. Practically we do have a potential divider constructed by R 2 and R 4 from the main supply V dd here, which generates a DC voltage. Now it is also having Thevenin equivalent resistance which is R 2 and R 4 in parallel and we like to keep the base node of transistor 2 to AC ground and that is done by this capacitor.

So, in summary we require the gate bias for Q 2, we require gate bias DC bias for Q 1, but then emitter bias of a transistor 2 and collector bias of transistor 1 they are eliminated by making them helping each other right. And of course, at the collector of Q 2 we do have the biasing arrangement I bias we do have maybe that bias circuit is having some finite conductance represented by R 3 there ok. So, that is how we got the cascode amplifier and as I said it is a special kind of amplifier and it is having higher gain and to appreciate or to really acknowledge that let we do the detail analysis of the cascode amplifier.

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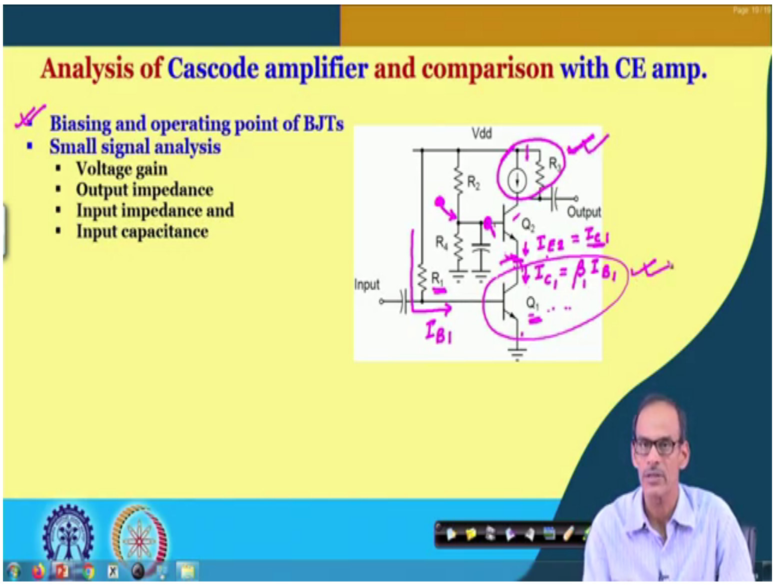

So, we do have the yeah. So, here we do have the cascode amplifier and let us see it is analysis, so, biasing and all we have discussed. So, let me yeah. So, we do have this biasing and it is operating point of those BJTs it has been discussed. So, what we need to do here, it is the R 1; it is the value should be set such that the I B of transistor 1 it is properly set here, which produces it is corresponding collector current I C 1 which is beta times this I B 1. And that is eventually gives us the emitter current I E of transistor 2 which is I C 1.

Now this current of course, it should be consistent with whatever the current we do have. So, as long as we make sure that this current, it is consistent with I C 1 then we do not have any problem. But, then if there is any mismatch then of course, the transistors maybe this transistor or this transistor they may be pushed into a saturated condition and that may create ill operation of the circuit. So, definitely while we are making this biasing, we need to be careful about that the current source here must be consistent with whatever the current we do have here which is set by this R 1 ok.

So, here we assume that this balancing of the current source and this current sink defined by Q 1, they are consistent and hence rest of the things are it is I should say it is taken care. But of course, one minor thing that the base terminal here of Q 2 should be set at a voltage such that after deducting, it is V be namely around 0.6 whatever the voltage you do have that should not force Q 1 into saturation.

So I should say that it is collector current should be higher than V CE sat and then plus 0.6. So, that is the required voltage here. So, the DC voltage here it should be at least 0.6 plus V CE sat maybe whatever 0.3. So, now, this voltage if it is higher than the minimum required voltage, then we do not have any problem, this both the transistor particularly Q 1 it will be in active region of operation. So, maintaining this voltage on the other hand to ensure the consistency of the operation of the circuit is not so difficult. So, I think typically that is not the main concern; the main concern is that as I said that matching this current with this current is the main concern ok.

Now, coming to the small signal analysis so, now, let us see the small signal analysis and in in the small signal analysis we do have voltage gain and then output impedance, input impedance, input capacitances, those things we can compare with what are the corresponding performance matrices coming out of simple CE amplifier. So, in the next slide we will be doing the analysis with a small signal equivalent circuit of the cascode amplifier.

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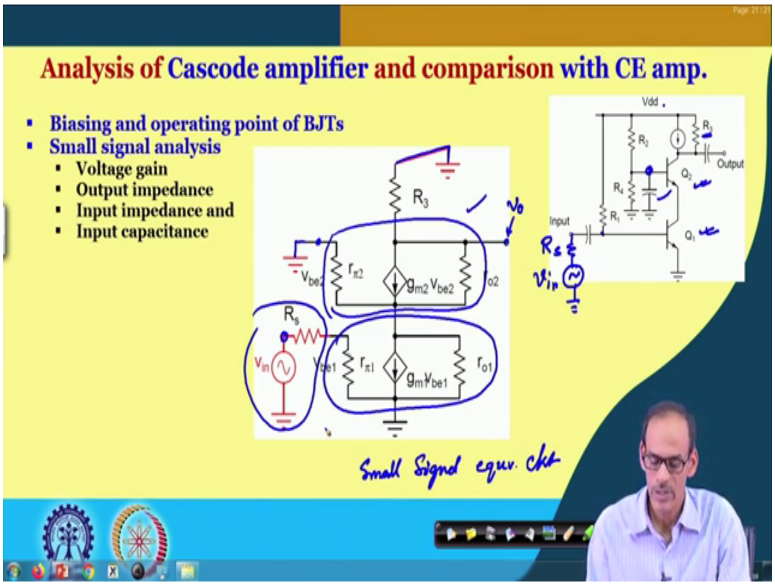

So, I think you yourself can try out, but then I have done it for myself. So, here we do have the small signal equivalent circuit. So we do have the model small signal equivalent circuit for Q 1 and then we do have small signal model for Q 2. And the base node of Q 2 it is connected to a ground through this capacitor so, we are saying that this is AC ground. Then R 3 here it is connected to DC supply so that is also connected to ground and at the input you are feeding the signal maybe the signal source maybe having source resistance. So, we are feeding the signal here is V in and the source is having source resistance of R S. So, this is the corresponding model for that.

Now so, we can then of course, this is the primary output so, we will be observing the output here. So, to get the gain from this primary input to this output we need to analyze this circuit. So, either we can analyze this entire circuit or probably we can go little intuitive way to simplify the analysis.

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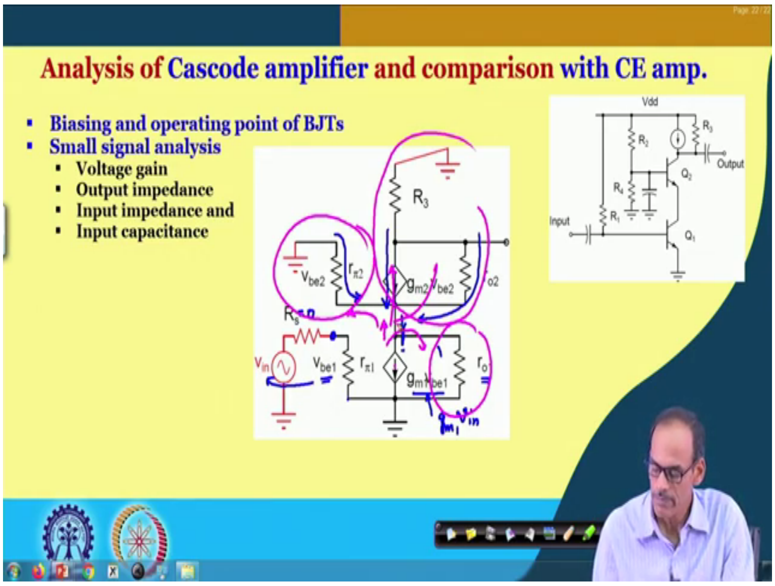

So, let us see, what is the simplification we do have for the time being; let me assume that this R s equals to it is very small. So, V in it is directly coming here and that makes this V be equals to V in. So, the voltage dependent current source we do have gm into V in here. So, this is gm 1 into V in so; that means, it is expecting that signal current it will be coming through this. In fact, this current partially it will be coming from upper side as well as it may be coming from this r o 1. So, when I say upper side it is primarily it is coming from r pi 2 as well as the combination of whatever the circuit we do have.

So either you can say that the current here it is signal current is flowing in this direction or you may say that the signal produced by this circuit it is getting injected here and then part of this is going here part of this is going here and the rest of the things it is going here and here. Now depending on the impedance offered by each of these paths, say this path, this path and this path this current it will be getting segregated.

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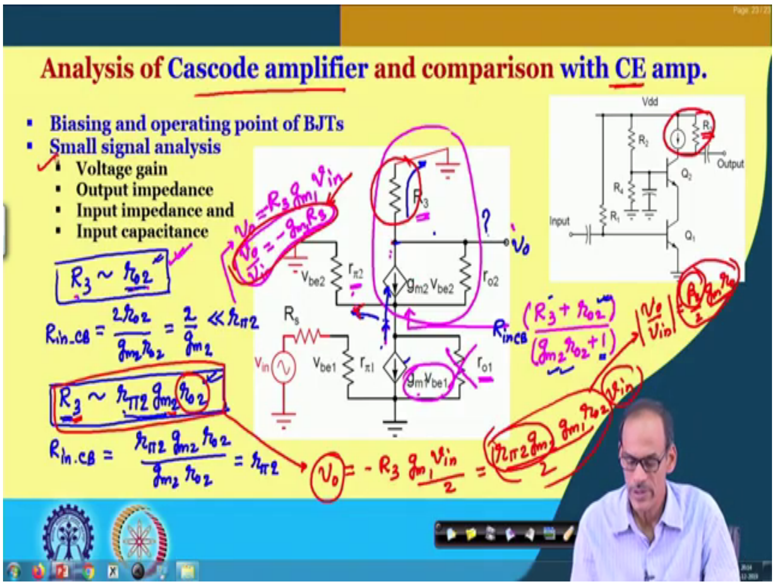

So, if you see the impedance. Now, if you look at the impedance of the main amplifier if you see this part. So, what is the impedance, impedance of this part it is R 3 plus r o 2 divided by gm 2 r o 2 plus 1, on the other hand this is straight forward this is r pi 2. So, if I say that this is the signal current it is entering and this is the resistance which is quite high compared to r pi and maybe compared to this. So, we may ignore this path. So, we can say that gm into V b e 1 is essentially coming from these 2 paths.

So, then depending on this value of this resistance of course, there will be bifurcation. So, if I consider say R 3 in the order of say r o 2 so, if I consider it is value it is in this order then this resistance; if I call R in of the common base. So with this R in CB it is say r o 2 and in the denominator we may ignore this 1 and we can written only this part so, which is gm 2 r o 2. So, this is becoming 1 2 by gm 2 and we know that this is much smaller than r pi 2. So, as long as this R 3 it is maybe in this order. So, we can say that major part of the signal it is entering into this device and then it is whatever the things it will do we will see that part.

So, on the other hand if I say that R 3 it is in the order of r pi and then let me call this is r pi 2 and then gm 2 r o 2. So if I consider that R 3 it is in this order then corresponding R in of the common base circuit it is so, compared to r o 2 this will be dominating because we do have this multiplication factor which is r pi 2 multiplied by gm 2 that is nothing, but beta of the transistor so; obviously, that will be dominating. So, we can say that this is r pi 2 g m 2 r o 2 divided by gm 2 r o 2 and that becomes r pi 2.

So, if R 3 it is in this order which is much higher than the previous case then we may say that half of the current it is flowing here and remaining half of the current it is entering there. But even then even then you may say that major part of the signal it is coming here and once or at least half of the signal it is coming there and once that current is flowing through this resistance it develops the corresponding voltage here. So, for the two cases if I consider say this case, then we can say that almost entire current is flowing here and the corresponding voltage getting developed here.

So, this gives us the output voltage which is R 3 multiplied by the signal current which is gm 1 times V be 1 which is V in. So, we can say that of course, there will be a polarity difference. So, that gives us the voltage gain V o divided by V in equals to minus gm 1 into R 3. On the other hand so, you can say that if R 3 it is in the order of r o 2 so, definitely this gain, it will be quite high depending on the value of this R 3 and the corresponding gm 1.

On the other hand if I consider the R 3 it is in this order and then only half of the current it is entering to this circuit and in this case the corresponding V o it will be the minus R 3 into gm

1 V in by 2, why by 2 that is because half of the current it is entering into this r pi 2 which is wastage for us, but then the corresponding R 3 it is quite high. So, which is r pi 2 g m 2, then we do have gm 1 r o 2 divided by 2 into V in. So, that gives this V o divided by V in it is quite high.

In fact, if you see here this part it is beta so, we can say that the corresponding gain V o divided by V in and if I particularly keep the focus on gain magnitude, then this is beta of transistor 2 by 2 gm into r naught, which means that if I consider simple CE amplifier where the gain may be in this order where [vocalized- noise] this R 3 maybe in the order of r o whereas, for this case the gain, it is higher than the CE amplifiers gain by a factor of beta 2. But then that can be obtained by considering a situation where R 3 it is much higher than a standard r o 2.

So, we may require additional circuit we may require really a clever circuit here which offers high value of this R 3. Assuming that it is possible to get that then we will be getting very good gain out of good voltage gain out of this one. So, that is the basis of this claim that the cascode amplifier, it provides higher gain much higher gain than the CE amplifier.

Now let us look into the output impedance.

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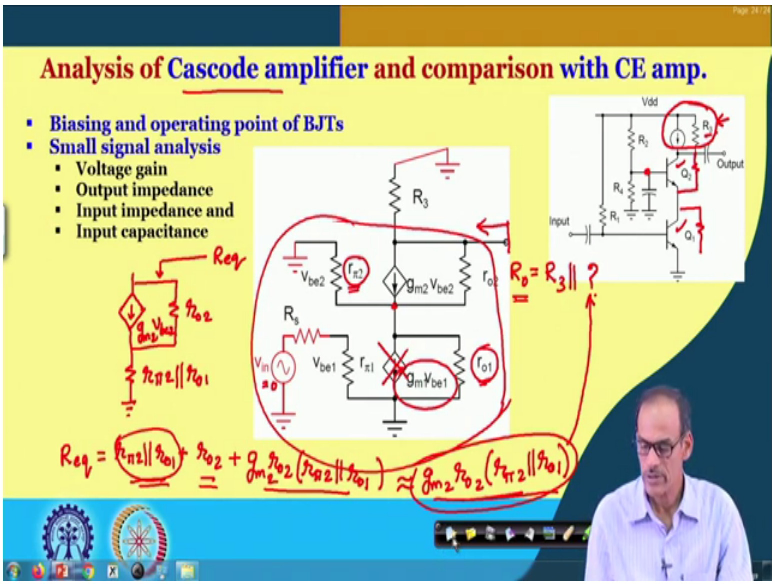

So, this is the output port and R o which is R 3 coming in parallel with whatever the resistance coming out of this entire circuit. So, if I want to know what will be the resistance of this circuit the circle circuit what it can say that this r pi 2 and r o 1, they are coming in parallel this one of course, I have to make the signal is equal to 0. So, that makes this is equal to 0. So, this part it is 0. So, we can ignore that part. So, to know this resistance what we can do? We can draw the rest of the circuit to get the equivalent resistance.

So, we do have r o 2 and then we do have gm 2 V be 2 and at this node at this node we do have r pi 2 connected to ground and also we do have r o 1 connected to ground. So, we can say these two resistances they are coming in parallel and such kind of circuit, we have seen before the equivalent resistance of this circuit you may recall that R equivalent is equal to r pi 2 in parallel with r o 1 plus r o 2 plus gm r o 2 into r pi 2 in parallel with r o 1.

In fact if you see here compared to this part and this part; this is quite high. So, we can approximate that this is gm 2 multiplied by r o 2 multiplied by r pi 2 in parallel with r o 1, which means that the output resistance coming here it is quite big and it is expression it is given here. In fact, if you see these two transistors while these two transistors are connected in series and if the gate of the first transistor, it is connected to AC ground then it is not only it is r o and this r o coming in series in fact, we do have some nice amplification here ok.

So, this kind of tricks can be utilized to make the impedance here much higher than normal r o 1 which is referred as cascode current source, later we will be talking about that in detail. So, while you are talking about cascode amplifier, this cascode terms [vocalized- noise] it may be coming while we will be you know designing this part to achieve high value of this impedance R 3. So, anyway so, that is the output impedance we do have R 3 in parallel with this and then coming to the input impedance. Let me clear the board yeah.

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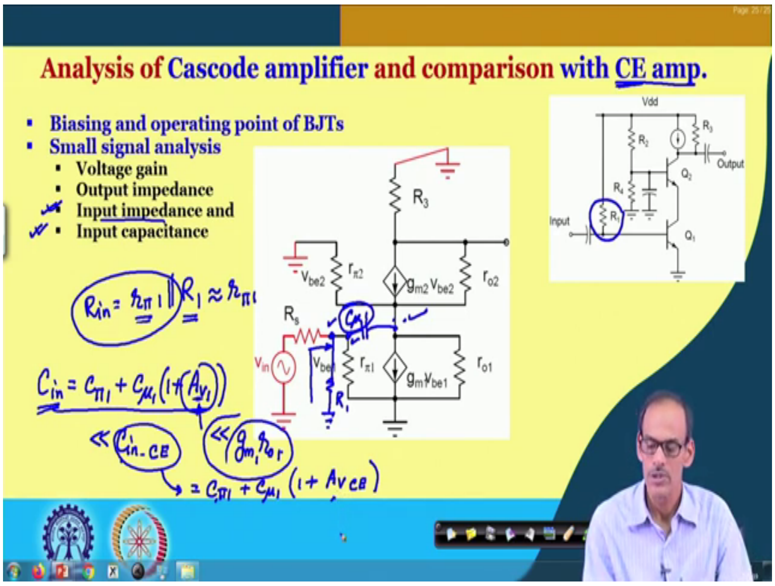

So, the input impedance on the other hand so, if you see this is the input port input impedance is very straight forward. So, R in it is same as r pi 1, but then input capacitance. So, this is very important thing. So, input impedance wise if you see hardly there is no difference compared to input impedance of normal CE amplifier. In fact, we also need to consider R 1 in parallel with that, but. So, this R 1 in this model I have not drawn you can draw that 1 also. So, typically this R 1 it is much higher than r pi 1.

So, you may consider this is approximately equal to r pi 1 which is same as the input resistance of normal CE amplifier. So, I should say there is no change in input impedance; however, in input capacitance if you see the C mu this C mu it is which is integral part of Q 1 which is breezing the base and collector terminals of Q 1.

Now from this node to this node we claim that the gain of the circuit is not very high. So as a result the miller factor coming for this C mu 1 it may not be very high. So, of course, you will be getting C pi 1 and then C mu 1 multiplied by 1 plus A V 1 gain and we claim that this A V 1 gain, it is much lower than gm 1 r o 1. So, if we if we agree with this that this is this is much lower than gm 1 multiplied by r o 1.

So, we can say that this capacitance is much smaller than C in or a standard CE amplifier, where for standard CE amplifier the corresponding input capacitance is C pi 1 plus C mu 1 multiplied by 1 plus the corresponding voltage gain of CE amplifier. Now to really acknowledge the improvement of this input capacitance namely reduction of the input capacitance, we need to establish that this gain the circuit gain here from this point to this point it is much lower than the [vocalized- noise] voltage gain of CE amplifier.

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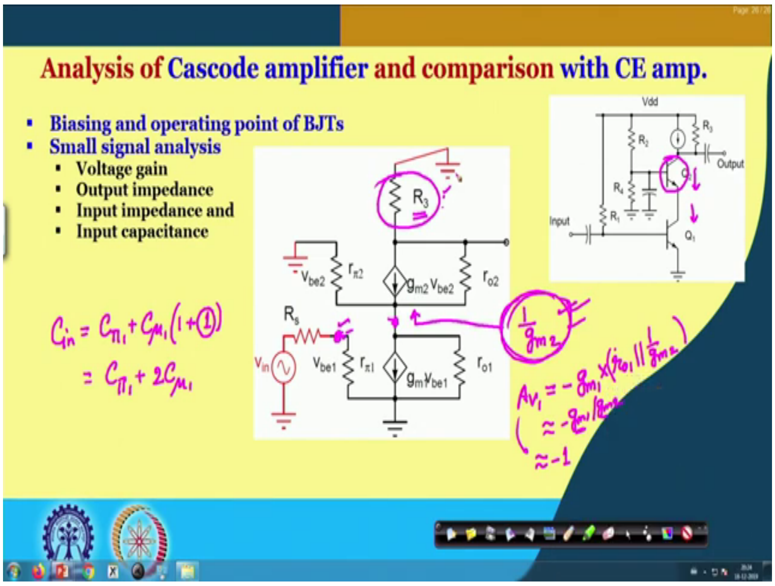

So let us see how we establish that. So, if you see this circuit if you see this circuit and if you want to know what will be the gain from here to here, we need to know what is the corresponding impedance we do have here and we have seen that based on the value of this R 3 this impedance maybe in the order of you know 1 by gm 2.

So, the voltage gain from here to here it is I should say A V 1 if I call it is A V 1 minus gm 1 multiplied by r o 1 coming in parallel with whatever the impedance. We are seeing here and that may be in the order of 1 by gm 2 ok. So, this is approximately gm 1 divided by gm 2 and since the current here and current here they are same, we can say that gm 1 and gm 2 they are same. So, further we can say that this is approximately minus 1. So, that makes the input capacitance of this circuit it is C pi plus C mu into 1 plus 1 or to be more precise C pi 1 plus 2 times or C mu 1.

Here of course, we have assumed that this [vocalized- noise] input impedance the input impedance of the cascode transistor this is referred as the cascode transistor so, it is in the order of 1 by gm 2, but we know that it depends on [vocalized- noise] it highly depends on the value of R 3. So, if this R 3 on the other hand if it is very high that may increase the increase this resistance and the consequence here of course, then the voltage gain here it will increase. So, here to here the voltage gain if it is increasing, then this factor instead of one that will also increase.

So, but then typically this gain from this point to this point it is, it is quite fair to approximate that that is gain it will be around 1 or 2 depending on this corresponding load practical load here. Let me take a short break and I will come back after the break for the MOS circuit.