Analog Electronic Circuits
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Lecture – 75
Differential Amplifier: Basic Structure and Principle of Operation

Dear students, welcome back to our NPTEL online certification course on Analog Electronic Circuit; myself Pradip Mandal from E and EC department of IIT, Kharagpur. Today's topic of discussion is Differential Amplifier and we will be talking primarily the Basic Structure and Operating Principle.

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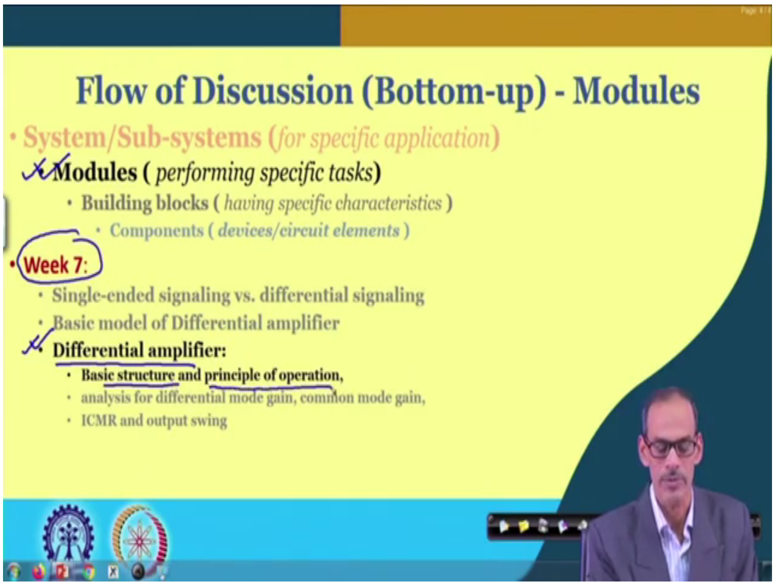

So, in our overall flow where we stand, we are in module 7 and we are talking about different circuit modules and this module particularly in our discussion today it is differential amplifier. We have given basic motivation of going for differential amplifier and today we will be talking about the basic structure, how the construction of the differential amplifier it is there and it is operating principle.

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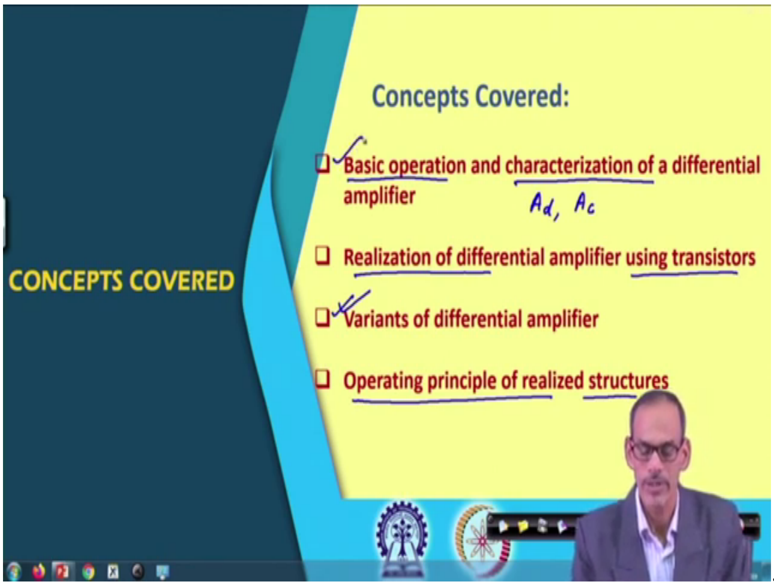

So, the concepts covered in this talk, in this lecture are the following. So, we are going to start with basic operation and then we will be going to discuss detail of characterization of differential amplifier. Namely, how we find the basic parameter values particularly, differential mode gain and common mode gain and so and so, from a given circuit.

And then we will be talking about realization of differential amplifier at transistor level. So, transistor maybe BJT or MOSFET. So, we will start with very basic structure and then we may discuss about different variants of differential amplifier, particularly the code differential amplifier. And then we will talk about operating principle of a realized structure.

So, we may consider two structures namely, one is using BJT and other one it is using MOSFET. So, let us discuss about the basic operation and characterization of differential amplifier.

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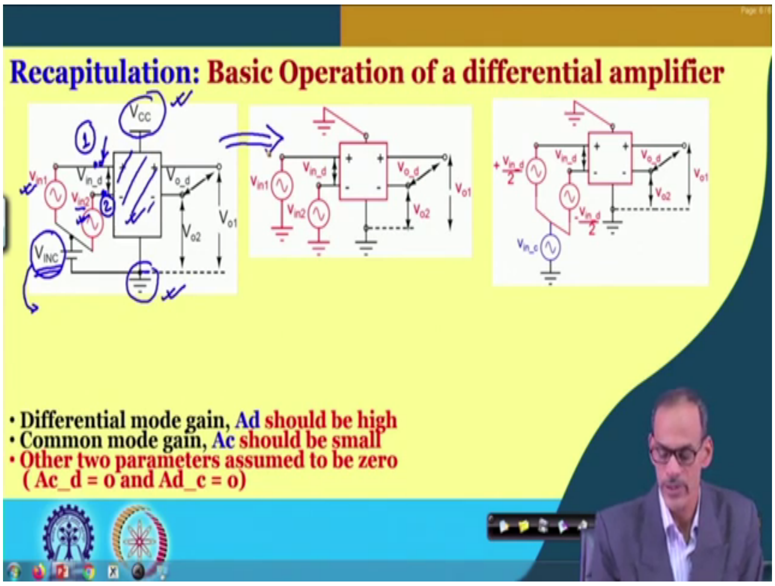

So, to recapitulate whatever we have discussed in our previous lecture we do have say this is a main differential amplifier. Where we have the power supply DC supply and ground and then at the input we do have the differential input port having two terminals 1 and 2 and at this input we are given signal or I should say voltage signal and it is having a DC part meaningful DC part and on top of that we do have two signals. One is V in 1 and V in 2.

So, these are the two signals, but we must be careful that while you are feeding the signal the voltage DC voltage at this point and DC voltage at this point should be appropriate. So, that this differential amplifier should be working properly. Since in this connection supply connection we do have only one supply namely, V cc and the common terminal is ground here invariably we need a DC positive DC voltage at both terminal 1 and terminal 2.

So, unless other unless otherwise it is stated we assume that the DC voltage at terminal 1 and terminal 2, they are equal and we refer this DC voltage at input common mode DC voltage capital V capital INC. Now if we concentrate on linearized circuit. So, here we do have the linearized circuit, once we are sure that all the transistors are in proper region of operation, then we may focus on linearized circuit or something called small signal equivalent circuit. And they are what they do the DC parts we will be considering it is 0.

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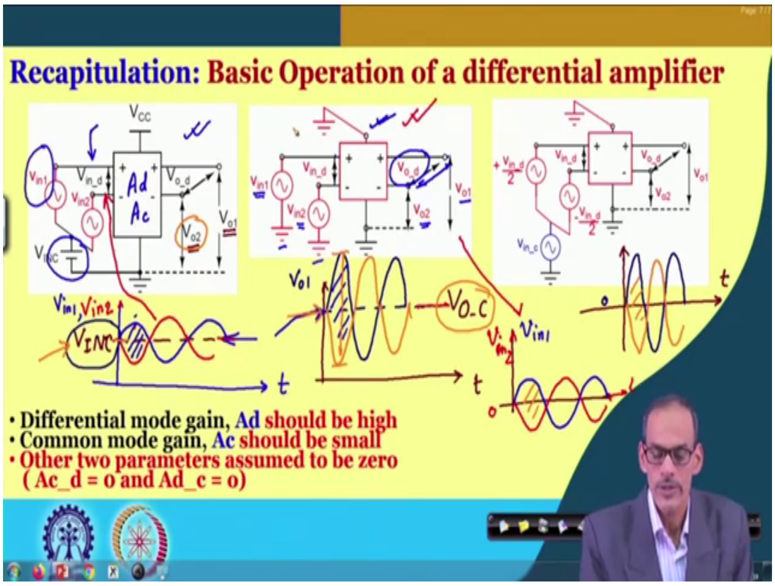

So, we do have this terminal supply terminal it is ground and whatever the input signal we are given it is with respect to AC ground. And then this is the differential signal coming to the circuit and then the corresponding output we are observing at either terminal output terminal 1 and output terminal 2 or maybe we can compare this to voltage and then we call this is the differential output.

So, if you see the voltage at this point it may be having say with respect to time it may be having a DC voltage, it may be having a DC voltage and this DC voltage it is capital V INC and then on top of that we do have say this signal this signal V in 1.

So, let you consider this is one signal on the other hand if I consider the second terminal there we do have same DC voltage on top of that we do have the complimentary signal, so this signal is this one. Now so, these are the two inputs IN, V in 2 and then V in 1. And the corresponding output what we are expecting at terminal 1 of the output port and terminal 2 of the output port namely, V o 1 and V o 2 respectively.

So, we are expecting that here we do have say V o 1, it may be having it is DC voltage level and on top of that it may be having the corresponding signal. So, we are expecting that it will be amplified version of whatever the signal we are applying and at the other output probably, it will be having the same DC level and then on top of that it will be having complimentary signal.

Now, whenever we are talking about the DC level at the output and the DC level at the input, they may be having some relationship, but that relationship cannot be expressed by the two parameter what we have discussed is A d and Ac. A d and ac they are essentially representing small signal relationship.

This DC voltage relationship can be obtained by considering non-linear characteristic of the entire circuit. So, whenever we will be talking about actual realization we may discuss about the relationship of this DC voltage level and to whatever the DC voltage level at the output.

This DC voltage level we may call it is V capital O C, output common mode DC voltage level. And then whenever we are at say small signal equivalent circuit we are primarily focusing on the signal and we need to adjust this DC level to ground level ok. So, same thing here also.

So, in this circuit, whenever we will be talking about it is corresponding input and output what we will be talking is the input it is with respect to ground. So, this is one input and the corresponding complimentary input is like this.

So, this is 0 level, this is small V o V in sorry, V in 2 and the blue one it is small V in 1. So, likewise when you when you see the output signal. So, there also we will be discussing only the signal part not the DC part. And so, whenever we are focusing on signal, we are assuming that this DC level is aligned with 0 and we are focusing on the signal part right.

And now it is it is very important that though the focus is here, but it is also very important to properly adjust this input DC voltage level and also it is important to get this meaningful DC voltage level. So, that the signal swing undistorted signal swing it is very good and this DC level should be such that the entire circuit is properly operating.

So, as I said that whenever we will be talking about actual circuit we will be talking about this level and this DC level and their implication, but for the time being we are in this small signal equivalent circuit.

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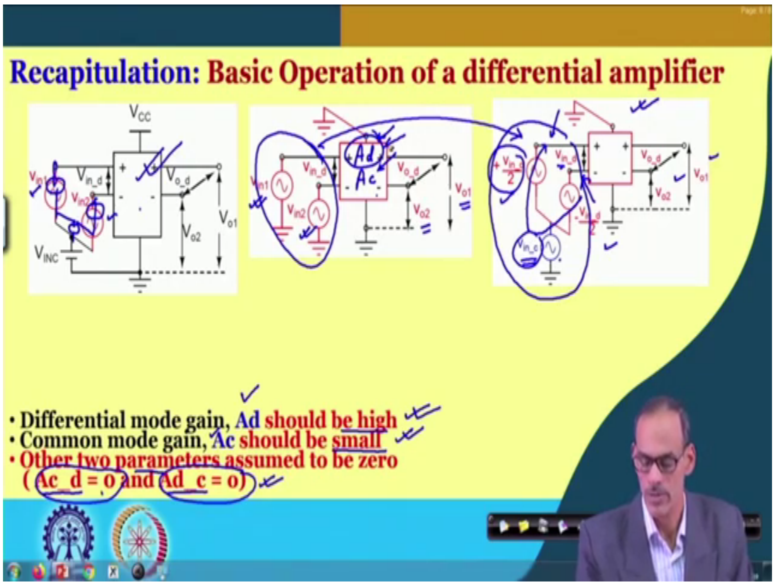

Now once we are in small signal equivalent circuit, then it is basic parameters are differential mode gain and common mode gain as you can see here and we say that ideally we want this differential mode gain it should be as high as possible and this common mode gain on the other hand it should be as small as possible.

Apart from that, you also have two more parameters namely, common mode to differential gain and differential to common mode gain. But unless other unless otherwise it is stated we assume that both of them are equal to 0. So, henceforward we will be assuming that this two are 0. Later we will be talking about how to achieve this property in the actual realization.

Now, to see the output in terms of whatever the input we are applying here and in case if we have say these two parameters namely the common mode gain and differential mode gain. We need to translate this if this pair of signals in the form of common mode component and differential component.

So, this circuit it is equivalent only thing is that it is it is a representation of the input stimulus it is different. In fact, in actual circuit when you see, we may consider the similar kind of arrangement namely a common mode signal going to both the circuits and then we do have say two half's of the differential signal as you can see here.

So, we do have positive half it is going to say terminal 1 and negative half it is going to terminal 2. And then, the common mode signal it is going to both terminal 1 as well as terminal 2. And then we do see the signal here. So, that is what we have discussed in our previous lecture, now next thing is that further to that.

Suppose, we do have a circuit whether in this form or in the model form then, how do we find the value of this differential mode gain and common mode gain? For say analysis of a circuit or maybe in actual hardware, how do we how do you find this parameter? So, which is referred as characterization of the existing circuit to find the value of differential mode gain and common mode gain; so, in the next slide we are going to discuss about that.

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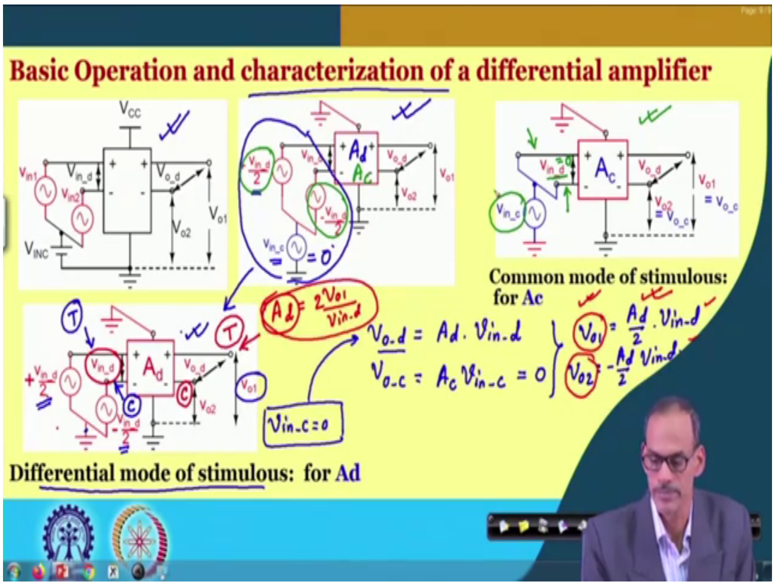

So, the basic operation and most important thing is that characterization of a differential amplifier.

So, this is what we have discussed and this is what the corresponding small signal equivalent circuit and it is stimulus which is having combination of the common mode part and the differential parts. Now to find A d differential mode gain of this circuit, what we do we take this circuit and then we consider that this part is equal to 0.

So, then the corresponding stimulus what you can see here it is common mode signal it is 0, we do have only the differential signal coming to the circuit. So, this kind of stimulus it is referred as differential mode of stimulus which means that the common mode component it is completely 0 and the signal coming here and here, they are perfectly complimentary to each other.

So, you may say that one of them it is it true signal and this is complimentary signal and there is no common mode component and in case if we have say A c d equals to 0 and since in this case V in c equals to 0, which implies that V o d equals to of course, A d into V in d and V o c, even though it is A c may be nonzero, but since V in c in this stimulus in this stimulus it is 0, so that is why this equal to 0.

As a result if we see the individual output see V o 1, it is it is which is V Vod by 2 and that is A d by 2 into V in d on the other hand V o 2 equals to minus A d by 2 into V in d. So, what we can see here it is that these two outputs they are perfectly complimentary to each other.

So, we may say that this is true output and this is the corresponding complimentary output. Now in this arrangement if you simply observes a this signal namely this signal and then if we know what is the V in d. So, from that you can calculate what is the A d. Namely, A d it is given by V o 1 divided by maybe one of these two signals.

So, that is equal to so, V in d by 2 so, that 2 it is coming here and that is how we can get the value or expression of the differential mode gain ok. So, likewise in case if you want to know what will be the common mode gain Ac, then you can consider say this circuit. And in this circuit what you do we are making this two differential halfs equal to 0 namely, differential part equals to 0. So, we can see that this differential part is equal to 0 and both terminal 1 and terminal 2 are getting common mode signal.

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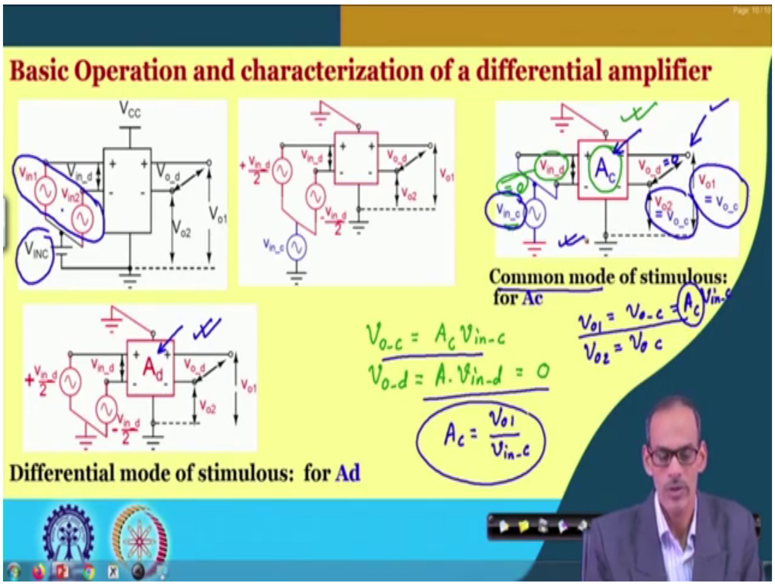

So, in this the second circuit, in the second circuit to find the common mode gain we are making these differential particles to 0. So, naturally, the Voc it is equal to Ac multiplied by V in c whatever the V in c we are applying and Vod on the other hand A d multiplied by V in d. Now V in d equals to 0, so, that gives us Vod equals to 0. And hence the corresponding output V o 1 it is just V o c and V o 2, it is also V o c.

So, that is why we are writing that both this output and this output they are same because this signal it is 0. So, here again by considering say this equation say this equation and if you consider this is equal to A c into V in c. So, just by observing one of them maybe say this signal and then if you take the ratio of this signal with respect to V in c, then you can find corresponding Ac.

Namely, the ac equals to ac equals to by observing one of them either V o 1 or V o 2 divided by V in c. So, that is how we characterize a given circuit to find these two important parameter, differential mode gain and common mode gain right. Now of course, again we like to say that while we will do this operation in actual circuit we have to retain this DC voltage and then, we can see what kind of signal we can apply here to get this differential mode of stimulus and then common mode of stimulus. So, now let us see the realization of this circuit.

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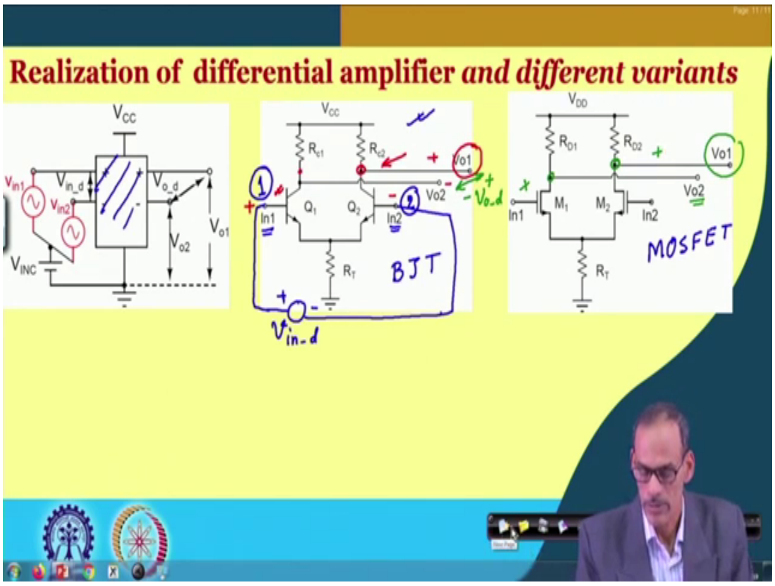

So, how do we realize this differential amplifier. There may be different possible realization of differential amplifier, but here we do have a very basic realization of differential amplifier I should say it is basic, but still it is it is I should say practical circuit.

Many of times it is also used in actual circuit and whatever the concepts we will be discussing related to differential amplifier for that this circuits are good enough to discuss that. So, here we so, the we are showing that the realization of this differential amplifier. So, like so, this is BJT version and here it is MOSFET version.

Now, here I like to tell you one important point here if we consider say this is one terminal input terminal, this is the other input terminal in 1 and in 2 and then if I consider the corresponding output, output at this point; it is in phase with this input and hence instead of calling this is V o 1, we are calling this is V o 1 ok.

Just to say that if this is positive side of the signal and this is negative side of the signal, the corresponding output will be having this side is this terminal showing the positive side of the output and on the other hand this terminal will be showing the negative side of the output. Or we may say that if I am applying say V in d having say positive side here and negative side here. So, negative side we are giving to terminal 1 and positive side at terminal sorry, negative side at terminal 2 and positive side it is going to terminal 1.

Then whatever the voltage we are observing here at the output. So, for this output, this is plus and this is minus and we call this is the differential output. Now, in and this is true for the other realization also, we call this is V o 1 and this is V o 2. So, that the polarity of this terminal and this terminal they are same ok.

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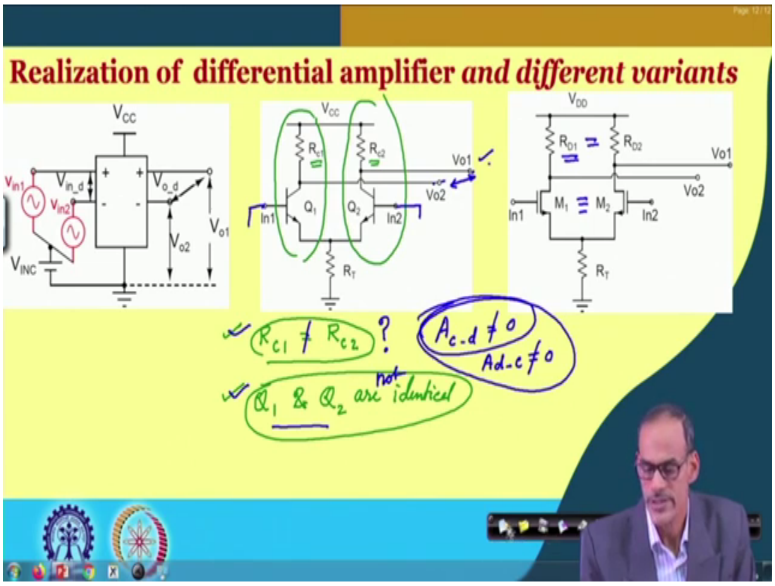

Now coming to the other information which is also very important, that you might have seen that we do have this circuit is having two parts structurally they are identical. In fact, this R c 1 and R c 2 we want they should be equal, R c 1 we want R c 2 should also be identical.

So, likewise Q 1 and Q 2 are identical right. So, once we have these two halfs they are identical not only in schematic, but their actual value then only we can see that whatever the parameters other parameters we have ignored namely, A c d equals to 0 and A d c equals to 0.

Which means that whenever we are applying say differential signal at the input the corresponding output it is perfectly differential and whenever we are applying say input signal in the form of common mode, perfectly common mode which means differential component is

0 then you can say that at the output whatever the signal we are getting signal at terminal 1 and terminal 2 they are identical and hence differential output is 0.

So, these two matching as I said that these two matching's are very important to achieve this the other parameter to remain silent they need to be equal to 0. So, same thing here also, we want r d one and rd two they should be equal and these two should be identical, M 1 and M 2 should be identical.

Now, the natural question is that in practical realization if they are they are not possible to achieve whatever the little variation is there. So, same thing it may happen for Q 1 and Q 2, then their consequences it will be if they are not and if are not identical then these two parameter we cannot consider they are 0 and we have seen their consequences. Particularly A c d it is very dangerous. So, we prefer to avoid such kind of situation ok.

Now next thing is that here of course, there are different possible realization and as I said that these two realizations are very basic and very fundamental.

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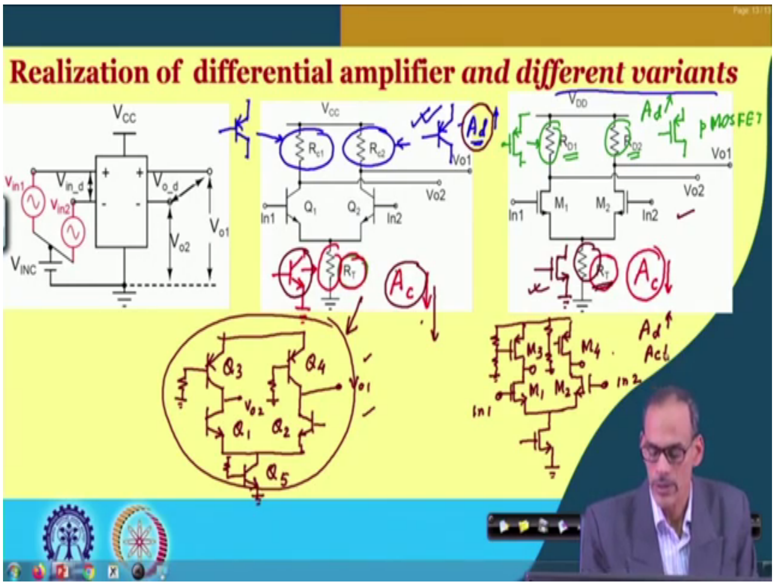

Now, what are the different variants we do have? First of all we have seen that for common emitter amplifier instead of having passive registered we can have active device. So, we can probably replace this passive element by 2 identical PNP transistor. So, here and here. So, as I said that they should be identical. So, and by doing that we can get higher differential gain.

So, by doing this we can increase the differential mode gain ok. In fact, same thing it is also applicable if we replace this R D 1 and R D 2 by their corresponding counterpart in transistor realization namely p MOSFET. So, same thing here also identical PMOS transistor with of course, meaningful bias here.

So, if we replace this resistor and this resistor by their corresponding active devices. So, here also the differential mode gain it increases. So, so that is how we can get different variants. On the other hand if we consider this resistor it is role is to play to decrease the common mode gain this Rt it decreases not only it is working as bias circuit, but it helps to decrease the common mode gain.

We will see how it is getting achieved, but higher the value of this Rt, we can get smaller the value the corresponding common mode gain. So, naturally if we replace this resistor by one active device say one NPN transistor. So, if you replace this one so, that will help us to decrease this. So, that that helps to decrease the common mode gain. So, by replacing this resistor by active device, it helps to decrease this one. So, same thing here also, if you want to decrease the common mode gain then you can replace this resistor by corresponding NMOS transistor.

So, we may say that if we have a circuit like this, if we have a circuit where the load part it is active it may be having meaningful bias here and here and then of course, the main differential pair this Q 1 and Q 2 normally it is referred as in differential pair. So, same thing M 1 and M 2 it is also referred as differential pair. So, if you if you have this kind of circuit of course, again with a meaningful bias here and then if you consider this is the output and this is the other output terminal.

So, this is V o 1 and this is V o 2 and so and so. And again we consider Q 1 Q 2 their identical likewise Q 3 and Q 4 should be identical. So, that A c d and A dc should be maintained 0 and then you do have the Q 5 here. So, by doing this we can we can get one enhanced version of whatever the basic differential amplifier we have discussed where of course, the differential mode gain it is much higher and then common mode again it is much lower.

So, same thing you can get the active version for both load as well as the and the lower till resistor. So, we do have the differential pair here and then we do have the tail transistor by the way this Rt it is referred as tail element it is referred as tail transistor.

So, we do have M 1 and M 2 identical and then M 3 and M 4, they are identical of course, here we should be having meaningful bias here. So, same thing here also these are PMOS transistors and then you can get one output here another output here and this is i n 1 and this is i n 2. And again this circuit will be having better A d and lower ac. So, that is how you can you can derive different variants. In fact, I also must say that there are other possible way of getting other variants of differential amplifier.

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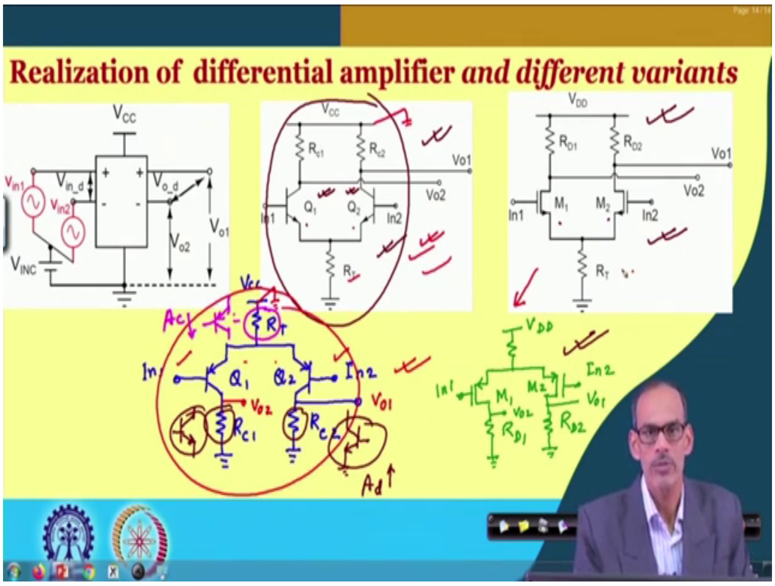

Particularly, if you consider this basic structure; here we have used Q 1 and Q 2 to really amplify the signal and these transistors are NPN and here we do have NMOS device.

So, you can develop one complimentary circuit where PNP transistor can be used to amplify the circuit. In other words, the differential pair it can be PNP so, we do have say now we call this is Q 1 and Q 2 and as I said that this would be identical then, we can have say passive resistors called R c 1 and R c 2 and they may be connected to ground and then the tail resistor R t now it is connected to the supply V cc.

So, we may call this is input 1 and this is input terminal 2 and we may call this is vo vo 1 and this is a V o 2. So, here again the operation of the circuit using PNP differential pair it is very similar to on this circuit only thing is that while we will be applying the bias we need to be careful that we need to have meaningful DC voltage here and here so that, devices are in active region of operation.

But, then once you go in small signal equivalent circuit this terminal it is AC ground, this terminal it is A C ground, this is actual ground and then the equivalent circuit of this part and this part I should say it is essentially same. In fact, same thing you can do for for the MOS version also we can put a tail resistor and then we do have the differential pair using PMOS transistor and then we do have two passive loads.

We do have R D 1 and R D 2 and then we do have M 1 and M 2 right and this is we do have the supply. This is one output and this is the other output, this is input 1 and this is input 2. And of course, again if you want to enhance this circuit performance you can replace these resistors by active device to enhance the differential mode gain and likewise you can replace this tail resistor by PNP transistor to decrease the common mode gain.

So, this transistor helping to decrease the common mode gain whereas, these two transistors they are helping to increase the differential mode gained. Now I think it is very logical you can, so, similar thing you can do for the MOS version also. So, at least we understand that it is not just only these two are the realizations of differential amplifier, there are many possible variants, but then their basic structure can be understand by considering this simple structure.

And in our subsequent discussion, we will be talking about these two circuits only ok. So, let me take a short break and then we will come back.