# Analog Electronic Circuits
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## Lecture – 77
## Differential Amplifier: Analysis and Numerical Examples

So, 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 it is: Differential Amplifier and in fact, today we are continuing differential amplifier, but today we will be primarily focusing on Circuit Analysis and maybe towards the Numerical examples.

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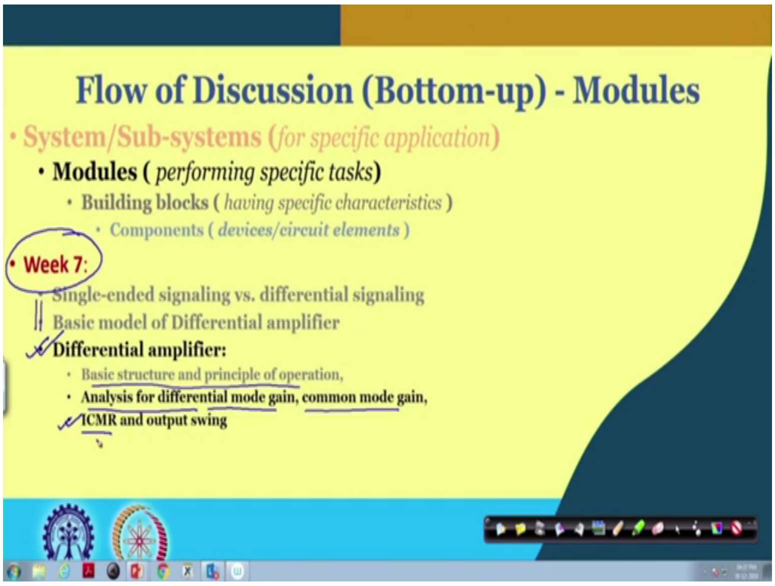

Flow of Discussion (Bottom-up) - Modules

- System/Sub-systems (*for specific application*)
  - **Modules** ( *performing specific tasks*)
    - **Building blocks** ( *having specific characteristics* )
      - Components ( *devices/circuit elements* )
- **Week 7**:
  - Single-ended signaling vs. differential signaling
  - Basic model of Differential amplifier
  - **Differential amplifier:**
    - Basic structure and principle of operation,
    - Analysis for differential mode gain, common mode gain,
    - ICMR and output swing

So, in overall plan we are in module 7 and; under the module 7 we do have the plan of going for Differential Amplifier. So, in our previous lecture we have talked about basic structure and working principle of differential amplifier, prior to that we have discussed about single ended signaling versus differential signaling, they are part of the differential amplifier background. And today we are going to discuss more on analysis of differential amplifier.

Specifically, for two modes of operation differential mode and common mode operation and their corresponding gain. And, then we will also talk about large signal analysis from where we can get the signal swing possible output signal swing and the range of DC voltage which is referred as Input Common Mode Range. So, that is the overall plan, so, the concepts we are going to covers are the following.

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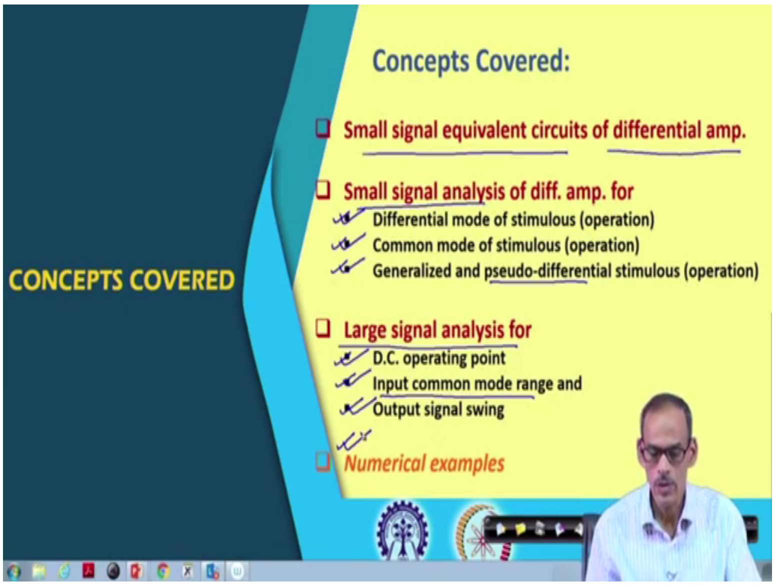

CONCEPTS COVERED

Concepts Covered:

- ☐ Small signal equivalent circuits of differential amp.
- ☐ Small signal analysis of diff. amp. for
  - ✓ Differential mode of stimulous (operation)
  - ✓ Common mode of stimulous (operation)
  - ✓ Generalized and pseudo-differential stimulous (operation)
- ☐ Large signal analysis for
  - ✓ D.C. operating point
  - ✓ Input common mode range and
  - ✓ Output signal swing
- ☐ Numerical examples

So, we shall start with small signal equivalent circuit of differential amplifier both; implemented by BJT as well as MOSFET. And, then we shall talk about small signal analysis. Specifically, for Differential mode of stimulus or Differential mode of operation then, Common mode stimulus or Common mode operation and then combined one which is referred as generalized stimulus and then we may have a special case which is referred as pseudo differential stimulus.

And then we will be going for Large signal analysis to start with, we shall discuss about DC operating point analysis and then we shall talk about; the input DC voltage range over which devices are in proper region of operation which is commonly known as Input common mode range and then, we shall talk about the possible signal swing for a given circuit which referred as Output signal swing.

Numerical examples it will be followed after that, but I am not sure whether we will be able to cover today, but yes, this is the overall flow. Now coming to small signal equivalent circuit of differential amplifier. So, here we do have the basic; the overall model namely, we do have a differential amplifier and then we do have the input port which is differential in nature and the signaling we do it is in the form of differential.

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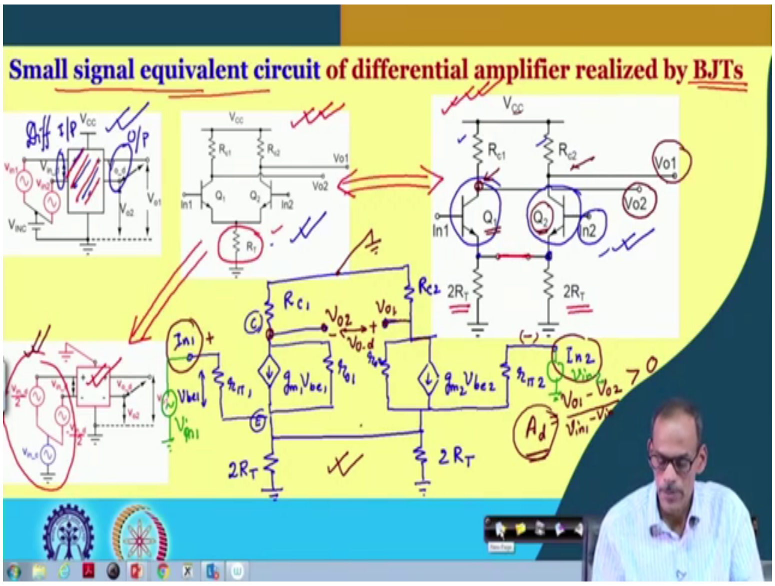

Small signal equivalent circuit of differential amplifier realized by BJTs

Likewise, at the output whenever we are observing the signal the signal we are receiving in the form of differential. So, both input as well as the output port they are differential in nature; which is referred as fully differential amplifier. And, then here is the one possible implementation the basic implementation of the differential amplifier; by BJT Bipolar Transistor and then we like to go for its analysis particularly small signal analysis.

So, for small signal analysis we require small signal equivalent circuit. So, for this circuit we need to have equivalent circuit where, we can drop the DC part and components of this current as well as the voltage and then the linearized circuit which is referred as a small signal equivalent circuit and then there, we can stimulate the circuit. So, before we go for small signal analysis, we need to know the we need to get the small signal equivalent circuit of this differential amplifier.

Now, in our previous lecture we have discussed for better understanding of the circuit operation. We do have here we do have equivalent circuit. In fact, if you see this circuit it is essentially same except this resistor it is it has been splitted into two parts; one is 2RT connected to transistor 1 and then, second one is 2RT connected to transistor 2 and we are keeping they are disconnected.

If we connect the two emitters then of course, this is same as this circuit. So, in our small signal equivalent circuit though we will be drawing the small signal equivalent circuit of this circuit, but once we connect it, we know that we are going back to this circuit. So, then I must say that in literature this is the circuit it is referred as differential circuit, but for our internal analysis we are going to analyze the circuit in this form ok.

So, let us try to see the small signal equivalent circuit of this one. First of all, transistor 1 we can replace by its equivalent model; namely g m 1 into V be 1 and so, this current is between its collector and emitter. And then, we may consider the r o collector to emitter resistance r o 1 and then, we do have r pi call r pi 1 and the voltage across this r pi it is V be 1.

So, this is for transistor 1 so, likewise for transistor 2 we do have r o 2 then, we do have g m 2 g m 2 multiplied by its corresponding V be 2 this is the voltage dependent current source and then we do have r pi of transistor 2 r pi 2 and then we do have the input terminal here. So, we call this is I n 2 and this is I n 1.

These two emitter node they are connected together, but in our analysis we like to keep this resistor splitted into two parts; one is 2 R T connected to the emitter of transistor 1, the other one it is 2 R T connected to the emitter of transistor 2. And, then we do have R C R C 1 the load resistor here and then we do have R C 2 which is the load resistor here.

And, then we do have output at this node and then also we do have the output at this point; you might have observed that naming convention wise even though we are calling this is this is Q 1 and this is Q 2, but whenever we have called this node, we call this is V o 2. So, we may say that the output one of the output we are observing here, which is named as V o 2.

On the other hand, the output at this node at the collector of transistor 2 we call this is Vo 1 and of course, this node it is AC ground so, that is the DC node. Now why do you call this is V o 1 and V o 2? That is just to take care of the polarity of the signal in differential mode. So, if I consider this input it is the non-inverting input and this is the inverting input and then, the corresponding output if we say that this is the true signal and this is the complimentary signal and the difference of these two voltages we call say V o differential.

Then with this convention we do get A d differential mode gain defined as V o 1 minus V o 2 divided by voltage here called V in 1 minus V in 2. So, this becomes positive. So, we had just like to have this A d positive. It is just a convention in many of the textbook we do we have seen that this voltage it is considered as the non-inverting output and this is considered as inverting output; and kinds in in that convention of course, A d it will be negative.

So, it is not so important it is just a convention that is all. So, with this convention namely if I consider this is the V o 1 and this is V o 2 then we are getting A d is positive. So, now, with this model; with this model; what we can do? We can put stimulus and then we can get the subsequent analysis to find the expression of at differential mode gain ok.

So, this is what the small signal equivalent circuit of differential amplifier realized by BJT and here we will be; we will be giving the signal namely we will be applying the signal here this may be called V o V in sorry V in 1. And, the signal here it is V in 2 right ok. So, in summary we have drawn the clean small signal equivalent circuit here.

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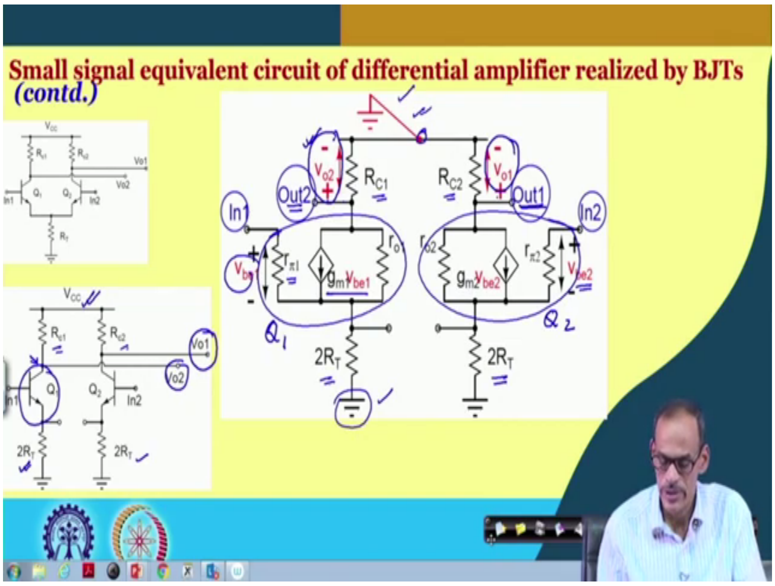
**Small signal equivalent circuit of differential amplifier realized by BJTs** *(contd.)*

So, just now what we discussed it is shown here. So, what we have it is out of Q 1 we have drawn the small signal equivalent circuit here. So, this is for Q 1. So, likewise we do have the small signal equivalent circuit for Q 2 and then the 2 RT. So, till resistors and then the load resistors are here R C 1 and R C 2.

And as I said that; this side we like to call V out 1 output 1 and the voltage here it is V o 1 on the other hand, voltage at this node at the collector of transistor 1 we call it is out 2 and the voltage here it is V o 2. Note that this node this node it is AC ground. So, the voltage here we are considering the voltage here with respect to this AC ground itself. In fact, we may consider with respect to the common ground, but anyway for small signal analysis both this node and this node they are equal.

So, they are essentially same; and then we do have the g m into V be of transistor 1 and the V be it is the voltage across this r pi 1. So, likewise we do have here V be 2. So, that is the small signal equivalent circuit and likewise if we consider differential amplifier realized by MOSFET transistor then we will be getting the similar kind of circuit.

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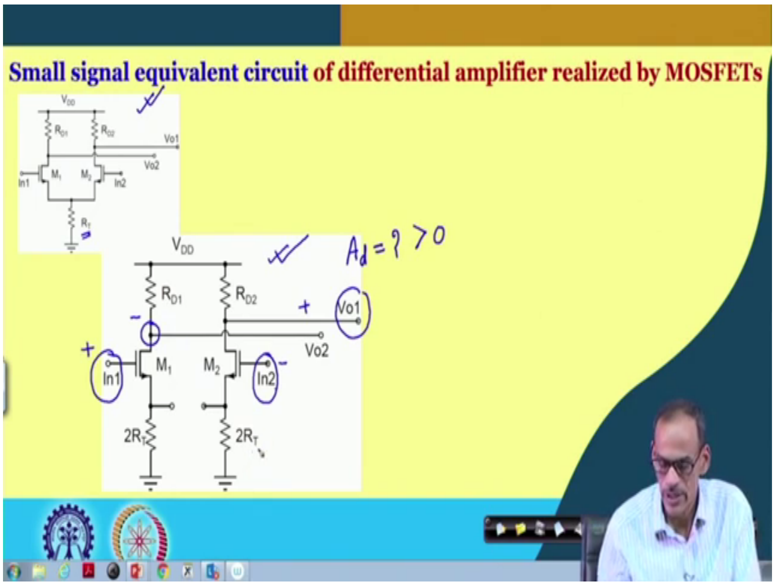

Small signal equivalent circuit of differential amplifier realized by MOSFETs

$A_d = ? > 0$

So, in the next slide here we do have the differential amplifier differential amplifier we may consider this one or the customized one here after splitting the tail resistor into identical elements. And, here again we call this is the positive side of the input namely; non-inverting input and this side this node into it is we consider negative side of the input. And, with this we like to declare this is positive side of the output and on the other hand this is negative side of the output.

So, that we do get the differential mode gain is whatever it is positive. Now let us draw the small signal equivalent circuit of the differential amplifier. In fact, I already have drawn in the next slide. So, let me directly go there yeah. So, here we do have the small signal equivalent circuit for transistor 1 m 1. So, likewise for transistor 2 we do have the small signal equivalent circuit and then we do have R D 1 here R D 2 here.

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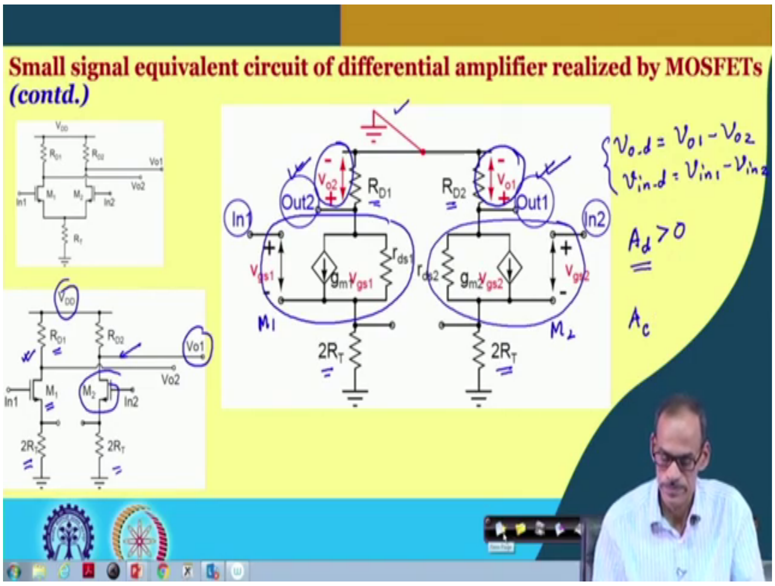

**Small signal equivalent circuit of differential amplifier realized by MOSFETs *(contd.)***

$V_{o,d} = V_{o1} - V_{o2}$

$V_{in,d} = V_{in1} - V_{in2}$

$A_d > 0$

$A_c$

And the two tail resistors split tail resistors are there; and then this node it is AC ground and then this side the drain node of transistor 2, we call it is Out 1 on the other hand drain node of transistor 1 we call it is Out 2. Accordingly, we are declaring this is V o 1 and this is V o 2 and the output we considered particularly the differential output we are defining by considering V o 1 minus V o 2 and V in differential it is V in 1 minus V in 2.

And, with this definition of output polarity output and input polarity and this convention A d we are getting positive. So, now, we like to stimulate this circuit in two modes of operation and we like to get the expression of differential mode gain and the common mode gain for the two small signal equivalent circuits one for BJT another is for MOSFET.

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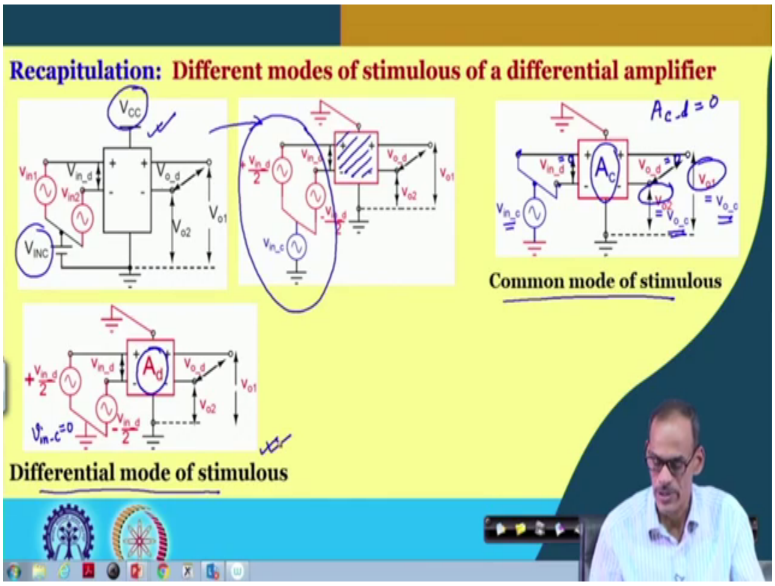

**Recapitulation: Different modes of stimulous of a differential amplifier**

Common mode of stimulous

Differential mode of stimulous

So, you may recapitulate that whenever we do have differential amplifier so, we do have main differential amplifier containing DC sources and DC bias condition; we like to convert into small signal equivalent circuit. So, by now we do have small signal equivalent circuit for differential amplifier and then we like to stimulate it at the input in this convention. And it is having two modes of operation; one is differential modes of operation or differential stimulus that is that will help us to get the parameter A d or expression of A d in this case.

And, then we do have another mode of operation called Common mode operation where, at both the inputs we are giving the same signal V in C making the differential equal to 0, for this case common mode we are making it 0. So, if we make the differential equal to 0 and whatever the differential output, we are expecting it should be 0 assuming of course, A c d equals to 0.

And, whatever the voltage you will be getting at both the outputs are essentially the common mode output and they are identical. So, now, what we will be doing is that let us start with differential mode of stimulus for the small signal equivalent circuit obtained out of BJT's implementation. So, we do have here the small signal equivalent circuit and we like to put the differential mode of stimulus as we can see here.

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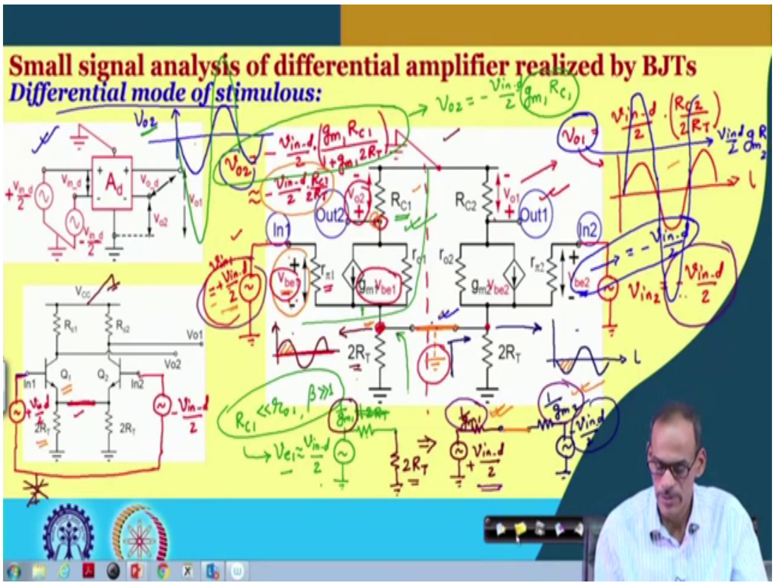
Small signal analysis of differential amplifier realized by BJTs

Differential mode of stimulus:

So, we like to put the signal let me use a different color. So, we like to put differential signal here perfectly differential; which means that, here we like to put V in d by 2 and here plus V in d by 2 and both of them are with respect to a DC voltage. And, once we get the small signal equivalent circuit, once we get the small signal equivalent circuit of course, we will be dropping this part and then we will be considering this is AC ground.

So, that is what we do have here and so, in the small signal equivalent circuit at this input we are applying see V in 1 equals to plus V in d by 2. So, likewise at the other input we are applying V in 2 equals to minus V in d by 2 and in our intuitive analysis what we have said is that if I consider see the two halves of the circuit, if I say that the emitter nodes here and emitter nodes there disconnected.

So, we can then split the circuit into two parts then we can observe what is the signal we are getting at this node and we can observe the signal at this node. So, if you see this circuit the expected signal coming at this point it is minus V in d by 2 into the gain of this circuit which is g m 1 into R C 1 divided by 1 plus g m 1 into 2 R T. So, this is what we are expecting at V o 2.

So, it is having a minus sign and then we do have this gain. In fact, we can drop this 1 and we can as well approximate this by V in d by 2 into R C 1 divided by 2 R T. So, likewise when you consider this node and at this point whatever V Out 1, we are getting V o 1 equals to minus and minus we do have both the minuses together. So, we do have V in d by 2.

So, this minus and the minus here polarity of this amplifier it is getting cancelled and. So, this is R c 2 divided by 2 R T. And, the signal coming at the emitter here it is approximately equal to the signal we are applying at the base, because it is working as in fact, it is working as the emitter follower.

And so, the voltage signal we are getting here it is V e 1 approximately equal to whatever the voltage we are applying there; namely V in d by 2 and then its Thevenin equivalent resistance it is 1 by g m 1 multiplied in parallel with 2 R T right. In fact, I should say that let me go step by step. So, if I consider only this part and if I consider this resistance R C 1 it is less than r o 1 much less than r o 1 which is typically the case, then we do get this relationship and also, we assume that the beta is very high.

So, we consider beta is very high. So, with this approximation we obtain the V e 1 equals to V in d by 2 and then Thevenin equivalent resistance it is 1 by g m 1 and then we do have the 2 R T. So, we do have this 2 R T and again if I consider this resistance 1 by g m 1 it is very small compare to 2 R T. So, that is getting translated into Thevenin equivalent voltage source it is almost remaining the same and Thevenin equivalent resistance it is 1 by g m 1.

So, the signal we are getting here it is V in d by 2 with a plus sign. So, likewise if you consider the other emitter, transistor 2 the corresponding signal source, we will be getting a signal which is equals to V in d by 2 with a minus sign and the impedance here it is approximately equal to 1 by g m 2.

So, in this mode of operation in this differential mode of operation namely if the input 2 and input 1, if they are complementary to each other then at this point and this point the two signals you are getting they are complementary, their impedances Thevenin equivalent impedances are also equal.

So, if we connect it ok. If we connect it then the signal here it will be getting 0 as a result; as a result here, we can consider this is ground. In fact, before we make this connection the signal if I draw. So, before you make this connection signal here it was like this and on the other hand signal at this node it was having the same strength, but having opposite phase ok.

So, this is the signal and this signal it is shown here and the corresponding output what we have observed at this point we do have signal which is in phase with the In 1 and it is having some decent amplification. So, we can say this is V Out 1. On the other hand, signal at this point it is similar, but having opposite phase. So, this is V o 2. Now so, this was the case before we made this connection now the moment, we make this connection ok.

Before we make the connection why the signal here it was low? That is because emitter of transistor 1 it was getting degenerated by 2 R T. So, only a small part of the applied signal it was appearing across this V be even though we said that this voltage and this voltage they are equal, but actually this voltage it was slightly smaller than this one and that it was the V be.

Now and since this V be it is only a small fraction of this applied input voltage and hence the obtained signal at the collector it was only; I should say it was having amplification, but the corresponding amplification it was not really big it depends on the ratio of R C 1 and 2 R T. So, same thing it was the case here at the other output.

Now, the moment we make this connection that makes this signal and this signal they are cancelling each other and particularly since their phases it was opposite, amplitude it was equal and also their Thevenin equivalent resistances, they are equal. So, the moment we make this connection the signal here it was it completely got vanished. So, the emitter node the combined emitter node it becomes 0.

So, the moment we make this is in fact, connected it may be having only a DC voltage, but you will not be finding any signal. So, equivalently you can see that after making this connection it becomes AC ground right. And, once it is ac ground then the available V be it becomes equal to V in d by 2. So, the voltage appearing across this r pi 1 it becomes equal to V in d by 2 and once it is getting the full signal the corresponding current here voltage dependent current source that also got increased.

As a result the corresponding signal here it got changed it becomes now; so instead of this or this it got changed to V o 2 equals to minus V in d by 2 into g m 1 into R C 1. Why? That is because now, if this node it is ground. So, this circuit it becomes like same as common emitter amplifier and we know common emitters, common emitter amplifiers gain it is G m into R C, R C is a load.

So, with this connection now, V o 2 it got changed and changes in magnitude of the output. So, same thing or equivalent things it happened in at the other end namely once you make this connection this voltage it got increased. Because, this the V be 2 now it becomes equal to entire V in d by 2 with a minus sign. As a result, the corresponding output here, it got increased and this output now it is; so, this output it becomes V in d by 2 into g m 2 into R C 2.

So, in let me clear and again summarize; what we said is that the moment we. So, we do have the signal here V in d by 2 with a positive sign polarity and here we do have the complementary part namely; minus V in d by 2. And, the moment we are making this connection to get this circuit same as the original one, then the signal here it is 0, it is 0 here that means, this is AC ground. On the other hand, the signal coming at this point it is amplified one, but having opposite phase.

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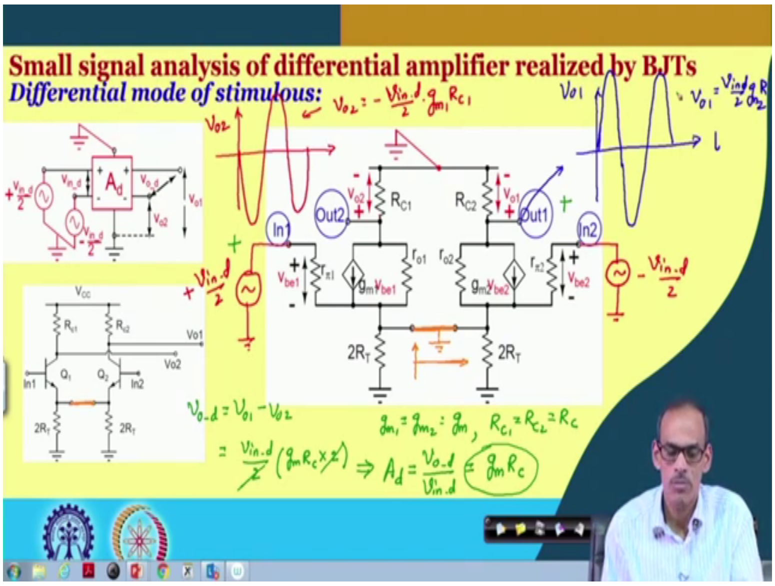

**Small signal analysis of differential amplifier realized by BJTs**

***Differential mode of stimulous:***

$V_{o2} = -\frac{V_{in.d}}{2} \cdot g_{m1} R_{C1}$

$V_{o1} = \frac{V_{in.d}}{2} g_{m2} R$

$V_{o\text{-}d} = V_{o1} - V_{o2}$

$= \frac{V_{in.d}}{\cancel{2}} (g_m R_c \times \cancel{2}) \Rightarrow A_d = \frac{V_{o\text{-}d}}{V_{in.d}} = \boxed{g_m R_c}$

$g_{m1} = g_{m2} = g_m, \quad R_{C1} = R_{C2} = R_c$

So, this is V o 2 and this V o 2 it is equals to minus V in d by 2 into g m 1 into R C 1 likewise if you see the other side; we do have V o 1 which is in phase with the with the differential input and the signal here it is V o 1 equals to V in d by 2 g m 2 into R C 2. So, the differential output V o d which is defined as V o 1 minus V o 2. So, it becomes V in d by 2 into g m into R C into 2 and here we have assume that g m 1 equals to g m 2 equals to g m and R C 1 equals to R C 2 equals to R C.

So, that gives us so, this 2 and this 2 they are getting cancelled. So, that gives us the differential mode gain expression is equal to which is defined as V o d divided by V in d this is equal to g m into R C right. Note, that our polarity convention helps us to avoid this minus sign otherwise it is its gain it is same as common emitter amplifier.

Now, similar to this circuit then similar to the differential amplifier using BJT if you consider the differential amplifier realized by MOSFET transistor we can do similar kind of analysis. So, in the next slide we do have the small signal equivalent circuit. So, we do have the small signal equivalent circuit of the differential amplifier.

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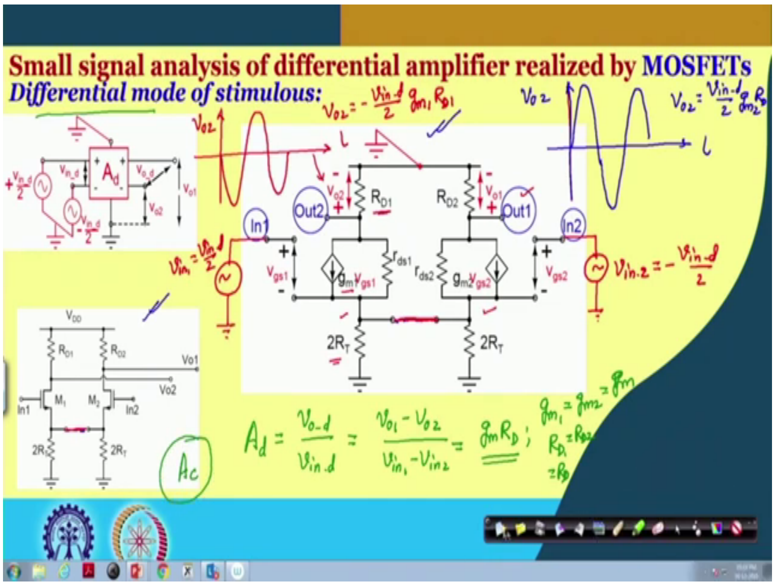

**Small signal analysis of differential amplifier realized by MOSFETs**

*Differential mode of stimulous:*

And, the actual circuit of course, will be getting when we are making this connection and here also if we stimulate the circuit in perfectly in differential mode of operation namely; V in 1 equals to V in d by 2 and the signal here it is V in 2 equals to minus V in d by 2. Then, before we make this connection we are having signal here and here, but the two signals it was in opposite phase and the gain here we obtained, it was only R D divided by 2 R T, but the moment we make this connection to get the actual differential amplifier, then the corresponding output we obtain here it is amplified version with 180 degree phase shift.

And the corresponding output V o 2 equals to minus V in d by 2 into g m 1 into R D 1. So, we do have g m 1 here and then we do have R D 1. And likewise, if I consider this output and the corresponding output it is similar, but 180 degree phase shift. So, this is V o 2 and V o 2 is equal to V in d by 2 gm 2 into R D 2. So, again for this case the differential mode gain A D defined as V o d divided by V in d which is equal to V o 1 minus V o 2 divided by V in 1 minus V in 2.

So, it becomes g m into R D where g m is we are assuming g m 1 equals to g m 2 equal to g m and R D 1 equals to R D 2 equals to R D. In fact, lot of common things are there across these two differential amplifier. So, we can use the same concept in this differential amplifier to understand so, that is why I did not go in detail of this circuit.

So, now, we can go for so, we have covered the differential mode of operation and we obtain the differential mode gain of the circuit. And, next thing is that we can go for common mode stimulus and then we can find the corresponding gain of the circuit called AC and to start with let me go with the MOSFET version first right and then we will be doing the analysis ok. Before we go into that let me take a short break and then we will come back.