

CMOS Analog VLSI Design
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Lecture - 08
Cascode Amplifier

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Cascode Amplifier.

Need :- Larger Gain (Gain↑)
without Losing Bandwidth.

We know for an Amplifying System
Gain × Bandwidth = Constant (for a Technology mode)

Hence if we boost Gain, then Bandwidth goes down.

Gain Improvement :-

→ A → A₂ →

$$\left[\begin{array}{l} A_0 = g_{m1} r_{o1} \cdot g_{m2} r_{o2} \\ \text{bandwidth} = \text{GBW} / A_0 \end{array} \right]$$

Gain = $A_1 \cdot A_2 = A_0$

This is the case of CASCODE AMPLIFIER.

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So, we were looking last time about the Cascode part and ONE other thing which I said last time, what cascode amplifiers has the advantage, I am just recapitulating what we did last time. And we said it can you can increase the gain without loss of gain bandwidth product points and that is the strength of cascode over cascaded system and essentially this is what makes cascode very interesting.

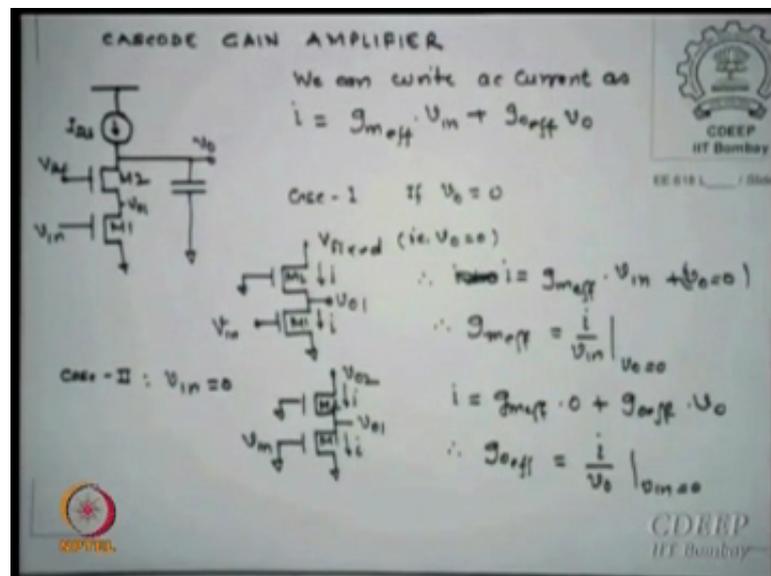
How where you may find in many applications cascades are not used in that, I am not saying it will never be used there are different variety of cascades, opamps or variable telescopic or holded or otherwise each has some value, but they are not the ones which are commonly used for every specific purpose, yes cascode is the best amplifier. In most cases the amplifier which has used is we shall see later, simple 1 stage 2 stage amplifier which is good enough for many applications, but in the integrate circuit you will be suddenly actually told to match with something else in a digital domain or it is inputs is very different and then you need specific amplifiers to drive that.

So, why we are teaching this because these are the real life systems in which any odd application may require any odd kinds of amplifiers. However, we will first learn basics and then the application comes now we know this you want, so this is better for you. That is where the designer should know if this is an application this is the input, it has to then what amplification I should have, so that it can drive better.

So, this fact last time I will said that cascode amplifiers are superior to cascades because, in cascade the gain bandwidth of a single stage remains constant for any cascading stage and therefore as you increase the gain by cascading the bandwidth keeps going down, if you have 3 stage is the bandwidth will further go down. Whereas, in cascode a gain bandwidth product does not change even if you boost the gain and that is something fantastic about cascodes penalty. We shall see soon what is the big penalty we pay at least in integrate circuit, that is a big penalty we are paying for all of it ok.

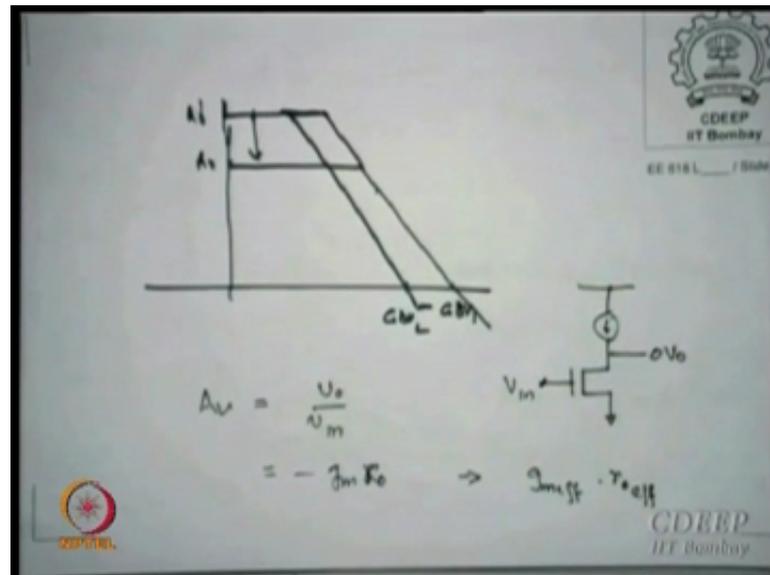
So, this is what last time I was talking, so I will start again basically I start now my amplifier.

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A typical cascode amplifier shown here is driven by biasing current of IDs fixed current source as you can say and we want to find the gain of this amplifier and we also want to find it is gain bandwidth product. Now the way I write that we have been already designing a amplifiers, what is a typical amplifier last time I showed very simple amplifier just few seconds.

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A simple amplifier we have discussed already, can have a current source node or whatever biasing you wish and this is your V in this is your V out and we are interested in this amplifier is V_0 by V in and we know typically this will come minus g_m times sorry r_o , you know derive this earlier. So, we just know this.

So, what now I am going to do is I have a cascode which has more than 1 transistor sitting there in series there. And therefore I will say can I get g_m effective and r_o effective, so that the gain remains $g_m r_o$. So, instead of just g_m therefore the cascode, I am saying g_m effective into r_o effective and if I derive these 2 values for this cascode case, I still have the gain which is minus g_m effective into r_o effective.

Now, this is what follows and therefore I thought before I start you should know that, I am basically trying to replicate what I already know and convert that into my earlier knowledge is that all of you. So, they are the after all this when I will show you the actual solving circuits is the best way of doing things using Kirchhoff's law. So, some other amplify show you do not know anything fair enough, you can always put equivalent circuits ok.

So, I will show you some examples of solving with any kind of 3 series, 4 series or n series or n parallel, anything can be connected and then we can have equivalent circuit which may become quite complicated sometimes, but can always be solved using Kirchhoff's laws. So, it is not necessary that this technique which I show you is the

ultimate or something, but this why we choose this kind of this is actually trying to compare with the earlier amplifier.

So, if I do you equivalently that then you say in comparison what is going on. So, is that clear as I say, I am this method which I am showing you only to show you comparisons, these need not be always used by anyone, but can also if you feel. So, you think very great about. So, then we say if it is equivalent transistor situation, is I is equal to g_m effective times V_{in} plus g_o effective times V_0 , as we did for normal amplifier instead of g_m and g_o I will now say maybe if you, I should do something like this.

So, we can write that AC current through this equivalent amplifier stage, will be I is equal to I is the current through the amplifier. So, g_m effective times V_{in} plus g_o effective times V_0 , we already done for common source normal so this is the extension on that. So, what is the game I am trying to say I will figure it out what is g_m effective for the cascode and what is r_o effective or g_o effective for the cascode and continue to use this same method of solving further, is that clear what is the method I am suggesting. I am only trying to why I did I repeat, I want to see how much that g_m effective is different from single stage amplifier g_m and how much r_o effective different from r_o of the single stage amplifier, does that change because you said gain is boosting ok.

So that means, then $g_m r_o$ product must be increasing. So, it is possible the g_m effective may be higher and also r_o effective may be higher or 1 of them may be higher other may not change are whatever it is; there are possibilities we like to see which 1 is really pushing the gain and why then in spite of increasing gain the g GBW or gain bandwidth point does not move so that is this.

So, to say it let me put it this is a capacitance C which is load capacitance, this amplifier is drawing a load capacitance. This load capacitance is such that all other capacitance are can be neglected except the output capacitance, which takes as it net load capacitance is that clear, remember bandwidth can be a function of input capacitances, series capacitances and output capacitor, I say this is giving you what we call dominant pole as of for the case of solving.

So, we start with the case 1 I say if V_0 is 0 in this expression, I is equal to g_m effective V_{in} then g_m effective is I by V_{in} when V_0 is 0, just substitute 0 the g_m effect is I by V_{in} when V_0 is 0 look at this expression put V_0 is 0. So, I by V_{in} is essentially g_m

effective when V_0 is 0. Now similarly I can say if V_{in} is 0 and then we figure out I by V_0 is nothing but g_m effective is that just either this 0 or this 0. So, I want to solve these 2 cases when V_0 is 0 and V_{in} is 0 and this equivalently then I get go effect is I by V_0 and g_m effect is I by V_{in} .

So, now I want to find I and V_{in} ratio or in few have to ratio for the 2 conditions which I have written here, is that as simple as that nothing great to make V_0 is 0 I say it is a fixed v , so no change. So, V_0 is 0 there let us say I flows through this both transistor should have, please remember for an AC circuit any DC point is at 0. So, V reference which is a V_{DC} for this is essentially grounded for the AC purposes.

So, for this if I say this point is 0 and then I solve I by V_{in} ratio for this circuit and I will g_m effective, if I say V_{in} is 0 and I measure I by V_0 here and I will say I will get go effective. So, the technique it is simple and this is only trellis, I say keep trying to equal the g_m and r_o values of earlier this. So, that I_c comparisons is that. So, the method is trivial to some extent, but it does give you some physics behind what is going to happen is that everyone to start with of course in reality.

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Let us assume $M1$ & $M2$ are identical in specs.

Case I: AC circuit for case $V_0 = 0$, or $V_0 = V_{DC} = \text{fixed}$

For transistor $M1$ ($V_{in} = V_{gs}$)
 $i = \beta (V_{in} - V_T)^2 (1 + \lambda V_{o1})$ — (i)

Also $i = g_{m1} \cdot V_{in} + g_{o1} V_{o1}$ — (ii)

For transistor $M2$, $V_{gs2} = 0 - V_{o1} = -V_{o1}$
 $i = \beta (0 - V_{o1} - V_T)^2 (1 + \lambda (-V_{o1}))$ — (iii)

And $i = g_{m2} (-V_{o1}) + g_{o2} (0 - V_{o1})$ — (iv)
 or $i = -(g_{m2} + g_{o2}) V_{o1}$

The slide also features a circuit diagram of two NMOS transistors, $M1$ and $M2$, connected in a cascode configuration. The gates of both are tied together and connected to an input V_{in} . The source of $M1$ is connected to the gate of $M2$. The drain of $M1$ is connected to the drain of $M2$, which is also connected to a load resistor R_L . The output voltage V_0 is taken from the drain node. The source of $M2$ is connected to ground. The drain current i is shown flowing out of the drain node. The gate-source voltage of $M1$ is $V_{gs1} = V_{in}$ and the gate-source voltage of $M2$ is $V_{gs2} = -V_{o1}$. The drain-source voltage of $M1$ is $V_{ds1} = V_0$ and the drain-source voltage of $M2$ is $V_{ds2} = -V_{o1}$.

This may not be necessary but in most integrated circuits unless specified otherwise transistors are always made equal, for variety of results we shall come to see actually if they are not identical it creates hell of an issue ok.

So, we will try to make transistors identical in many cases, but if needed we can modify the what that change will be normally thresholds are rarely change, only it is the W by l ratio which may be different for 2 cases ok. So, now write now for the simplicity I shown M_1 M_2 identical that is the thresholds are same, the W by l also same everything else is also same μ is same, cox is same everything same, for the transistor M_1 this is the lower one the current flowing in this transistor V_{gs} is nothing, but V_{in} V_{gs} for this M_1 is V_{in} .

So, $\beta (V_{in} - V_T)^2 / (1 + \lambda V_{01})$ is the current flowing in M_1 it clear to you, $\beta (V_{gs} - V_T)^2 / (1 + \lambda V_{ds})$. So, I just substitute I am not actually using I am just trying to show you what current is flowing there; however, if I only look this transistor a from the a small signal point of view, then I say here I is equal to $g_{m1} V_{in}$ $g_{m1} V_{in}$, is the current source going outs current going in the output plus g_{o1} of this into V_{01} ok.

Now, for this transistor M_2 slightly the current is similarly, now I is equal to $\beta (0 - V_{01} - V_T)^2 / (1 + \lambda (V_{ds} - V_{01}))$. So, it is substitute this can be a current in M_2 please remember these 2 current should be identical, because in a circuit only 1 current can flow 1 circuit point; however, I write similar expression for I in for M_2 . So, I is equal to g_{m2} and what is V_{gs} for this transistor $0 - V_{01}$ is that correct, what is the V_{gs} for M_2 $0 - V_{01}$.

So, it is $g_{m2} (0 - V_{01})$ I repeat what is V_{gs} for this M_2 gate voltage is 0 source voltage is V_{01} . So, $g_{m2} (0 - V_{01})$, so g_{m2} is into $g_{m2} (0 - V_{01})$ plus g_{o2} , now how much is V_{ds} $0 - V_{01}$. So, $g_{m2} (0 - V_{01})$ which can be written as $g_{m2} (0 - V_{01})$ into V_{01} is that correct. So, I have an equation which gives me relationship between for M_2 and M_1 and what is the ultimatum I am looking for, what is first I am trying to derive what g_m effective. So, what value I am really looking for I by V_{in} . So, this equation is what is important for me, so I want to find g_m effective. So, I want to find I by V_{in} .

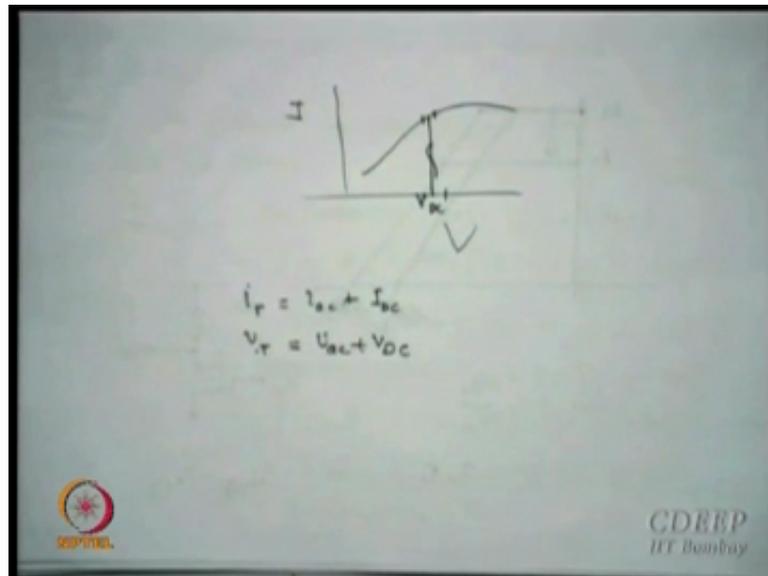
Student: (Refer Time: 14:17).

All small signals.

Student: (Refer Time: 14:19).

You always valid it is we had just told you already V small, I think you should now go back and do some little more calculations yourself, the way small signal analysis is done in any IV characteristics.

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Let us say this is the characteristics any idea, what we fixed is this DC point is that clear and superimpose on this some signal assuming that the slope here does not change. So, small signal analysis currents are similar except that the DC value has been taken out of it, essentially saying I total is I_{ac} plus I_{DC} V total is V_{ac} plus V_{DC} .

So, anytime you substitute the DC value together and subtract, so the difference is only AC you subtract total minus this. So, we will get the AC value so the expressions are valid. The current I is so adjusted that both M_1 and M_2 are in saturation is that clear. So, I has that is what I say bias point is fixed by I_{DC} this value. So, if I fix that value I am making device saturated, if it does not occur yes I will have a problem because there is no gain then possibly, I may not get enough gain on 0 gain sometimes but I assure you as of to solve this problem that I is. So, adjusted that the device both devices can enter into saturation is that clear, the only word which I am not stated which I see soon. I will say there is another word which I will use going to use is called headroom; what is that word headroom?

Student: (Refer Time: 16:13).

How much maximum I can shift that device still remains in saturation or go below till remains in saturation is called headroom, I have that play available. So, I assume that my device has sufficient headroom's. So, that device remains in saturation this is assumption, which can be proved otherwise it is something saying that first you assume and then prove that is all mathematicians do, so why not do it.

Student: The V_1 gain be taller the small AC.

Small AC signals.

Student: Sir, we just cannot directly apply the DC.

And I say you add total V_{DC} plus V_0 , everywhere DC and subtract DC value out of at you will get similar equations is that clear to you.

Student: Is you are in the very small. (Refer Time: 17:00).

Very small as long as you are in a small signal this is all small signal circuits we are solving, as long as you way keep doing this it is fair enough though nominal as I you may say that the slope slightly goes away your headroom is so small, then you actually will never remain in saturation. So, where do you bias is a very crucial point for us ok, right now will come back to this issue in case it is needed, but let us move quickly. So, from the first that first second equation which I just derived V_{01} can be derived as $\frac{-I}{g_{m2} + g_o}$, just now I wrote an expression. I now want to find V_{01} and substitute this V_{01} in that equation for M_1 is that correct, what did I do evaluate V_{01} from M_2 and substitute in value for M_1 .

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$$\therefore V_{o1} = \frac{-i}{g_{m2} + g_{o2}} - (v_i)$$

Substituting (v) in (ii), we have

$$i = g_{m1} \cdot V_{in} + g_{o1} \left(\frac{-i}{g_{m2} + g_{o2}} \right) - (v_i)$$

$$\therefore i \left(1 + \frac{g_{o1}}{g_{m2} + g_{o2}} \right) = g_{m1} V_{in}$$

But $g_{m_{eff}} = \frac{i}{V_{in}}$ and hence $= \frac{g_{m1}}{1 + \frac{g_{o1}}{g_{m2} + g_{o2}}}$

$$\therefore g_{m_{eff}} = \frac{g_{m1} (g_{m2} + g_{o2})}{g_{o1} + g_{o2} + g_{m2}} - (vii)$$

$g_m > g_o$ for both Transistors we have $g_{m_{eff}} = g_{m1} \cdot g_{m2}$

So, if I do this, I get I is equal to $g_m 1 V$ in which was the term any way there and I have $g_{o1} V_{o1}$ was the product there. So, it is V_{o1} is now replaced by this minus $I g_{m2}$ by g_{o2} then I collect items. So, I is equal to $1 + \frac{g_{o1}}{g_{o2} + g_{m2}}$ is equal to g_{m1} into V_{in} and then evaluate g_m effective.

As I say better method surveys what put a equivalent circuit and solve nothing better than that, but why I keep saying you why I am using this technique, just to show you how much difference will do if I go from single stage to cascode, because that gives you some numbers immediately to see, this may not be the method you should use for real circuit solvers even spice does not use this, but why I chose this is not even given in many books because people do not believe that this is way I, but I want to explain you how much cascode is really affecting you and this is the way of explaining that.

So, $I g_{o1}$ into $1 + \frac{g_{o1}}{g_{o2} + g_{m2}}$ just collect this term on the other side and I is equal to $1 + \frac{g_{o1}}{g_{o2} + g_{m2}}$ by g_{m2} is equal to $g_{m1} V_{in}$ and therefore, g_m effective is I by V_{in} that is what you said, for this condition we already said V_{o2} is 0 we already assumed and for that we are solved. So, g_m effective is g_{m1} upon $1 + \frac{g_{o1}}{g_{o2} + g_{m2}}$, if I connect the term properly I will get g_m effective is $g_{m1} \times \frac{g_{m2} + g_{o2}}{g_{o1} + g_{o2} + g_{m2}}$ is that, ok.

Now, g_m typically Trans conductance of an amplifier should be higher or lower for a good amplifier gains Higher.

Student: Amplifier.

So, typically g_0 which is $1/r_0$; that means, g_0 should be very small if you want larger gains. So, in general this is the output resistance of a transistor is the order of mega ohms, typically g_m is the order of milliohms or millisiemens, since this is million that is mega or 1 upon micro you can say g_m are always much higher than g_0 of course, given a value please check it devices till saturation and this is valid if not use the full expression I am not saying.

But let us say g_m are much higher than g_0 which normally will be in 2 to 3 orders, then you can leave g_0 and figure it out. This term if I leave g_0^2 , so g_m^2 plus this compared to g_m^2 plus g_0^2 will use g_0 this by this is 1. So, effective g_m is nothing but equal to g_m .

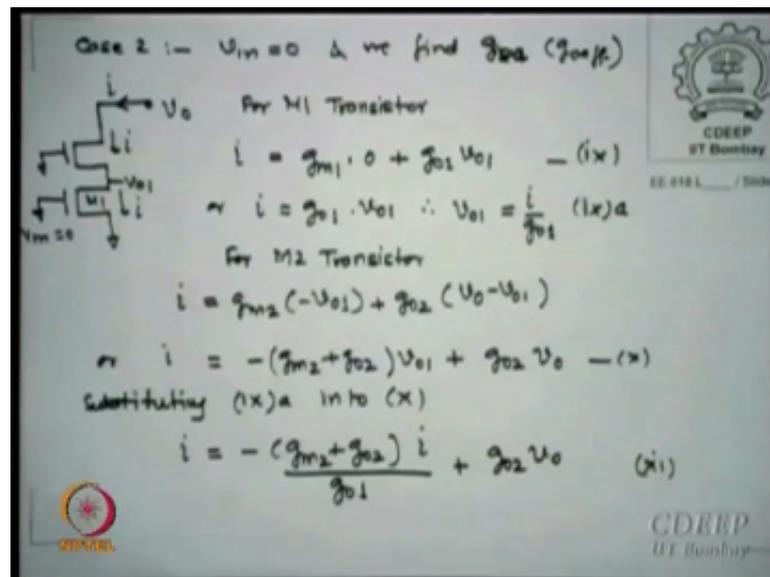
So, after even cascading, I have not really modified my g_m terms it is modified I am not saying it is not, if you substitute this value it will be slightly different from the just g_m because, this term is slightly larger than this g_0 is smaller, but let us say it is this is 10 to the power minus 3 minus 6 minus 8, so even if there is a slightly more values in the denominator, but ratio wise it is extremely small 0.99999 something kind of thing.

So, we say practically g_m is effective g_m one. So, 1 on the feature of a cascode was that it did not change g_m , then if gain has to move we already said what is g_m gain is g_m effective times r_0 effective, so obviously, if your g_m is not changing the other term must be getting boosted otherwise there is no way I can boost the gain ok.

So, then we must now evaluate r_0 effective and figure it out how much it is more than the normal r_0 I have and if it is much higher, that means my gains will be proportionately higher is that correct. As the ratio of r_0 effective to r_0 is essentially times that much times the normal gain will be boosted without losing g_m value is that correct, now we will see why we are interested so strongly talking of g_m .

So, is that in cascode we are not gone out of our everything done, we just say g_m effect is a g_m is that everyone has written? Case 2 I want to find r_0 effective. So, what is the technique we said put V_{in} equal to 0.

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Is that for AC everywhere this is anyway grounded and put a output voltage V_0 which inters a current I , you see this standard method of finding output resistance; short all dependent independent voltage current open the current sources and short all voltage sources independent ones is that clear to you and then apply a voltage at the output and measure the current there for the circuit V by I there is the output resistance. So, same technique has been employed bias is that ok.

So, for M1 transistor V_{in} is 0, so g_{m1} into 0 plus g_{o1} into V_{o1} or to say V_{o1} is I by g_{o1} is that for the transistor M1 V_{in} is 0. So V_{o1} is I by g_{o1} for the M2 transistor a upper one maybe, I should write I think you are know you already have that, but for the M 2 transistor the current is g_{m2} times V_{gs} , how much is V_{gs} ? 0 minus V_{o1} .

Student: Minus 0.

So, minus V_{o1} and how much is V_{ds} for this g_{m2} times V_{ds} or this minus this. So, V_o minus V_{o1} is that ok, I collect the terms again minus g_{m2} plus g_{o2} into V_{o1} plus $g_{o2} V_o$ just connect V_{o1} terms and then substitute V_{o1} from this into the second one, last time what did I substitute I picked up from M 2 and substitute in M 1. Now I picked up from M 1 and substituted in M 2, then I get I is equal to minus $g_{m2} g_{o2}$ by g_{o1} into I plus $g_{o2} V_o$ just substitute V_{o1} from here and you get these expressions. What do I then collect items and then V_o by I is r_{o} effective, I collect I terms and then V_o by I is the output resistance as seen from the output terminal net.

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$$\begin{aligned} \text{or } \left(1 + \frac{g_{m2}}{g_{o1}}\right) i &= g_{o2} V_o \\ \text{But } \frac{i}{V_o} &= g_{o\text{eff}} \\ \therefore g_{o\text{eff}} &= \frac{g_{o1} g_{o2}}{g_{o1} + g_{o2} + g_{m2}} \\ \text{or } Y_{o\text{eff}} &= \frac{g_{o1} + g_{o2} + g_{m2}}{g_{o1} g_{o2}} \\ &= \frac{1}{g_{o2}} + \frac{1}{g_{o1}} + \frac{g_{m2}}{g_{o1}} \\ &= g_{o1} + \left(g_{o2} + \frac{g_{m2} g_{o2}}{g_{o1}}\right) \frac{1}{g_{o1}} \\ &= g_{o1} + \left(g_{o2} + g_{m2} g_{o2} g_{o1}\right) \frac{1}{g_{o1}^2} \end{aligned}$$

So, I collect the terms of I and then figure out I by V 0 is go effective substitute everything and I get go effective is go1 into g o2 upon go1 plus g o2 plus g m2 and I invert it to make it ro effective. So, ro effective go1 plus g o2 plus g m2 upon go1 g o2 divide this each term 1 upon g o2 plus 1 upon g m2 go 1 plus g m2 by go 1 into r o2, till do some collection of terms and you get r o1 plus r o2 plus g m2 r o2 r o1, what is the ro effective r o1 plus r o2 plus g m2 r o2 ro 1 that is something fantastic is happening ok.

But what is g m2 r o2 the gain of second stage amplifier individually is that correct. So, A V2 we can I have say if you are noted down I will just write down the expression. So, if I collect all this term and write g m2 r o2 as A Vo2, then I get ro effective is precisely if you seek it I think there is some mischief here.

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$$g_{m2} r_{o2} = A_{v2} = A_{v2}$$

$$\therefore r_{o,eff} = r_{o1} + (1 + A_{v2} r_{o1}) r_{o2}$$

$$= r_{o1} + r_{o2} + A_{v2} r_{o1} r_{o2}$$

$$= r_{o2} + (1 + A_{v2}) r_{o1}$$
 Even if $r_{o1} = r_{o2} = r_o$ & has typical value of $10^6 \Omega$
 Then for typical $g_m = 10^3 \text{ S}$, $A_{v2} = 10^3$
 Then $r_{o,eff} = 10^6 + (10^3) \times 10^6 \approx 10^9 \Omega$.
 Also $A_{v0} = g_{m,eff} \cdot r_{o,eff}$

This will come r_{o1} into r_o plus that r_{o2} term we should on A_{v2} into r_{o1} [FL]. So, r_{o2} plus $A_{v2} r_{o2} r_{o1}$ and r_{o2} are equal, why are they equal we said transistors are equal currents are equal $1/\lambda$ is constants. So, r_o are equal.

So, essentially what is it trying to tell and gains are typically of the what order 100 to 1000 to 10000 maybe million, gains of amplifiers can be as high as 1000, 10000 a million is 10 to the power 6 gains are possible, not that every time you will use them but possible opamps have 10 to power 6 or anyway available is that current gains are available.

So, you normally A_{v2} will be very high compared to any other term there and neglect all r_o , but A_{v2} into r_o will be heavily increasing the r_o value, A_{v2} is 1000 and r_o is mega ohm. So, from mega ohm it has gone to giga ohms. So, now the output resistance of a cascode amplifier can be boosted by this A_{v2} term and if r_o effective is high A_{v0} which is nothing, but $g_{m,eff}$ into r_o effect is as much high, though $g_{m,eff}$ is same as g_{m1} is that correct; $g_{m,eff}$ is same as g_{m1} , but r_o effective is gain times the r_o is now pushed there one of the stage, gain A_{v2} into r_o is boosting the gain r_o and therefore the gain equally get.

Now, we were making a statement that if I would have done a cascade, what would have been the gain? Instead of putting cascade; let us say A_{v1} is the gain of first stage A_{v2} is the gains second stage on that equal then it will be $A_{v1} A_{v2}$ is that correct. So, here

also if you see if you just look at this expression A_{Vo} , it can also be expressed in do not write all of it just writes this.

(Refer Slide Time: 29:20)

$$A_{Vo} = \frac{g_{m1}(g_{m2} + g_{o2})}{g_{o1} + g_{o2} + g_{m2}} \cdot \frac{g_{o1} + g_{o2} + g_{m2}}{g_{o1} g_{o2}}$$

$$= g_{m1} g_{m2} r_{o1} r_{o2} + g_{m1} r_{o1}$$

$$= A_{Vo1} \cdot A_{Vo2} + A_{Vo1}$$

$$\approx A_{Vo1} \cdot A_{Vo2} \quad \text{as } A_V \gg 1$$

$$\approx A_{Vo1}^2$$

Hence Cascode Amplifier Boosts the Gain
 in same way as Cascade case.
 But we wish to know now about GBW

Function A_{Vo} is A_{Vo1} plus A_{Vo2} plus additional this since, A_V s are much larger square terms are larger than single terms.

So, typically gain is gain square same as what cascade could have got it is that clear, cascade could have got how much gain square of 2 of them here also I am getting same gain little more, but almost same order of gain. Then what did I achieve I have you said gain in boost gain product would seem to be similar for the case of cascade as well as cascode, but what is changing or not changing is the gain bandwidth product is that point clear, the effective gain probably in a 2 stage cascade is same as one single cascode, it has not of course additional term is there. So, you may say it is still boosting, but in 10^6 plus 10^3 it is still 10^6 . So, you say gain is only AV^2 it is not really boosted as I thought, but then what is that I keep saying boosted from the single stage I certainly I only is one single stage there and I have boosted the gain from 1000 to 10000 6 , which is what I did for the cascode because ro effective I could boost thousand times ok.

Now, the term which is most important for us as I say you write down, this expression they are simply derivational and there is nothing great about; the point I was trying to make is essentially cascode single stage is not very great compared to 2 stage cascade because,

we are comparing all the time is that why not connect to amplifiers in series which is always done many places.

So, what is this cascode is actually doing. So, we say there what was the problem I said if I make A_{V1} and A_{V2} there or AV square the gain bandwidth will have new gain, but the bandwidth will go down because GBW is constant. So, as I keep putting cascade stage my bandwidth will keep on going reducing by that number, but that is does cascode does the same then why do a cascode, if it does not then we say I have beaten up please remember GBW to some extent is called figure of merit or technology constraint, we always GBW constant [FL].

Now, with cascode can be beat this. So, called technology constraint and here is that explain everyone written on this is what it is saying.

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Gain Bandwidth Product = GBW_{eff}
 $= \frac{g_{m,eff}}{C_L}$
 Now Gain of Cascode = $A_{V,eff}^2$
 However GBW for single stage of normal Amplifier
 $= \frac{g_{m1}}{C_L}$ Since $g_{m,eff} \cong g_{m1}$
 $\therefore GBW_{cascode} = GBW_{single\ transistor}$
 In Cascode, therefore the increase of Gain ($A_{V,eff}^2 \cdot A_{V,eff}$)
reduces Bandwidth to maintain $GBW_{single\ transistor}$

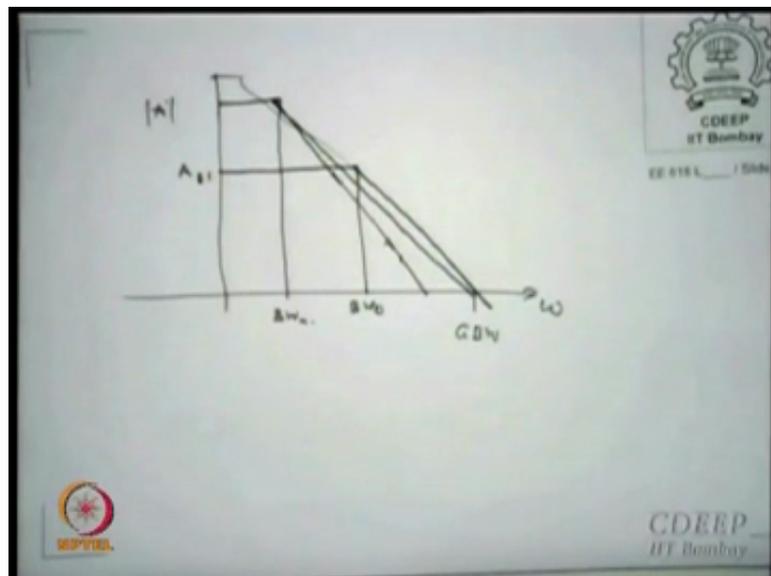
Gain bandwidth product of a cascode is g_m effective by C_L , but what is g_m effective g_m 1 by C effective is that correct, C effective means C_L plus any other capacitance you put there is fair enough. The gain of a cascode is AV square the bandwidth is g_m effective by C_L , g_m effect is how much g_m 1 for a single stage the gain bandwidth product is g_m by C because, g_m 1 is this which is same as the earlier one. So, what is it trying to say gain bandwidth product of a cascode is same as single stage amplifier?

But from the single stage amplifier what does it change gain? How many times thousand times or whatever the gain of that amplifier initials this? That many times I have boosted the gain, but my gain bandwidth product has a change is that correct. So, that is something I achieved that I have not missed the point of GBW, but I still boosted please last time showed you some figure maybe I will repeat for you just write on this. In the case of cascade what would have I lost in case, I boosted the gain by that much amount I would have lost the bandwidth is that correct.

Now, I say no gain bandwidth is not changing even with the cascode stage, but gain has been independently as if boosted by me is that clear, by increasing the this because g_m by C_L is the no different from g_m by C_L for the 2 cases. So, the GBW point did not move that helped that g_m effective is g_m 1 has help me now to fix that point independent of which amplifier I use that.

So, here is the figure will come back to it, maybe I should draw better figure just a minute. I will come back to this expression once again in case you will have written let us say I have an amplifier which is gain in db is versus frequency.

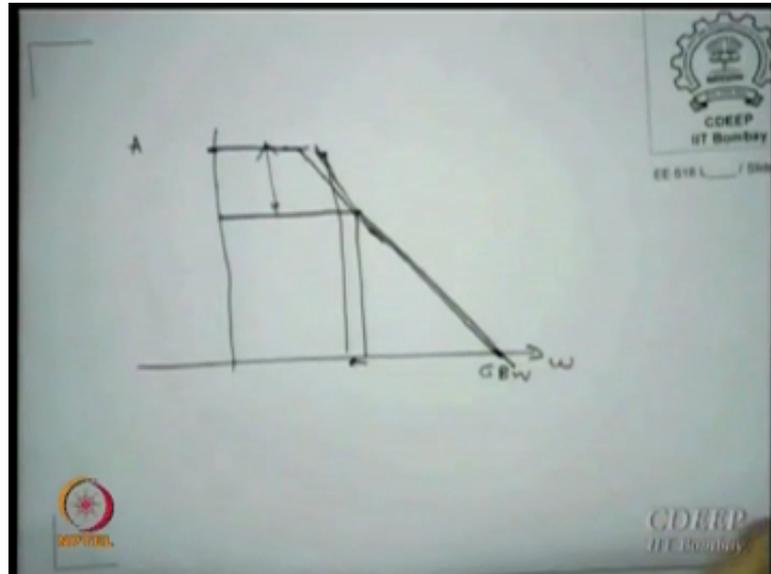
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So, this is my again and let us say it has a single pole as I have taken the case, this is my GBW this is my A_{o1} or something. If I would have boosted the gain so what and this is my bandwidth, if what have boosted the gain for my cascading let us say I go here then this bandwidth point would have itself sorry it is enough.

So, what is the change you would have occurred Bw original and Bw new. So, I would have lost the bandwidth I increase further, I would do this again this further bandwidth will go down.

(Refer Slide Time: 35:38)



Now if I do the same thing for Cascode, what I am doing is the following a versus omega this is my normal single stage amplifier, now I am boosting the gain I am going from here to here, I may still lose some bandwidth I am not trying to say because that ratio is not exactly 1. So, some part I may, but this slope is such that it still meets the same point.

So, what has change occur you should have this slightly this side? So, bandwidth reduction is still there it is not there it is not there, but it is the way figure is not very good it is very close to the original bandwidth, but what a shifted the gain boosted the gain to keep the same slope now my bandwidth slightly is going down, but marginally going down and I say as if I am not even worried about that small change. So, I say I am retaining bandwidth what I had, but I have boosted the gain is that correct that is the strength of cascode.

Student: How can we say?

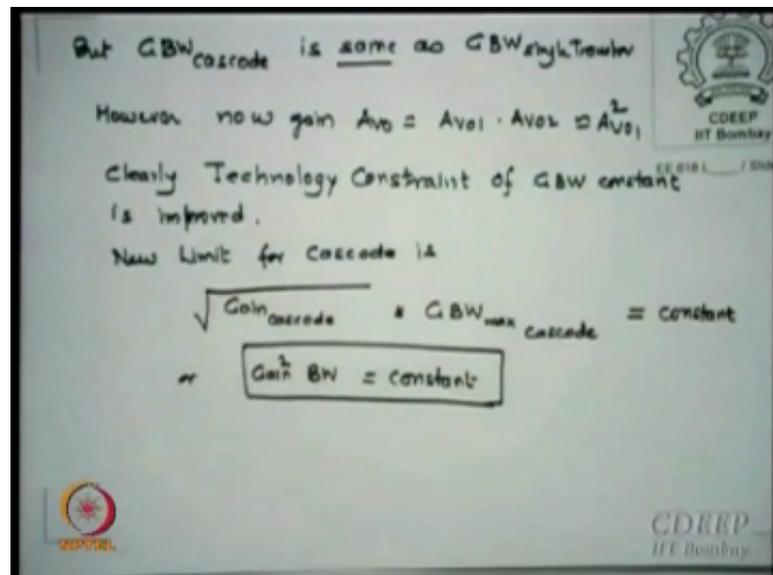
We will solve example give you the result.

Student: Bandwidth is cut by all output bandwidth.

(Refer Time: 37:00) I agree, but it is not related only to that that is what I say because this go effective has many terms, so a gm effective so overall since you have to meet GBW if you extrapolate it for higher gains, essentially what I am saying you keep extrapolating that value then we will find gain has been boosted, but bandwidth is not reduce in the same ratio is that clear that is exactly the strength of cascode.

Now, catchword in this all game was which is why I said you all the figures and everything was this, we should realize what I did actually I just fooled myself I said look at this last line you can read down that is most important.

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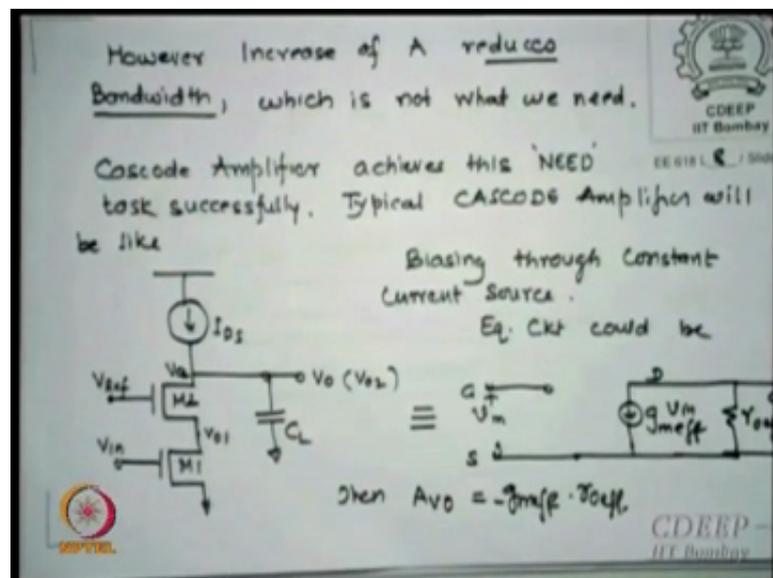
The gain bandwidth of cascode is same as gain bandwidth of a single stage amplifier; however, A_{v0} is A_{v1}^2 clearly the technology constraint is now new is under root gain cascode into the old GBW is now constraint is that correct because, the new gains square who can cascode [FL] gain square Ir single stage [FL] equivalently it is gain under root gains this of cascode multiplied by old GBW, is the new constant which you have got it this is called the new parameter figure of merit for a amplifier. Normally this would have been your figure of merit and now cross that limit that is exactly what I was trying to achieve think of it; how did I solve?

So, gain square into bandwidth is now constant, not gain bandwidth that is something is great we have achieved out of this is that clear to you.

Student: (Refer Time: 38:57).

Because, further increase will shift now you I mean not that infinitum it can go is that clear to you. So, it is no bandwidth is reducing it is not that, but it is gain square time bandwidth is constant not get into bandwidth, now all this game which I did not show you or did not say specifically if you see your cascode amplifier. Once again very seriously I am just trying to fool myself I kept on telling this is a single stage cascode it is called single stage cascode, but in reality it is also cascading 2 things. You have 1 amplifier which is common source; Output of a common source which is V_{O1} is fed to this amplifier which is common gate.

(Refer Slide Time: 39:55)



So, I am actually cascading 2 amplifiers, even now only thing is instead of 2 common source amplifiers the second stage now is common gate and the advantage of when I now show you common gate this will be very obvious like in the case of common base amplifiers. The current gain is unity same is in this case the common gate amplifiers do not give you any current, because source current drain current same. So, it is almost unity current gains, but what is the advantage it allows you to shift the let us say what is the first stage is doing raj you look at it, M1 is a common source amplifier. So, what does common source amplifiers characteristics converts voltage into current, common gate amplifier improves the output impedance just now you have said.

So, unstill available this is the gives the same current. So, what are improving the current source equal and voltage dependent current source has become far superior compared to single stage is that clear. So, I have not really achieved fantastic or something I was trying to boost every time, but the idea was to show I have improved the current source from the normal stage amplifier, which has now higher output register which is a good current source, how higher output resistance means good current source? So, all that I have done is by this technique is to improve good current source which normal, we see normal voltage to current converters have been relatively r_o is not very bad even there 10 to power 6 or kind, but this has actually how many how much I want for a good current source infinite.

So, by boosting this I am trying to get better current source out of the amplifier is that equivalently. So, actually all statement [FL] the funda point is that, if I connect the twos which we can get me what really I am looking for. So, analog design [FL] 3 amplifier will discuss quickly from the rezarvis book common source, common gate, source followers and when see which ones have what property and when connected what it will do for you is that correct.

So, as a designer I will do analysis because I then I have to no values. So, I will have to do analysis substitute the values, but I like to know a priory that which once I should use for purpose spec of I am looking for and this is what I am trying to hint every now and then that this course is not just solving a problem, but just to tell you that by doing this I can achieve something which a prior I was not aware I could solve a cascode I will show you r_o increase, but why I did all this because I figured out this actually can do this job.

So, tomorrow there is some biomedical instrumentation requirement comes you want a constant current to be driven because, the time taken for charging the input capacitor there has to be constant ECG monitor, may at that time you may require a cascode amplifier because you need a quotient current source as good as possible, other it has a time constraint it will not switch quickly. This is an issue which in real life applications I can see which ones to use.

So, as a designer I will not be told [FL], but for I doing analysis, I will figure it out what is that characteristics I get out of it which when needed I can then employ. So, their difference is that clear analysis is always required to put a point, but you must remember

the point is more important than the analysis and then we are doing all this to show if this need appears, I will pick up this. Design now what people designers are expert about as I keep saying they are very good in coping all of you are, but may be all of us also. So, they try to use someone else's result, but many a times the kind of value or some spec is not same between the 2 and that may actually kill you the other way because, that is what the analysis totally. If you do twinkle on this may also go like gm effective here remain gm, you do something else that also changes than the whole purpose would have actually lost to you is that clear.

So, in future the difference between analog circuit course and analog design course is only this let us we still solve the same circuits, which we have done any times. But we now learn from them what the advantage of using this. So, these issues you should keep in mind all the time because these are the only things which are required for a good designers, given an application decide this spec can I do this plus this. So, that must strike you and there is no solution for each case available in the market is that correct. So, each application will require different thinking and therefore, different design and therefore people say it is slightly difficult [FL] is a digital [FL], but to some extent yes sorry.

Student: Sir, gm by C gains bandwidth product or only the bandwidth.

It is always gain bandwidth product gm by C is a gain bandwidth product, I will solve this is right now take from me I will not solve for frequency response so far. So, I am not come to it I will prove it what you are asking, it is always gain bandwidth product a not bandwidth.

Student: If as a gain bandwidth product is constant gain is increasing then bandwidth (Refer Time: 45:55).

For a cascade yes but cascode that is what I proved you that the GMC does not change, but gain still boosted.

Student: Can with product remain constant?

Correct.

Student: Gain boosted.

Gain increased which is in cascade did not happen because, any single stage I follow another stage the gain if gain increased bandwidth automatically goes down GBW may still remain your point, but the bandwidth reduction is too strong, if I keep increasing the gain stages thousand times [FL] thousands time bandwidth [FL].

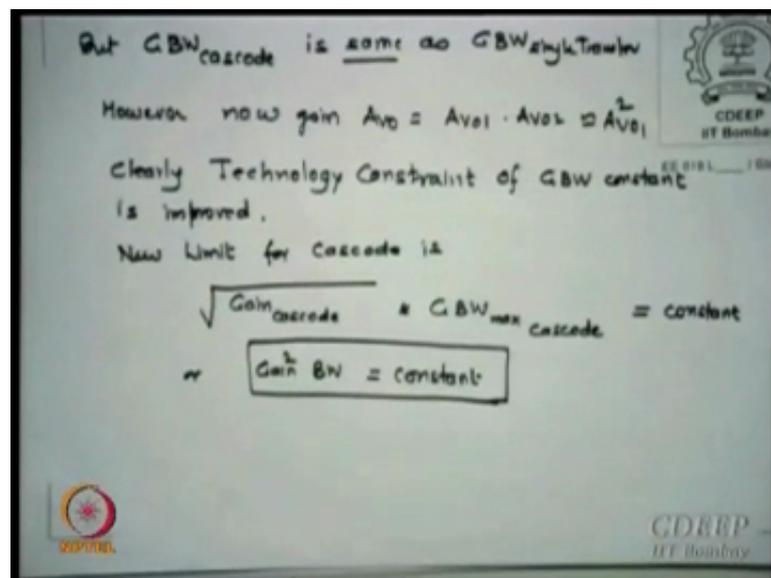
Student: But cascode (Refer Time: 46:27).

Cascode does that since it actually allows you to slope to be modified compared to cascade I am able to reduce bandwidth, I am still reducing bandwidth, but marginal compared to the cascade stage, we will solve a problem plot a bodes plot and show you where they match ok. Now before we go this cascode stage.

Student: (Refer Time: 46:46).

I am very sorry is this sorry, just note down I will come back to solve the values of

(Refer Slide Time: 47:00)



This and then I show you all that I am trying to say, I have changed the constraint now using cascode I change the constraint. Because gain square [FL] a again square [FL] under root [FL] gain into gain bandwidth is gain square bandwidth gain cascode is A V square, under root of that is AV. So, gain into gain bandwidth is gain square into bandwidth is now constraint this is the new constraint is that.

Student: (Refer Time: 47:29).

Cascode is not a single stage amplifier that is what I have proved just now, this is only true for cascode stages this has been derived for cascode otherwise gain bandwidth is a constant, single stage we have done put second stage again increases bandwidth goes down nothing you can do on that that is [FL] ok.

Student: Bandwidth decreases by the square of that. (Refer Time: 48:00).

No it is does not under root of that that is what I am saying it will actually reduce by under root of that, I show I will give as value I will actually plot the real values for that then we will see actually slope changing is how much ok.

Student: Bandwidth square is constant.

I will check it but this is correct, someone says is this gain increases enough can I do something more than that, I think cascode people came out with another circuit as a here is another cascode amplifier which is gain boosted cascode amplifier. Now already you have boosted the gain.

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Gain Boosted Cascode Amplifier

new N1 & N2 equations are

$$i = g_{m1} V_{in} + g_{o1} V_{o1} - C_i$$

$$i = g_{m2} (-V_{o1} - A_{o2} V_{o1}) + g_{o2} (-V_{o1}) - C_{i2}$$

Solving

$$g_{m\text{eff}} = g_{m1} \frac{g_{m2} Y_{o1} (1 + A_{o2}) + Y_{o1}/Y_{o2}}{g_{m2} Y_{o1} (1 + A_{o2}) + Y_{o1}/Y_{o2} + 1}$$

Further

$$g_{o\text{eff}} = [(1 + A_{o2}) g_{m2} Y_{o2} + 1] Y_{o1} + Y_{o2}$$

$$= Y_{o1} + Y_{o2} + A_{o2} (1 + A_{o2}) Y_{o1}$$

Now I am in amplifier which further boost the gain, what it should not change a gain being cascode stage the gm should not change, but what should therefore it increases ro effective.

So, you want even better current source now you have another case in which I can have gain boosted cascode amplifier, the method here is simple in the first cascode case you just first draw the circuit and then expression. You start looking at my first 1 than you right; I have a same as M1 M 2 here I actually put a ground there the gate of 2 was reference to a DC value or grounded for AC, instead have an amplifier sitting there which is receive an input V_{01} and transferring minus a times V_{01} to the gate of M 2 is that clear; all that I did that I have boosted earlier it was $0 \text{ minus } V_{01}$.

Now, $A_{V01} \text{ minus } V_{01}$, so it is slightly a plus 1 times V_{01} is what now I am giving to the gate of M2 this is called boosted gains or boosted r_o , same way I can repeat the same expression for M 1 and M 2 and figure out by same logic instead of V_{ds} what should I use for the first 1 V_{ds} same as V_{01} no change, for this the V_{gs} is how much now minus V_{01} minus $AGB \text{ times } V_{01}$ is that, how much is this V_{gs} this minus this. What is output of first amplifier here at the gate A? So, a minus a times V_{01} or AGB I called gain boost.

So, $AGB \text{ times } V_{01} \text{ minus } V_{01}$ that is $AGB \text{ plus } 1 \text{ times } V_{01}$ is the V_{gs} substitute there, this term does not change why it does not change because that this remains same there is nothing change at the V_{ds} is that ok, only V_{gs} has changed for M 2 V_{01} V_{ds} has not changed for M2. So, I am only changing the V_{gs} please this voltage is the gate voltage which is minus a V_{01} is that correct this is still V_{01} . So, V_{gs} is minus a V_{01} minus V_{01} . So, minus A plus 1 V_{01} , if I substitute this I get g_m effective long enough expression I derived and if I say r_{o1} by r_{o2} is close to same. So, these are ones these are larger this terms are larger this can be neglected if everything cancels, so g_m effective still a g_m .

So however, if I look at g_m effective now for the same expression instead of $0 \text{ minus } V_{01}$, where you are using it should use $1 \text{ plus } AGB \text{ times } V_{01}$ terms. So, now you are going to get g_m effective is $r_{o1} \text{ plus } r_{o2} \text{ AV}_2 \text{ into } 1 \text{ plus } AGB \text{ times } r_{o1}$ [FL] is not it. So, it was $A \text{ V}_2 \text{ times } r_{o1}$. So, gain was resistance are only boosted by the gain stage of this normal stage, now that itself is getting multiplied by the boost stage gain of this stage is it to you not clear, I am only substituting where it was $1 \text{ one plus } AGB$ and rewriting the same.

So, now how much is r_o effective precisely saying A_{V1} times A_{GB} times r_{o1} this into this into these are small terms. So, what is the earlier 1 equivalent we say A_{V2} times r_{o1} , now I multiply it by A_{GB} . Now this A_G amplifier could be what kind of amplifier it could be, even another cascode that cascode may be driven by another cascode and may be the minimum value 0 finally can be there at the input.

So, 1 stage 2 stage n stage is of cascode can bring a desired gain what boost your really is that point clear, the amplifier I am using can itself be a cascode amplifier which may be driven by another cascode and an go till 3 stage 4 stage. So, that the net gain is what you are gain in looking for, in that case we will be able to get whatever A_{GB} you are looking for that can be attain without losing what bandwidths anywhere.

So, you just boost it there no poles will hit you there. So, keep doing and then you will get heavily boosted gain in this case is that correct. So, what is the advantage of gain boosting?

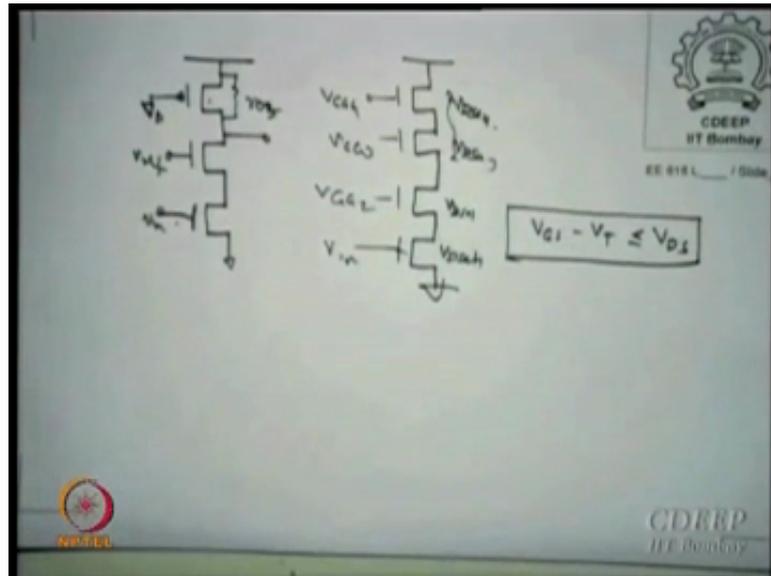
Student: Sir, gain might be the chances of oscillation or instability.

Possibility that is was a I am not discuss about the stability issue, we have we will come if there are this is equivalent circuit assuming very clean stage, but in real life not only the instability the 0 may be a issue not the pole as much the worry may actually come from A_0 the 0, may not be even on the imaginary exceed it may actually lie on the left are plane, which means it will oscillate. What is that it makes this is a good current source I put there, but this current source cannot be created out of nothing.

So, it could have a p channel device it could have an n channel device, it could have be series of 2 devices even there whose output resistance will also be there is that clear to you, show is now what I assume this is a ideal current source. So, $[F_L]$ infinite $[F_L]$, but in real life this may not be infinite, where that resistant will hit you then at the output node whatever is r_o here this r_o will shunted and if that r_o is smaller all that this cascode where people were doing is useless, because that resistance is smaller output is only seeing that resistance is that clear. So, that is why say as an amplifier you may worry you should not use that because, the actual r_o may not be very normal amplifier it will be say r_d is there then what we do?

So, r_d is the output resistance nothing r_o effective r_o effective is 1 billion the ohms parallel to 1 k. So, issue was that you have this you may have more than 1 transistor in series, now my worries start something like this. Let us say for some reasons this is 1 example that many others this may be p channel may be grounded for the heck of it or maybe I put V_b here which is bias something.

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Now, this V in here this is my output this is equivalent to some $r_o 2$ or $r_o 3$ you may call, now the 1 is of course, as I say- what is the major worry you have boosted r_o here and if this $r_o 3$ is smaller. So, the output is $r_o 3$, so what should I do here then I should also cascode the upper ones the v_{g2} v_{g3} and v_{g4} , if I do this I have the r_o of this stage maybe as much as r_o of the lower stage and maybe half it may still at least it is in giga or higher values you can create out of this. But this is the issue if you are boosting your r_o and if you are 3 or 4 transistor in series that madam surbhi was asking me how do guarantee there? What is the guarantee of a saturation a transistor is in saturation, if it is $V_{gs} - V_T$ is equal to V_{ds} or smaller than V_{ds} only then devices in saturation.

If that is so V_{d1} let us called this $V_{d sat 1}$ $V_{d sat 2}$ $V_{d sat 3}$ and $V_{d sat 4}$ for this case for r_o boosting, you did 4 r_o has got what you wanted good current source everything you say achieved. Now you have a issue that there are 4 V_{ds} in series is that correct a minimum you have $V_{gs} - V_T$ V_{d} chart is $V_{gs} - V_{T1}$ value, typically how much is the excess voltage I said 100, 200 mill volts ok.

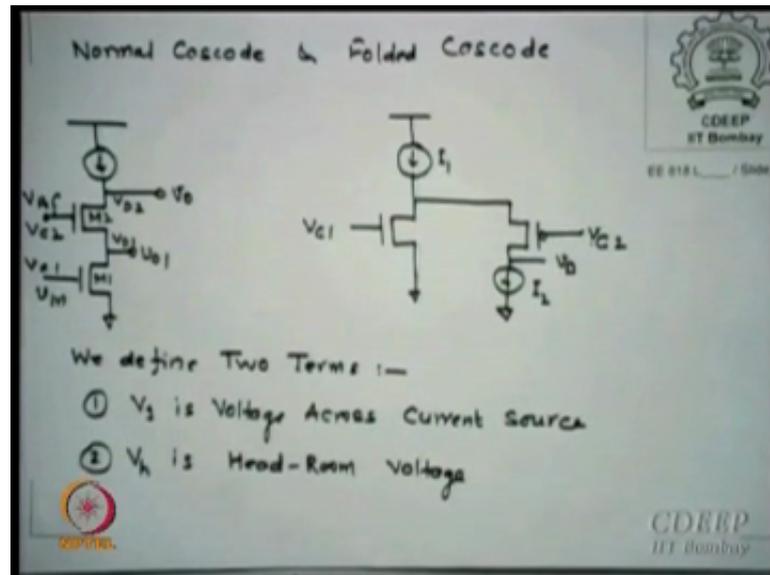
But now you have 800 mill volts your supply is 1 point 2 volt or 1 volt a times keep it saturated your headroom is practically will there. So, now you are worried that whether this amplifier will remain amplifier for a long any change in values of V_{ins} or V_{gs} , then I have a problem this amplifier may not remain in saturation, all transistor may not remain in saturation. If they do not remain in saturation, all the theory which I derived as she said; how do know I also do not know, but possibility is there that will be lost.

So, now I am worried that is this good solution, if I had to boost so much I must ensure that I am not using this essentially as an amplifier is that correct, but this is called telescopic. So, I can I will have a shown an op amp which is telescopic op amp which has is own advantages at some cost. So, will like to see that all the time putting things in series may not be that advantageous as it looks, if you are a 3 word supply fantastic no problems 11.2 there is an issue and why I keep saying.

Now, that is there is a issue because now power supply for digital part is 1 volt and I am forced to work with them independently [FL] why I do all this I am doing all this because, I am forced to work on cmos and also on the technology node which is digital node. So, I figure it out it was not so trivial as I thought I just thought everything is good everything is good is not really that good as I thought. So, do not use cascode as a very though as a concept it is fantastic no 1 can beat it is concept, but remember where to use that is a very crucial factors, we will use in a cascode opamps show you.

So, to avoid this to some extend I have I quickly last few slides and show you which is the word I use, I will do this cascode amplifier with resistive load later. There are 2 ways of doing this cascoding 1 is called normal cascade the another is called folded cascode.

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The right is folded left is normal, what is the difference I did here both transistor were n channels, the common gate amplifier transistor was also n channel and the driver was also n channel is that ok.

However, in the folded cascode the driver or the input of an amplifier is n channel device, but there is another device which is p type and it is look at it is instead of going up it is folded down by me now you say what it is. So, bring about we will see what it bring about by some things is that point clear this is called folded cascode, it has advantage of layouts and it has the advantage of supply voltage requirements both [FL], ok.

So, there is nothing very new I am teaching, I am trying to bring those issues which at times they do not want to hammer on. So, I am hammering that those issue nothing great is really being told, I will write give the sheets I will quickly read for you and explain you please keep your figure write with you because I cannot repeat both together.

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CASCODE

$$V_{G1} = V_{OV} + V_{TN}$$

$$V_{D1} = V_{OV} + V_h$$

$$V_{G2} = V_{OV} + V_{D1} + V_{OV} + V_{TN}$$

$$\text{or } V_{G2} = 2V_{OV} + V_h + V_{TN}$$

$$V_{D2} = 2V_{OV} + V_i + V_0 + V_h$$

$$\therefore V_{supply_CAS} = 2V_{OV} + V_h + V_i + V_0$$

Folded Cascode

$$V_{D2} = V_i + V_0$$

$$V_{G2} = V_{D2} - |V_{TP}|$$

$$V_{GS2} = V_{D1} = V_i + V_{OV} + V_0$$

$$V_{supply} = V_{D1} + V_i$$

$$V_{supply} = 2V_i + V_{OV} + V_0$$

Clearly $V_{supply_FCAS} < V_{supply_CAS}$

So, I will use figure from my board on sheet and I will show you what for the first normal cascode, what is how do we define V_{OV} V_{G1} minus a source is grounded. So, v_{g1} minus V_T is V_{OV} , so v_{g1} is V_{OV} plus what is V_{OV} V_{GS} minus V_T .

Student: (Refer Time: 63:20).

Is that clear so I will just trying to be little funny on that what is V_{D1} ? which is our V_{D1} shown there what is V_{D1} is the over voltage which is V_{D} saturation plus additional voltage which will allow transistor still remaining in that is the limit, which I want to go to. So, we say V_{D1} is the over voltage which is V_{D} sat plus some headroom voltage is that clear, what is why this V_h has been added with this additional this also device should remain in saturation, V_{G2} look for the term for the V_{G2} which is V_{D1} plus V_{OV} for the second transistor, which is V_{GS} minus V_T for that plus V_T because this is essentially V_{GS} of the 2 to second transistor.

So, it is V_{OV} plus V_{TN} then the v_{g2} can be written as substituting here V_{D1} from here into this I get $2V_{OV}$ plus V_h plus V_{TN} , then I evaluate V_{D2} which I get $2V_{OV}$ plus V_h plus $V_2 V_0$. A small V_0 is a average value of a signal which may actually because of the capacitors there average value which can be treated 0 in many cases, but just say swing [FL] because V_0 is swinging on the output.

So, what is the maximum value should be taken care in case it takes you out then. So, we want to keep it otherwise in many cases V_0 can be treated as 0 values, but for the sake of evaluation the peak value I should know, I add that also in my calculations is that correct the small V_0 is the peak value of the output which may not be very small at times small larger signal. So, I assume V_0 is present which in normal case is very small and neglected, but for the sake of clarity I say add that also. So, I get supply voltage should be $2 V_{ov}$.

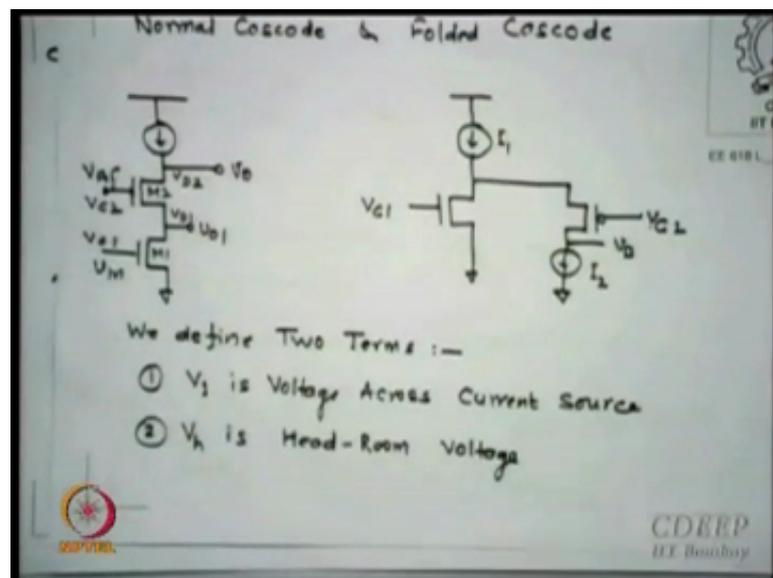
Student: Sir.

Yes.

Student: (Refer Time: 65:35).

V_{d2} is the voltage at this node is that correct this essentially is this plus or directly this.

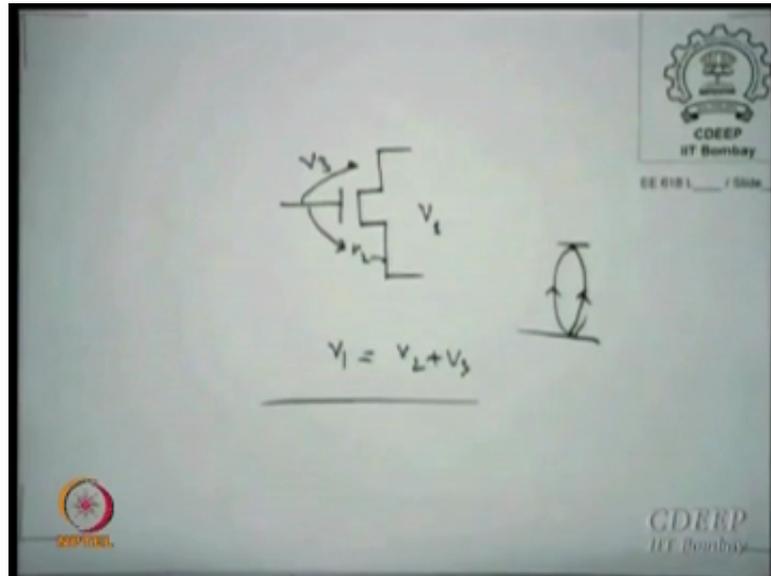
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Student: (Refer Time: 65:53).

Please remember in a transistor whichever way go in a circuit a theory [FL] easily [FL] if that is not happening then there is an issue.

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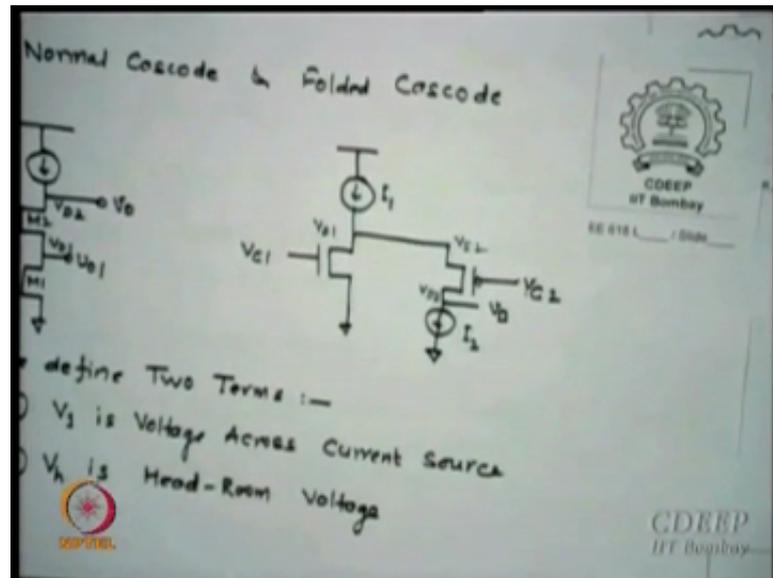


This voltage whatever is V_1 if this voltage is V_2 and this voltage is V_3 , V_1 must be sign wise V_2 plus this is the gate, either you through go through gate and from gate to the drain or source or you come from directly this, if I want to evaluate this and I do not know some things. So, I can go through gate and come to the drain is that point clear this is 1 way of doing it this is what I have used, this method is very strong used in bipolar is that clear this is your V_{be} this is your V_{bc} and this is your V_{cb} .

So, we keep saying when the transistor is externally reverse bias, but may become forward bias because this may become forward, that is exactly saturation stage in bipolar this is exactly how they do. So, this technique please be clear at a given 2 nodes give whichever path you come sum total of voltage must be same because between 2 nodes this is the difference that cannot be change. So, method is this or this must be same loops cannot be go through this or go through this, voltage difference is same irrespective ok.

So, tricks of the trade is try gains whichever you know you use that value to achieve the other one. So, [FL] hurriedly [FL] I may be small mistake here there, but the point I am saying if I do similarly for folded cascode please note down that, V_{d2} there V_{d2} sorry [FL] I am sorry she is right.

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Please remember this is V_{d2} p channel device please remember this is p channel device drain is down words, this is V_{s2} this is V_{d1} is that correct. The source voltage of p channel is same as drain voltage of n channels I_1 I_2 are the current sources which are biasing an np device they may be same in most cases they will be same ok.

But yes V_0 is essentially small 1 this is V_{d1} . So, V_{s2} is same as V_{d1} .

Student: V_{d2} (Refer Time: 68:35).

V_{d2} essentially is reference to either this or this minus this plus this, that is what I am saying.

Student: Normal.

Normal either find V_{d2} is equal to this plus V_{ds} of this, but V_{ds} can be derived from V_{gs} side also is that clear to you, I repeat V_{gs} minus V_T is V_{ds} saturation. So, I can go this way or I can go through gate and still arrive at the same equivalent values, try it yourself. The point I am saying is this v_{g2} is what V_1 drop is across current source V_1 is the drop across current source.

So, V_{d2} small AC signal the average value plus V_1 is V_{d2} is that, I repeat this voltage plus whatever is AC on that which may be not be small peak of that. So, this value is

drop across this plus small average extra value of V_0 is essentially the V_{d2} , what is V_{g2} gate voltage. I know this value I know V_{ov} so I can reach v_{g2} is that correct.

So, v_{g2} is nothing, but V_{g2} minus V_{gp} , please remembers V_{s2} is same as V_{d1} which is V_1 plus V_{ov} plus V_0 then the V supply voltage is V_{d1} plus V_1 , what is supply voltage? this value plus the drop across source or this value plus V_0 is to same as V_{d2} . So, I calculate V supply for folded cascode is $2V_1$ plus V_{ov} plus V_0 . I repeat V_0 is a very small term, but an larger signal the peak value may not be that small, therefore we kept it for the security. Why did we keep because you should not go there it is taking transistor is in linear mode. So, we put that value.

So, if I compare these 2 values what do see really, the V supply voltage of a folded cascode is slightly smaller than V supply voltage of full cascode normal cascode. So, what does that did we achieve something better what was the problem I first did told you, if I put everything in series I have that problem was huge supply voltage requirement.

So, partly I can save myself from that great trouble by putting folding, now in this case folded cascode has used n channel has driver p channel has the other side folding you can do otherwise. These are essentially therefore called cmos folded cascodes is that correct, the complementary word in digital they say gates are common in analog. We never say they are common p and n channel if there. Then we say they are cmos please do not think at no time, [FL] exception I should not at no time. Most cases we only use independent p channel in n channel and never use they as a common; so common gate terminals.

So, in that sense it is not equivalent of a digital cmos it is always both p and n channel have been used and therefore, it is cmos amplifier is that clear. Otherwise please do not compare it with the other side. So, the problem of power supply probably can be taken care by folding techniques and that is what will use in the folded cascode op amp we will actually folded to said some supply requirements.

See you then.