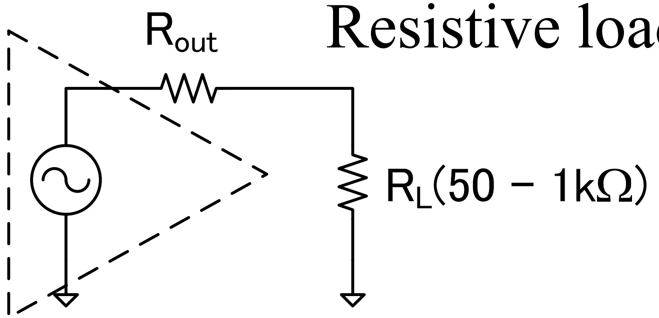
14. Output buffers

Kanazawa University
Microelectronics Research Lab.
Akio Kitagawa

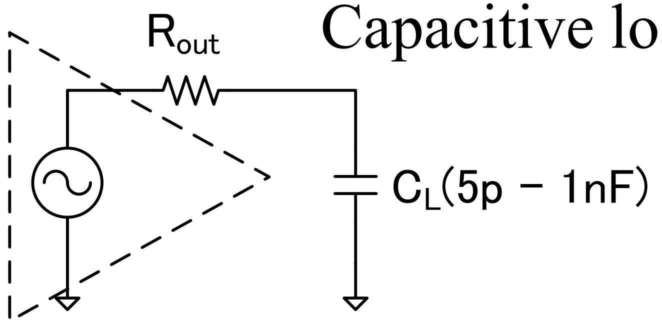
14.1 The foundations of output buffers

A drive of the load

Resistive load



Capacitive load



In any frequency, the output voltage is dropped for the low R_L.

In the low frequency, the output voltage is not dropped, but the cut-off frequency is lowered for the large C_L.

The low R_{out} (i.e. low gain amplifier) is required for the voltage output, i.e. the output stage of voltage amplifier should be buffered.

Required characteristic for the analog buffer amplifiers

- Low output resistance (The low voltage gain is acceptable.)
- Wide output swing (The source follower has a practical problem.)
- High Slew Rate (SR)
- Small distortion (i.e. good linearity)
- High power conversion efficiency (PEC)

$$\mathrm{PCE}(\%) = 100\frac{\mathrm{P}_{R_L}}{\mathrm{P}_{\mathrm{Supply}}} = 100\frac{\text{Load power}}{\text{Supply power}}$$

Class of the amplifier operation

Configuration	Class	Bias current	Linearity	Output swing	Output resistance
Common source	A	Large	Good	Wide	Medium
	AB	Small	Good	Wide	Medium
	B	Zero	Not good	Wide	Medium
Source follower	A	Large	Good	Narrow	Low
	AB	Small	Good	Narrow	Low
	B	Zero	Good	Narrow	Low

The class AB and class B amplifiers are called the push-pull amplifier.
The common gate amplifier cannot be used as a output buffer because of the large output impedance.

Evaluation of the distortion

Input signal $v_{IN} = V_P \sin(\omega t)$

Distorted output signal $v_{OUT} = a_1 V_P \sin(\omega t) + a_2 V_P \sin(2\omega t) + \cdots + a_n V_P \sin(n\omega t)$

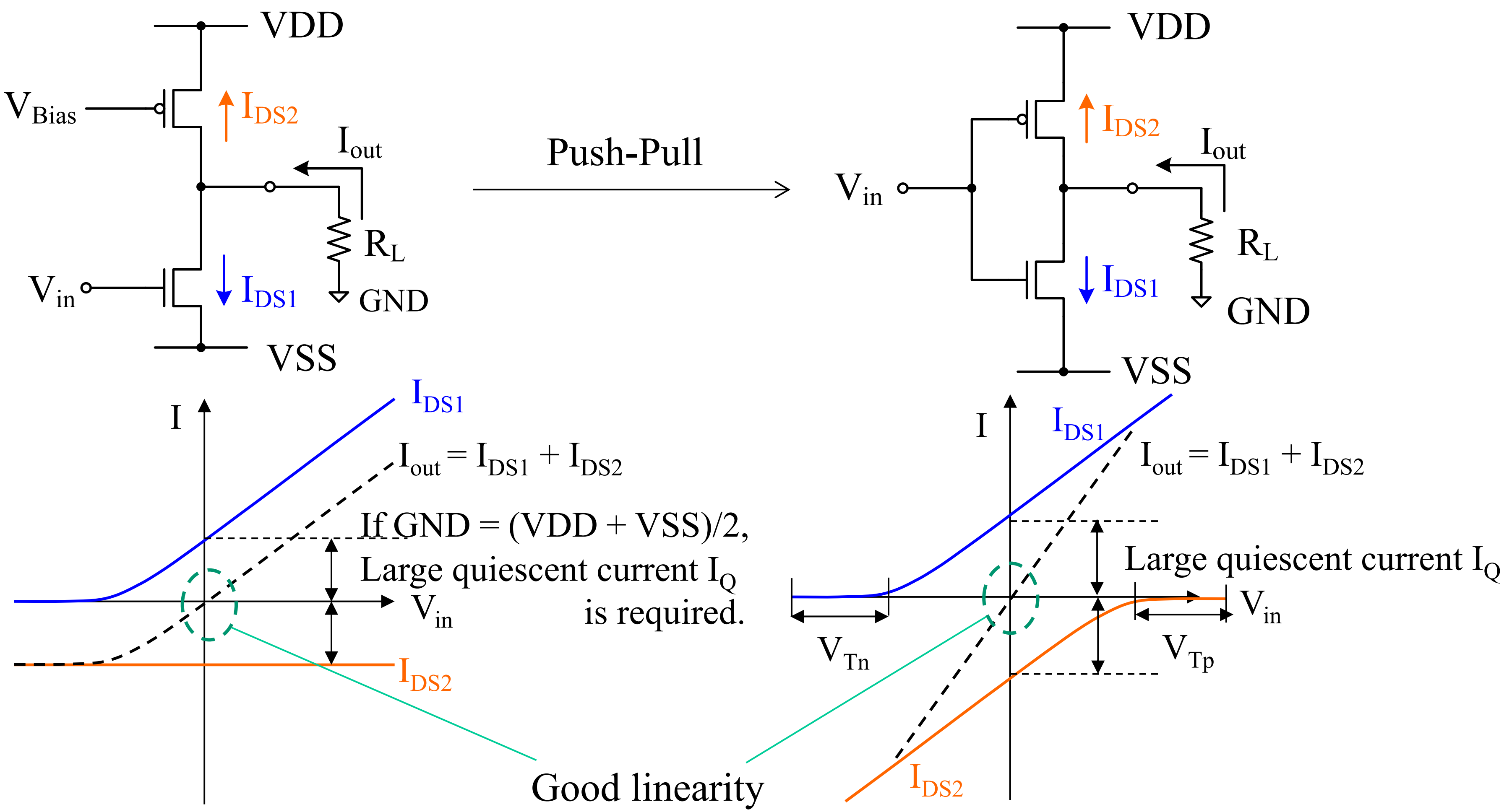
i-th Harmonic Distortion (HD)

$$HD_i = \frac{a_i}{a_1} \qquad (5.5\text{-}11)$$

Total Harmonic Distortion (THD)

$$THD = \frac{\sqrt{a_2^2 + a_3^2 + a_4^2 + \cdots + a_n^2}}{a_1}$$

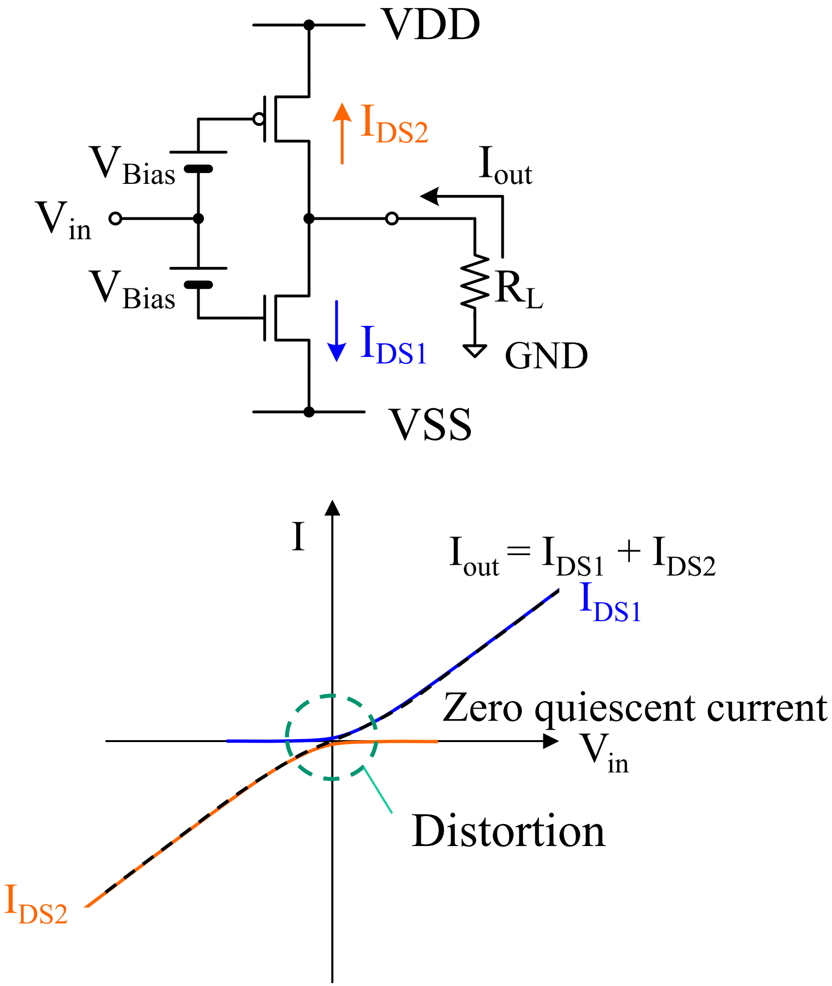
Class-A CS amplifier and Inverter



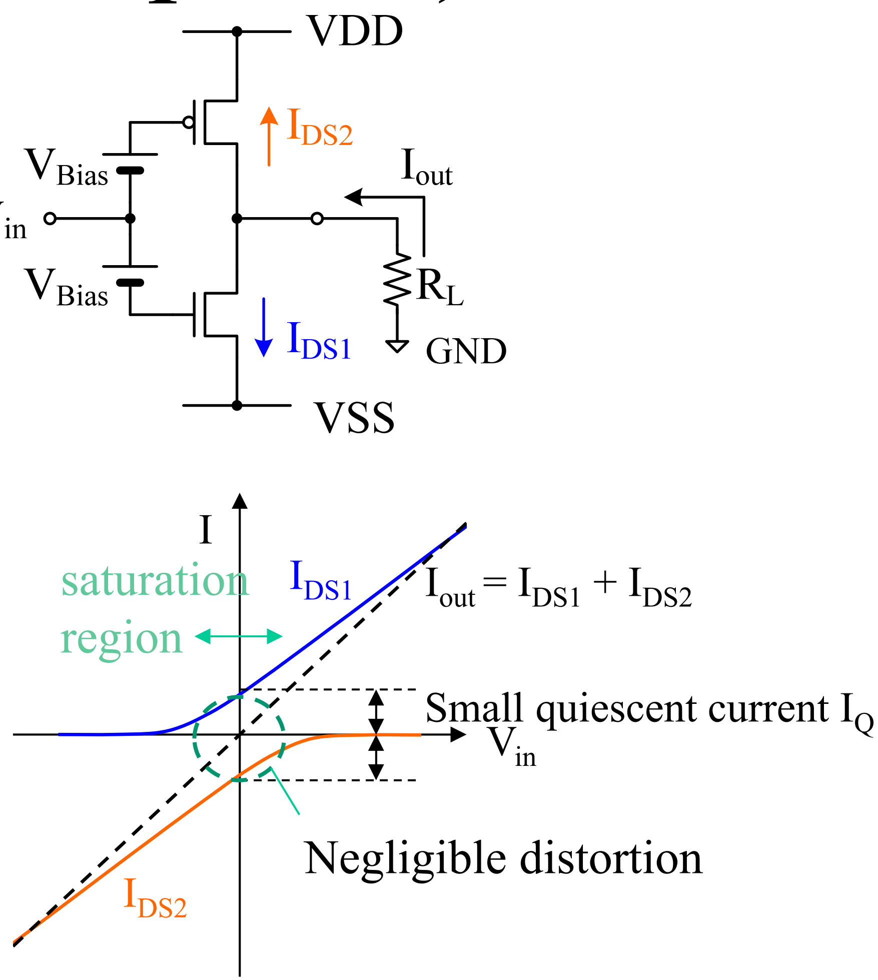
Class-A amplifier

Inverter (Class-AB)

Class-B and AB CS amplifier (Push-Pull Amplifier)



Class-B amplifier



Class-AB amplifier

PCE of class-A amplifier

$$\mathrm{PCE}(\%) = 100\frac{\mathrm{P}_{R_L}}{P_{Supply}} = 100\frac{\dfrac{(\frac{v_{out}(amplitude)}{\sqrt{2}})^2}{R_L}}{(VDD - VSS)I_Q} = 100(\frac{v_{out}(amplitude)}{VDD - VSS})^2$$

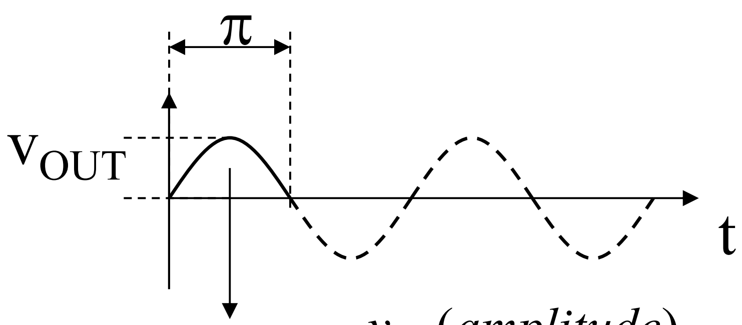
If the GND potential is (VDD + VSS)/2 and the full swing is VSS to VDD, I_Q = (VDD-VSS)/2R_L

Maximum voltage amplitude (Rail-to-rail) of class-A amplifier v_{out_max}

$$v_{out\_max} = \frac{VDD - VSS}{2}$$

$$\text{Maximum PCE} = 100(\frac{\frac{VDD - VSS}{2}}{VDD - VSS})^2 = 25\%$$

PCE of class-B amplifier



$$\text{Avarage} = \frac{v_{out}(amplitude)}{\pi}$$

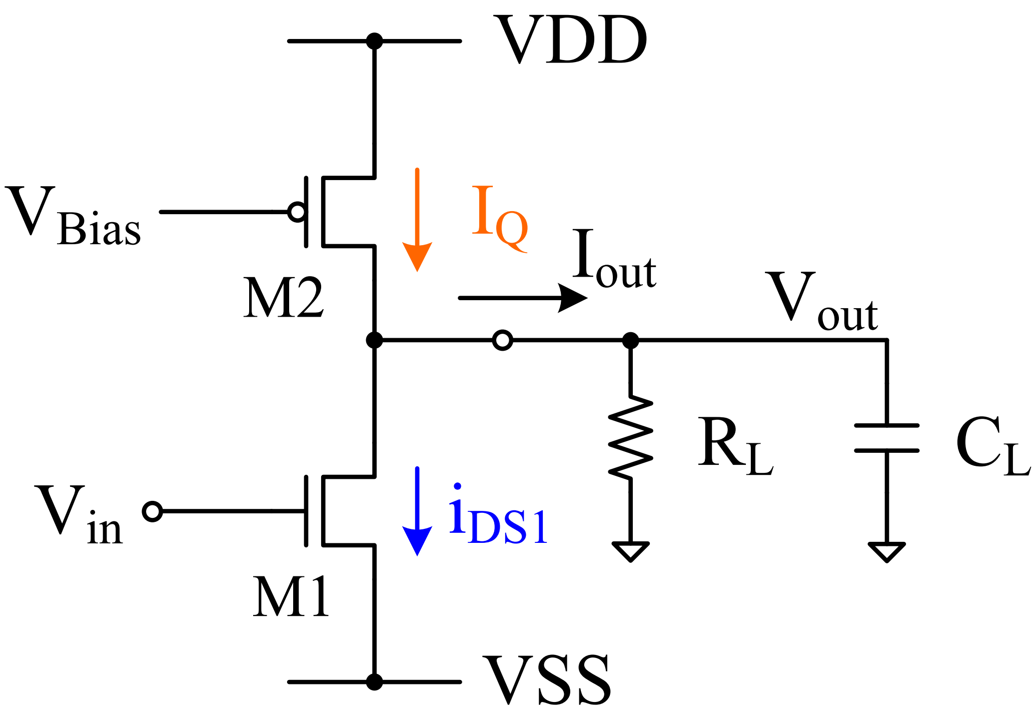
$$PCE(\%) = \frac{P_{R_L}}{P_{Suuply}} = \frac{(\frac{v_{out}}{\sqrt{2}})^2 \frac{1}{R_L}}{(VDD - VSS)\frac{v_{out}}{\pi \cdot R_L}} = \frac{\pi}{2}\frac{v_{out}}{VDD - VSS}$$

$$= \frac{\pi}{4} = 78.5\%$$

The PCE of the class-B amplifier is higher then the class-A amplifier, because of no quiescent current. <u>The class-AB amplifier is often designed to attain the PCE around 70%.</u>

14.2 Class-A CS amplifier

Circuit configuration



Output resistance $r_{out} = \dfrac{1}{g_{ds1} + g_{ds2}} = \dfrac{1}{(\lambda_1 + \lambda_2) I_Q}$

Output current swing

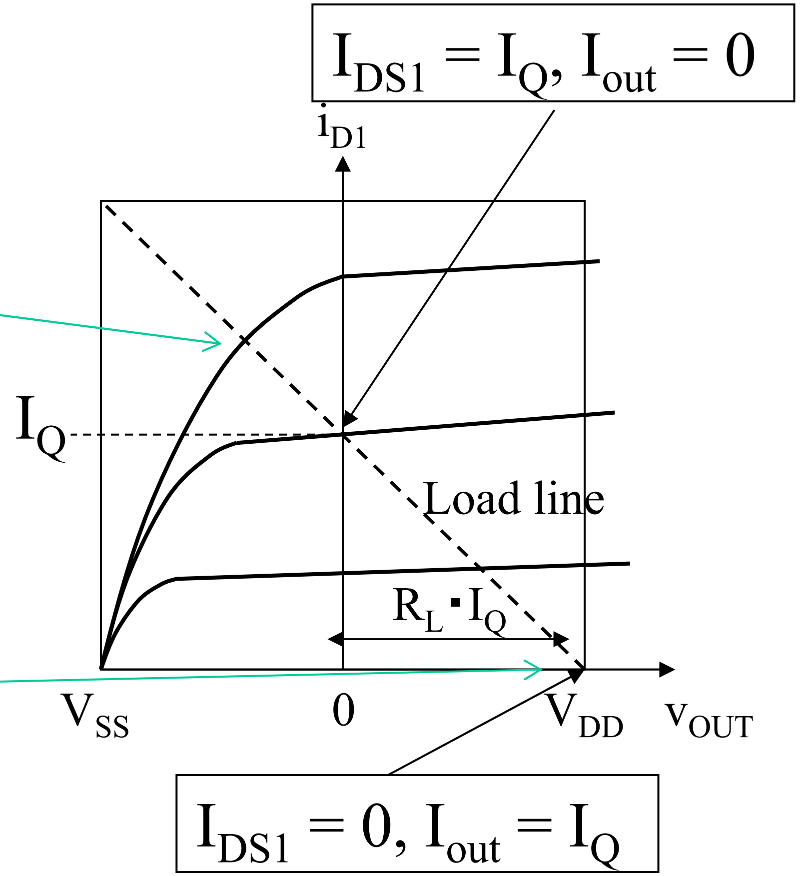
$$I_{out} = I_Q - I_{DS1}$$

Maximum sink current

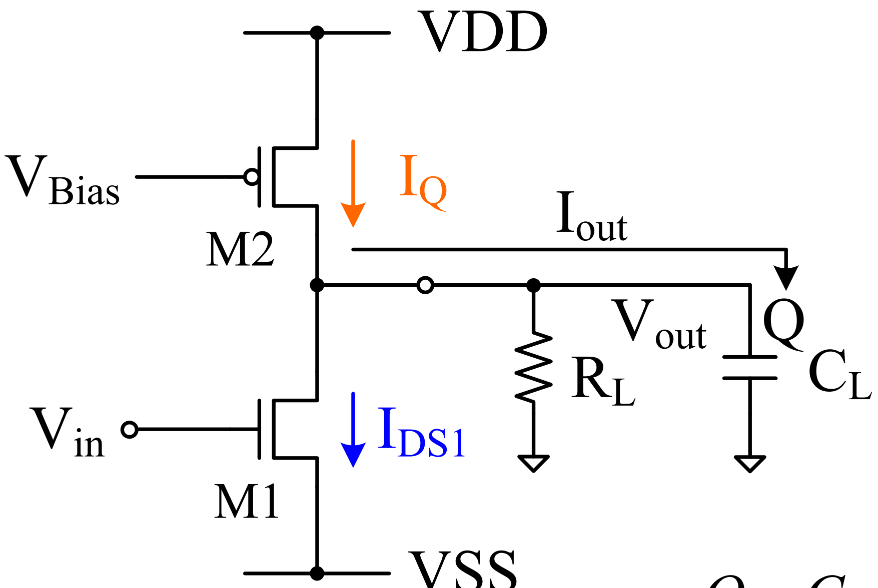
$$I_{out}(\min) = I_Q - I_{DS1}(\max)$$
$$= I_Q - \frac{\beta_1}{2}\{(VDD - VSS) - V_{Tn})^2$$

Maximum source current

$$I_{out}(\max) = I_Q - I_{DS1}(\min)$$
$$\leq I_Q$$



SR (Slew Rate)

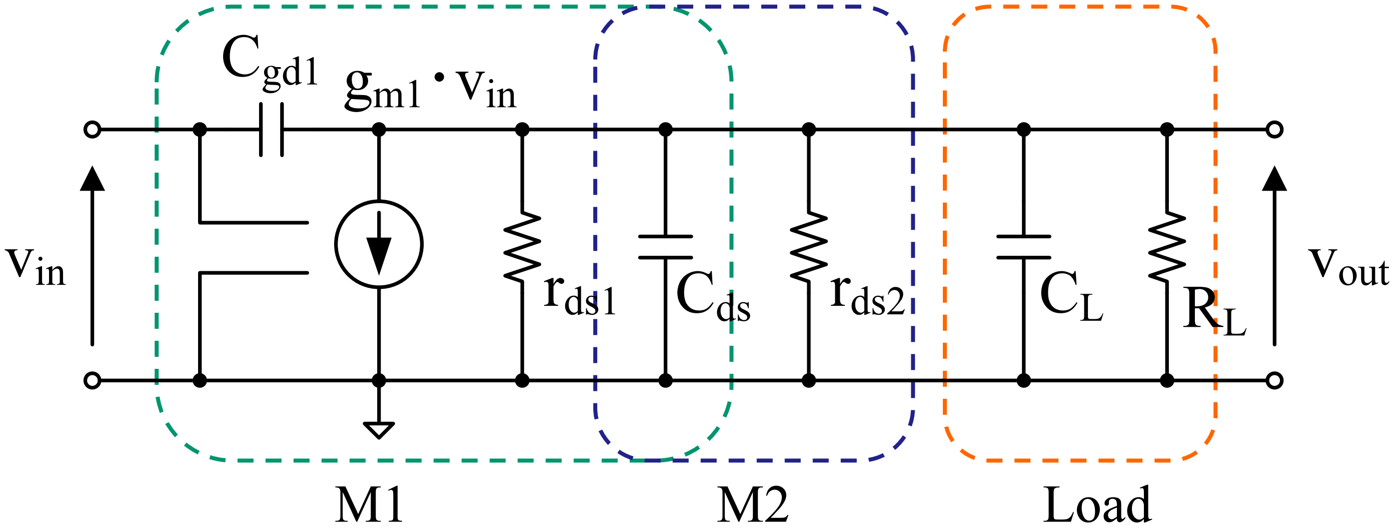


$$Q = C_L \cdot V_{out}$$

The R_L is approximately infinite, ⟶ $$\frac{dQ}{dt} = I_{out} = C_L \frac{dV_{out}}{dt}$$

$$SR = \frac{dV_{out}(\max)}{dt} = \frac{I_{out}(\max)}{C_L} = \frac{I_Q}{C_L}$$

Voltage gain

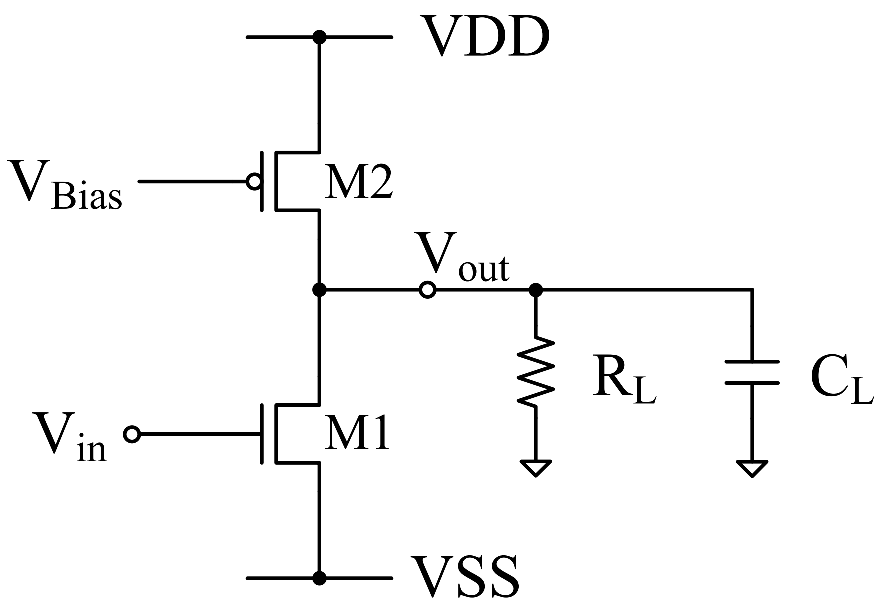


$$C_{ds} = C_{db1} + C_{db2} + C_{dg2}$$

In the low frequency, $\dfrac{v_{OUT}}{v_{IN}} = \dfrac{-g_{m1}}{\dfrac{1}{r_{ds1}} + \dfrac{1}{r_{ds2}} + \dfrac{1}{R_L}} = \dfrac{-g_{m1}}{g_{ds1} + g_{ds2} + G_L}$

(Practically, the C_{gd1} and C_{ds} generate a zero and a pole.)

Design example (1)



Specification	
Output swing	±2.2V
SR	10.0V/us
R_L	2kΩ
C_L	100pF
VDD/VSS	2.5V/-2.5V
V_{Offset} (GND)	0V
L_1/L_2	2/2

C_{gd1}, C_{gd2} = 35fF
Gate length scale factor = 1um

Design example (2)

Output voltage swing = ±2.2V, R_L = 2kΩ,

Output current swing: $I_{out} = \frac{\pm 2.2V}{2k\Omega} = \pm 1.1mA$ ← High priority

SR = 1V/us, C_L = 100pF, SR = $I_{out}(max)/C_L$

$$I_{out}(\max) = 100pF \cdot (\pm 10V/us) = \pm 1.0mA$$

Therefore, the output current swing must be over ±1.1mA to attain the required output swing.

Hereinafter, the dimensions of M2 are determined.

VDD = 2.5V, V_{Bias} = 0.0V, and V_{GS2} = -2.5V.

The M2 is able to conducts the current I_Q

$$I_Q = \frac{33uA/V^2}{2} \frac{W_2(um)}{2um} (-2.5V + 0.86V)^2$$

$$= 22.2uA/um \cdot W_2(um) \geq 1.1mA$$

$$\therefore W_2 \cong 50um$$

Parameters of MOSFETs

	n-ch	p-ch
V_T(V)	0.78	-0.86
$\mu C_{OX}(uA/V^2)$	98	33
$\lambda(V^{-1})$	0.019	0.011
$\gamma(V^{1/2})$	0.4	0.4

Design example (3)

The maximum current sink of M1:

$$-I_{out}(\min) = I_Q - I_{DS1}(\max) = 1.1\text{mA} - \frac{98\text{uA/V}^2}{2}\frac{W_1(\text{um})}{2\text{um}}(5.0\text{V} - 0.78\text{V})^2$$

$$= 1.1\text{mA} - 436\text{uA/um}\cdot W_1(\text{um}) \le -1.1\text{mA}$$

$$\therefore W_1 \ge 6\text{um}$$

The constraint condition for the GND = (VDD + VSS)/2

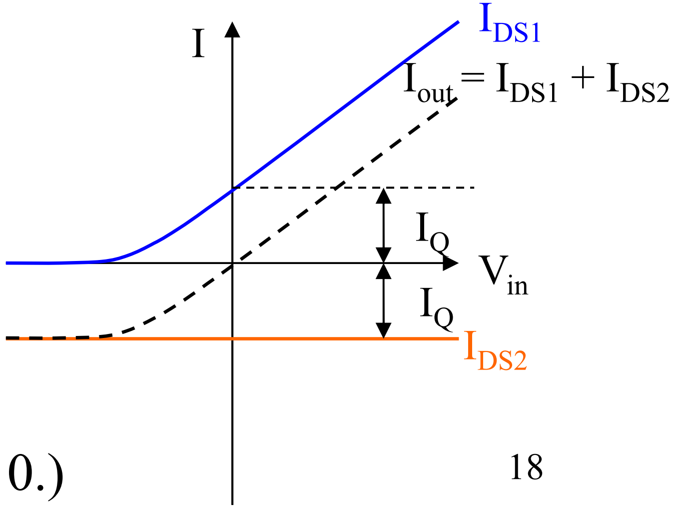
GND = (2.5V - 2.5V)/2 = 0V

$$I_{DS1}(0V) = \frac{98\text{uA/V}^2}{2}\frac{W_1(\text{um})}{2\text{um}}(2.5\text{V} - 0.78\text{V})^2$$

$$= 72.5\text{uA/um}\cdot W_1(\text{um}) = 1.1\text{mA}$$

$$\therefore W_1 \cong 15.2\text{um}$$

(If you need to set the GND to 0.)



Design example (4)

DC gain at GND potential

$$g_{ds1} = \lambda_1 I_Q = 0.019\mathrm{V}^{-1} \cdot 1.1\mathrm{mA} = 20.9\mathrm{uS}$$

$$g_{ds2} = \lambda_2 I_Q = 0.011\mathrm{V}^{-1} \cdot 1.1\mathrm{mA} = 12.1\mathrm{uS}$$

$$G_L = \frac{1}{R_L} = \frac{1}{2k\Omega} = 500\mathrm{uS}$$

$$g_{m1} = \sqrt{2\beta_1 I_Q} = \sqrt{2 \cdot 98\mathrm{uA/V}^2 \frac{6\mathrm{um}}{2\mathrm{um}} 1.1\mathrm{mA}} = 0.804\mathrm{mS}$$

$$Gain = \frac{v_{out}}{v_{in}} = \frac{-g_{m1}}{g_{ds1} + g_{ds2} + G_L} = \frac{-0.804\mathrm{mS}}{533\mathrm{uS}} = -1.51 = 3.57\mathrm{dB}$$

Small signal output resistance

$$r_{out} = \frac{1}{g_{ds1} + g_{ds2}} = \frac{1}{33.0\mathrm{uS}} = 30.3k\Omega$$

Design example (5)

The frequency of pole and zero can be estimated from the value of C_{gd1}, C_{gd2}, C_{db1}, C_{db2}, C_L, where usually $C_L >> C_{gd1}$, C_{gd2}, C_{db1}, C_{db2}.

$$z_1 = \frac{g_{m1}}{C_{gd1}} = \frac{0.804\text{mS}}{35\text{fF}} = 2.30 \cdot 10^{10}\,\text{rad/s} = 3.66\text{GHz}$$

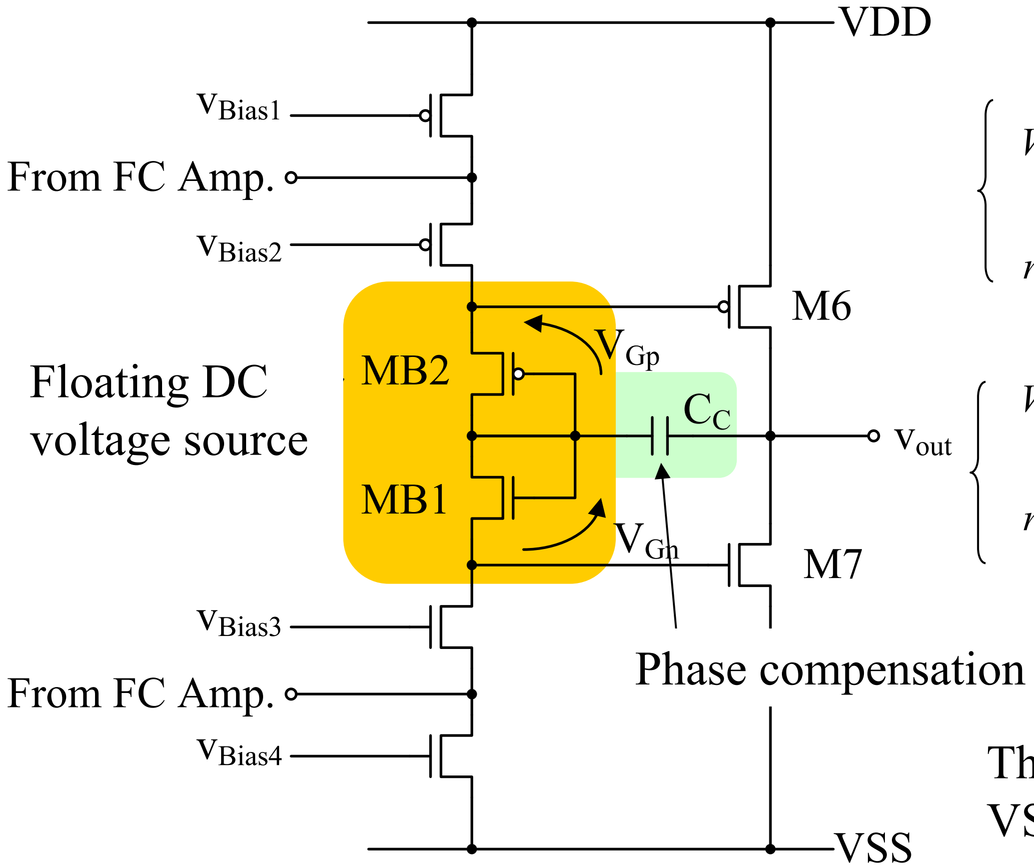
$$p_1 = \frac{-(g_{ds1} + g_{ds2} + G_L)}{C_{gd2} + C_{bd1} + C_{bd2} + C_L} \approx \frac{-(g_{ds1} + g_{ds2} + G_L)}{C_L}$$

$$= \frac{-533\mu\text{S}}{100\text{pF}} = -5.33\text{Mrad/s} = -848\text{kHz}$$

NOTE: We will learn these equations in a following chapter in detail.

14.3 Class-AB CS amplifier

Class-AB amplifier with Floating DC voltage source



$$V_{Gp} = |V_{Tp}| + \sqrt{\frac{2I_{DS\_MB2}}{\beta_p}}$$ Floating DC voltage

$$r_{ds\_MB2} \cong \frac{1}{g_{m\_MB2}} = 1/\sqrt{2\beta_p I_{DS}} \ge \frac{1}{g_{m6}}$$ Zero cancel

$$V_{Gn} = V_{Tn} + \sqrt{\frac{2I_{DS\_MB1}}{\beta_n}}$$ Floating DC voltage

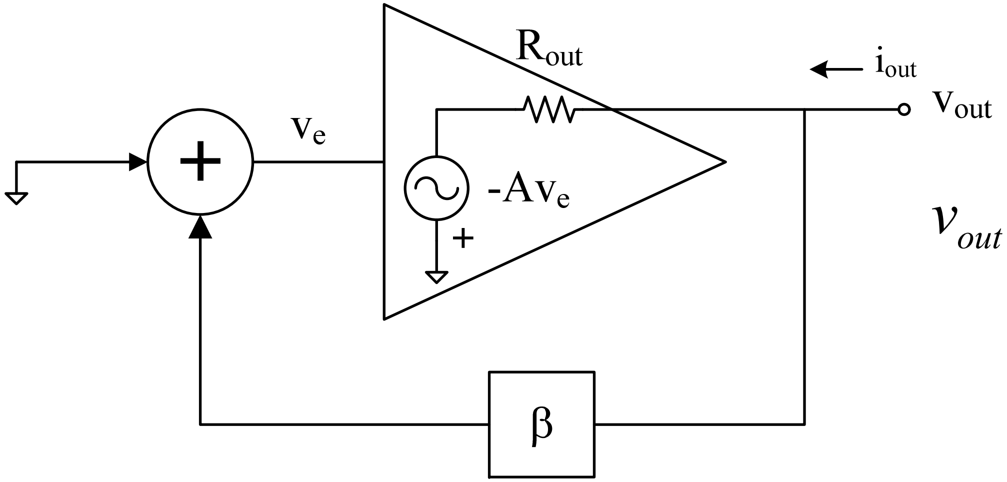
$$r_{ds\_MB1} \cong \frac{1}{g_{m\_MB1}} = 1/\sqrt{2\beta_n I_{DS}} \ge \frac{1}{g_{m7}}$$ Zero cancel

The output voltage swing is limited within VSS + V_{Tn} + $3\Delta_{OV}$ and VDD - $|V_{Tp}|$ - $3\Delta_{OV}$.

NOTE: FC Amp. = Folded cascade amplifier (See chapter 14).

Reduction of the output resistance with NFB

Voltage feedback → Low output impedance
Current feedback → High output impedance

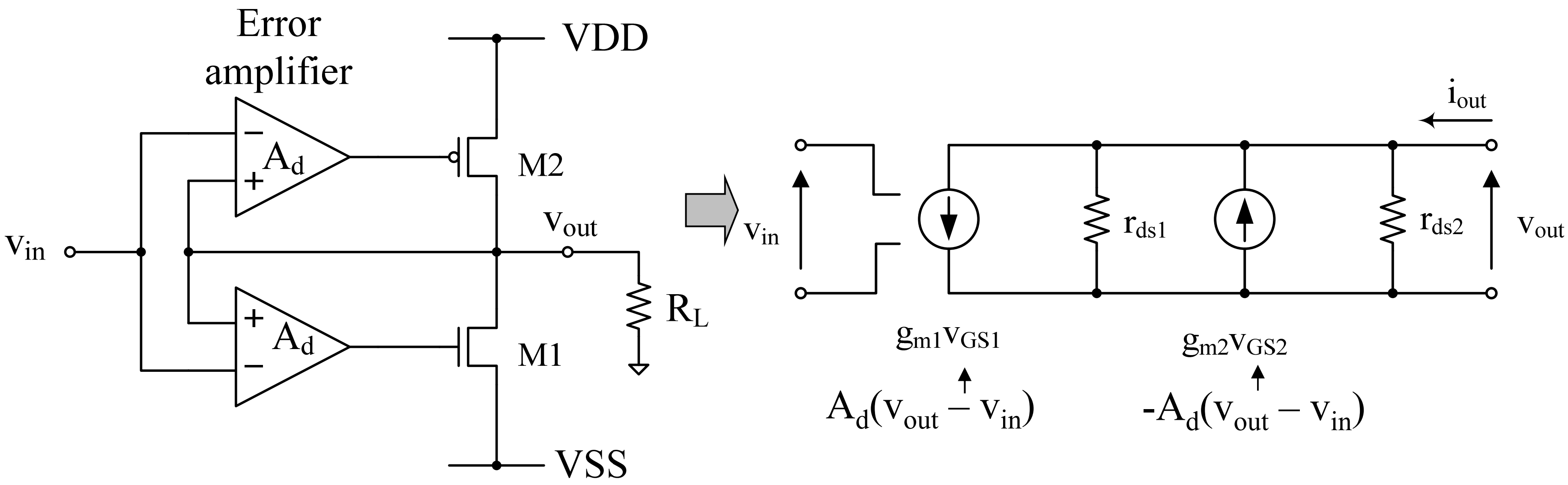


$$v_{out} - (-Av_e) = i_{out} R_{out}$$

$$v_e = \beta \cdot v_{out}$$

$$R_{out\_NFB} = \frac{v_{out}}{i_{out}} = \frac{R_{out}}{1 + A\beta}$$

Shunt negative feedback

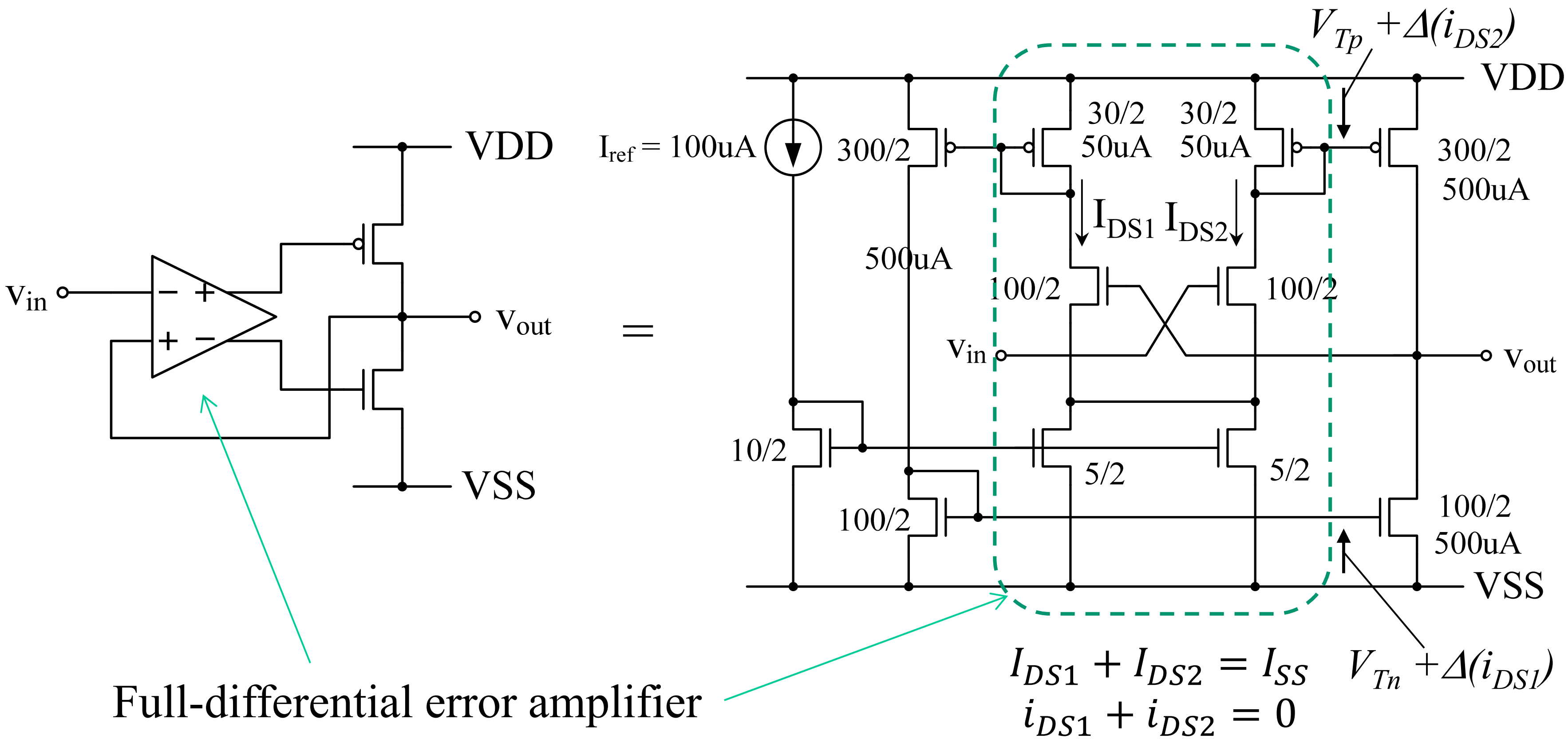


$$i_{out} = g_{m1} \cdot A_d \cdot (v_{out} - v_{in}) + \frac{1}{r_{ds1}} v_{out} - g_{m2} \cdot (-A_d \cdot (v_{out} - v_{in})) + \frac{1}{r_{ds2}} v_{out}$$

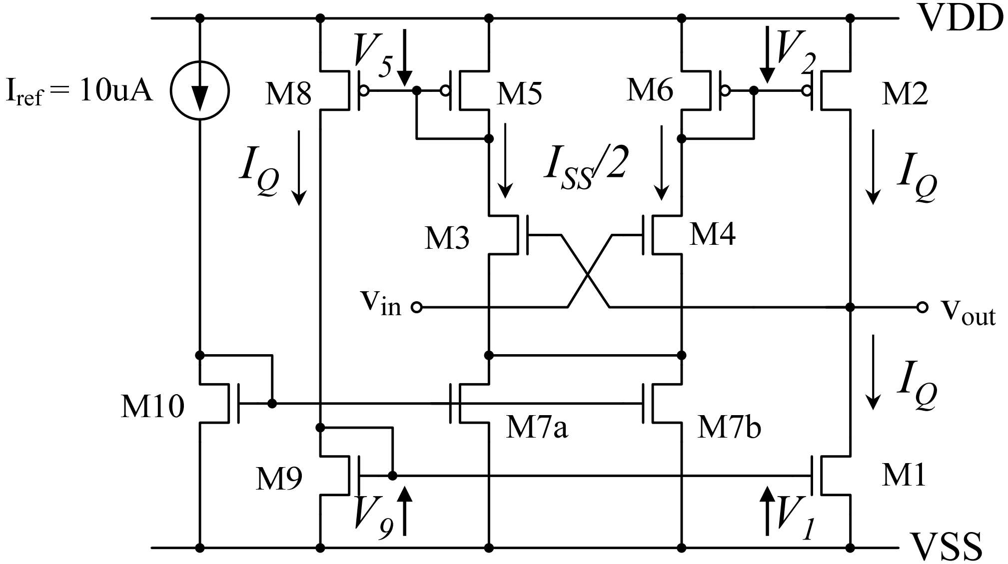
$$= g_{m1} \cdot A_d \cdot v_{out} + \frac{1}{r_{ds1}} v_{out} + g_{m2} \cdot A_d \cdot v_{out} + \frac{1}{r_{ds2}} v_{out} \quad \text{, for } v_{in} = 0$$

$$R_{out} = \frac{v_{out}}{i_{out}} = \frac{1}{A_d(g_{m1} + g_{m2}) + g_{ds1} + g_{ds2}} \quad \text{, and Total gain} \sim \text{0dB}$$

Simplified class-AB shunt negative feedback amplifier



Design example (1)



$$\left(\frac{W}{L}\right)_2 = K_m\left(\frac{W}{L}\right)_6, \left(\frac{W}{L}\right)_8 = K_m\left(\frac{W}{L}\right)_5, \left(\frac{W}{L}\right)_9 = \left(\frac{W}{L}\right)_1$$

$$I_{DS5\_CM} = I_{DS6\_CM} = \frac{I_{SS}}{2}, I_Q = K_m\frac{I_{SS}}{2}$$

$$\begin{cases} V_{2\_CM} = V_{5\_CM} = |V_{Tp}| + \sqrt{\dfrac{2I_{DS6}}{\beta_6}} = |V_{Tp}| + \sqrt{\dfrac{I_{SS}}{\beta_6}} = |V_{Tp}| + \sqrt{\dfrac{K_m I_{SS}}{\beta_2}} \\ V_{1\_CM} = V_{9\_CM} = V_{Tn} + \sqrt{\dfrac{2I_Q}{\beta_9}} = V_{Tn} + \sqrt{\dfrac{K_m I_{SS}}{\beta_1}} \end{cases}$$

Specification	
Output swing	±2.2V
SR	10V/us
R_{out}	200Ω
R_L	20kΩ
C_L	10pF
VDD/VSS	2.5V/-2.5V
I_{SS}	10uA
V_{Offset}	0V
L	2

Gate length scale factor = 1um

Design example (2)

Output voltage swing = ±2.2V, R_L = 20kΩ,

$$\text{Output current swing: } I_{out} = \frac{\pm 2.2\text{V}}{20k\Omega} = \pm 110\text{uA}$$

SR = 10V/us, C_L = 10pF, SR = I_{out}(max)/C_L

$$I_{out}(\max) = 10\text{pF} \cdot (\pm 10\text{V/us}) = \pm 100\text{uA}$$

Therefore, the output current swing must be over ±110uA to attain the output voltage swing required.

$$I_{out}(\max) = K_m I_{SS}$$

$$K_m = \frac{I_{out}(\max)}{I_{SS}} = \frac{110\text{uA}}{10\text{uA}} = 11$$

The size of M6 and M5 may be given arbitrarily, if any other constraints is not imposed. Say $(W/L)_6 = (W/L)_5 = 30/2$, $(W/L)_2 = (W/L)_8 = K_m(W/L)_{5,6} = 330/2$.

Design example (3)

A class-AB (push-pull) amplifier requires the same gm value between the p-ch and n-ch devices to avoid the nonlinear distortion.

$$g_{m1} = \sqrt{2\beta_1 I_Q}, g_{m2} = \sqrt{2\beta_2 I_Q}$$

$$\beta_1 = \beta_2$$

$$\mu_n C_{OX}\left(\frac{W}{L}\right)_1 = \mu_p C_{OX}\left(\frac{W}{L}\right)_2$$

$$\left(\frac{W}{L}\right)_1 = \frac{\mu_p C_{OX}}{\mu_n C_{OX}}\left(\frac{W}{L}\right)_2 = \frac{33\text{uA/V}^2}{98\text{uA/V}^2}\frac{330}{2} \cong \frac{112}{2}$$

$$\left(\frac{W}{L}\right)_9 = \left(\frac{W}{L}\right)_1 = \frac{112}{2}$$

Estimation of R_{out} and A_d

$$R_{out} = \frac{1}{A_d(g_{m1}+g_{m2}) + g_{ds1} + g_{ds2}} \leq 100\Omega$$

$$\therefore A_d = \frac{1/R_{out} - g_{ds1} - g_{ds2}}{g_{m1}+g_{m2}}$$

Design example (4)

$$g_{m1} = \sqrt{2\beta_1 I_Q} = \sqrt{2\beta_1 K_m \frac{I_{SS}}{2}} = \sqrt{2 \cdot 98\text{uA/V}^2 \frac{112}{2} 11 \frac{10u}{2}} = 777\text{uS}$$

$$g_{m2} = \sqrt{2\beta_2 I_Q} = \sqrt{2\beta_2 K_m \frac{I_{SS}}{2}} = \sqrt{2 \cdot 33\text{uA/V}^2 \frac{330}{2} 11 \frac{10u}{2}} = 774\text{uS}$$

$$g_{ds1} = \lambda_1 I_Q = \lambda_1 K_m \frac{I_{SS}}{2} = 0.019\text{V}^{-1} 11 \frac{10\text{uA}}{2} = 1.05\text{uS}$$

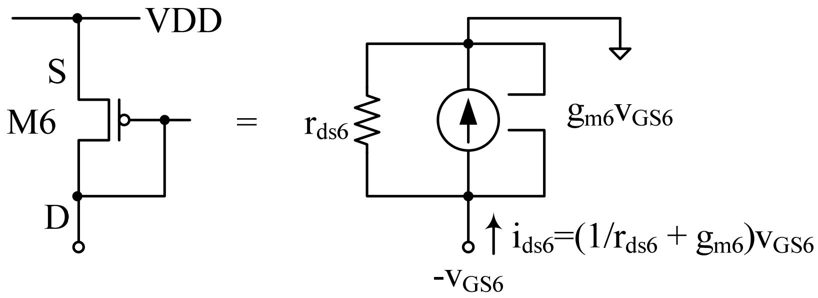
$$g_{ds2} = \lambda_2 I_Q = \lambda_2 K_m \frac{I_{SS}}{2} = 0.011\text{V}^{-1} 11 \frac{10\text{uA}}{2} = 0.605\text{uS}$$

$$A_d = \frac{1/R_{out} - g_{ds1} - g_{ds2}}{g_{m1} + g_{m2}} \geq \frac{1/200 - 1.05\text{uS} - 0.605\text{uS}}{777\text{uS} + 774\text{uS}} = 3.22 \qquad \text{(Required)}$$

The voltage gain of the differential amplifier is described as follows.

$$A_d = \frac{g_{m4}}{g_{ds4} + g_{ds6} + g_{m6}}$$

$$g_{m4} = A_d \left(g_{ds4} + g_{ds6} + g_{m6} \right)$$



Design example (4)

$$g_{ds3,4} = \lambda_4 \frac{I_{SS}}{2} = 0.019\text{V}^{-1}\frac{10\text{uA}}{2} = 0.095\text{uS}$$

$$g_{ds5,6} = \lambda_6 \frac{I_{SS}}{2} = 0.011\text{V}^{-1}\frac{10\text{uA}}{2} = 0.055\text{uS}$$

$$g_{m5,6} = \sqrt{2\beta_5 \frac{I_{SS}}{2}} = \sqrt{2\cdot 33\text{uA/V}^2\left(\frac{30}{2}\right)10\text{uA}} = 99.5\text{uS}$$

$$g_{m3,4} = A_d(g_{ds4} + g_{ds6} + g_{m6}) \geq 3.22(0.095\text{uS} + 0.055\text{uS} + 99.5\text{uS}) = 320\text{uS}$$

$$g_{m3,4} = \sqrt{2\mu_n C_{OX}\left(\frac{W}{L}\right)_{3,4}\frac{I_{SS}}{2}} \geq 320\text{uS}$$

$$\left(\frac{W}{L}\right)_3 = \left(\frac{W}{L}\right)_4 = 104 = \frac{208}{2}$$

The large W of M10 and M7 extend the input voltage range of the differential amplifier. In this design, it is difficult to meet the given output swing, because of the large threshold voltage of MOSFET. Anyway, let's assume that the size of M10 and M7. Thus, $(W/L)_{10} = 2(W/L)_{7a} = 2(W/L)_{7b} = 20/2$.

Tr. #	W/L
M1	112/2
M2	330/2
M3	208/2
M4	208/2
M5	30/2
M6	30/2
M7a	10/2
M7b	10/2
M8	330/2
M9	112/2
M10	20/2