Module 2:

Module:2 MOSFET Power Amplifiers **4 hours**

- Power Amplifiers, Power Transistors, Classes of Amplifiers, Class A Power Amplifiers, **Class B, Class AB Push-Pull Complementary Output Stages**.

Design

Class A design

Give

$$I_D = 0.028 = 28mA$$
$$K_n = 1A/V^2$$
$$V_{DD} = 20V$$
$$R_D = 120\Omega$$

$$V_{DS} = V_{DD} - I_D R_D$$

$$V_{DS} = 20 - (28\times 10^{-3})(120) = 16.64V = 17V$$

$$V_{DS}(\mathrm{sat}) = V_{GS} - V_{TN}$$

$$I_D = K_n(V_{GS} - V_{TN})^2$$

$$V_{DS}(\mathrm{sat}) = V_{DD} - K_n R_D V_{DS}^2(\mathrm{sat})$$

$$V_{DS(sat)} = V_{DD} - K_n R_D V^2{}_{DS}(sat)$$
$$V_{DS(sat)} = 20 - 1(120)V^2{}_{DS}$$
$$V_{DS(sat)} + 1(120)V^2{}_{DS} - 20 = 0$$
$$solving:$$
$$V_{DS(sat)} = 0.404$$

To obtain the maximum symmetrical swing under the conditions specified, we want the *Q-point midway between* V_{DS} *=0.4 and* V_{DS} *= 17*

$$V_{DSQ} = \frac{V_{DS} + V_{DS(sat)}}{2} = \frac{17 + 0.4}{2} = 8.702$$

$$v_P = V_{DS} - V_{DSQ} = 17 - 8.702 = 8.3\ \sin\omega \text{t}$$

$$P_L = \frac{1}{2}\frac{(Vp)^2}{R_D} = \frac{1}{2}\frac{(8.3)^2}{120k} = 0.28mW$$

$$P_s = V_{DD} I_{DQ}$$

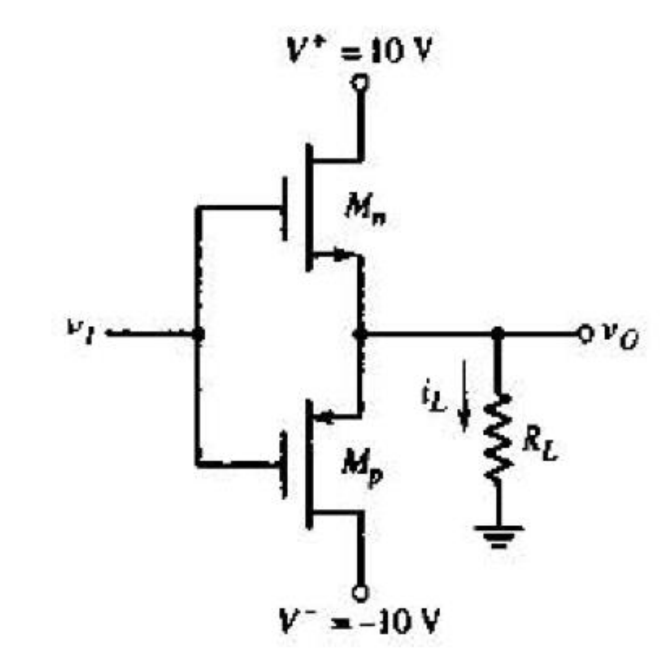
$$I_{DQ} = \frac{V_{DD} - V_{DSQ}}{R_D} = \frac{20 - 8.702}{120k} = 0.09415mA$$

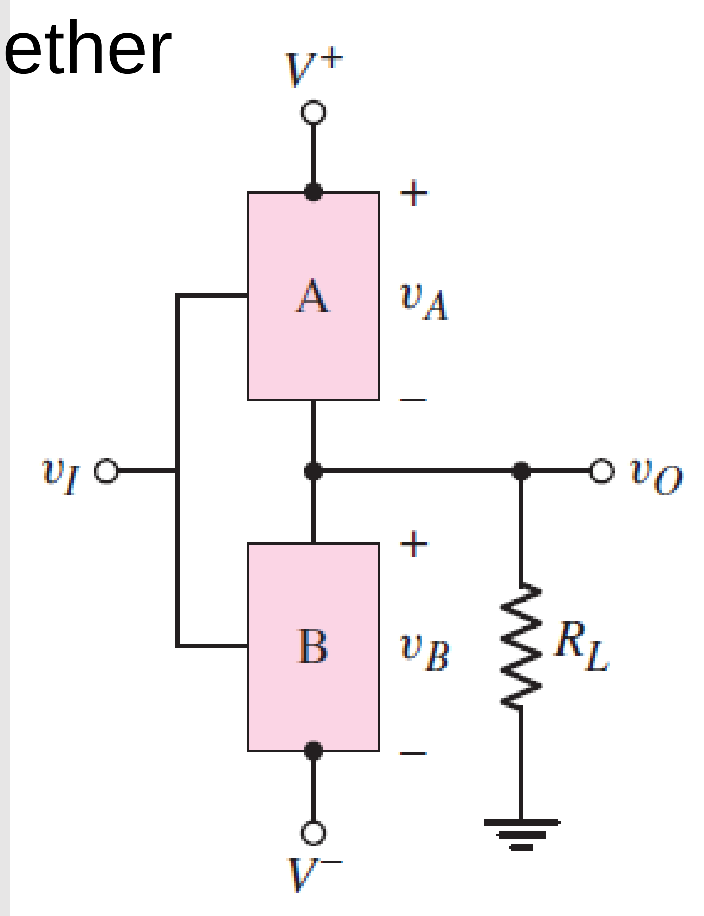
$$P_s = V_{DD} I_{DQ} = 20 \times 0.09415mA = 1.88mW$$

$$\eta = \frac{P_L}{P_S} = \frac{0.28mW}{1.88mW} \times 100 = 14\%$$

Class B operation (Ideal)

- Complementary pair of electronic devices (NMOS and PMOS)
- Device A: NMOS   ; Device B: PMOS
- Output is at drain (v_0) Note: Source is connected together
- **Case 1:** $v_I = 0$: Both devices are OFF:
  Zero bias currents: $v_0 = 0$





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- Case 1: $v_I = 0$: Both devices are OFF:
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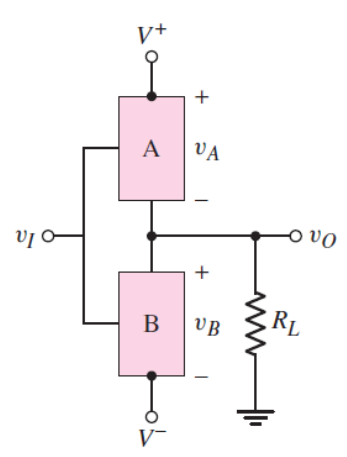
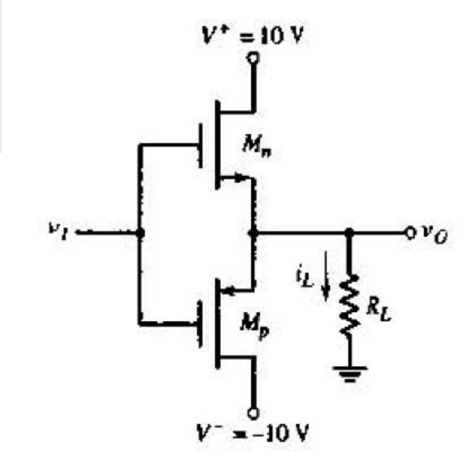
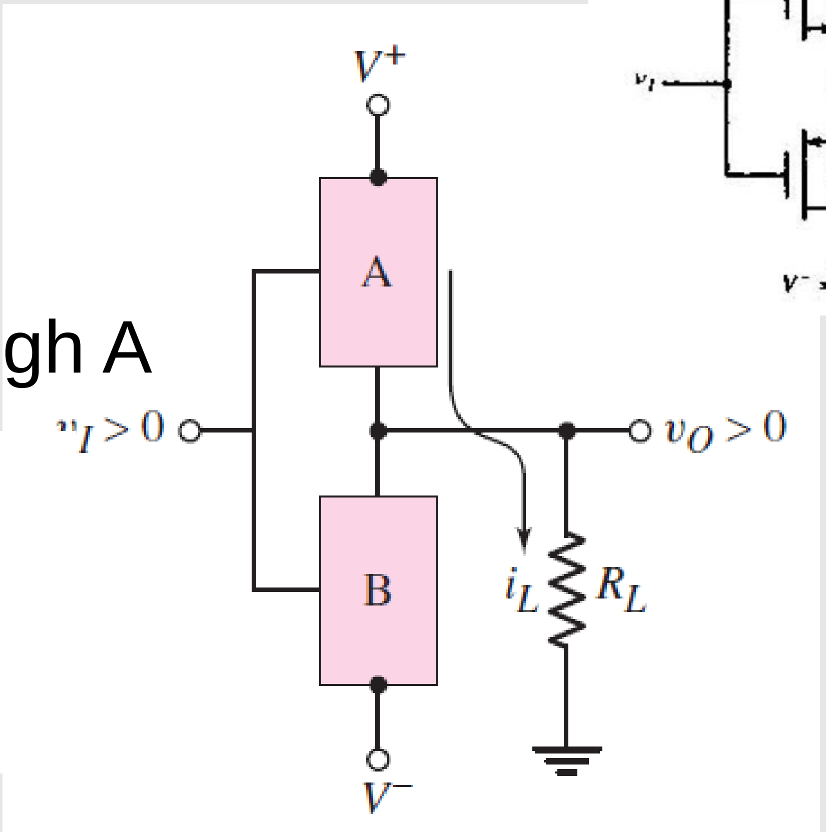
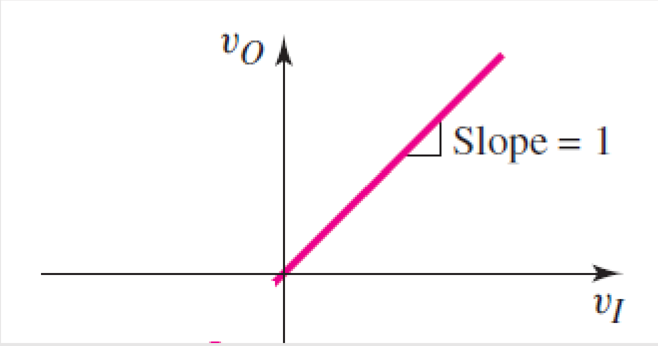
- **<u>Case 2:</u>** $v_I > 0$: **Device A is ON**
  Device B is OFF

Current supplied from V^+ to load R_L through A









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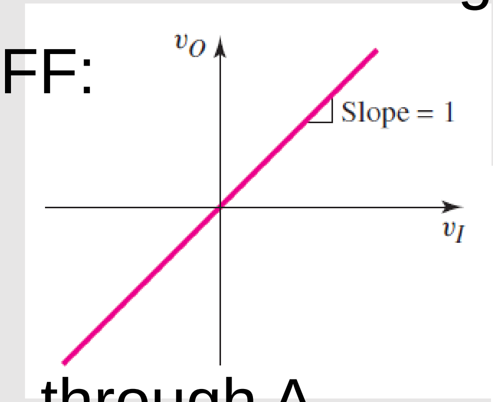
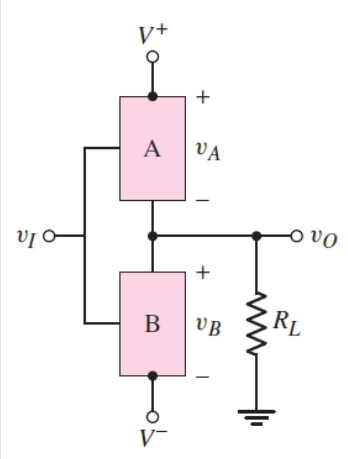
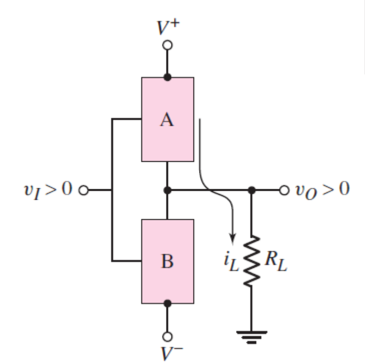
- Output is at drain (v_0) Note: Source is connected togethe
- Case 1: $v_I = 0$: Both devices are OFF:
  Zero bias currents: $v_0 = 0$
- Case 2: $v_I > 0$: Device A is ON
  Device B is OFF

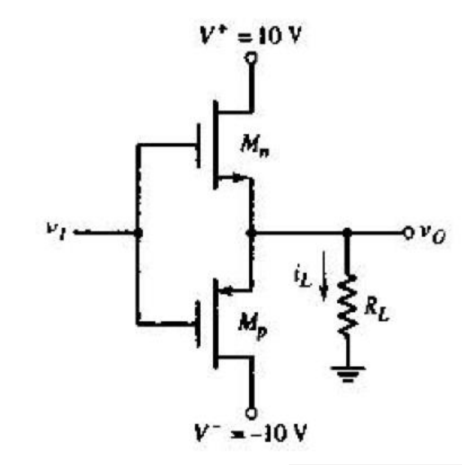
  Current supplied from V^+ to load R_L through A
- **<u>Case 3:</u>** $\boldsymbol{v_I < 0}$: Device B is ON
  Device A is OFF

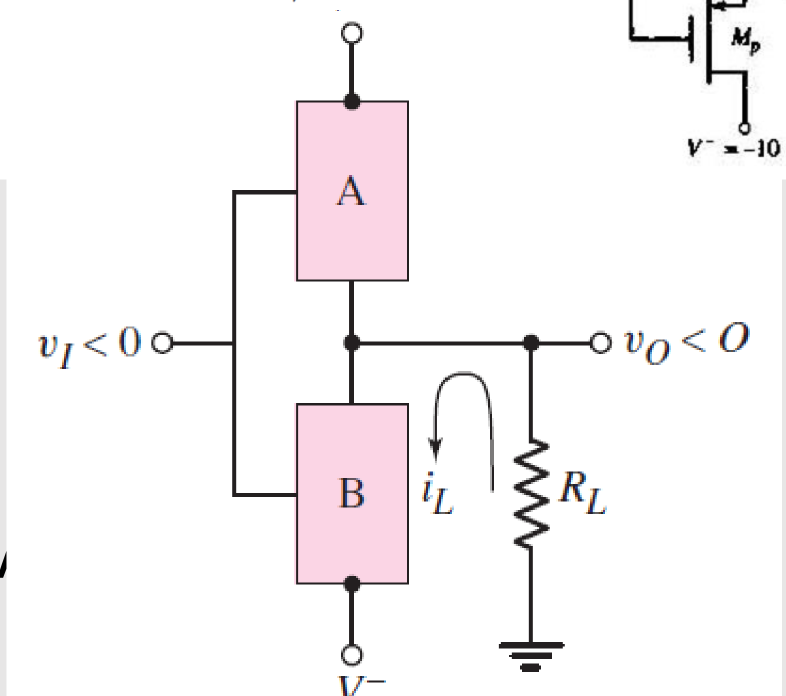
  Current supplied from V^- to load R_L through
  (**Sinking current from load**: Output negativ





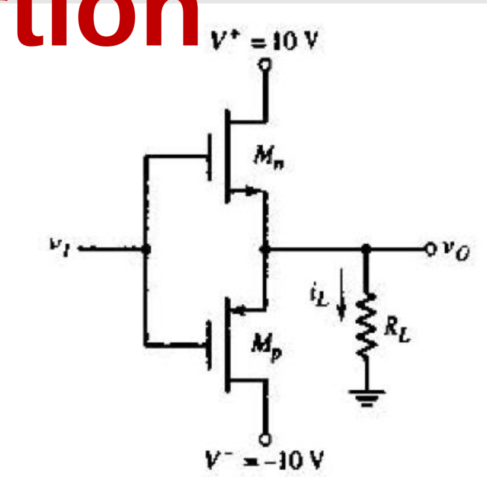


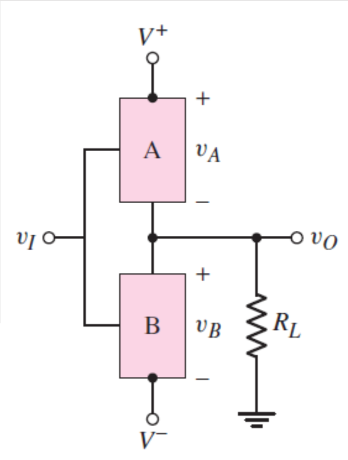


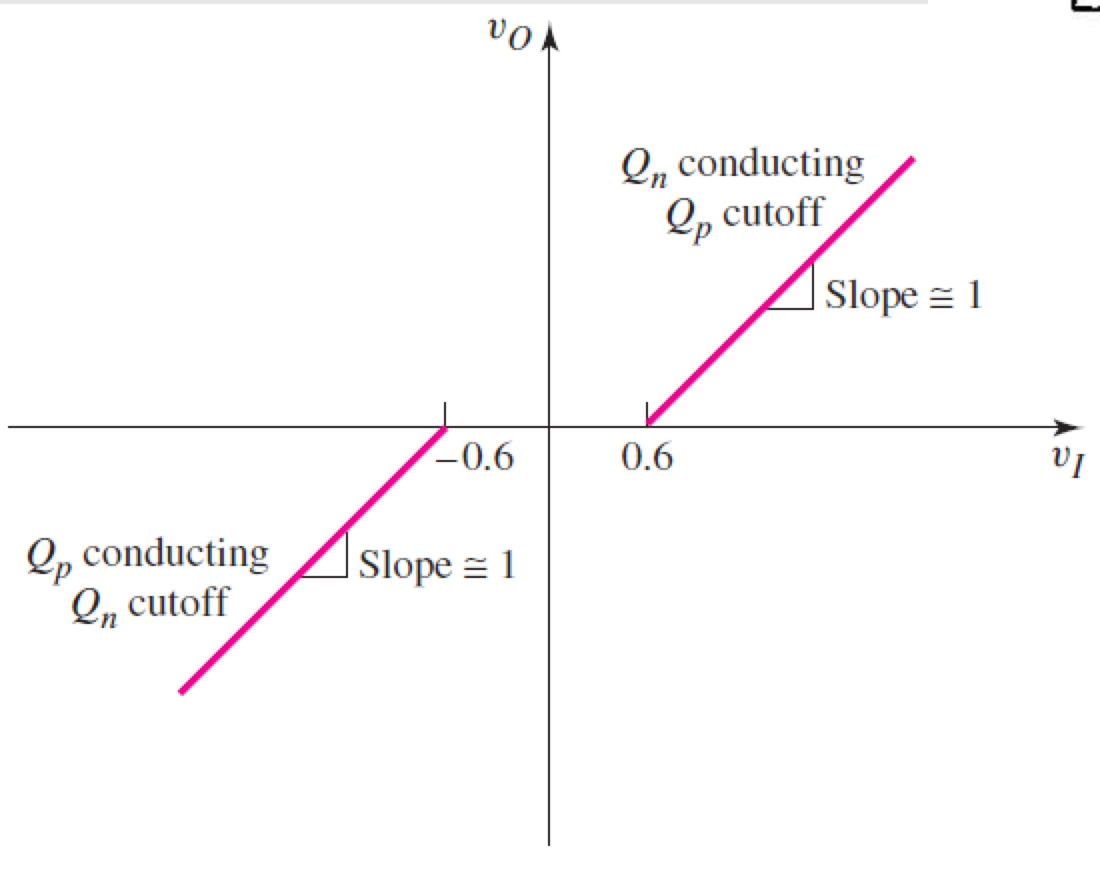


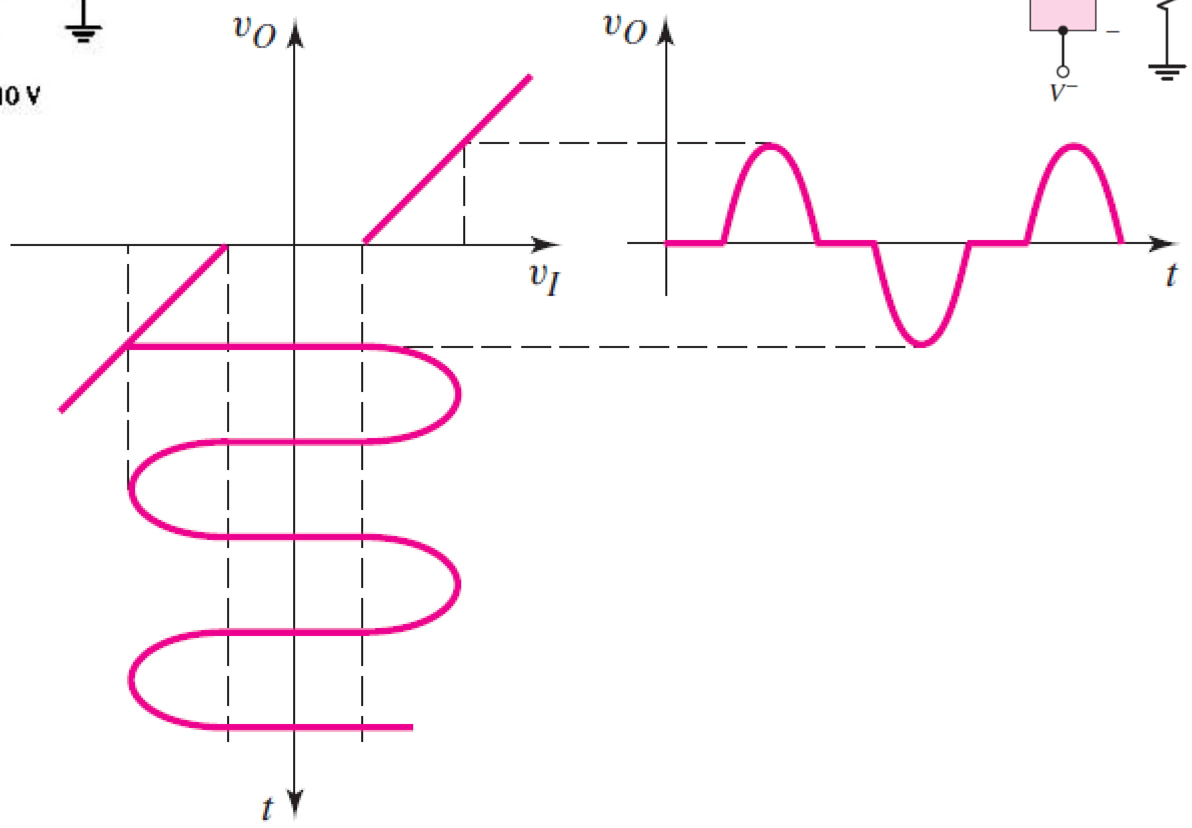
Class B operation (Practical) – Threshold Cross over distortion

- Threshold voltages :





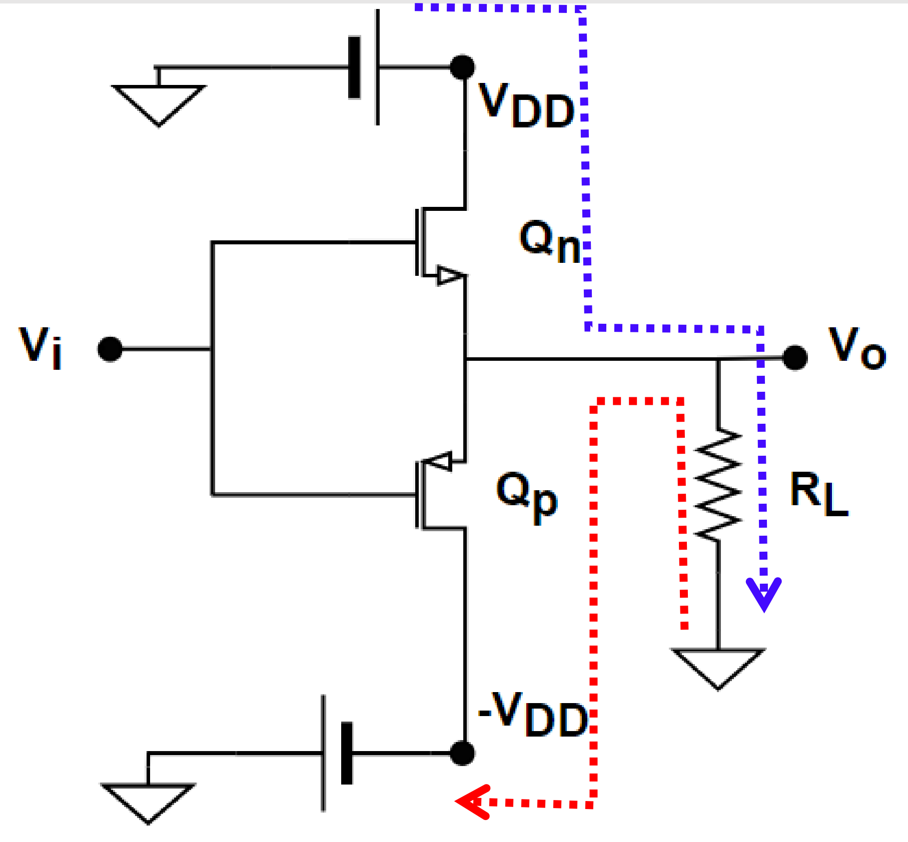




- Crossover distortion can be virtually eliminated by biasing both PMOS and NMOS with a small quiescent drain current when v_I is zero. The crossover distortion effect can also be minimized with an op-amp used in a feedback configuration.

Conversion efficiency of Class B MOSFET amplifier

- as $\omega t = 2\pi f t = 2\pi.\frac{1}{T}.t$ Based on t, ωt will be the respective angle
- **At $\mathbf{0 \leq \omega t \leq \pi : v_i \geq 0}$; NMOS is ON; PMOS is OFF**
- **At $\boldsymbol{\pi \leq \omega t \leq 2\pi : v_i \leq 0}$; NMOS is OFF; PMOS is ON**
- Output of class B amplifier: $\mathrm{v_O = V_P \sin \omega t}$ with V_P (maximum possible output is V_{DD})



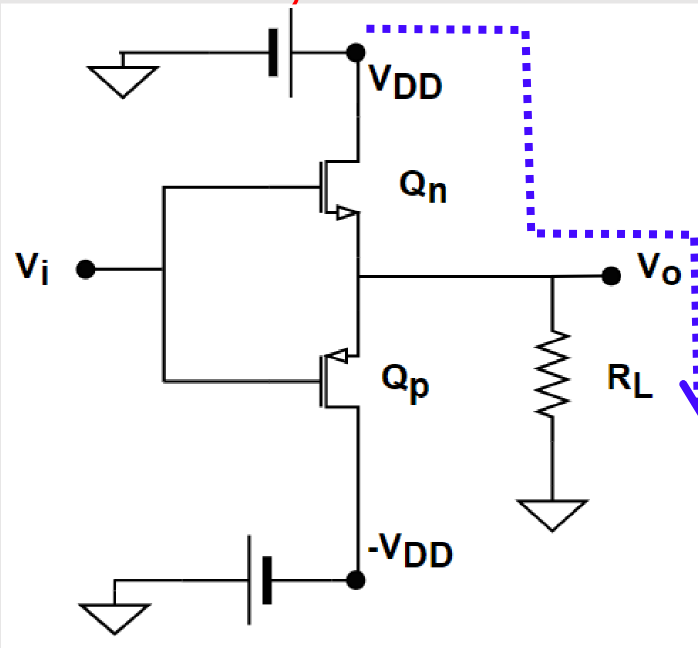
Conversion efficiency of Class B MOSFET amplifier

At $0 \leq \omega t \leq \pi : v_i \geq 0$; NMOS is ON; PMOS is OFF
At $\pi \leq \omega t \leq 2\pi : v_i \leq 0$; NMOS is OFF; PMOS is ON

- $v_O = V_P \sin \omega t$
- **Consider only NMOS Qn:**
- $\boldsymbol{0 \leq \omega t \leq \pi : v_i \geq 0}$: **NMOS ON**

Sinusoidal Drain current: $i_{Dn} = \frac{v_0}{R_L} = \frac{V_P}{R_L} \sin \omega t$

$V_{DSn} = V_{DD} - v_o = V_{DD} - V_P \sin \omega t$



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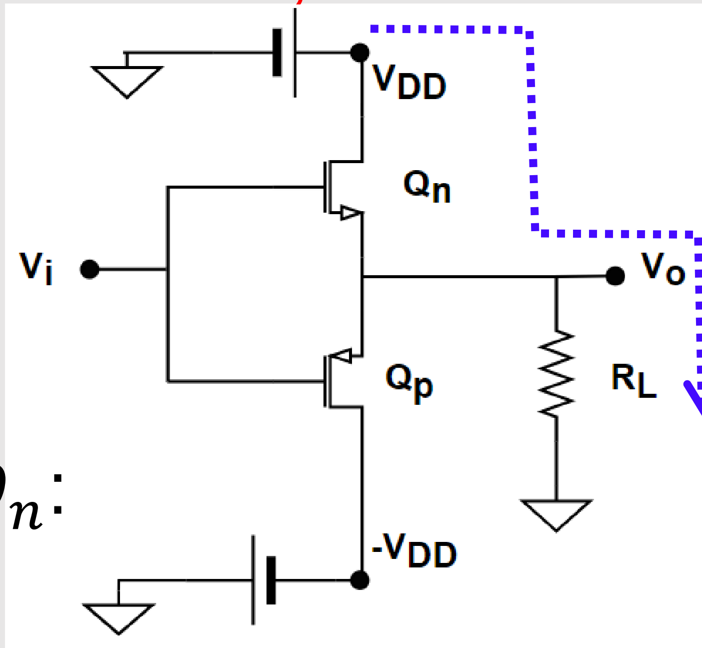

Sinusoidal Drain current: $i_{Dn} = \frac{v_0}{R_L} = \frac{V_P}{R_L} \sin \omega t$

$V_{DSn} = V_{DD} - v_o = V_{DD} - V_P \sin \omega t$

Instantaneous value of power dissipation in NMOS Q_n:

$P_{Qn(inst)} = V_{DSn} i_{Dn}$

$P_{Qn(inst)} =$

Conversion efficiency of Class B MOSFET amplifier

At $0 \le \omega t \le \pi : v_i \ge 0$; NMOS is ON; PMOS is OFF

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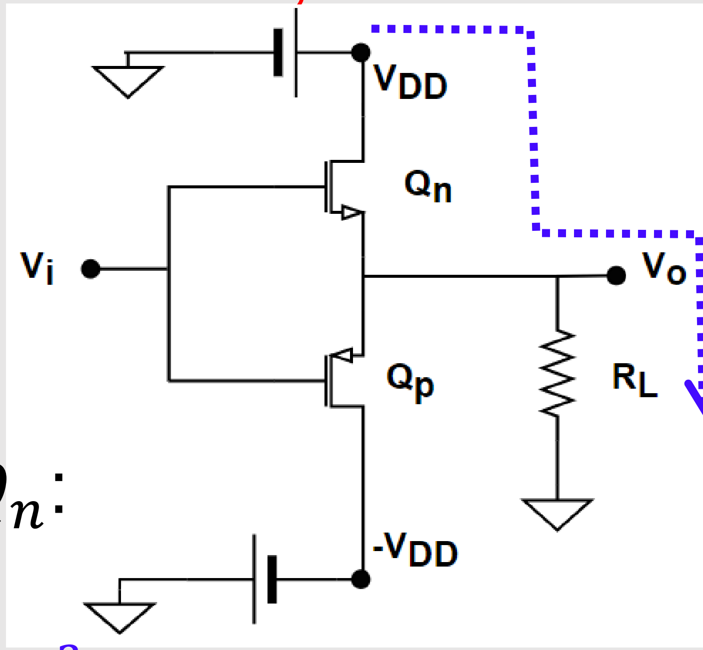

- $v_O = V_P \sin \omega t$
- **Consider only NMOS Qn:**
- $0 \le \omega t \le \pi : v_i \ge 0$: **NMOS ON**

Sinusoidal Drain current: $i_{Dn} = \frac{v_0}{R_L} = \frac{V_P}{R_L} \sin \omega t$

$V_{DSn} = V_{DD} - v_o = V_{DD} - V_P \sin \omega t$

Instantaneous value of power dissipation in NMOS Q_n:

$P_{Qn(inst)} = V_{DSn} i_{Dn}$

$$P_{Qn(inst)} = (V_{DD} - V_P \sin \omega t)\frac{V_P}{R_L} \sin \omega t = \frac{V_{DD} V_P}{R_L} \sin \omega t - \frac{V_P^2}{R_L} \sin^2 \omega t$$

- $\pi \le \omega t \le 2\pi : v_i \le 0$; **NMOS is OFF** : $P_{Qn(inst)} = 0$

Conversion efficiency of Class B MOSFET amplifier

- $v_O = V_P \sin \omega t$
- **Consider only NMOS Qn:**

At $0 \leq \omega t \leq \pi$: $v_i \geq 0$; NMOS is ON; PMOS is OFF
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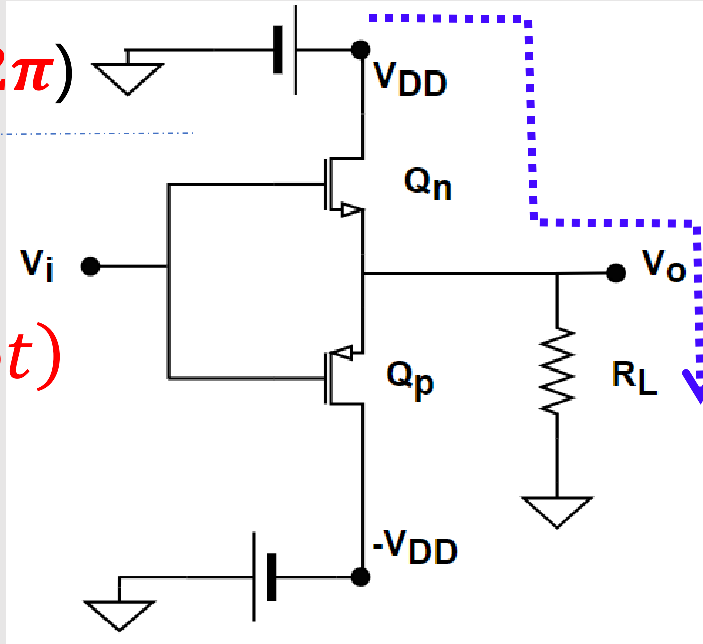
- $\mathbf{0 \leq \omega t \leq \pi : v_i \geq 0}$: **NMOS ON** $\quad i_{Dn} = \frac{v_0}{R_L} = \frac{V_P}{R_L} \sin \omega t \; ; \quad V_{DSn} = V_{DD} - V_P \sin \omega t$

$$P_{Qn(inst)} = \frac{V_{DD}V_P}{R_L} \sin \omega t - \frac{V_P^2}{R_L} \sin^2 \omega t \;\; ; P_{Qn(inst)} = 0 \; (\boldsymbol{\pi \leq \omega t \leq 2\pi})$$



Average power $P_{Qn} = \frac{1}{2\pi} \int_0^{2\pi} P_{Qn(inst)} \, d(\omega t)$

$$= \frac{1}{2\pi} \int_0^{\pi} P_{Qn(inst)} \, d(\omega t) + \frac{1}{2\pi} \int_{\pi}^{2\pi} P_{Qn(inst)} \, d(\omega t)$$

$$=$$

Conversion efficiency of Class B MOSFET amplifier

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- **Consider only NMOS Qn:**

At $0 \le \omega t \le \pi$: $v_i \ge 0$; NMOS is ON; PMOS is OFF

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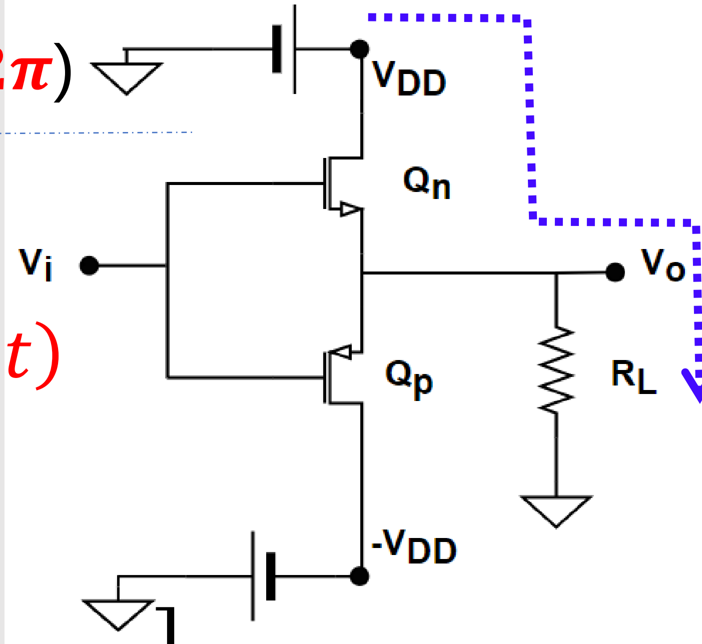
$$P_{Qn(inst)} = \frac{V_{DD} V_P}{R_L} \sin \omega t - \frac{V_P^2}{R_L} \sin^2 \omega t \ ; \ P_{Qn(inst)} = 0 \ (\pi \le \omega t \le 2\pi)$$



$$\text{Average power } P_{Qn} = \frac{1}{2\pi} \int_0^{2\pi} P_{Qn(inst)} \, d(\omega t)$$

$$= \frac{1}{2\pi} \int_0^{\pi} P_{Qn(inst)} \, d(\omega t) + \frac{1}{2\pi} \int_{\pi}^{2\pi} P_{Qn(inst)} \, d(\omega t)$$

$$= \frac{1}{2\pi} \int_0^{\pi} \left(\frac{V_{DD} V_P}{R_L} \sin \omega t - \frac{V_P^2}{R_L} \sin^2 \omega t \right) d(\omega t)$$

$$= \frac{1}{2\pi} \left[\frac{V_{DD} V_P}{R_L} \int_0^{\pi} \sin \omega t \, d(\omega t) - \frac{V_P^2}{R_L} \int_0^{\pi} (\sin^2 \omega t) d(\omega t) \right]$$

Conversion efficiency of Class B MOSFET amplifier

- $v_O = V_P \sin \omega t$
- <u>**Consider only NMOS Qn:**</u>

At $0 \le \omega t \le \pi : v_i \ge 0$; NMOS is ON; PMOS is OFF

At $\pi \le \omega t \le 2\pi : v_i \le 0$; NMOS is OFF; PMOS is ON

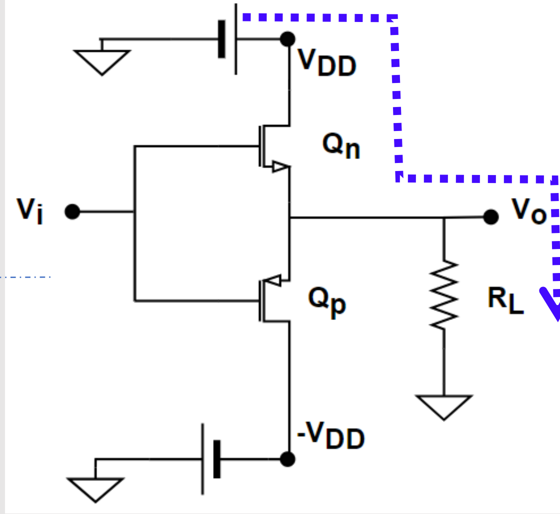
- $\mathbf{0 \le \omega t \le \pi : v_i \ge 0}$**: NMOS ON** $\quad i_{Dn} = \dfrac{v_0}{R_L} = \dfrac{V_P}{R_L} \sin \omega t \;\; ; \;\; V_{DSn} = V_{DD} - V_P \sin \omega t$

$$P_{Qn(inst)} = \frac{V_{DD}V_P}{R_L} \sin \omega t - \frac{V_P^2}{R_L} \sin^2 \omega t \;\; ; P_{Qn(inst)} = 0 \; (\boldsymbol{\pi \le \omega t \le 2\pi})$$

$$\text{Avg } P_{Qn} = \frac{1}{2\pi}\left[\frac{V_{DD}V_P}{R_L}\int_0^\pi \sin \omega t \, d(\omega t) - \frac{V_P^2}{R_L}\int_0^\pi (\sin^2 \omega t) d(\omega t)\right]$$

Let $\theta = \omega t \quad \displaystyle\int_0^\pi \sin \theta \, d(\theta) = -\cos \theta \Big|_0^\pi =$

$\int_0^\pi \sin^2 \theta \, d(\theta) =$



Conversion efficiency of Class B MOSFET amplifier

- $v_O = V_P \sin \omega t$
- **Consider only NMOS Qn:**

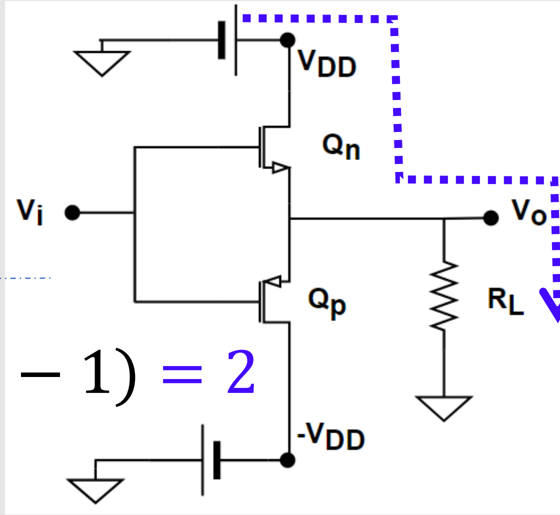
At $0 \le \omega t \le \pi : v_i \ge 0$; NMOS is ON; PMOS is OFF

At $\pi \le \omega t \le 2\pi : v_i \le 0$; NMOS is OFF; PMOS is ON

- $0 \le \omega t \le \pi : v_i \ge 0$: **NMOS ON** $\quad i_{Dn} = \frac{v_0}{R_L} = \frac{V_P}{R_L} \sin \omega t \;\; ; \;\; V_{DSn} = V_{DD} - V_P \sin \omega t$

$$P_{Qn(inst)} = \frac{V_{DD}V_P}{R_L} \sin \omega t - \frac{V_P^2}{R_L} \sin^2 \omega t \;\; ; P_{Qn(inst)} = 0 \; (\pi \le \omega t \le 2\pi)$$

$$\text{Avg } P_{Qn} = \frac{1}{2\pi}\left[\frac{V_{DD}V_P}{R_L}\int_0^\pi \sin \omega t \, d(\omega t) - \frac{V_P^2}{R_L}\int_0^\pi (\sin^2 \omega t) d(\omega t)\right]$$



Let $\theta = \omega t$ $\quad \displaystyle\int_0^\pi \sin \theta \, d(\theta) = -\cos \theta \Big|_0^\pi = -[\cos(\pi) - \cos 0] = -(-1-1) = 2$

$$\int_0^\pi \sin^2 \theta \, d(\theta) = \int_0^\pi \frac{1-\cos(2\theta)}{2} d(\theta) = \frac{1}{2}\int_0^\pi d(\theta) - \frac{1}{2}\int_0^\pi \cos(2\theta)\, d(\theta)$$

$$= \frac{1}{2}.(\theta)\Big|_0^\pi - \frac{1}{2}.\frac{\sin 2\theta}{2}\Big|_0^\pi = \frac{\pi}{2} - \frac{1}{4}(\sin(2\pi) - \sin 0) = \frac{\pi}{2} - 0 = \frac{\pi}{2}$$

Conversion efficiency of Class B MOSFET amplifier

- $v_O = V_P \sin \omega t$
- **Consider only NMOS Qn:**

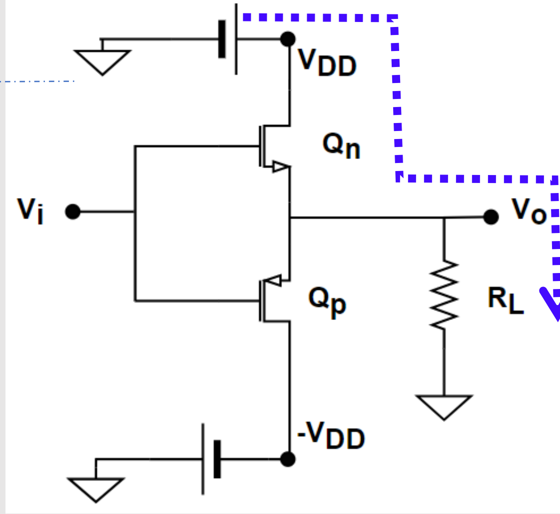
At $0 \le \omega t \le \pi : v_i \ge 0$; NMOS is ON; PMOS is OFF

At $\pi \le \omega t \le 2\pi : v_i \le 0$; NMOS is OFF; PMOS is ON

- $\mathbf{0 \le \omega t \le \pi : v_i \ge 0}$**: NMOS ON**

$$i_{Dn} = \frac{v_0}{R_L} = \frac{V_P}{R_L} \sin \omega t \quad ; \quad V_{DSn} = V_{DD} - V_P \sin \omega t$$

$$P_{Qn(inst)} = \frac{V_{DD}V_P}{R_L} \sin \omega t - \frac{V_P^2}{R_L} \sin^2 \omega t \quad ; P_{Qn(inst)} = 0 \ (\pi \le \omega t \le 2\pi)$$



$$\text{Avg } P_{Qn} = \frac{1}{2\pi}\left[\frac{V_{DD}V_P}{R_L}\int_0^{\pi} \sin \omega t \, d(\omega t) - \frac{V_P^2}{R_L}\int_0^{\pi} (\sin^2 \omega t) d(\omega t)\right]$$

$$= \frac{1}{2\pi}\left[\frac{V_{DD}V_P}{R_L}(2) - \frac{V_P^2}{R_L}\left(\frac{\pi}{2}\right)\right]$$

$$=$$

Conversion efficiency of Class B MOSFET amplifier

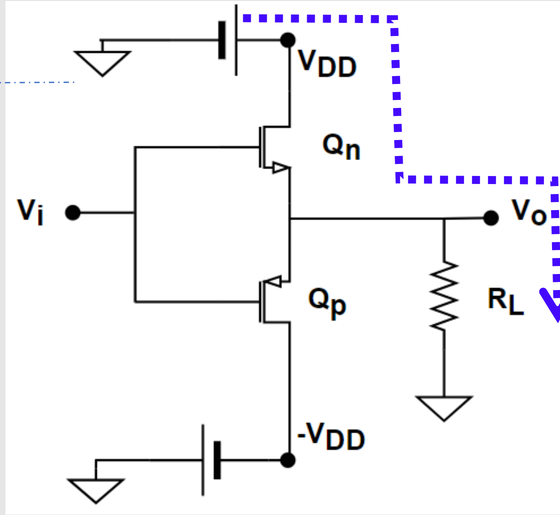
- $v_O = V_P \sin \omega t$
- **Consider only NMOS Qn:**

At $0 \le \omega t \le \pi : v_i \ge 0$; NMOS is ON; PMOS is OFF

At $\pi \le \omega t \le 2\pi : v_i \le 0$; NMOS is OFF; PMOS is ON

- $\boldsymbol{0 \le \omega t \le \pi : v_i \ge 0}$: **NMOS ON** $\quad i_{Dn} = \frac{v_O}{R_L} = \frac{V_P}{R_L} \sin \omega t \;;\quad V_{DSn} = V_{DD} - V_P \sin \omega t$

$$P_{Qn(inst)} = \frac{V_{DD} V_P}{R_L} \sin \omega t - \frac{V_P^2}{R_L} \sin^2 \omega t \;;\; P_{Qn(inst)} = 0 \; (\boldsymbol{\pi \le \omega t \le 2\pi})$$



$$\text{Avg } P_{Qn} = \frac{1}{2\pi}\left[\frac{V_{DD} V_P}{R_L} \int_0^{\pi} \sin \omega t \, d(\omega t) - \frac{V_P^2}{R_L} \int_0^{\pi} (\sin^2 \omega t) d(\omega t)\right]$$

$$= \frac{1}{2\pi}\left[\frac{V_{DD} V_P}{R_L}(2) - \frac{V_P^2}{R_L}\left(\frac{\pi}{2}\right)\right]$$

$$= \frac{V_{DD} V_P}{R_L \pi} - \frac{V_P^2}{4 R_L}$$

At max power: $\left.\frac{\partial P_{Qn}}{\partial V_P}\right|_{P\,max} = 0$

Example: If y has maxima,

At $\left.\frac{\partial y}{\partial x}\right|_{y\,max} = 0$

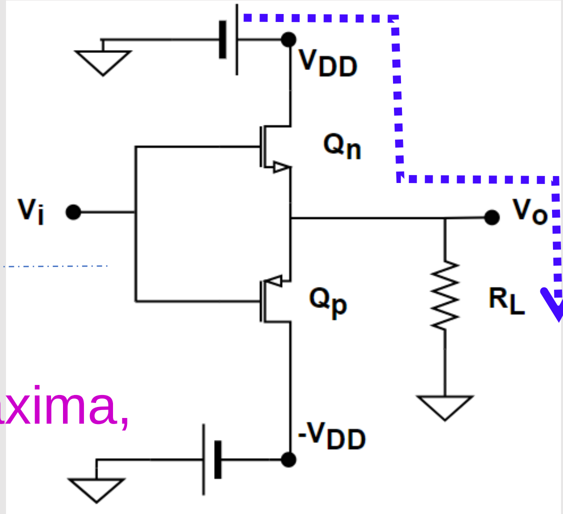
Conversion efficiency of Class B MOSFET amplifier

- $v_O = V_P \sin \omega t$
- <u>**Consider only NMOS Qn:**</u>
- $\mathbf{0 \leq \omega t \leq \pi : v_i \geq 0}$**: NMOS ON**

At $0 \leq \omega t \leq \pi : v_i \geq 0$; NMOS is ON; PMOS is OFF

At $\pi \leq \omega t \leq 2\pi : v_i \leq 0$; NMOS is OFF; PMOS is ON

$i_{Dn} = \frac{v_0}{R_L} = \frac{V_P}{R_L} \sin \omega t$; $V_{DSn} = V_{DD} - V_P \sin \omega t$



$$P_{Qn(inst)} = \frac{V_{DD}V_P}{R_L} \sin \omega t - \frac{V_P^2}{R_L} \sin^2 \omega t \quad ; P_{Qn(inst)} = 0 \; (\pi \leq \omega t \leq 2\pi)$$

$$\text{Avg } P_{Qn} = \frac{V_{DD}V_P}{R_L \pi} - \frac{V_P^2}{4R_L}$$

$$\boxed{\text{Note: } \frac{\partial P_{Qn}}{\partial V_P} = \frac{V_{DD}}{R_L \pi} - \frac{2V_P}{4R_L}}$$

$$\text{At max power: } \left.\frac{\partial P_{Qn}}{\partial V_P}\right|_{P\,max} = 0$$

$$\frac{V_{DD}}{R_L \pi} - \frac{2V_P}{4R_L} = 0 \quad \text{On rearranging: } V_P = \frac{2V_{DD}}{\pi}$$

Example: If y has maxima,

At $\frac{\partial y}{\partial x}\Big|_{y\,max} = 0$

$$\text{Max power: when } V_P = \frac{2V_{DD}}{\pi}$$

$$P_{Qn(max)} =$$

Conversion efficiency of Class B MOSFET amplifier

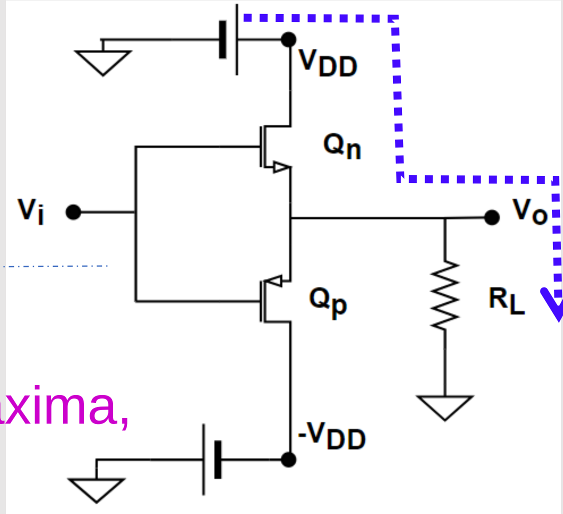
- $v_O = V_P \sin \omega t$
- **Consider only NMOS Qn:**
- $0 \le \omega t \le \pi : v_i \ge 0$: **NMOS ON**

At $0 \le \omega t \le \pi : v_i \ge 0$; NMOS is ON; PMOS is OFF

At $\pi \le \omega t \le 2\pi : v_i \le 0$; NMOS is OFF; PMOS is ON

$$i_{Dn} = \frac{v_0}{R_L} = \frac{V_P}{R_L}\sin \omega t \;;\quad V_{DSn} = V_{DD} - V_P \sin \omega t$$

$$P_{Qn(inst)} = \frac{V_{DD}V_P}{R_L}\sin \omega t - \frac{V_P^2}{R_L}\sin^2 \omega t \;;\; P_{Qn(inst)} = 0 \;(\pi \le \omega t \le 2\pi)$$



$$\text{Avg } P_{Qn} = \frac{V_{DD}V_P}{R_L\pi} - \frac{V_P^2}{4R_L}$$

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Example: If y has maxima,

At $\frac{\partial y}{\partial x}\Big|_{y\,max} = 0$

Max power: when $V_P = \frac{2V_{DD}}{\pi}$

$$P_{Qn(max)} = \frac{V_{DD}V_P}{R_L\pi} - \frac{V_P^2}{4R_L} = \frac{V_{DD}}{\pi R_L}.\frac{2V_{DD}}{\pi} - \frac{1}{4R_L}\left(\frac{2V_{DD}}{\pi}\right)^2 = \frac{V_{DD}^2}{\pi^2 R_L}$$

Conversion efficiency of Class B MOSFET amplifier

- $v_O = V_P \sin \omega t$
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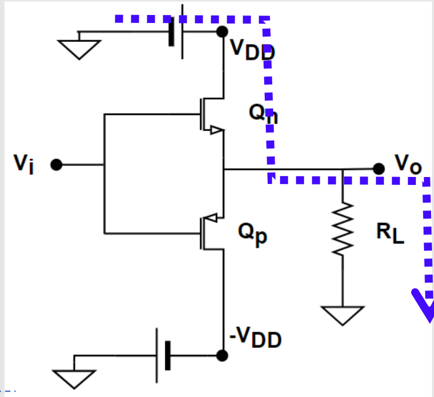
- **$0 \le \omega t \le \pi : v_i \ge 0$: NMOS ON** $\quad i_{Dn} = \frac{v_0}{R_L} = \frac{V_P}{R_L} \sin \omega t$; $V_{DSn} = V_{DD} - V_P \sin \omega t$



$$P_{Qn(inst)} = \frac{V_{DD}V_P}{R_L} \sin \omega t - \frac{V_P^2}{R_L} \sin^2 \omega t \quad ; P_{Qn(inst)} = 0 \ (\pi \le \omega t \le 2\pi)$$

Avg $P_{Qn} = \frac{V_{DD}V_P}{R_L \pi} - \frac{V_P^2}{4R_L}$; Max power: when $V_P = \frac{2V_{DD}}{\pi}$: $P_{Qn(max)} = \frac{V_{DD}^2}{\pi^2 R_L}$

Average current: $i_{Dn(avg)} = \frac{1}{2\pi}\left[\int_0^{\pi} \frac{V_P}{R_L} \sin \omega t \, d(\omega t) + \int_{\pi}^{2\pi} (0) d(\omega t)\right]$

$$= \frac{1}{2\pi} . \frac{V_P}{R_L}(2) = \frac{V_P}{\pi R_L}$$

$$\int_0^{\pi} \sin \theta \, d(\theta) = -\cos \theta \Big|_0^{\pi}$$

$$= -[\cos(\pi) - \cos 0] = -(-1 - 1)$$

$$= 2$$

Conversion efficiency of Class B MOSFET amplifier

- $v_O = V_P \sin \omega t$
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- $\mathbf{0 \le \omega t \le \pi : v_i \ge 0}$: **NMOS ON** $\quad i_{Dn} = \frac{v_0}{R_L} = \frac{V_P}{R_L} \sin \omega t$; $\quad V_{DSn} = V_{DD} - V_P \sin \omega t$

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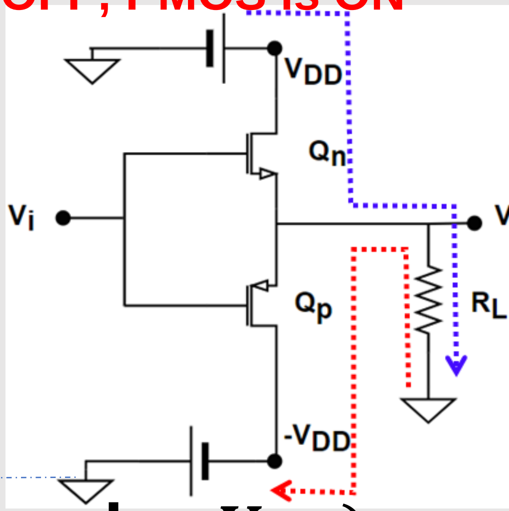


$$P_{Qn(inst)} = \frac{V_{DD}V_P}{R_L} \sin \omega t - \frac{V_P^2}{R_L} \sin^2 \omega t \quad ; P_{Qn(inst)} = 0 \ (\pi \le \omega t \le 2\pi)$$

Avg $P_{Qn} = \frac{V_{DD}V_P}{R_L\pi} - \frac{V_P^2}{4R_L}$; Max power: when $V_P = \frac{2V_{DD}}{\pi}$: $\ P_{Qn(max)} = \frac{V_{DD}^2}{\pi^2 R_L}$

Average current: $\ i_{Dn(avg)} = \frac{V_P}{\pi R_L}$

<u>**Consider only PMOS Qp:**</u> $\mathbf{\pi \le \omega t \le 2\pi : v_i \le 0}$: **PMOS ON (through $-V_{DD}$)**

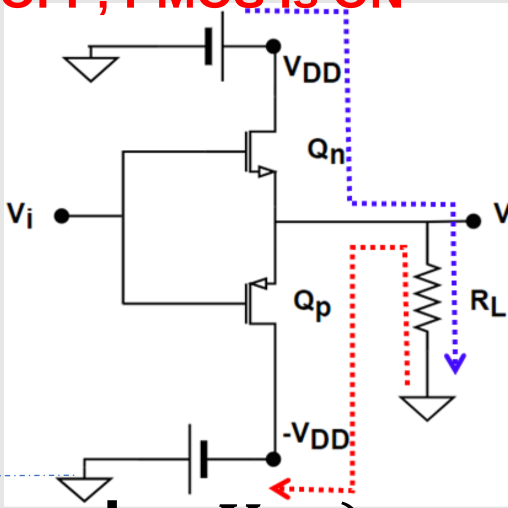
$P_{Qp(max)} = \frac{V_{DD}^2}{\pi^2 R_L}$ and avg current through Q_p: $i_{Dp(avg)} = \frac{V_P}{\pi R_L}$

Conversion efficiency of Class B MOSFET amplifier

- $v_O = V_P \sin \omega t$
- <u>Consider only NMOS Qn:</u>

At $0 \le \omega t \le \pi$: $v_i \ge 0$; NMOS is ON; PMOS is OFF

At $\pi \le \omega t \le 2\pi$: $v_i \le 0$; NMOS is OFF; PMOS is ON



- $\boldsymbol{0 \le \omega t \le \pi : v_i \ge 0}$: **NMOS ON** $\quad i_{Dn} = \frac{v_0}{R_L} = \frac{V_P}{R_L} \sin \omega t$; $V_{DSn} = V_{DD} - V_P \sin \omega t$

$P_{Qn(inst)} = \frac{V_{DD}V_P}{R_L} \sin \omega t - \frac{V_P^2}{R_L} \sin^2 \omega t$; $P_{Qn(inst)} = 0 \; (\pi \le \omega t \le 2\pi)$

Avg $P_{Qn} = \frac{V_{DD}V_P}{R_L \pi} - \frac{V_P^2}{4R_L}$; Max power: when $V_P = \frac{2V_{DD}}{\pi}$: $P_{Qn(max)} = \frac{V_{DD}^2}{\pi^2 R_L}$

Average current: $i_{Dn(avg)} = \frac{V_P}{\pi R_L}$

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Average power supplied by 2 sources: $P_S = 2V_{DD}\left(\frac{V_P}{\pi R_L}\right)$ (Voltage x current)

Average power delivered to load: $P_L = \frac{1}{2}\frac{V_P^2}{R_L}$

Conversion efficiency of Class B MOSFET amplifier

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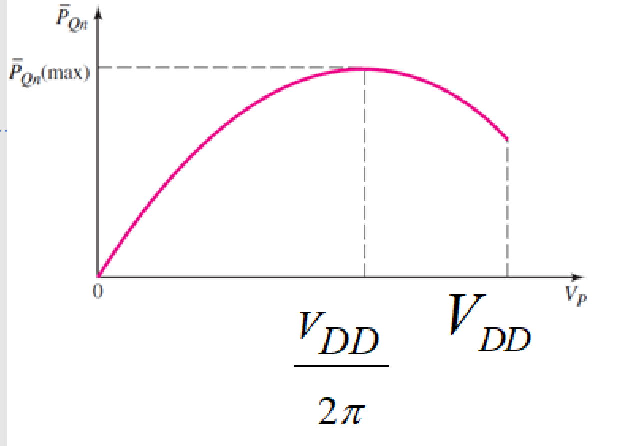

Power conversion efficiency: $\eta = \frac{P_L}{P_S}$

$$\eta = \frac{1}{2}\frac{V_P^2}{R_L}.\frac{1}{2V_{DD}\left(\frac{V_P}{R_L}\right)} = \frac{\pi}{4}.\frac{V_P}{V_{DD}}$$

Max power conversion efficiency: Ideally when $V_P = V_{DD}$

$$\eta_{max} = \frac{\pi}{4}.\frac{V_P}{V_{DD}} = \frac{\pi}{4} = \frac{3.1416}{4} \times 100\% = 78.5\% \quad \text{and } P_{Lmax} = \frac{1}{2}.\frac{V_{DD}^2}{R_L}$$

But, we know that $V_P = \frac{2V_{DD}}{\pi}$ is the maximum possible value:

$$\eta_{max} = \frac{\pi}{4}.\frac{V_P}{V_{DD}} = \frac{\pi}{4}\frac{2V_{DD}}{\pi V_{DD}} \times 100\% = 50\%$$