# EE210: HW-11 Solution

Date: 28/03/2019

Unless stated otherwise, the BJT in the problems given below has the following characteristics:

$$I_S = 2.03 \times 10^{-15}A;\ \beta_F = 100;\ \beta_R = 1;\ V_A = \infty;\ r_{bb} = 200\Omega;\ V_T = 26mV$$
$$C_{jeo} = 1pF;\ C_{jco} = 0.5pF;\ C_{jso} = 3pF;\ m = 0.5;\ V_{bi} = 0.85;\ \tau_F = 1ns$$

(For simplicity, include $r_{bb}$only in high frequency analysis and ignore $C_{js}$)

**Q.1** Determine the efficiency of the amplifier shown in Fig. 1, when the input is a sinusoid of magnitude 1V.

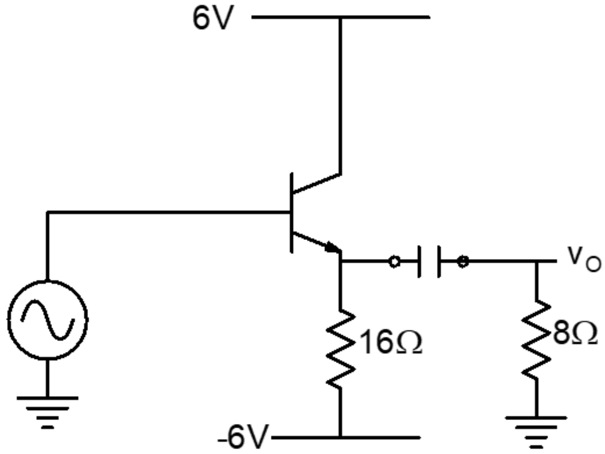



Fig. 1

**Sol.:**

Given: input is a sinusoid of magnitude 1V.

$$v_{in} = 1V \sin \omega t$$

Efficiency:

$$\eta = \frac{P_L}{P_S} \times 100$$

For CC amplifier,

$$A_V \approx 1 \Rightarrow\ v_o = v_{in}$$

$$P_L = \frac{v_o^2}{2R_L} = \frac{1}{2 \times 8} = 0.0625W$$

For $P_S$ calculation:

$$I_{EQ} = \frac{-0.7 - (-V_{CC})}{R_E} = \frac{-0.7 + 6}{16} = 0.33A$$

$$P_S = 2 * V_{CC} * I_{EQ} = 3.975W$$

$$\eta = \frac{P_L}{P_S} \times 100 = \frac{0.0625}{3.975} \times 100 = 1.57\%$$

**Q.2** Design the amplifier shown in Fig. 2 to deliver a maximum power of 0.5W to the load. As part of the design, determine $V_{CC}$, $R_E$ and maximum values of collector current, collector emitter voltage and power dissipated in the transistor.

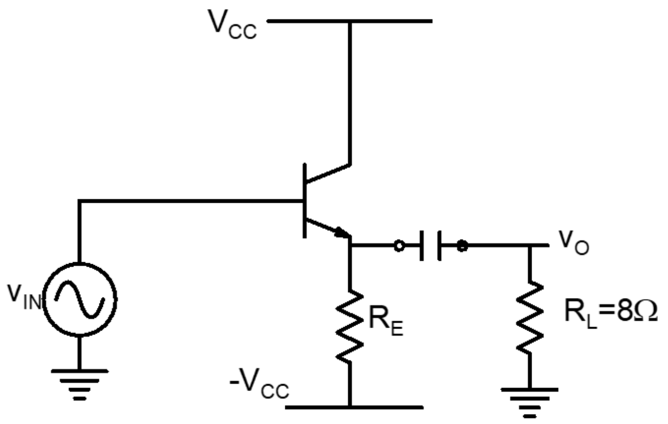



Fig. 2

**Sol.:**

$$P_L = 0.5W = \frac{v_{om}^2}{2R_L}$$

$$v_{om} = \sqrt{2R_L P_L} = 2.83V$$

For max efficiency, choose $R_E = R_L$.

$$v_{om} = I_{EQ}.R_E||R_L \Rightarrow I_{EQ} = 0.707A$$

$$V_{cc} = I_{EQ}.R_E + 0.7 \Rightarrow V_{CC} = 6.356V$$

Choose $V_{CC}$ as close as possible to this value to keep efficiency maximum. Let's take

$$V_{CC} = 6.5V$$

$$P_S = V_{CC}I_{CQ} + V_{CC}I_{EQ} \cong 2V_{CC}I_{EQ} \cong 9.2W$$

$$\eta = \frac{P_L}{P_S} \times 100 = \frac{0.5}{9.2} \times 100 = 5.43\%$$

$$I_{C(max)} = I_E + \frac{v_{om}}{R_E||R_L} = 1.4A$$

Power dissipation:

$$P_D = P_S - P_L \cong 2V_{CC}I_{EQ} - \frac{v_{om}^2}{2R_L} = 9.2 - 0.5 = 8.7W$$

$$V_{CE(max)} = V_{CC} - (-0.7 - v_{om}) = 10.03V$$

**Q.3** Design the amplifier shown below in Fig. 3 to deliver a maximum power of 2W to the load. As part of the design, determine $V_{CC}$ and maximum values of collector current, collector emitter voltage and power dissipated in the transistor.

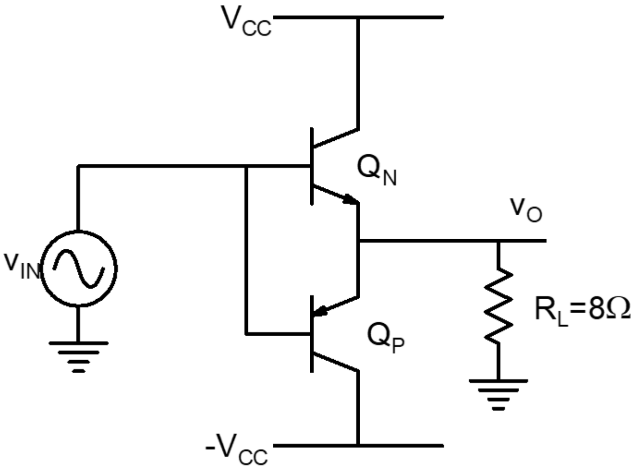



Fig. 3

**General Comments on this circuit:**

Fig. 3 shows a class B output stage. It consists of a complementary pair of transistors (an *npn* and a *pnp*) connected in such a way that both cannot conduct simultaneously.

When the input voltage $v_{IN}$ is zero, both transistors are cut-off and the output voltage $v_O$ is zero. As $v_{IN}$ goes positive and exceeds about 0.5 V (different books take different values: 0.5-0.65V), $Q_N$ conducts and operates as an emitter follower. In this case $v_O$ follows $v_{IN}$ (i.e., $v_O = v_{IN} - v_{BEN}$) and $Q_N$ supplies the load current. Meanwhile, the emitter–base junction of $Q_P$ will be reverse-biased by the $V_{BE}$ of *QN*, which is approximately 0.7 V. Thus, $Q_P$ will be cut off.

If the input goes negative by more than about 0.5 V, $Q_P$ turns on and acts as an emitter follower. Again, $v_O$ follows $v_{IN}$ (i.e., $v_O = v_{IN} + v_{EBP}$), but in this case *QP* supplies the load current and $Q_N$ will be cut off. We conclude that the transistors in the class B stage of Fig. 3 are biased at zero current and conduct only when the input signal is present. The circuit operates in a **push–pull** fashion: $Q_N$ *pushes* (sources) current into the load when $v_{IN}$ is positive, and $Q_P$ *pulls* (sinks) current from the load when $v_{IN}$ is negative.

A sketch of the transfer characteristic of the class B stage is shown in the figure. Note that there exists a range of $v_{IN}$ centered around zero where both transistors are cut off and $v_O$ is zero. This **dead band** results in the **crossover distortion** illustrated in the figure for the case of an input sine wave. The effect of crossover distortion will be most pronounced when the amplitude of the input signal is small. Crossover distortion in audio power amplifiers gives rise to unpleasant sounds.

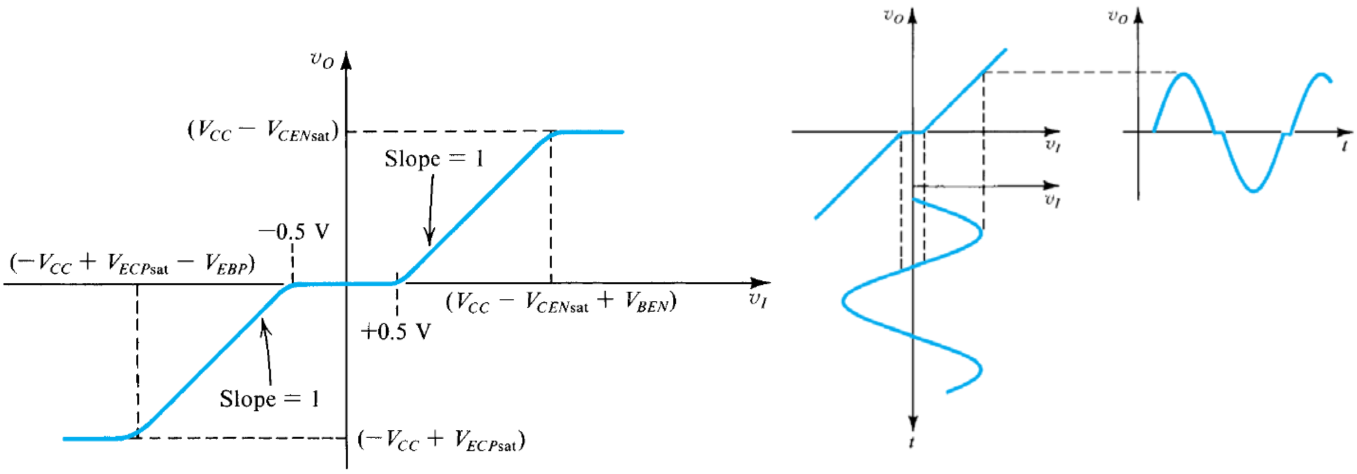
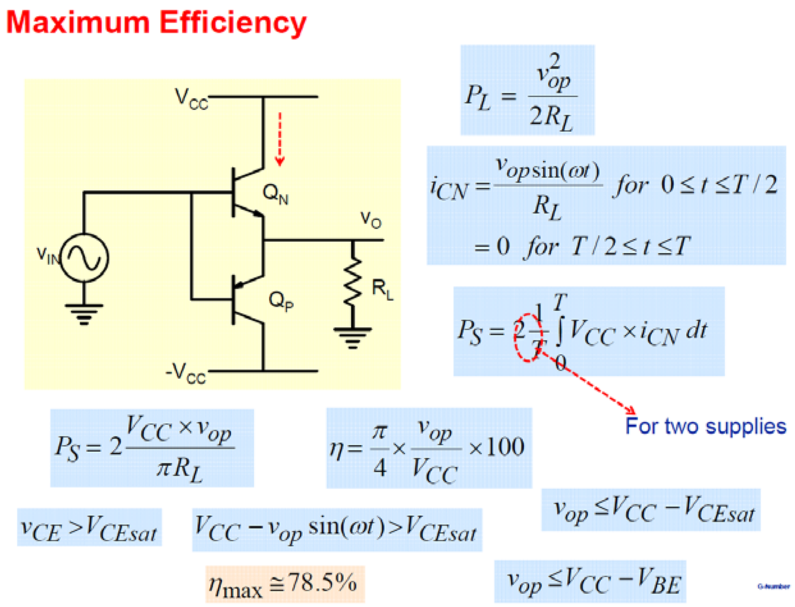



Fig. (a) Transfer characteristic for the class B output stage in Fig. 3. (b) Illustrating how the dead band in the class B transfer characteristic results in crossover distortion.

**Sol.:**




We will neglect crossover distortion in the calculation. Given – deliver a maximum power of 2W to the load.

$$P_L = 2W \text{ and } P_L = \frac{v_{om}^2}{2R_L}$$

$$v_{om} = \sqrt{2R_L P_L} = 5.65V$$

$$V_{CC} = v_{om} + V_{CE} = 5.65 + 0.2 = 5.85\text{V}$$

Let's take $V_{CC}$ = 6V.

For Class B amplifier:

$$P_S = \frac{2V_{CC}.v_{om}}{\pi R_L} \cong 2.7W$$

$$\eta = \frac{P_L}{P_S} \times 100 = \frac{2}{2.7} \times 100 \cong 74\ \%$$

$$I_{Cmax} \approx \frac{v_{om}}{R_L} = 0.706A$$

$$V_{CE}(max) = V_{CC} + v_{om} = 11.65\ V$$

Maximum <u>instantaneous</u> device power dissipation:

$$P_c = V_{ce} * I_c = (V_{CC} - I_c R_L) * I_c = V_{CC} I_c - I_c^2 R_L$$

$\frac{\partial P_c}{\partial I_c} = 0$ gives the maximum $P_c$ for $I_c = V_{CC}/(2R_L)$ and correspondingly, $V_{ce} = V_{CC}/2$.

$$P_c = V_{ce} * I_c = \frac{V_{CC}}{2} * \frac{V_{CC}}{2R_L}$$

<u>Maximum Power dissipation in the transistors vs. $v_{om}$</u>:

$$P_L = \frac{v_{om}^2}{2R_L};\ P_{S+} = \frac{V_{CC}.v_{om}}{\pi R_L};\ P_{S-} = \frac{V_{CC}.v_{om}}{\pi R_L}$$

$$P_D = P_S - P_L = \frac{2V_{CC}.v_{om}}{\pi R_L} - \frac{v_{om}^2}{2R_L}$$

From symmetry we see that half of $P_D$ is dissipated in $Q_N$ and the other half in $Q_P$. Thus, $Q_N$ and $Q_P$ must be capable of safely dissipating ½ $P_D$ watts. Since $P_D$ depends on $V_{om}$, we must find the worst-case power dissipation, $P_{Dmax}$. For maximum average power dissipation,

$$\frac{\partial P_D}{\partial v_{om}} = 0 \Rightarrow v_{om} = \frac{2V_{CC}}{\pi}$$

$$P_{Dmax} = \frac{2V_{CC}^2}{\pi^2 R_L}$$

$$P_{DNmax} = P_{DPmax} = \frac{V_{CC}^2}{\pi^2 R_L}$$

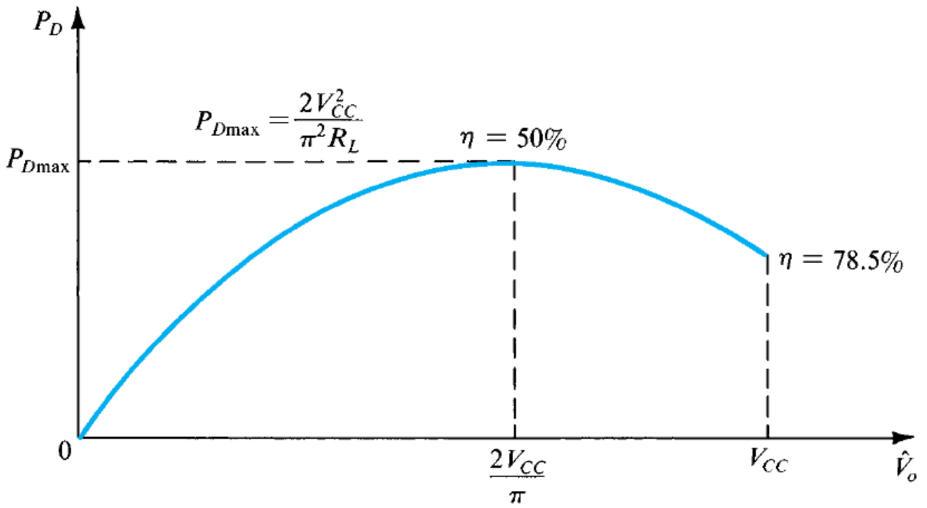
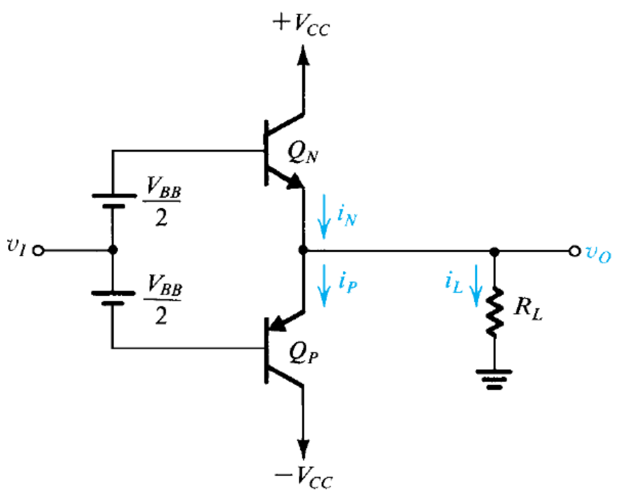
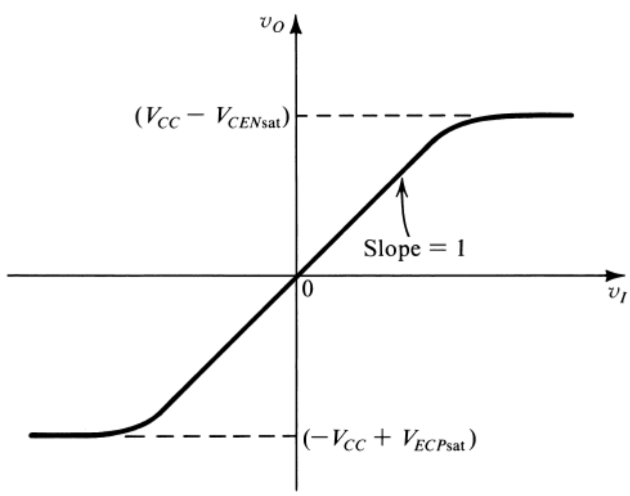



Fig. Power dissipation of the class B output stage versus amplitude of the output sinusoid.

**Q.4** Draw the complete schematic of class AB amplifier.

**Sol.:** Class AB amplifier output stage combines the advantages of the Class A amplifier and the Class B amplifier producing a better amplifier design. The amplifiers' two output transistors conduct somewhere between 180°and 360° of the input waveform. As there is some overlap in conduction of two transistors, efficiency of class AB amplifier is less than class B amplifier.



A bias voltage $V_{BB}$ is applied between the bases of $Q_N$ and $Q_P$. For $v_I = 0$, $v_O = 0$, and a voltage appears across the base–emitter junction of each of $Q_N$ and $Q_P$. Assuming matched devices,

$$i_N = i_P = I_Q = I_S e^{\frac{V_{BB}}{2V_T}}$$

The value of $V_{BB}$ is selected to yield the required quiescent current $I_Q$.

When $v_I$ goes positive by a certain amount, the voltage at the base of $Q_N$ increases by the same amount and the output becomes positive at an almost equal value,

$$v_O = v_I + \frac{V_{BB}}{2} - v_{BEN}$$

The positive $v_O$ causes a current $i_L$ to flow through $R_L$, and thus $i_N$ must increase; that is,

$$i_N = i_N + i_L$$

The increase in $i_N$ will be accompanied by a corresponding increase in $v_{BEN}$ (above the quiescent value of $V_{BB/2}$). However, since the voltage between the two bases remains constant at $V_{BB}$, the increase in $v_{BEN}$ will result in an equal decrease in $v_{EBP}$ and hence in $i_P$.

The relationship between $i_N$ and $i_P$ can be derived as follows:

$$v_{BEN} + v_{BEP} = V_{BB}$$

$$V_T \ln\frac{i_N}{I_S} + V_T \ln\frac{i_P}{I_S} = 2V_T \ln\frac{I_Q}{I_S}$$

$$i_N * i_P = {I_Q}^2$$

Thus, as $i_N$ increases, $i_P$ decreases by the same ratio while the product remains constant. From above equations, we also see,

$$i_N{}^2 - i_L * i_N - I_Q{}^2 = 0$$

From the equations above, we can see that for positive output voltages, the load current is supplied by $Q_N$, which acts as the output emitter follower. Meanwhile, $Q_P$ will be conducting a current that decreases as $v_O$ increases; for large $v_O$ the current in $Q_P$ can be ignored altogether. For negative input voltages the opposite occurs.

The power relationships in the class AB stage are almost identical to those derived for the class B circuit. The only difference is that under quiescent conditions the class AB circuit dissipates a power of $V_{CC}*I_Q$ per transistor, which can be neglected as $I_Q$ is usually much smaller than the peak load current.