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ELECTRONIC CIRCUITS
Darlington Amplifier

12^{th} **July, 2020**

Numerical 1:
For each of the transistor, $\beta = 100$ and $V_A = \infty$, determine:
1. Q-point for both transistors
2. Overall small signal voltage gain $A_V = V_o/V_i$
3. Input and output resistance R_i and R_o

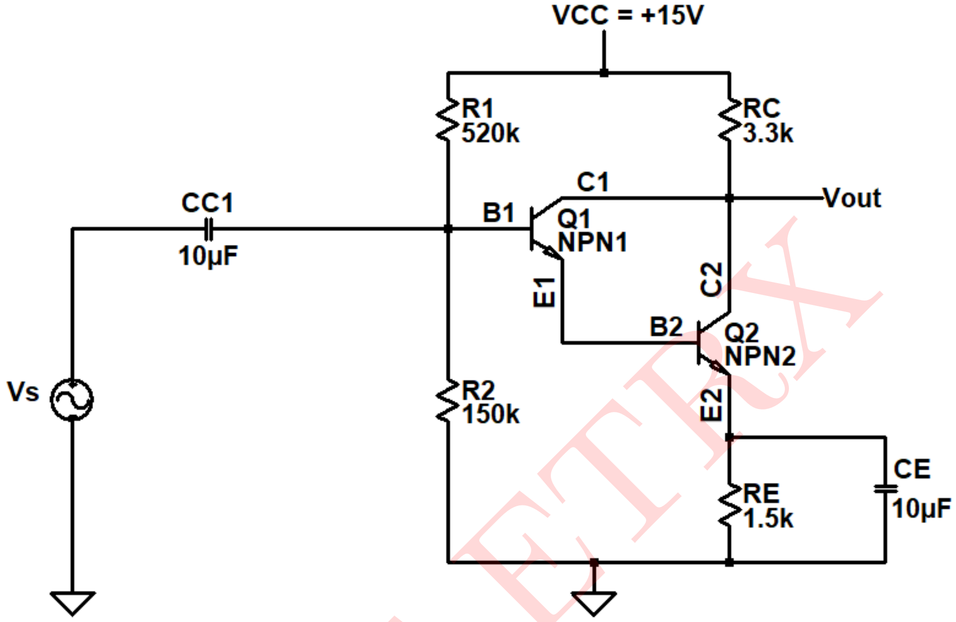

Figure 1: Circuit diagram

Solution: Circuit shown in figure 1 is a CE Darlington pair circuit.
DC equivalent circuit is shown in figure 2:

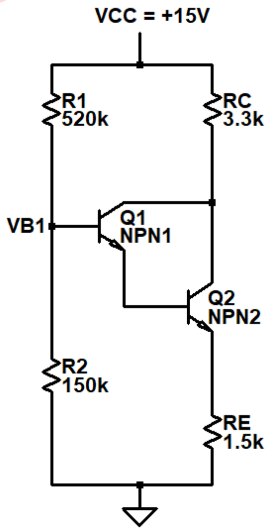

Figure 2: DC equivalent circuit

$$V_{TH} = \frac{R_2}{R_1 + R_2} \times V_{CC} = \frac{159k\Omega}{520k\Omega + 150k\Omega} \times 15$$

$\therefore V_{TH} = 3.3582V$

$R_{TH} = 150k\Omega \parallel 520k\Omega$

$\therefore R_{TH} = 116.4179k\Omega$

Applying KVL to B-E loop:
$V_{TH} - I_{B1}R_B - V_{BE} - I_{E2}R_E = 0 \quad ...(\text{here } R_B = R_{TH})$

$V_{BE} = V_{BE1} + V_{BE2} = 0.7 + 0.7$

$\therefore V_{BE} = 1.4V$

$I_{E2} = (1 + \beta_2)I_{B2}$

$\therefore I_{E2} = (1 + \beta_2)I_{E1}) \quad ...(\because I_{B2} = I_{E1})$

$\therefore I_{E2} = (1 + \beta_2)(1 + \beta_1)I_{B1}$

$\therefore V_{TH} - I_{B1}R_B - V_{BE} - (1 + \beta_1)(1 + \beta_2)I_{B1}R_E = 0$

$$\therefore I_{B1} = \frac{V_{TH} - V_{BE}}{R_B + (1 + \beta_1)(1 + \beta_2)R_E} = \frac{3.3582 - 1.4}{116.4179k\Omega + (101)(101)(1.5k\Omega)}$$

$\therefore I_{B1} = 0.12701\mu A$

$I_{C1} = \beta_1 I_{B1} = 100(0.12701\mu\text{A})$

$\therefore I_{C1} = 0.0127mA$

$I_{E1} = I_{C1} + I_{B1} = 0.01283mA$

$\therefore I_{C2} = \beta_2 I_{B2} = (100)(0.01083\text{mA}) = 1.2827\text{mA}$

$I_{E2} = I_{C2} + I_{B2} = 1.2955\text{mA}$

$\therefore V_{E2} = I_{E2}R_E = (1.2955mA)(1.5k\Omega)$

$\therefore V_{E2} = 1.9433V$

$V_{C2} = V_{CC} - I_{C2}R_C$

$\therefore V_{C2} = 15 - (1.2827mA)(3.3k\Omega)$

$\therefore V_{C2} = 10.7671V$

Small signal parameters:

$$r_{\pi 1} = \frac{\beta V_T}{I_{C1}} = \frac{100 \times 26mV}{0.0127mA}$$

$$\therefore r_{\pi 1} = 204.724k\Omega$$

$$g_{m1} = \frac{I_{C1}}{V_T} = \frac{0.0127mA}{26}$$

$$\therefore g_{m1} = 0.4885mA/V$$

$$r_{\pi 2} = \frac{\beta V_T}{I_{C2}} = \frac{(100)(26mV)}{1.2827mA}$$

$$\therefore r_{\pi 2} = 2.0269k\Omega$$

$$g_{m2} = \frac{I_{C2}}{V_T} = \frac{1.2827mA}{26mV}$$

$$\therefore g_{m2} = 49.335mA/V$$

Small signal equivalent circuit is shown in figure 3:

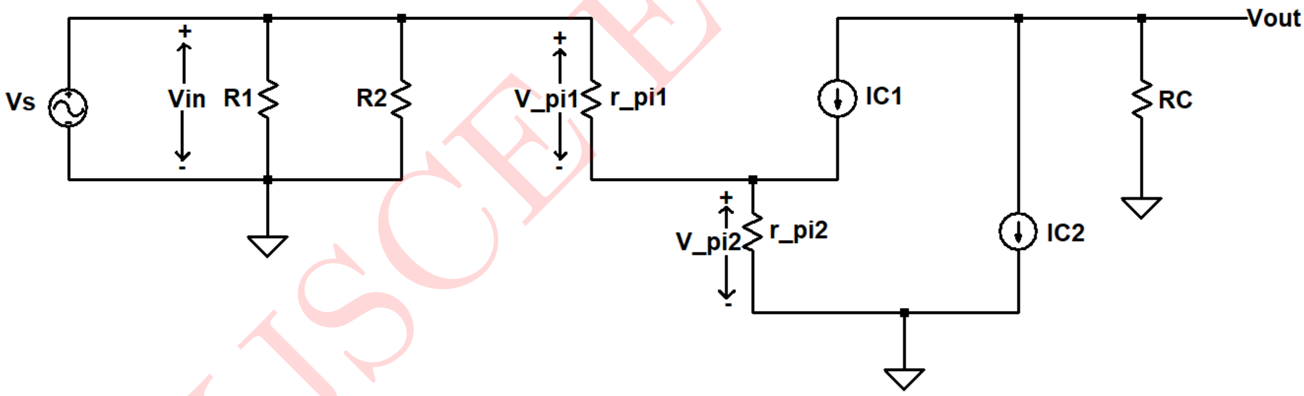

Figure 3: Small signal equivalent circuit

$$Z_{1i} = r_{\pi 1} + (1 + \beta_1) r_{\pi 2}$$

$$Z_{1i} = 204.724 + (101)(2.0269k\Omega)$$

$$\therefore Z_{1i} = 409.44k\Omega$$

Input impedance: $Z_i = R_1 \parallel R_2 \parallel Z_{i1}$

$$\therefore Z_i = 116.4179k\Omega \parallel 409.44k\Omega$$

$$\therefore Z_i = 90.645k\Omega$$

Output impedances: $Z_{o1} = \dfrac{R_1 \parallel R_2 + r_{\pi 1}}{1+\beta_1} = \dfrac{116.4179k\Omega + 204.724k\Omega}{101}$

$\therefore Z_{o1} = 3.1796k\Omega$

$Z_{o2} = \dfrac{Z_{o1} + r_{\pi 2}}{1+\beta_2} = \dfrac{3.1796k\Omega + 2.0269k\Omega}{101}$

$\therefore Z_{o2} = 0.5155k\Omega$

$\therefore Z_o = Z_{o2} \parallel R_C = 0.05155k\Omega \parallel 3.3k\Omega$

$\therefore Z_o = 0.0508k\Omega$

Current gain of Stage 1: $A_{i1} = \dfrac{I_{C1}}{I_{B1}} = \dfrac{\beta_1 I_{B1}}{I_{B1}} = \beta_1$

$\therefore A_{i1} = 100$

Current gain of Stage 2: $A_{i2} = \dfrac{I_{C2}}{I_{B2}} = \dfrac{\beta_2 I_{B2}}{I_{B2}} = \beta_2$

$\therefore A_{i2} = 100$

$A_{id} = A_{i1} \times A_{i2} = 10000$

Overall current gain:

$A_{is} = \dfrac{I_o}{I_i} = \dfrac{I_o}{I_{B2}} \times \dfrac{I_{B2}}{I_{B1}} \times \dfrac{I_{B1}}{I_i}$

$\therefore A_{is} = A_{i2} \times A_{i1} \times \dfrac{I_B}{I_i}$

$\because I_{B2} = I_{E1}$ and $I_{E1} = I_{C1}$

$\therefore A_{is} = A_{i2} \times A_{i1} \times \dfrac{R_1 \parallel R_2}{R_1 \parallel R_2 + Z_i}$

$\therefore A_{is} = 100 \times 100 \times \dfrac{116.4179k\Omega}{116.4179k\Omega + 409.44k\Omega}$

$\therefore A_{is} = 2213.866$

Voltage gain for stage 1:

$A_{V1} = \dfrac{V_1}{V_s} = \dfrac{I_{E1}}{I_{B1}} \times \dfrac{r_{\pi 2}}{Z_{i1}}$

$\therefore A_{V1} = \dfrac{I_{C1}}{I_{B1}} \times \dfrac{r_{\pi 2}}{Z_{i1}} = A_{i1} \times \dfrac{r_{\pi 2}}{Z_{i1}}$

$\therefore A_{V1} = 100 \times \dfrac{2.0269k\Omega}{409.44k\Omega}$

$\therefore A_{V1} = 0.4950$

Voltage gain for stage 2:

$$A_{V2} = \frac{V_o}{V_1} = \frac{I_o}{I_{B2}} \times \frac{R_C}{r_{\pi 2}}$$

$$\therefore A_{V2} = A_{i2} \times \frac{R_C}{r_{\pi 2}} = 100 \times \frac{3.3k\Omega}{2.0269k\Omega}$$

$$\therefore A_{V2} = 162.81$$

$$\therefore A_{Vt} = A_{V1} \times A_{V2} = 80.591$$

$$A_V = \frac{V_{out}}{V_s}$$

$$\therefore V_{out} = A_{Vt} \times V_s$$

For $V_s = 20mV$,

$$\therefore V_{out} = 80.591(20mA) = -1.6118V$$

SIMULATED RESULTS:

Above circuit was simulated in LTspice and results obtained are as follows:

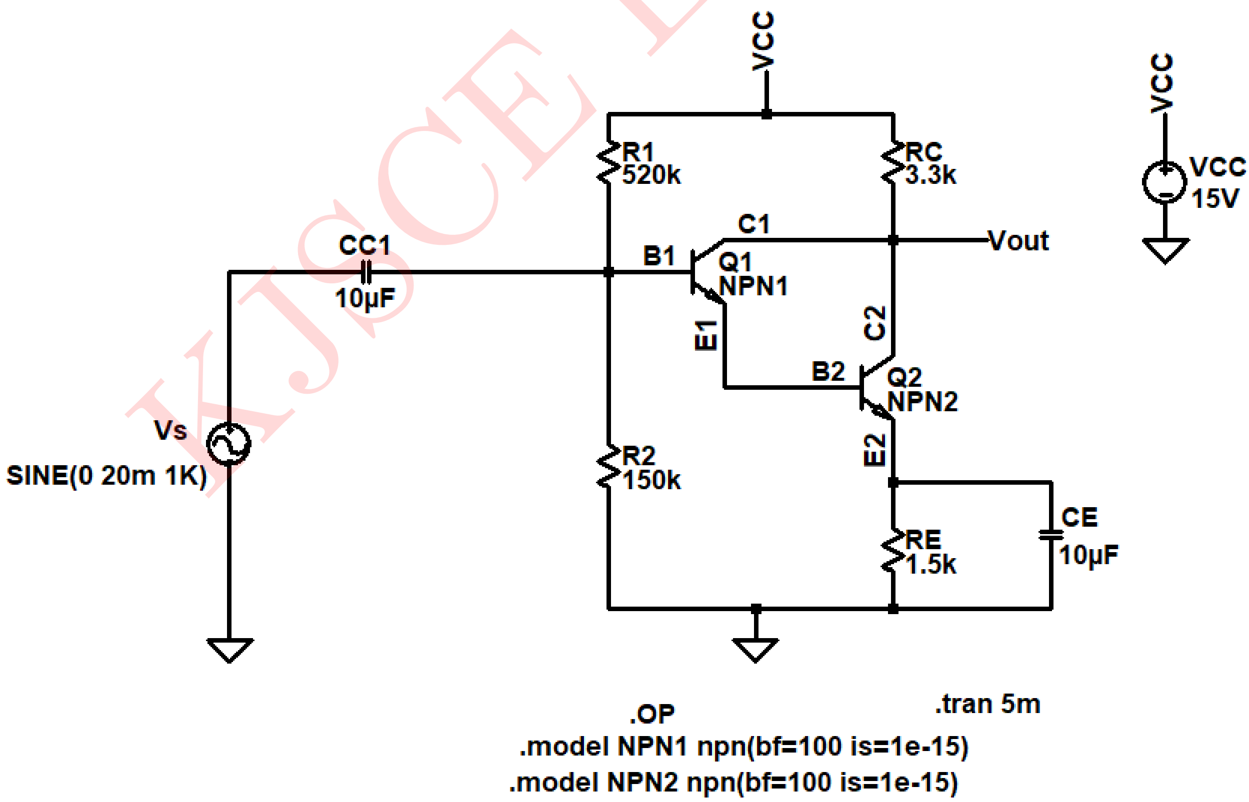

Figure 4: Circuit Schematic: Results

Input and output waveforms for each stage are shown below:

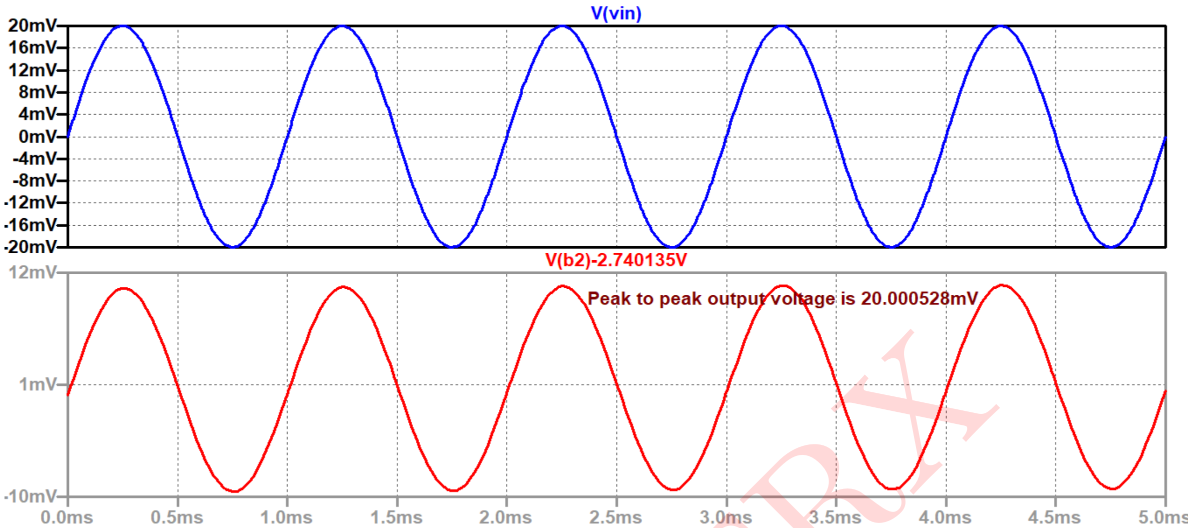

Figure 5: Input and output voltage waveform for Stage 1

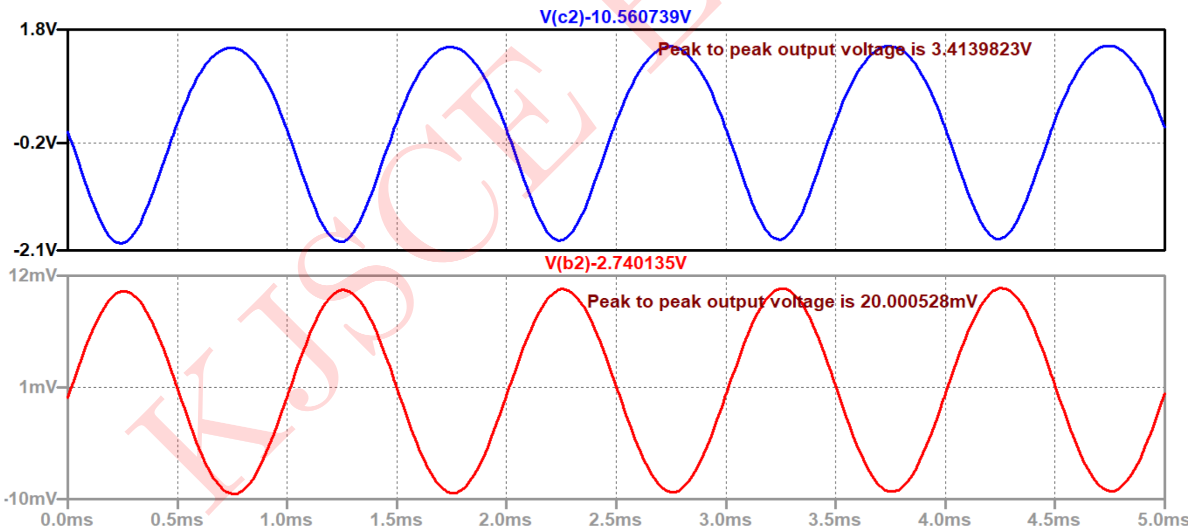

Figure 6: Input and output voltage waveform for Stage 2

Input and output waveforms for each stage are shown below:

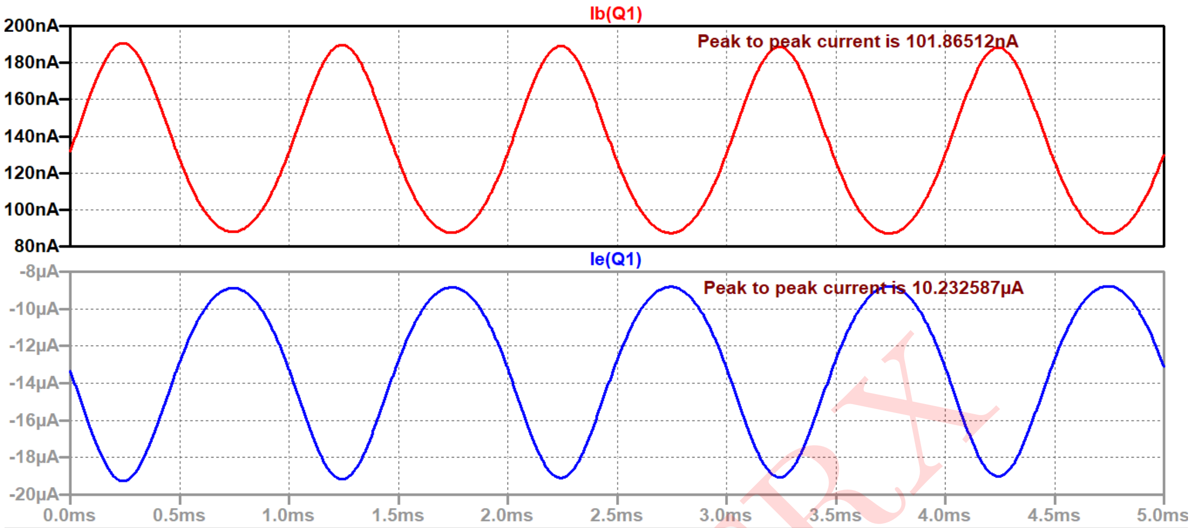

Figure 7: Input and output current waveform for Stage 1

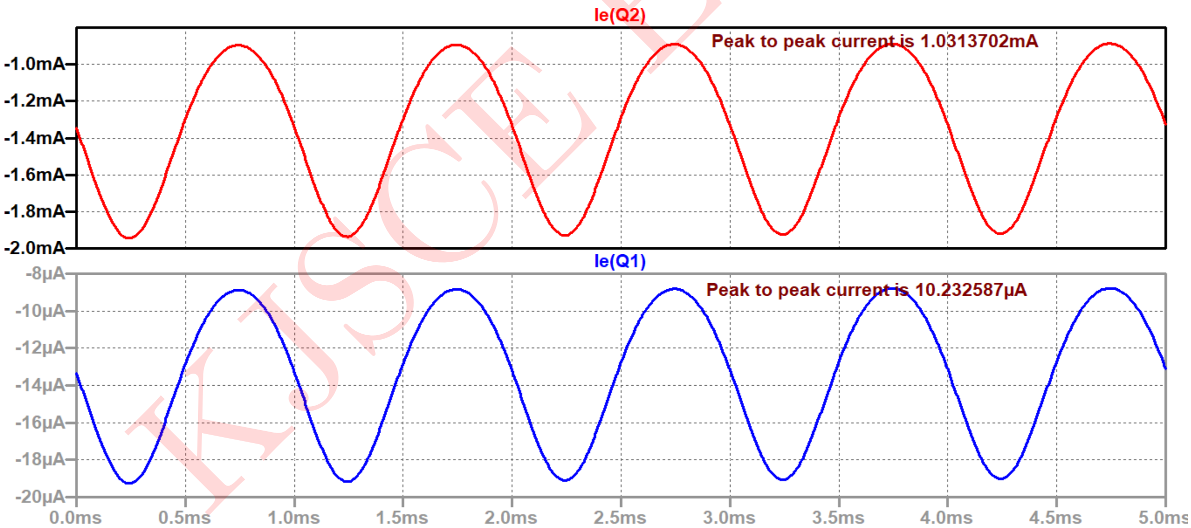

Figure 8: Input and output current waveform for Stage 2

Comparsion between theoretical and simulated values:

Parameter	Theoretical value	Simulated value
I_{B1}	$0.12701\mu A$	$0.13188\mu A$
I_{C1}	$0.0127mA$	$0.013189mA$
I_{E1}	$0.01283mA$	$0.01392mA$
I_{B2}	0.01283mA	0.01332mA
I_{E2}	1.2955mA	1.3454mA
V_{E2}	1.9433V	2.0180V
V_{C2}	10.7671V	10.5607V
Voltage gain of stage 1: A_{V1}	0.4950	0.5
Voltage gain of stage 2: A_{V2}	162.81	170.695
Overall gain: A_{Vt}	80.591	85.3475
Current gain of Stage 1: A_{i1}	100	100.8013
Current gain of Stage 2: A_{i2}	100	100.7926
Darlington pair gain: A_{id}	10000	10160.025
Input impedance of Stage 1	90.645 kΩ	–
Output impedance of Stage 2	0.0508 kΩ	–
Output voltage	$-1.6118V$	-1.7069

Table 1: Numerical 1