Lab 5.3 – Current Mirror

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Lab 5-3 Current Mirror

- Purpose (Summary of the experiment)
  - This lab aims to compare output(copy) currents of current mirrors realized through discrete transistors and matched transistors (using a monolithic transistor array integrated circuit). In particular, the effects of temperature and the Early Effect are demonstrated by comparing the output current with respect to the reference(program) current. Through experimental designs, it can be observed that in a transistor array in which proximity of transistors assure the same temperature and base-emitter junction voltages are matched, the output current matches the reference relatively better than that determined by the current mirror realized through discrete transistors.

- Schematic diagram
  - (A) LTspice schematic for a typical current mirror using discrete transistors
    * PNP – 2N3906

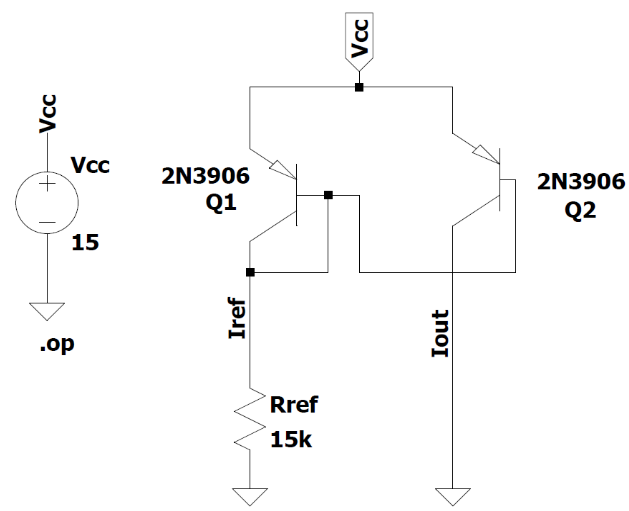

Figure 1. Part A LTspice Schematic

  - (B) Same as (A) but with a transistor array
    * MPQ6502 (replacement for CA3096)

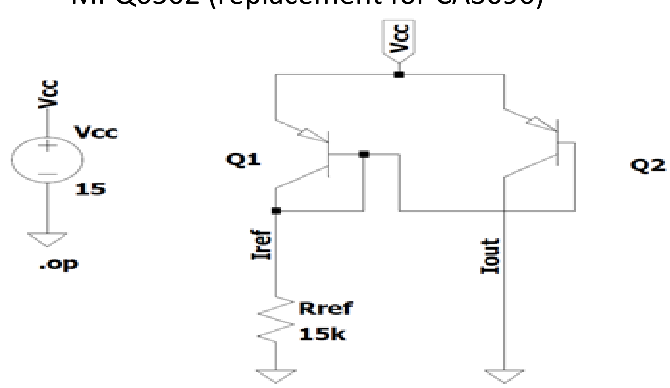

Figure 2. Part B LTspice Schematic

The simulation of the circuit above at the operating point gives the following results

```
       --- Operating Point ---

V(iref):        14.344         voltage
V(vcc):         15             voltage
Ic(Q2):         -0.00108208    device_current
Ib(Q2):         -4.73945e-006  device_current
Ie(Q2):         0.00108682     device_current
Ic(Q1):         -0.000946784   device_current
Ib(Q1):         -4.74192e-006  device_current
Ie(Q1):         0.000951526    device_current
I(Rref):        0.000956265    device_current
I(Vcc):         -0.00203834    device_current
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Figure 3. Part A LTspice operating point analysis

Comparison between the reference and output currents

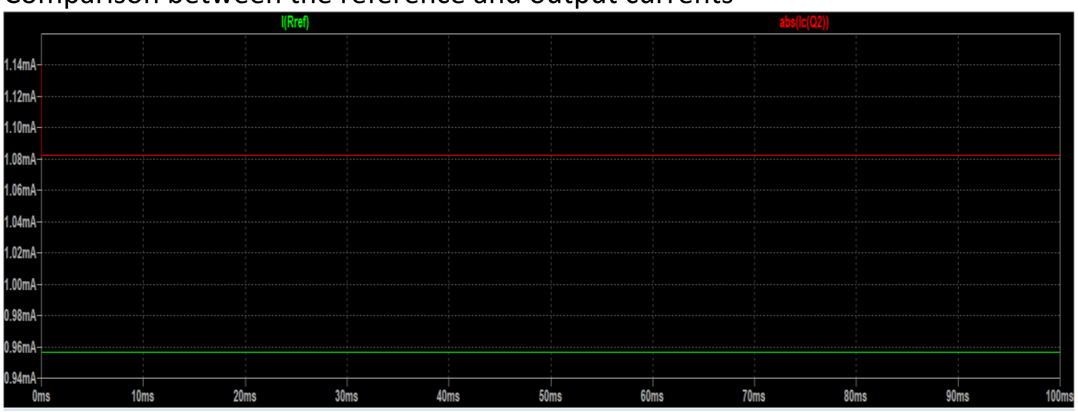


Figure 4. Part A LTspice comparison between I_{ref} and I_{out}

This shows the reference current being 0.956 mA, and the output current being 1.08 mA. The output current in this simulation is greater than the reference, possibly due to the Early Effect and temperature in action. The difference shown by the gap between the red (output) and green (reference) curves remarks the effect of the two factors. These factors, as described in calculations section, are taken into account in the equation $I_{out} = \frac{I_{ref}}{\left(1+\frac{2}{\beta}\right)}\left(1 + \frac{V_{EC}}{V_A}\right)$. The β factor is largely affected by device structures and temperature, and the addition of V_{EC} increases the output current.

In general, a current mirror is a circuit block which is intended to produce a copy of the current in “reference” at the input, by replicating it at the output terminal. Key characteristics in a current mirror are low input impedance and high output impedance. The low input impedance keeps the input current (reference) constant regardless of drive conditions, and the high output impedance keeps the output current constant regardless of load conditions. Through these impedances, the current at the output can then be “copied.” It is usually implemented to provide bias currents and active loads in amplifier stages.

- (C) LTspice schematic for Wilson Current Mirror

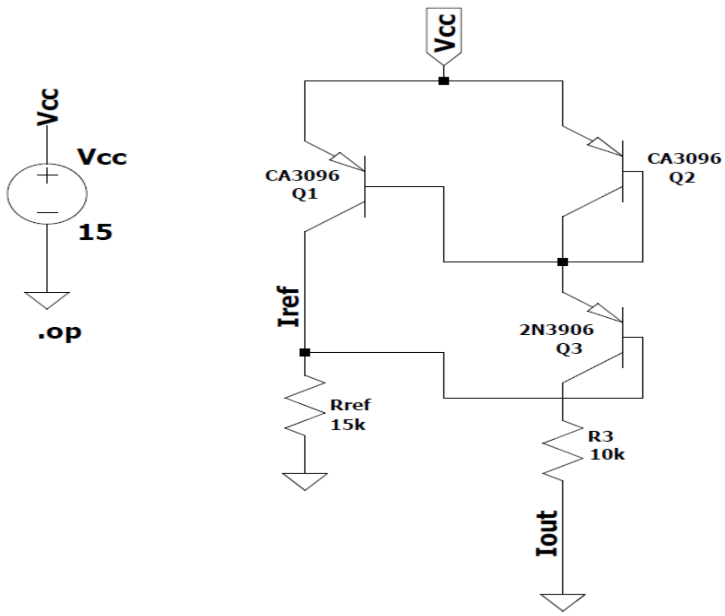


Figure 5. Part C LTspice Schematic

Since LTspice does not have CA3096 model, the simulation results could not be accurately shown. However, one can expect that since the top two pnp BJTs are operated at the same temperature with closer proximity, the output current will be close in value to the reference.

The Wilson current mirror has an advantage over typical current mirrors that it has a much higher output resistance, giving it a more constant output current. This is due to two positive feedback effects—they can be demonstrated by adding a test current source to the output (and ground). Since additional current is sourced to the output node, the voltage at the output increase, thereby causing a current to flow through ro3, and causing the emitter voltage of Q3 and the base voltage of Q1 to increase. Such increase in voltage at the emitter of Q3 then causes the collector voltage of itself to increase, since Q3 is a common-base topology for an emitter input. Then the increase in voltage at the base of Q1 increases the collector voltage of Q1, and the base of Q3 to decrease. Since Q3 is now a common-emitter stage for a base input, the decrease in voltage at the base causes the collector voltage to increase. Thus, there are two positive feedback effects, allowing the collector voltage of Q3 to increase to a greater value, and rout, the ratio of the collector voltage of Q3 to the test current source, the output resistance is increased for a Wilson current mirror.

- Theoretical calculations needed to predict the outcomes of the experiment
  - (A) and (B) ▷ **Without Early Effect**
    - Assumptions
      - $Q_{1\,(ref)} = Q_2 \rightarrow I_{s,\ ref} = I_{s,\ 2} = I_s,\ \beta_{ref} = \beta_2 = \beta$
      - $V_{BE,\ ref} = V_{BE,\ 2} \rightarrow I_{C,\ ref} = I_{c,\ 2}$
      - $V_A = \infty$ (No Early Effect)
    - Calculations
      - $I_{ref} = \frac{V_{cc} - V_{BE,ref}}{R_{ref}}$
      - $I_{C,\ ref} = I_s\, e^{\frac{V_{BE,ref}}{V_T}} \approx I_{c,ref} = I_s\, e^{\frac{V_{BE,2}}{V_T}}$
      - $I_{ref} = I_{c,\ ref} + I_{B,\ ref} + I_{B,\ 2} = I_{c,\ ref} + \frac{I_{c,ref}}{\beta_{ref}} + \frac{I_{c,2}}{\beta_2} = I_{c,2}(1 + \frac{2}{\beta})$
      - $I_{out} = \frac{I_{ref}}{(1+\frac{2}{\beta})} \rightarrow I_{out} < I_{ref}$ (if $\beta \rightarrow \infty$, where $I_{out} = I_{ref}$)
  - (A) and (B) ▷ **With Early Effect**
    - Assumptions
      - $Q_{1\,(ref)} = Q_2 \rightarrow I_{s,\ ref} = I_{s,\ 2} = I_s,\ \beta_{ref} = \beta_2 = \beta$
      - $V_{BE,\ ref} = V_{BE,\ 2} \rightarrow I_{C,\ ref} = I_{c,\ 2}$
      - $V_A < \infty$ (No Early Effect)
    - Calculations
      - $I_{ref} = \frac{V_{cc} - V_{BE,ref}}{R_{ref}}$
      - $I_{c,\ ref} = I_s\, e^{\frac{V_{BE,ref}}{V_T}},\ I_{B,ref} = \frac{I_{C,ref}}{\beta_{ref}}$
      - $I_{c,\ 2} = I_{out} = I_{s,2}\left(1 + \frac{V_{EC,2}}{V_A}\right) e^{\frac{V_{BE,1}}{V_T}} = I_{c,ref}\,(1 + \frac{V_{EC,2}}{V_A}),\ I_{B,2} = \frac{I_{out}}{\beta_2\left(1+\frac{V_{EC,2}}{V_A}\right)}$
      - $I_{ref} = I_{c,\ ref} + I_{b,\ ref} + I_{b,\ 2} = I_{c,\ ref} + \frac{I_{c,ref}}{\beta_{ref}} + \frac{I_{out}}{\beta_2\left(1+\frac{V_{EC,2}}{V_A}\right)}$

        $$= I_{c,\ ref}\,(1 + \frac{2}{\beta})$$

        $\rightarrow I_{c,\ ref} = \frac{I_{ref}}{(1+\frac{2}{\beta})}$
      - $I_{out} = I_{c,2} = \frac{I_{ref}}{\left(1+\frac{2}{\beta}\right)}\left(1 + \frac{V_{EC}}{V_A}\right)$

        $\rightarrow$ Temp $\uparrow \rightarrow \beta \uparrow \rightarrow I_{out} \uparrow$; Early Effect $\rightarrow I_{out} \uparrow$

        $\rightarrow I_{out} > I_{ref}$
      - $R_{out} = \frac{V_A + V_{EC}}{I_{C,2}}$

- (C) ▷ Wilson Current Mirror without Early Effect
  - Assumptions
    - $Q_{1\,(ref)} = Q_2 = Q_3 \rightarrow I_{s,\ ref} = I_{s,\ 2} = I_{s,\ 3} = I_s,\ \beta_{ref} = \beta_2 = \beta_3 = \beta$
    - $V_{BE,\ ref} = V_{BE,\ 2} = V_{BE,\ 3} \rightarrow I_{C,\ ref} = I_{c,\ 2} = I_{c,\ 3}$
    - $V_A = \infty$ (No Early Effect)
  - Calculations
    - *the diode-connected transistor is on the right side, thus
    - $I_{ref} = \frac{\frac{I_{out}}{\alpha}}{1+\frac{2}{\beta}} + \frac{I_{out}}{\beta} = I_{out}\left(\frac{1+\beta}{2+\beta}\right) + \frac{I_{out}}{\beta}, (also = \frac{V_{CC}-V_{BE2}-V_{BE3}}{R_{ref}})$
    - $I_{out} = \frac{I_{ref}}{\left(\frac{1+\beta}{2+\beta}\right)+\left(\frac{1}{\beta}\right)}$
    - $R_{out} = \left(1+\frac{\beta}{2}\right) r_{o3} \approx \frac{\beta}{2} r_{o3} \rightarrow \text{increased } R_{out} \rightarrow constant\ I_{out}$

- Circuit on board

(A) A common current mirror using discrete transistors

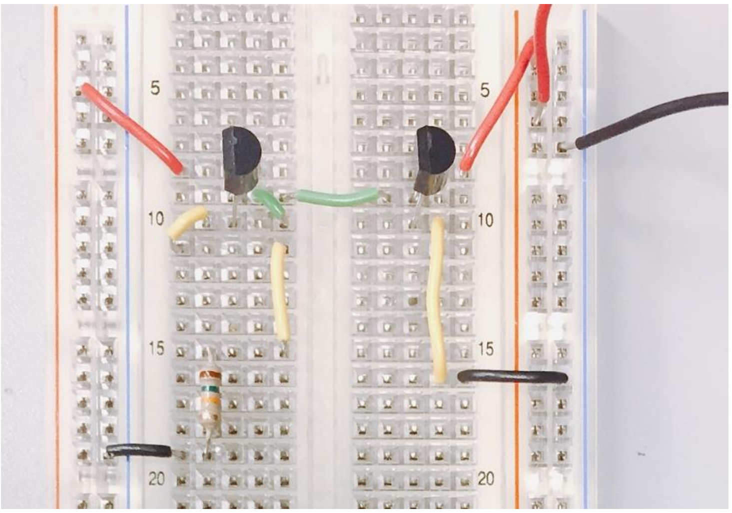


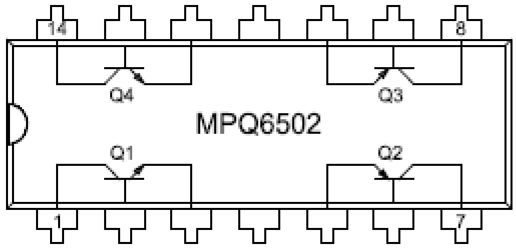
Figure 6. Part A circuit

- Red: power supply line
- **Black**: ground
- Yellow: connection from emitter to reference resistor/ground
- Green: connection between the bases of the PNP BJTs
- Resistor: 15kΩ, as shown in the schematic diagram
- BJT: as far as this lab is concerned, all discrete BJTs used are PNP (2N3906) model

(B) A common current mirror using a transistor array MPQ6502

* Background on MPQ6502 (replacement for CA3906)

- Pin configurations



- Q2 and Q3 PNP BJTs are used in this simulation
- Advantage: temperature matching and increased proximity

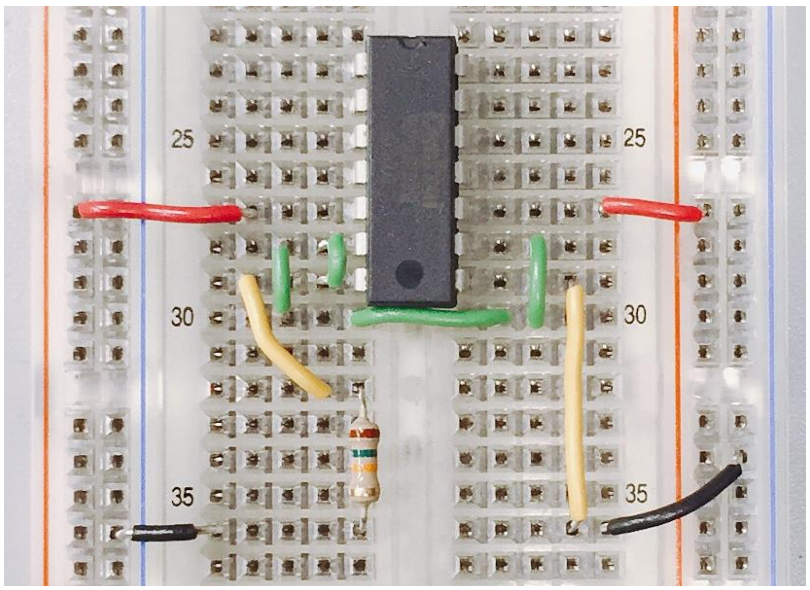


Figure 7. Part B circuit

- Red: power supply line
- **Black**: ground
- Yellow: connection from emitter to reference resistor/ground
- Green: connection between the bases of the PNP BJTs
- Resistor: 15kΩ, as shown in the schematic diagram
- BJT: as far as this lab is concerned, all discrete BJTs used are PNP (2N3906) model

(C) Wilson current mirror using a transistor array MPQ6502

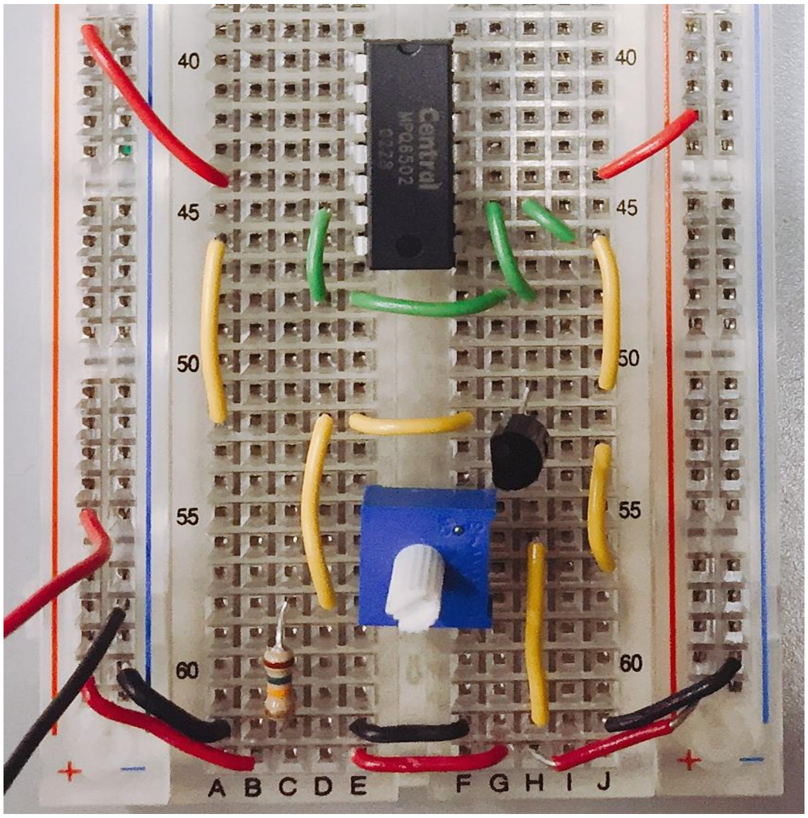


Figure 8. Part C circuit

- Red: power supply line
- **Black**: ground
- Yellow: connection from emitter to reference resistor/ground
- Green: connection between the bases of the PNP BJTs
- Resistor: 15kΩ, as shown in the schematic diagram
- BJT: as far as this lab is concerned, all discrete BJTs used are PNP (2N3906) model
- POT: 10k potentiometer at the load (to observe constant current)

- Measurements

Part	Reference (μA)	Output (μA)	Remarks
(A)	333	318	$I_{out} < I_{ref}$ (≈ No Early Effect)
(B)	295	312	$I_{out} > I_{ref}$, (Early Effect and temperature)
(C)	254	249	$I_{out} \approx I_{ref}$ (Temperature matching and Proximity increased)

  - One can observe that in part A, the output current is less than the reference, demonstrating the effect of no Early Effect in effect, in part B, the output current is greater than the refence due to the Early Effect and temperature acting such that V_{CE} and β are increased, and in part C, the Wilson mirror increases the output impedance, thereby achieving a more constant output current. The observed outputs are as expected in the above discussion of each mirror type.
  - As the load resistance is varied through the potentiometer, the current stays the same in the Wilson mirror. This is one of the advantages a Wilson mirror provides with respect to a common current mirror.
  - The output current of part A is observed through the oscilloscope, by attaching 10Ω resistor in series at the load and measuring the potential difference across it. However, since the current is constant with the DC input voltage (as shown below), the output is meaningless; the multimeter measurements show changes in the current better.

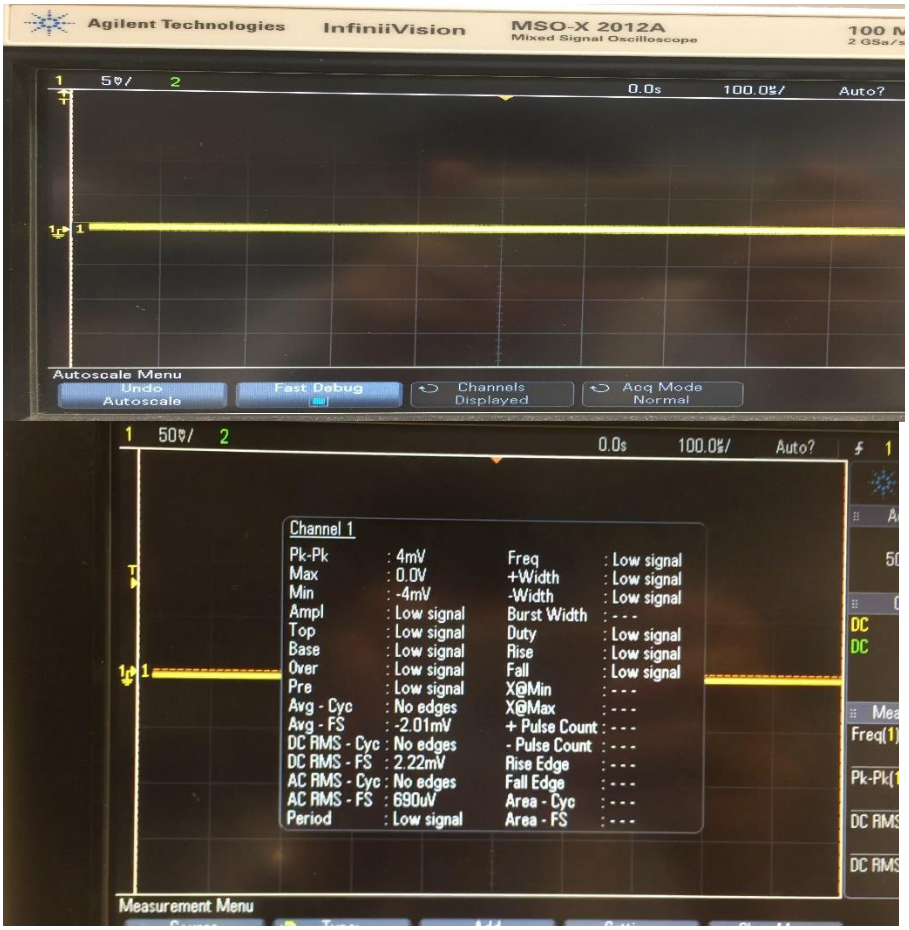


Figure 9. Part A output current oscilloscope output with 10-Ω resistor

- The potential difference across 10-ohm resistor gives approximately 222 microamperes of output current in the circuit in part A. This implies that the oscilloscope reads the voltage with its internal resistance and thus the output current is lower than what we expect.