

Low-Level Output Voltage Versus Sinking Current of a Bipolar Output Amplifier (LM2902-Q1 or LM2904-Q1 Used as Example)

This application report provides a summary of the expected dependency of the output voltage on the sinking current of a bipolar output amplifier. Using LM2902-Q1 or LM2904-Q1 as the example for this application report, the output of the op amp depends on the sinking current when the output is below V_{be} of 600 mV. This is due to the output bipolar structure, which consists of PNP lower transistors. The application report refers to the LM2902-Q1 data sheet; however, it also pertains to the LM2904-Q1 and bipolar-output amplifiers in general.

1 Output Voltage Versus Sinking Current

Figure 1 shows the internal structure of LM2902-Q1. The lower transistor of the output stage is a bipolar PNP. The lower transistor is only active when the output voltage is higher than the PN junction voltage, V_{be} , of 600 mV. If the output voltage is lower than 600 mV, the PNP lower transistor is idle and cannot sink any current. A current regulator of 50 μA is built in parallel to the PNP for sinking current when the output is below 600 mV.

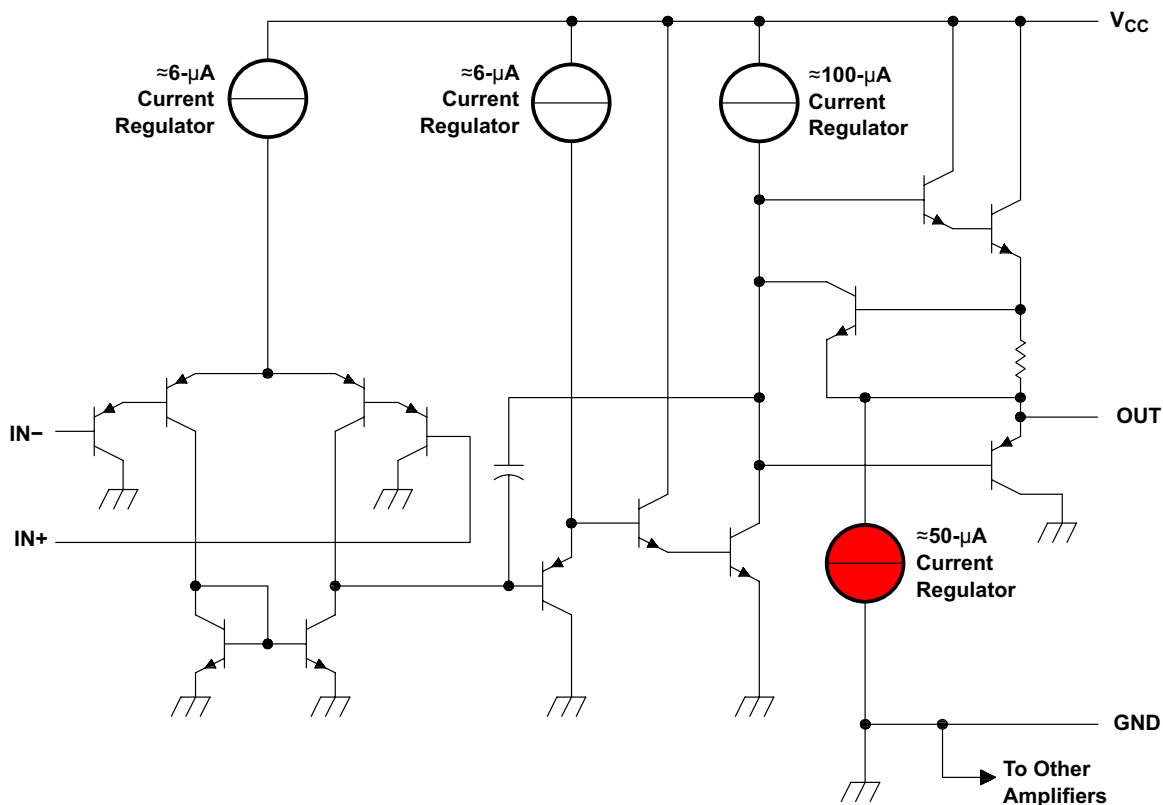


Figure 1. LM2902-Q1 Schematic Showing 50- μA Current Regulator

1.1 Data-Sheet and Bench-Test Verification of V_O Versus I_{sink}

When looking at the data sheet (see Figure 2), the parameter V_{OL} , low-level output voltage, is listed as 5 mV typical and 20mV maximum. This parameter is contingent on the fact that $R_L \leq 10k\Omega$. It is not stated though that this parameter is also contingent on the fact that sinking current is less than 50 μ A.

PARAMETER	TEST CONDITION†	T_A^\ddagger	LM2902-Q1			UNIT
			MIN	TYP§	MAX	
V_{OL} Low-level output voltage	$R_L \leq 10\text{ k}\Omega$	Full range		5	20	mV

Figure 2. Low-Level Output-Voltage Parameters

As mentioned previously, from Figure 1, there is a 50- μ A current regulator at the output of the device. Therefore, if the sinking current is less than 50 μ A, (the threshold is around 30 μ A to 50 μ A), then the output is within the data-sheet-specified range. If the sinking current is greater than 50 μ A, then the output is higher than 20 mV.

Figure 3 shows the correlation between the output sink current and the output voltage when the sinking current is both below and above 50 μ A. As the sinking current increases past 50 μ A, the output voltage increases non-linearly until it stabilizes at around 600 mV. This non-linearity is due to the base-emitter drop.

The Figure 3 graph is available in the LM2902-N data sheet (SNOSC16), and bench tests show that TI's op amp acts in the same manner (see Table 1). Note that the graph shows the output voltage versus sinking current for open-loop gain.

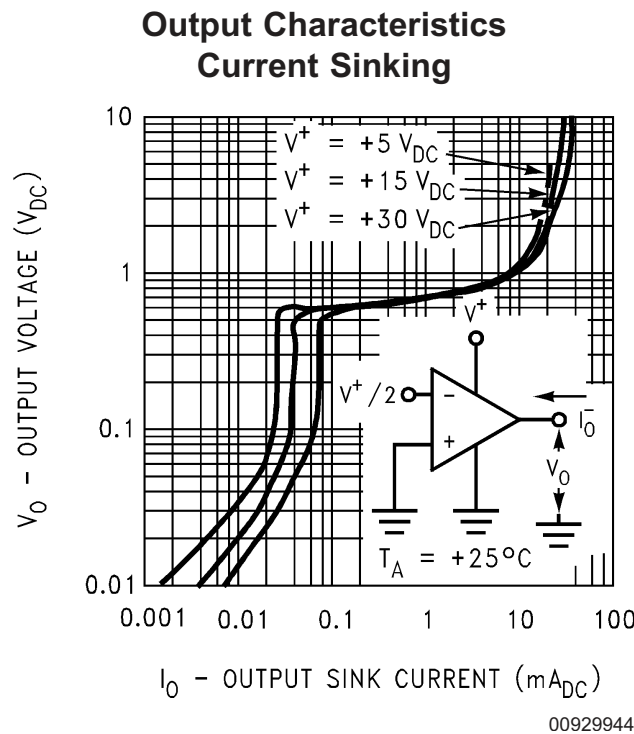


Figure 3. Output Voltage Versus Sinking Current

Table 1. Bench Data for Output Voltage Versus Sinking Current⁽¹⁾

Parameter ^{(2) (3)}	Min	Typ	Max	Unit
$V_o = 2\text{ V}, V_{cc} = 5\text{ V}$	8.7	12.9	15.2	mA
$V_o = 2\text{ V}, V_{cc} = 15\text{ V}$	9.2	13.2	16.7	mA
$V_o = 0.3\text{ V}, V_{cc} = 5\text{ V}$	23.1	43.6	68.1	μA
$V_o = 0.3\text{ V}, V_{cc} = 15\text{ V}$	29	52.9	81.3	μA
$V_o = 0.2\text{ V}, V_{cc} = 5\text{ V}$	22.9	40.5	55.7	μA
$V_o = 0.2\text{ V}, V_{cc} = 15\text{ V}$	28.9	50.6	69.9	μA
$V_o = 0.1\text{ V}, V_{cc} = 5\text{ V}$	22.2	34.1	47.9	μA
$V_o = 0.1\text{ V}, V_{cc} = 15\text{ V}$	25.7	41.8	58.7	μA
$V_o = 0.05\text{ V}, V_{cc} = 5\text{ V}$	15.4	20	26.7	μA
$V_o = 0.05\text{ V}, V_{cc} = 15\text{ V}$	18.2	23.8	36.7	μA

- ⁽¹⁾ Bench test schematic shown in [Figure 4](#)
- ⁽²⁾ Data is across the full temperature range of -40°C to 125°C
- ⁽³⁾ Performance of bench test was with V_o forced to the same voltage as V_{in} .

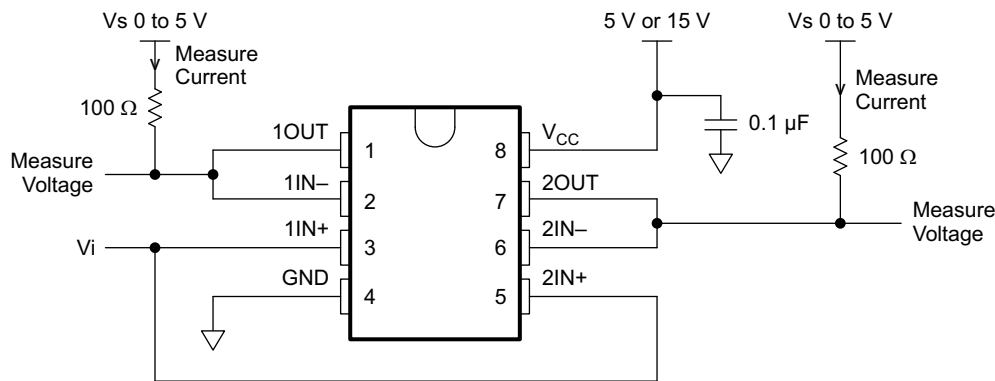


Figure 4. Bench-Test Schematic

2 Examples and Solutions

2.1 Resistor and Parameter Optimization

To avoid a non-linear output, optimize the resistor network as follows. For selection of optimum value and parameters for the resistors network, there are two cases to consider:

- When output voltage is higher than V_{be} of 600 mV, the PNP transistor is active and is capable of sinking current of a few mA. The output voltage is proportional to the input V_i , and $V_o = G \times V_i$, where G is the gain in a closed loop relative to the network resistors. Using the example in [Figure 5](#), $V_o = R_g / R_a \times (V_2 - V_1)$, where $V_2 - V_1$ can be the voltage drop across a sense resistor.
- When output voltage is lower than V_{be} of 600 mV, the PNP is idle and can not sink any current. In this case, the only available path is the 50- μA current regulator. Using [Figure 5](#) again, the output voltage is proportional to the input. $V_o = R_g / R_a \times (V_2 - V_1)$ only if the current sink is lower than the 50- μA current regulator. If the sinking current is higher than 50 μA , the output is no longer equal to $R_g / R_a \times (V_2 - V_1)$. The output voltage is at higher value.

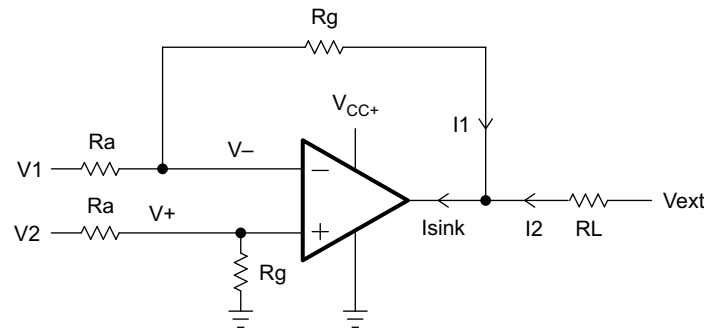


Figure 5. Typical Op-Amp Differential Circuit

Following are several points to consider for resistor and parameter optimization:

- Common-mode voltage V1
- $V_2 - V_1$ is the differential voltage, that is, the voltage drop across a sense resistor.
- External voltage V_{ext} can be at GND, Vcc or any other voltage.
- Gain network resistors R_a and R_g
- R_L load resistor
- Output current sink: $I_{sink} = I_1 + I_2$

As mentioned, from [Figure 5](#), the output voltage is proportional to the input as long as the sinking current is lower than the sinking capability according to:

$$V_O = \frac{R_g}{R_a}(V_2 - V_1) \tag{1}$$

Another formula for output voltage V_o in terms of other various parameters is:

$$V_O = \frac{R_L}{R_L + R_a + R_g} V_1 + \frac{R_a + R_g}{R_L + R_a + R_g} V_{ext} - \frac{R_L(R_a + R_g)}{R_L + R_a + R_g} I_{sink} \tag{2}$$

[Equation 1](#) is only valid if I_{sink} is lower than the capacity of the 50- μ A current regulator.

[Equation 2](#) is always valid regardless of current-sink capacity.

2.2 Numerical Calculation for Output Voltage Proportional to Input

When the output voltage is proportional to the input voltage (for any level if the sinking current is less than 50 μ A), one can combine [Equation 1](#) and [Equation 2](#) as:

$$\frac{R_g}{R_a}(V_2 - V_1) = \frac{R_L}{R_L + R_a + R_g} V_1 + \frac{R_a + R_g}{R_L + R_a + R_g} V_{ext} - \frac{R_L(R_a + R_g)}{R_L + R_a + R_g} I_{sink} \tag{3}$$

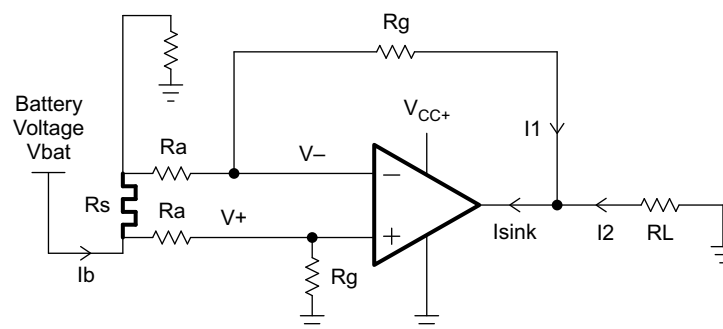


Figure 6. Differential Circuit Measuring Battery Current

Using [Figure 6](#) as an example:

- $V_{ext} = 0\text{ V}$, R_L is a load resistor
- V_1 is the common-mode voltage, very close to battery voltage V_{bat}
- R_s is the sense resistor and I_b is the measured current. Low drop across R_s
- $V_2 - V_1 = R_s \times I_b$

Now one can rewrite [Equation 3](#) as:

$$\frac{R_g}{R_a}(R_s I_b) = \frac{R_L}{R_L + R_a + R_g} V_{bat} - \frac{R_L(R_a + R_g)}{R_L + R_a + R_g} I_{sink} \quad (4)$$

[Equation 4](#) helps to calculate the resistor values, which are:

$R_L = 10\text{ k}\Omega$, $R_s = 0.49\ \Omega$, $V_{bat} = 12\text{ V}$, $I_{sink} = 50\ \mu\text{A}$,

Assuming the output voltage is 5 V at 1-A battery current:

The gain $R_g / R_a = V_o / (R_s \times I_b) = 5 / 0.49 \approx 10$

For precise measurement at an output voltage lower than 600 mV , the sinking current should be less than $50\ \mu\text{A}$.

Consider $V_o = R_g / R_a \times R_s \times I_b = 0.25\text{ V}$. Battery current $I_b = 0.25 / (10 \times 0.49) = 50\text{ mA}$

Therefore: $0.25\text{ V} = 10\text{ k}\Omega / (10\text{ k}\Omega + R_a + 10 R_a) \times 12\text{ V} - 10 \times 11 R_a / (10\text{ k}\Omega + R_a + 10 R_a) \times 0.05$

Solving this equation gives $R_a = 14.24\text{ k}\Omega$ and $R_g = 142.4\text{ k}\Omega$.

2.3 Example Simulations

In [Figure 7](#), the example circuit shows how initially, the major parameters of the device (such as V_{cc} and V_{in}) are all within spec; however, after analysis, it [Figure 8](#) shows that the circuit is pulling around $184\ \mu\text{A}$ and therefore out of data-sheet specifications at around 40 mV .

[Figure 9](#) shows how the non-linear relation is due to the base-emitter drop. The device in [Figure 9](#) is the TLV2374-Q1, a rail-to-rail quad op amp, which does not have this problem. Using the exact same test setup, the device is still within specification even though the output sinks around $185\ \mu\text{A}$.

Note that as these examples are simulations, they provide a general approximation of how the device should operate. The parameters can vary by device.

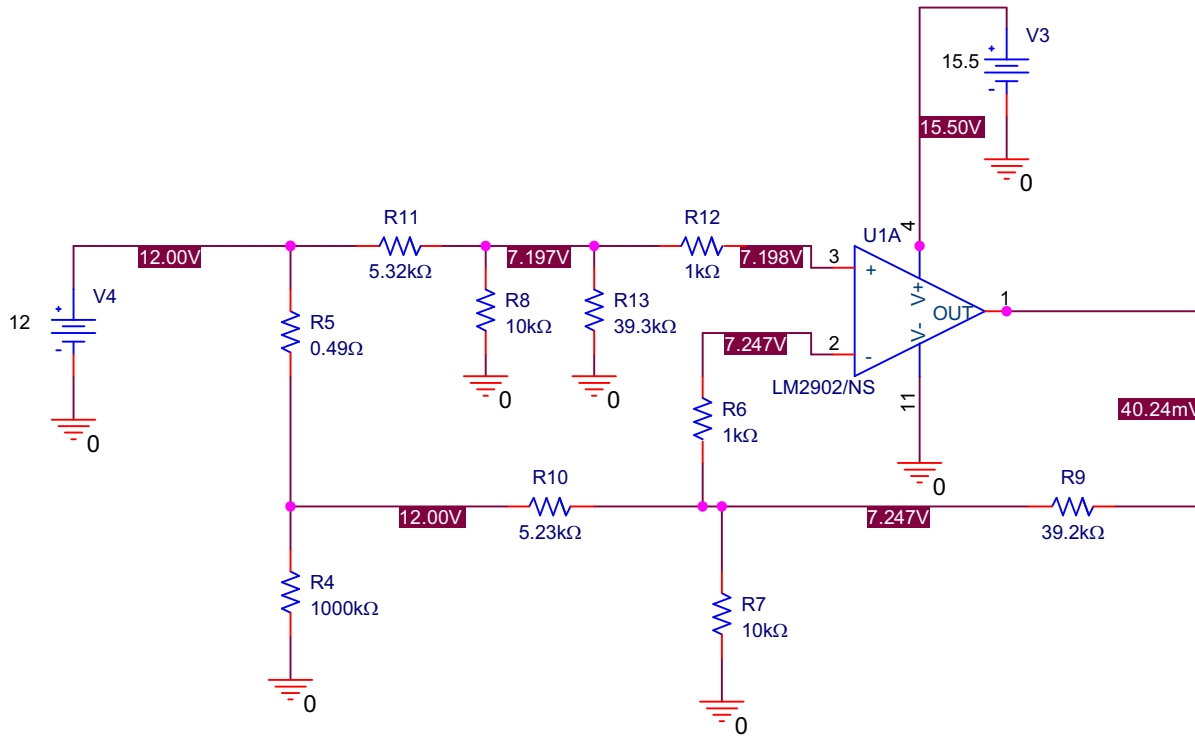


Figure 7. Example Circuit

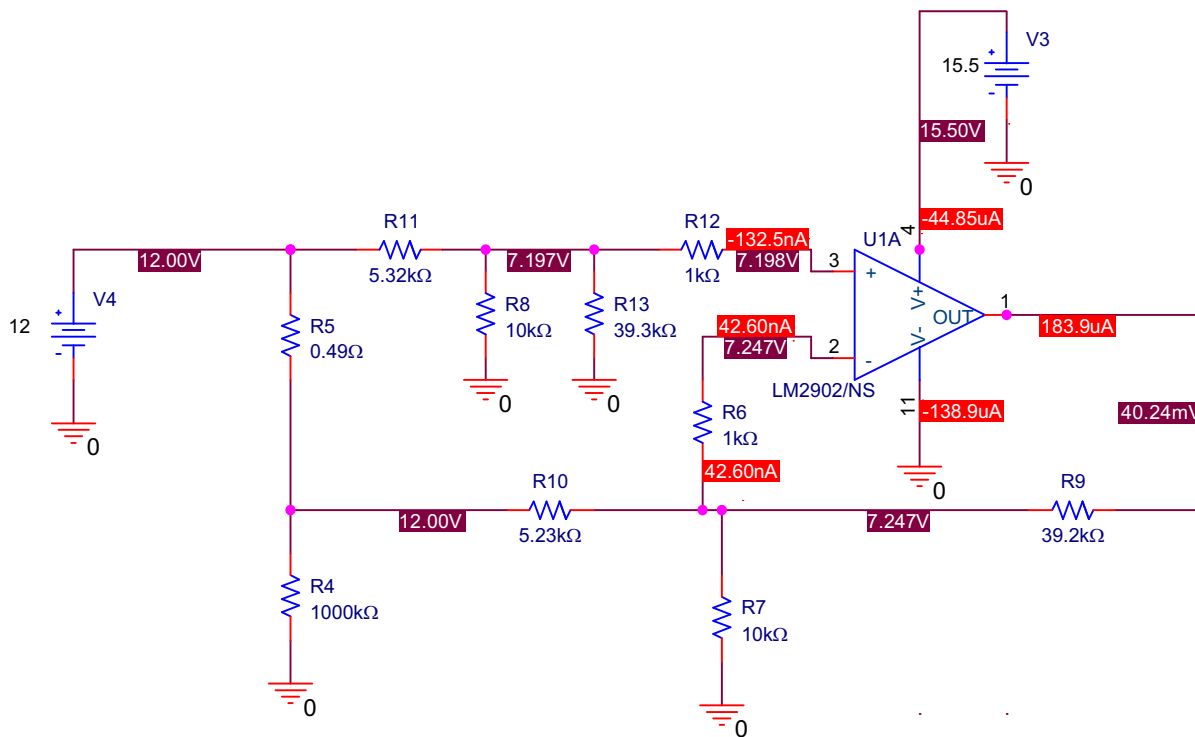


Figure 8. Example Circuit With Current Analysis

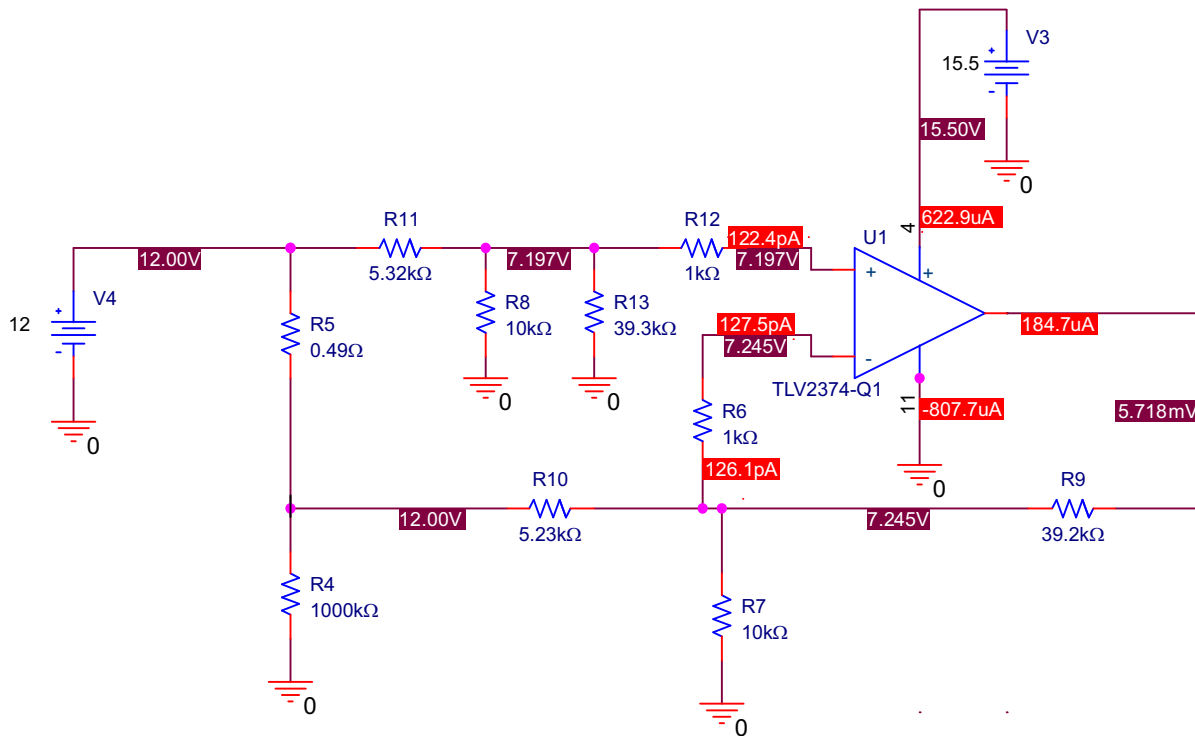


Figure 9. TLV2374-Q1 With Current Analysis

One solution for reducing sinking current would be to add a load resistor to the circuit. To be able to sink 50 μA or less and be within datasheet limits, R_L should be less than or equal to 100 Ω . See Figure 10 for an example.

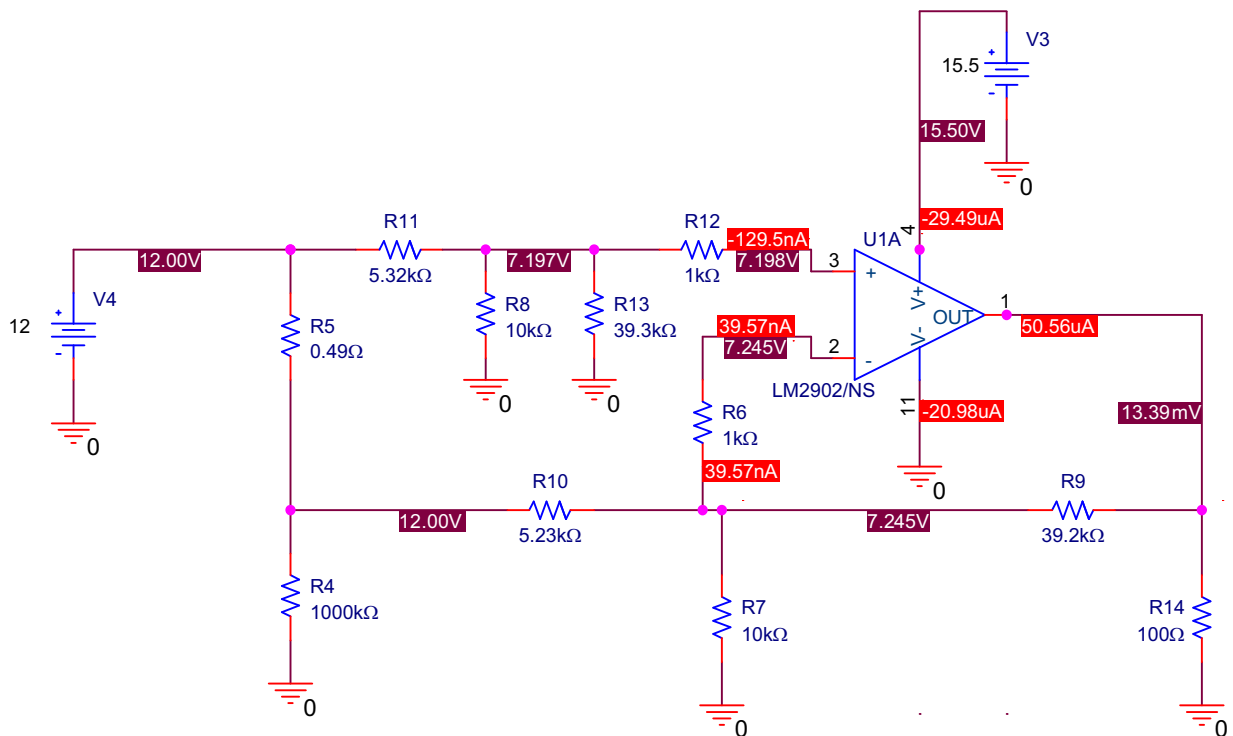


Figure 10. Example Circuit With Load Resistor

Another solution for reducing sinking current would be to add an offset to the circuit. In this case, an offset of at least 200 k Ω (to VCC) sets the input voltages to approximately what they were before and drops VOL to be within range of the data-sheet specification. Note that adding an intentional offset does not decrease the sinking current. See Figure 11 for example.

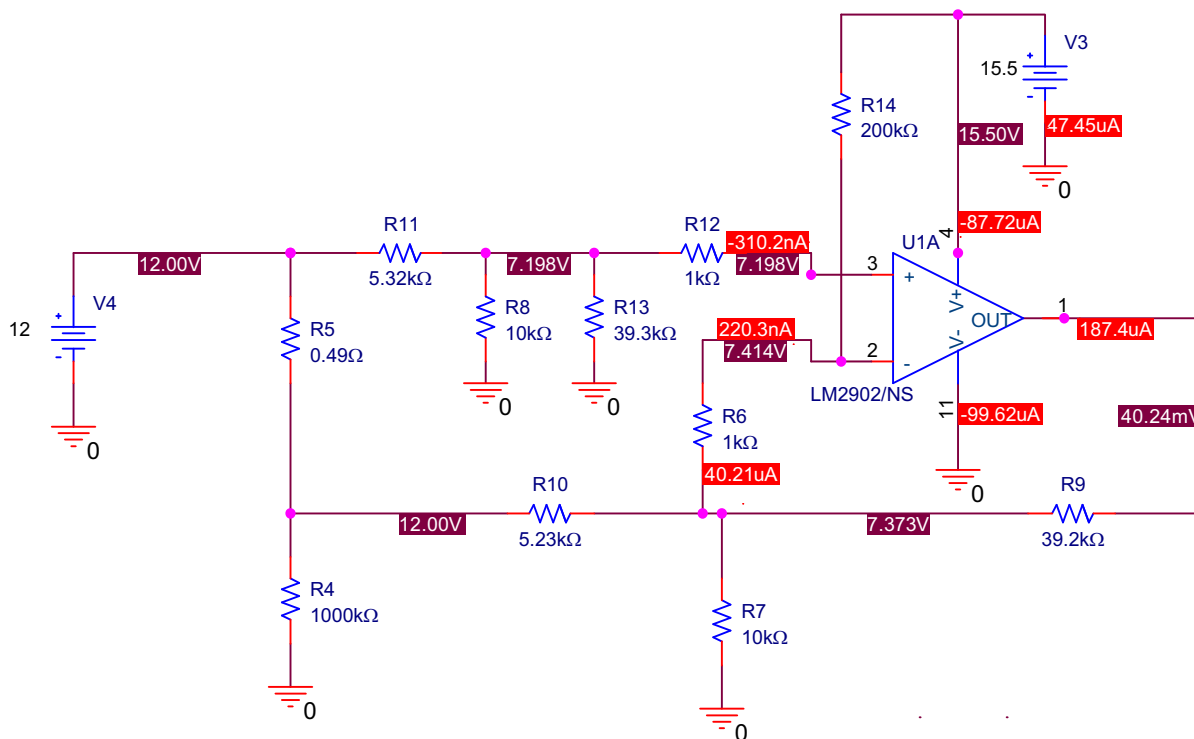


Figure 11. Example Circuit With Offset Resistor

3 Summary

When the op amp is stable and at 600 mV or above, the sinking current path goes through the PNP transistor. Otherwise, the 50- μ A current regulator holds the output low and within the range of the data-sheet specification when the sinking current is at or below 50 μ A. If the sinking current is higher than 50 μ A (but the output is still lower than 600 mV), then the output is non-linear and not within the stated data-sheet limits.

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