Designing fast, isolated microamp current sources: Part 1

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In order to test and characterize optical front end circuits, a controllable, high bandwidth, microamp-level current source is needed. However, most optocouplers on the market have large CTR variation, making them unsuitable. Using transistors to build current sources is one of the options. However, they can’t provide a floating output like photodiodes.

One solution to this problem is the HCNR200/201 high-linearity optocoupler from Broadcom (previously Avago Technologies). Unlike most optocouplers, the HCNR200/201 exhibits high linearity and stable gain characteristics, which makes it an excellent solution for floating current source design. Similar optocouplers are available from other manufacturers.

It achieves the high-linearity by illuminating two closely matched photodiodes using a high-performance AlGaAs LED (Figure 1). When a feedback network is used, the input photodiode (PD1 in Figure 1) can be used to monitor, and therefore stabilize, the light output of the LED. As a result, the non-linearity and drift characteristics of the LED can be virtually eliminated.

**Figure 1** HCNR200/201 internal circuit diagram
The datasheet of HCNR200/201 provides various circuit topologies to meet many low frequency design requirements such as high accuracy, offset-cancelling, and bipolarity. However, it has little information on how to address dynamic design challenges such as stability, bandwidth, step response, THD, noise, and PSRR. This article uses one of the circuit topologies in the datasheet as an example to go through the design process for all the dynamic requirements mentioned above. Readers can also apply the same analysis process and design techniques in this article to other topologies.

**Low frequency operation**

**Figure 2** shows a basic circuit using HCNR200/201 to generate a current that is highly linear to the input voltage.

![Figure 2 Basic application circuit](image)

When VIN is applied, the voltage at negative input of the left side op-amp tends to increase. This causes the op-amp’s output to go low, which draws current from the LED. As the current flows through the LED, a proportional current will also flow through photodiode, PD1. The photodiode current loads R1 more and more until the voltages at the op-amp’s negative and positive inputs are virtually the same, which is 0V in this case.

By applying KCL to the op-amp’s negative input, we have I_PD1 = VIN / R1. Because the PD2 and PD1 are arranged in a way to receive the same amount of light from the LED, I_PD2 = I_PD1 = VIN / R1.

This formula shows that the output current I_PD2 is independent from the optocoupler’s transfer characteristics as long as the feedback is strong enough. Therefore, a stable and linear relationship between input voltage and output current is established.

However, the circuit in **Figure 2** may not be stable. The optocoupler has at least two poles: one formed by R1 and the parasitic output capacitor of PD1, and the other one from the optocoupler’s own limited bandwidth, 9MHz. The op-amp also has a pole. That makes 3 poles for the circuit’s open-loop transfer function, meaning the circuit may not be stable.

To stabilize the circuit, circuit in **Figure 3** was introduced in HCNR200/201’s datasheet [1].
C1, R3, and R1 all play essential roles in the compensation, and impact the circuit’s dynamic performances. In next session, we will study how to design C1, R3, and R1 to stabilize the circuit.

The right part of the circuit (network around A2) is a typical TIA configuration. There are sufficient documents analyzing this type of circuit [3]. Therefore, the article will not cover, but only emphasize the input circuitry, the one on the left side in Figure 3.

**Stability and compensation**

To calculate for stability, we first obtain the circuit’s both forward and feedback paths’ transfer functions. For the sake of analysis we redraw the circuit network in Figure 4. We denote the output of the op-amp A1 as system output, VOUT. The op-amp subtracts two signals, and amplifies the error. The rest of the circuits form the feedback network. This network has two inputs: VIN and VOUT. V- is the output of the feedback network.

We then can draw a system diagram (Figure 5) based on the network in Figure 4. The system forward path’s gain A is the op-amp’s open-loop gain, and feedback gain $\beta_1$ is the feedback network’s transfer function between V- and VOUT when VIN is set to 0, while $\beta_2$ is the feedback network’s transfer function between V- and VIN when VOUT is set to 0. [3]
Since $A$ is the open-loop gain of an op-amp, the system will be stable if $\beta_1$ has $0^\circ$ phase shift and a less-than-0dB gain at $A$’s crossover frequency. Of course, commercial op-amps usually are design with some margin, and thus can tolerate some phase shift and gain from $\beta_1$. But a $0^\circ$ phase shift and a less-than-0dB gain is a good and safe starting point. Also, this surmises that $A$ is unit gain stable. If not, $\beta_1$ has to have an even lower gain to accommodate that.

To acquire $\beta_1$’s transfer function, the feedback network’s equivalent small signal circuit is drawn in Figure 6. In the circuit, $V_{IN}$ is grounded. The LED is treated as a DC voltage drop. This gives good approximation if $R_3$ is large enough. We will discuss the effect of a small $R_3$ in later sessions. $C_{OUT}$ is the parasitic output capacitor of PD1. $K$ is the current gain of the opotocoupler, which is at about 0.5% at low frequency.

Applying KCL and KVL to the circuit, we get:

\[
-V_{OUT} + \frac{V_-}{j\omega C_{OUT}} || R_1 + \frac{V_- - V_{OUT}}{j\omega C_{OUT}} + KI_1 = 0
\]
Solving the functions above, we arrive at the transfer function of the feedback network:

$$\beta_1 = \frac{V_-}{V_{OUT}} = \frac{R_1 K}{R_3} \cdot \frac{1 + j \omega \frac{R_3 C_1}{K}}{1 + j \omega R_1 (C_1 + C_{OUT})}$$

Note that the current gain $K$ is not a constant across frequency, but has a pole at 9 MHz. Hence,

$$\beta_1 = \frac{V_-}{V_{OUT}} = \frac{R_1 K_0 \frac{1}{1 + j \frac{\omega}{\omega_K}}}{R_3} \cdot \frac{1 + j \omega \frac{R_3 C_1}{K_0 \frac{1}{1 + j \frac{\omega}{\omega_K}}}}{1 + j \omega R_1 (C_1 + C_{OUT})}$$

Where $K_0$ is the low frequency gain of $K$, and $\omega_K = 2\pi \cdot 9$ MHz.

We model the op-amp as a single pole system with a crossover angular frequency at $\omega_c$. Then, a phase shift of 0° from $\beta_1$ indicates that $\omega_c$ is at a much higher frequency than $\beta_1$'s zeros and the poles. We therefore can write $\beta_1$ at $\omega_c$ as:

$$\beta_1(\omega_c) = \frac{R_{OUT} K_0}{R_3} \cdot \frac{j \omega_c \frac{R_3 C_1}{K_0}}{1 + j \frac{\omega_c}{\omega_K}} \cdot \frac{1}{j \omega_c R_1 (C_1 + C_{OUT})}$$

That means, $\beta_1$ always has a gain smaller than 0dB at $\omega_c$.

This result can be intuitively observed on the circuit. At high frequency, the $K$ becomes a small number due to its pole at 9 MHz, causing the photonic current at output negligible. Meanwhile, the capacitive currents through $C_1$ and $C_{OUT}$ increase with frequency, making current through $R_1$ also insignificant. As a result, the output voltage is only determined by the voltage divider formed by $C_1$ and $C_{OUT}$.

To guarantee that the zeros and poles are at much lower frequencies than $\omega_c$, we have

$$\omega_c R_1 (C_1 + C_{OUT}) \gg 1$$

$$\omega_c \frac{R_3 C_1}{K(\omega_c)} \gg 1$$

If $\omega_c$ is much higher than 9 MHz, $K(\omega_c)$ can be approximated by $K_0 \omega_K / \omega_c$.

Those two equations are then the design constrains to select $R_1$, $C_1$, and $R_3$ to ensure system stability.
There is a point worth pointing out: even though the feedback network has more than one pole, we can compensate it using only one capacitor, because the current gain $K$ will cancel itself at frequencies much higher than the zero frequency determined by $K/R3C1$.

The equations above tells us that to design a more stable system, we can increase $R1$, $C1$, or $R3$, choose an op-amp with high crossover frequency, or even put extra capacitor in parallel with $COUT$. All those methods can help stabilize the system. In Part 2, we'll explore how those parameters will impact the circuit's performance beyond stability.

Also see:

- Designing fast, isolated microamp current sources: Part 2
- Fast analog isolation with linear optocouplers
- Inexpensive analog isolation using a digital isolator
- Isolation has come a long way, baby!
- Designer's Notebook: Signal Isolation

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