Integrated logarithmic amplifiers for industrial applications

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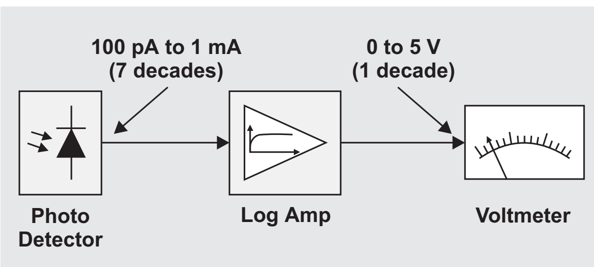
Many industrial applications measure physical quantities over a wide dynamic range. These applications use logarithmic amplifiers (log amps) to match a transmitter's dynamic output to the linear input range of a signal gauge. Figure 1 shows a typical signal chain to measure photo currents over a dynamic range of seven decades.

Log amps of the past were built with hybrid techniques. Today's CMOS technology enables the integration of the logging circuit and additional support functions, such as voltage references and uncommitted op amps, into a single chip.

This article describes the operation and architecture of integrated log amps and provides two application examples using the Texas Instruments (TI) LOG112 and LOG2112.

Figure 1. Matching a sensor's dynamic output to the linear input of a voltmeter



Operation

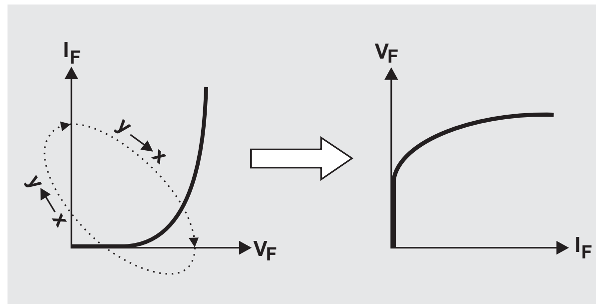
A log amp makes use of the logarithmic relationship between the voltage and current of a forward-biased diode. Figure 2 shows the characteristic of the forward current, given by the exponential function

$$I_F = I_{S(T)} \times \left(e^{\frac{V_F}{m \times V_T}} - 1 \right), \quad (1)$$

where V_F and I_F are the forward voltage and forward current of the diode, respectively; I_S is the theoretical reverse-saturation current; m is a correction factor; and V_T is the temperature-equivalent voltage. Exchanging the x for the y axes and vice versa yields the forward voltage as a logarithmic function of the forward current. Mathematically, this corresponds to solving Equation 1 for V_F:

$$V_F = m \times V_T \times \ln\left(\frac{I_F}{I_S} - 1 \right). \quad (2)$$

Figure 2. Diode characteristic in exponential and logarithmic form



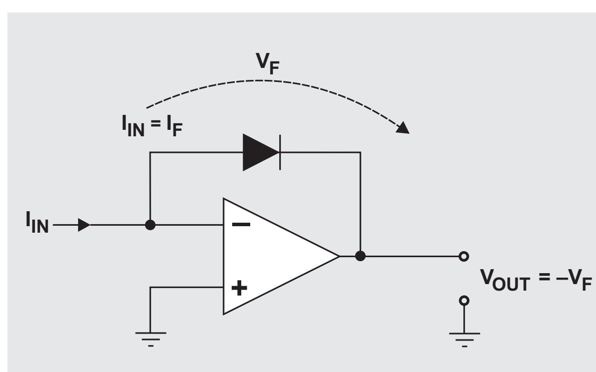
For a forward-biased diode, the forward current is larger by far than the reverse current ($I_F >> I_S$). Thus, Equation 2 simplifies to

$$V_F = m \times V_T \times \ln \frac{I_F}{I_S}. \quad (3)$$

A simple log amp whose transfer function satisfies Equation 3 is shown in Figure 3. The op amp operates as an inverting amplifier with a feedback diode. With the diode being virtually anode-grounded, the op amp needs to generate a negative output voltage to forward bias the diode. For a given input current, I_{IN}, the corresponding output voltage, V_{OUT}, is

$$V_{OUT} = -m \times V_T \times \ln \frac{I_{IN}}{I_S}. \quad (4)$$

Figure 3. Log amp with diode



The drawback of this circuit is that V_{OUT} depends not only on I_{IN} but also on m, $I_{S(T)}$, and V_T, all of which are either current- or temperature-dependent.

- The correction factor, m, takes into account the deviation between the diode characteristic and Shockley's simplified theory of diodes. However, m strongly depends on the forward current, thus varying its value between 1 and 2.
- The reverse-saturation current, I_S, is temperature-dependent. For a constant forward current, I_S doubles with every 10-K increase in temperature. Thus, for a 100-K rise in temperature, I_S increases by a factor of 1000.
- The temperature-equivalent voltage, $V_T = k \times T/e_0$, increases linearly with temperature. With Boltzman's constant $k = 1.38 \times 10^{-23}$ J/K, the electron charge $e_0 = 1.6 \times 10^{-19}$ C, and an ambient temperature of T = 296 K (23°C), V_T yields

$$V_T = \frac{1.38 \times 10^{-23}\ \text{J/K} \times 296\ \text{K}}{1.6 \times 10^{-19}\ \text{C}} = 25.5\ \text{mV}.$$

When the circuit operates at a constant temperature, the impact of m still limits the measurable input range to 1 or 2 decades of acceptable accuracy. To eliminate m, the diode is replaced by a transistor (Figure 4). Its exponential transfer characteristic in Figure 5 is similar to that of a diode. In contrast to a diode, however, the correction factor equals 1 and simplifies Equation 4 to

$$V_{OUT} = -V_T \times \ln\frac{I_C}{I_{ES}},\ \text{or}\ V_{BE} = V_T \times \ln\frac{I_C}{I_{ES}}. \qquad \textbf{(5)}$$

The input current, I_{IN}, becomes the collector current, I_C; and I_S becomes the emitter reverse-saturation current, I_{ES}. The elimination of m increases the measurable input range to several decades. V_{OUT}, however, is still temperature-dependent via $I_{ES(T)}$ and V_T. Therefore, it is impossible to determine whether a change in V_{OUT} is caused by the input current or by a change in temperature.

Figure 4. Log amp with transistor

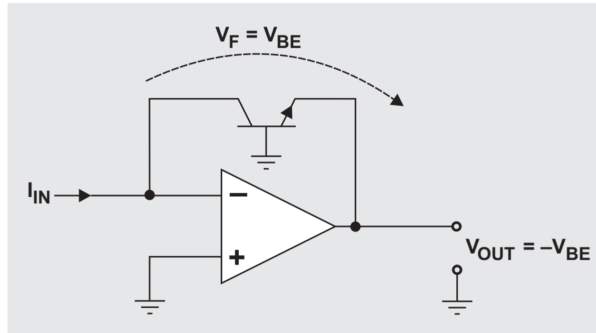
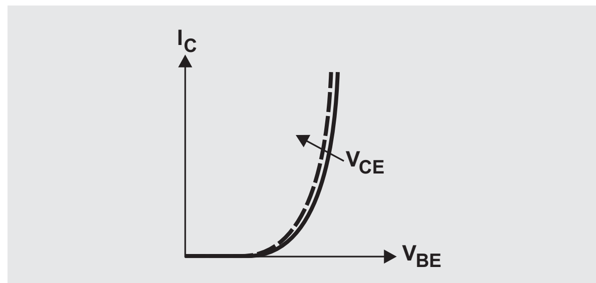


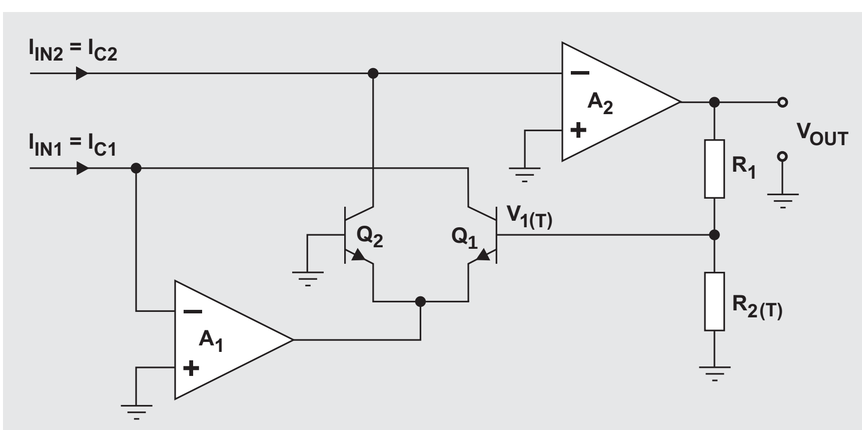
Figure 5. Transistor input characteristic



To avoid output changes due to temperature, the temperature-compensated log amp in Figure 6 is required. Here, generating the difference of two logarithms eliminates I_{ES}. From the previous example, we take the logarithmic relationship between the basis-emitter voltage, V_{BE}, and the collector current, I_C, for both transistors, Q_1 and Q_2:

$$V_{BE1} = V_T \times \ln\frac{I_{C1}}{I_{ES1}},\ \text{and}\ V_{BE2} = V_T \times \ln\frac{I_{C2}}{I_{ES2}}.$$

Figure 6. Temperature-compensated log amp



The two logging transistors build a difference amplifier whose output voltage, V_1, yields the difference of both base-emitter voltages:

$$V_1 = V_{BE1} - V_{BE2} = V_T \times \ln\frac{I_{C1}}{I_{ES1}} - V_T \times \ln\frac{I_{C2}}{I_{ES2}}. \qquad (6)$$

With matched and isothermal transistors, $I_{ES1} = I_{ES2} = I_S$, and Equation 6 simplifies to

$$V_{1(T)} = V_T \times \ln\frac{I_{C1}}{I_{C2}}. \qquad (7)$$

A remaining temperature dependency exists via only V_T. Via the voltage divider, R_1 and R_2, V_1 represents only a part of the entire circuit's output voltage, V_{OUT}:

$$V_{OUT(T)} = \left(1+\frac{R_1}{R_2}\right)\times V_1 = \left(1+\frac{R_1}{R_2}\right)\times V_T \times \ln\frac{I_{C1}}{I_{C2}}. \qquad (8)$$

To compensate for the effect of V_T, R_2 is replaced by a temperature-dependent resistor with a positive temperature coefficient. This keeps

$$\left(1+\frac{R_1}{R_{2(T)}}\right)\times V_T$$

constant over a certain temperature range. Practical values for the temperature coefficient vary between 3500 and 3700 ppm/K.

During the manufacturing process of log amps, the internal components and the temperature coefficient are trimmed to a fixed value. In addition, the natural logarithm is converted to $\log_{10}$ by applying a correction factor, n = 2.3, according to ln x = 2.3 × log x. The expression $(1 + R_1/R_{2(T)}) \times V_T \times 2.3$ becomes a constant, q, with the unit V/decade, simplifying the computation of V_{OUT} to

$$V_{OUT} = q \times \log\frac{I_{C1}}{I_{C2}}. \qquad (9)$$

Log-amp structure

Figure 7 shows a block diagram of the integrated log amp, LOG112. The actual logging circuit consists of the amplifiers, A_1 and A_2, and the transistors, Q_1 and Q_2. The designation of the collector currents, I_{C1} and I_{C2}, changes to I_1 and I_2. In most cases, I_1 represents the input current to be measured, while I_2 is the reference current for the logarithmic computation.

The device minimizes external component count by providing a voltage reference and an uncommitted op amp, A_3, on-chip. The reference allows I_2 to be generated via an external resistor, R_{REF}. Via A_3, the logarithmic output signal, V_{LOGOUT}, can be filtered or further amplified. A_3 also can be configured as a comparator to provide a loss-of-signal indication.

The LOG112 is trimmed to provide an output voltage of 0.5 V per decade of input current. The device uses patented temperature compensation in which R_2 is laid out as an aluminum frame with a temperature coefficient of 3700 ppm/K, resulting in extremely temperature-stable operation. For an input current of 10 µA, for example, the output voltage changes by only 50 µV/K.

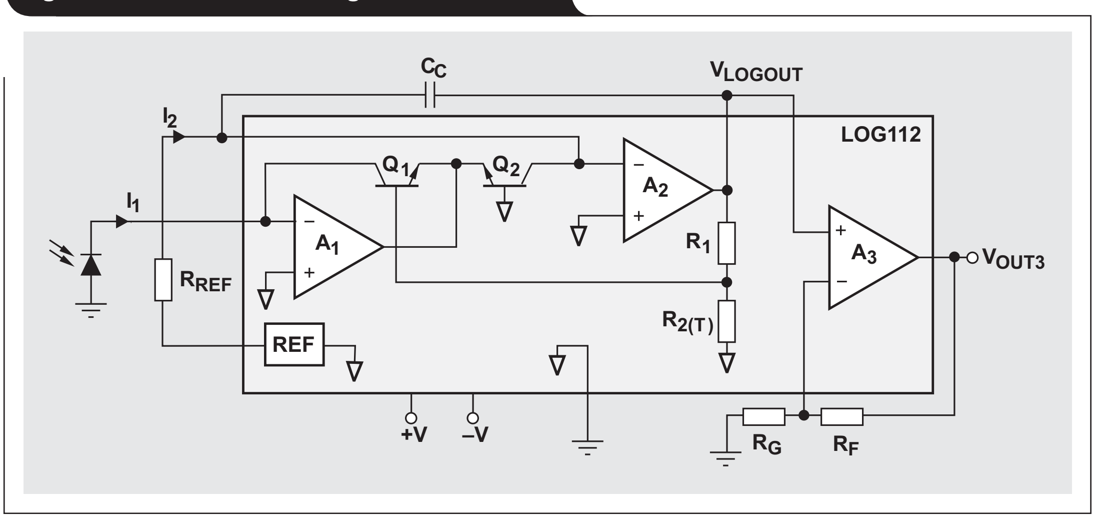
The output voltage of the log amp is made available at the V_{LOGOUT} pin:

$$V_{LOGOUT} = 0.5 \times \log\frac{I_1}{I_2},$$

with input currents ranging from 100 pA to 3.5 mA. The voltage at the V_{OUT3} pin is defined via the external gain, $G = 1 + R_F/R_G$, and yields

$$V_{OUT3} = G \times V_{LOGOUT} = G \times 0.5 \times \log\frac{I_1}{I_2}.$$

Figure 7. Internal block diagram of LOG112



Application examples

The circuit in Figure 8 controls the optical output power of a laser diode (LD_1). With the output power decreasing over the lifetime of the diode, a control loop that keeps the output power constant is required. In the feedback path, a fraction of the output signal is fed back via a photodiode (PD_1) and converted into electrical current.

The laser is calibrated by making the reference current, I_{REF}, equal to the PD_1 current, I_1. Deviations between I_{REF} and I_1 are converted into an error signal and applied to the bias input of the laser-diode driver. The driver then changes the bias current of LD_1 until the error signal diminishes to zero.

Another application example is the constant-gain control and gain adjustment of an op amp shown in Figure 9. Two log amps measure the optical input and output power of the amplifier. A difference amplifier subtracts the output signals of both log amps and applies an error voltage to the proportional-integral-derivative (PID) controller. The controller output adjusts a voltage-controlled current source (V_{CCS}), which then drives the actual pump laser. The amplifier operates at the desired optical gain when the error voltage at the PID output is zero.

Figure 8. Controlling the optical output power of a laser diode

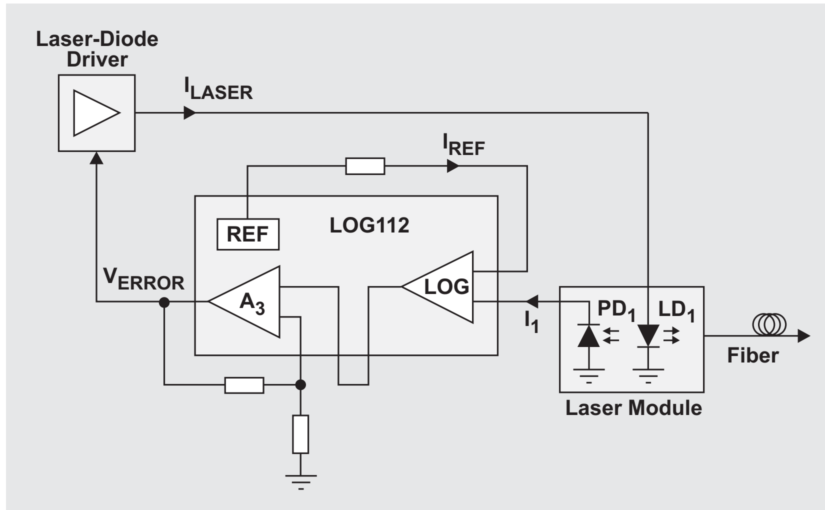
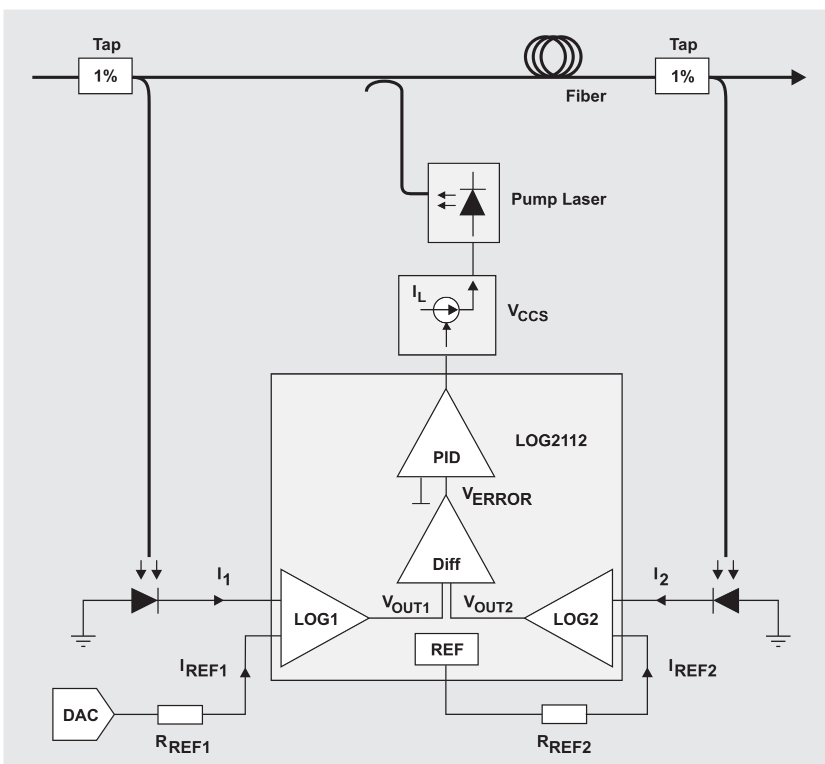


Figure 9. Constant-gain control and gain adjustment of an op amp



The log amp at the amplifier input builds the reference source. Its output voltage is

$$V_{OUT1} = \log \frac{I_1}{I_{REF1}},$$

where I_1 is the input photo current and I_{REF1} is an adjustable reference current. The log amp at the amplifier output provides an output voltage of

$$V_{OUT2} = \log \frac{I_2}{I_{REF2}},$$

where I_2 is the output photo current and I_{REF2} is a fixed reference current.

It is important to observe that $I_2 = I_1 \times G_{OPT}$, where G_{OPT} is the optical gain factor. In steady state, the output voltages of both log amps are equal ($V_1 = V_2$), and

$$\log \frac{I_1}{I_{REF1}} = \log \frac{I_1 \times G_{OPT}}{I_{REF2}}, \text{ or } \frac{I_1}{I_{REF1}} = \frac{I_1 \times G_{OPT}}{I_{REF2}}.$$

Solving for G_{OPT} yields

$$G_{OPT} = \frac{I_{REF2}}{I_{REF1}}.$$

The preceding equation shows that the optical gain of the amplifier is adjusted simply by reducing I_{REF1} by a factor of G_{OPT} smaller than I_{REF2}. In addition to the constant-gain control, this circuit also allows the electronic gain setting of G_{OPT} in the range of 0 to 30 dB.

LOG2112 is well suited for this application. The device contains two log amps to measure the input and output power; an on-chip voltage reference to generate I_{REF2}; and two uncommitted op amps configurable as difference amplifier and PID controller.

Conclusion

TI offers a series of integrated, high-precision log amps with varying input-current ranges and output-scale factors.

Related Web sites

analog.ti.com
www.ti.com/sc/device/LOG112

Following are URLs where you can obtain information on other Texas Instruments products and application solutions:

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