

What if this isn't good enough? You *could* get a better op amp. For example, an LH0022C has 10 pA max I_b . But it is silly to pay for such a good op amp, with low V offset errors, when only a low input current specification is needed. The circuit of *Figure 3a* shows the simple scheme of using FET followers ahead of a conventional op amp. An LF351 type is suitable because it is a cheap, quick amplifier, well suited for this work. The 2N5909s have a maximum I_b of 1.0 pA, and at room temperature it will drift only 0.1 pA/°C. Typical drift is 0.02 pA/°C.

The voltage offset adjust pot is used to bring the summing point within a millivolt of ground. With an input signal big enough to cause $f_{OUT}=1$ second per cycle, trim the V offset adjust pot so that closing the *test* switch makes no

effect on the output frequency (or, output period). Then adjust the input current offset pot, to get $f_{OUT}=1/1000$ of full-scale when I_{IN} is 1/1000 of full-scale. When I_{IN} covers the 140 dB range, from 200 μ A to 20 pA, the output will be stable, with very good zero offset stability, for a limited temperature range around room temperature. Note these precautions and special procedures:

1. Run the LM331 on 5V to 6V to keep leakage down and to cut the dissipation and temperature rise, too.
2. Run the FETs with a 6V drain supply.
3. Guard all summing point wiring away from all other voltages.

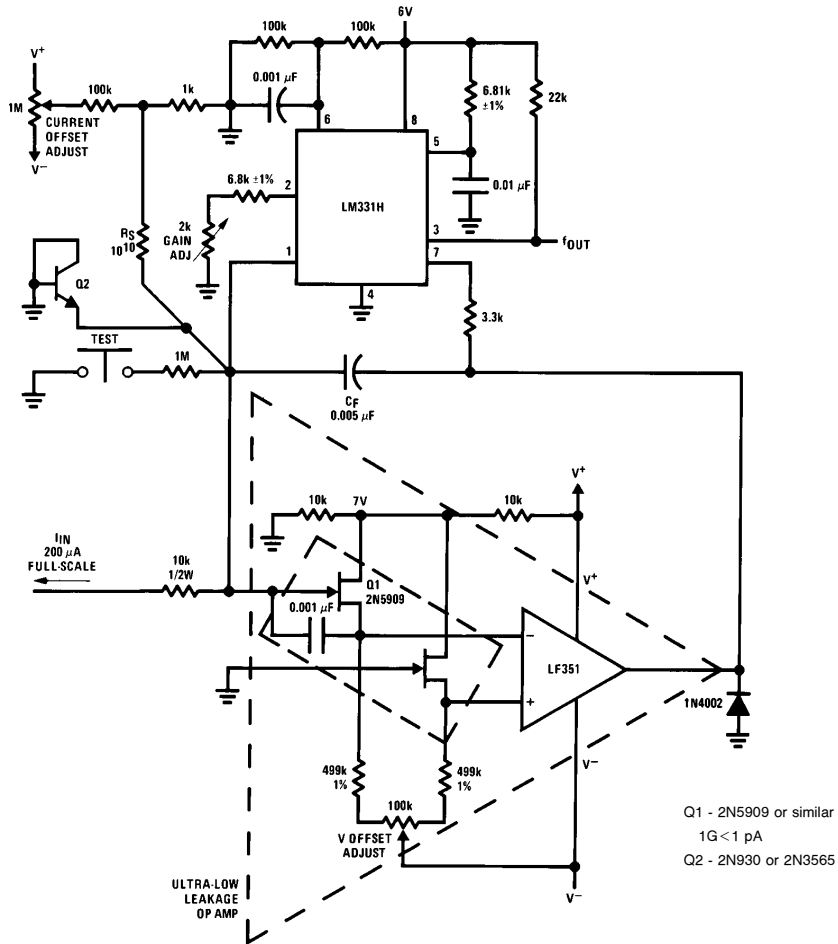


FIGURE 3a. Very-Wide-Range Current-to-Frequency Converter

An alternate approach, shown in *Figure 3b*, uses an LM11C as the input pre-amplifier. The LM11C has much better voltage drift than any of the other amplifiers shown here (normally less than $2 \mu\text{V}/^\circ\text{C}$) and excellent current drift, less than $1 \text{ pA}/^\circ\text{C}$ by itself, and typically $0.2 \text{ pA}/^\circ\text{C}$ when trimmed with the 2N3904 bias current compensation circuit as shown. Of course, the LM331's leakage of $1 \text{ pA}/^\circ\text{C}$ will still double every 10°C , so that having an amplifier with excellent I_b characteristics does not solve the whole problem, when trying to get good accuracy with a 100 pA signal. For that job, even the leakage of the LM331 must be guarded out!

What if even lower ranges of input current must be accepted? While it might be possible to use a current-to-voltage converter ahead of a V-to-F converter, offset voltage drifts would hurt dynamic range badly. Response and zero-drift of such an I-V will be disappointing. Also, it is not feasible to starve the LM331 to an arbitrary extent.

For example, while its I_{OUT} (full-scale) of $280 \mu\text{A}$ DC can be cut to $10 \mu\text{A}$ or $28 \mu\text{A}$, it cannot be cut to $1 \mu\text{A}$ or $2.8 \mu\text{A}$ with good accuracy at 10 kHz , because the internal switches in the integrated circuit will not operate with best speed and precision at such low currents.

Instead, the output current from pin 1 of the LM331 can be fed through a current attenuator circuit, as shown in *Figure 4*. The LM334 (temperature-to-current converter IC) causes -120 mV bias to appear at the base of Q2. When a current flows out of pin 1 of the LM331, $1/100$ of the current will flow out of Q1's collector, and the rest will go out of Q2's collector. As the LM334's current is linearly proportional to Kelvin temperature, the -120 mV at Q2's base will change linearly with temperature so that the Q1/Q2 current divider stays at 1:100, invariant of temperature, according to the equation:

$$i_1/i_2 = e^{\frac{q(V_{b1} - V_{b2})}{kT}}$$

This current attenuator will work stably and accurately, even at high speeds, such as for $4 \mu\text{s}$ current pulses. Thus, the output of Q1 is a charge pump which puts out only 10 picocoulombs per pulse, with surprisingly good accuracy. Note also that the LM331's leakage is substantially attenuated also, by a factor of 100 or more, so that source of error

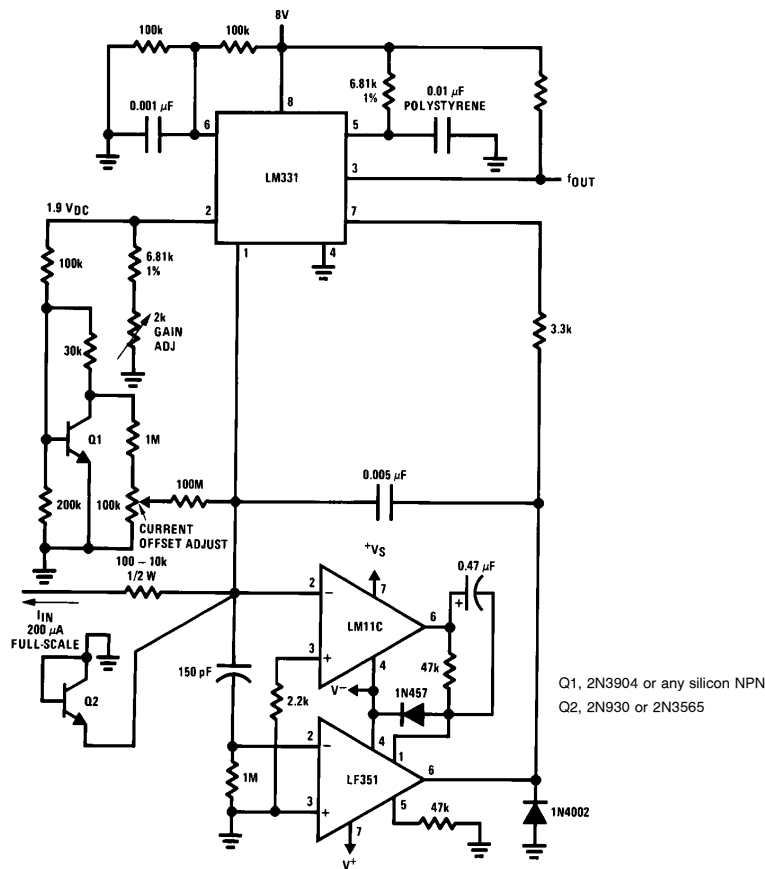


FIGURE 3b. Very-Wide-Range I-to-F Converter with Low Voltage Drift

virtually disappears. When Q1 is off, it is really *OFF*, and its leakage is typically 0.01 pA if the summing point is within a millivolt or two of ground.

To do justice to this low leakage of the VFC, the op amp should be made with MOSFETs for Q3 and Q4, such as the Intersil 3N165 or 3N190 dual MOSFET (with no gate-protection diodes). When MOSFETs have relatively poor offset voltage, offset voltage drift, and voltage noise, this circuit does not care much about these characteristics, but instead takes advantage of the MOSFET's superior current leakage and current drift.

Now, with an input current of 1 μA , the full-scale output frequency will be 100 kHz. At a 1 nA input, the output frequency will be 100 Hz. And, when the input current is 1 pA, the output frequency will drop to 1 cycle per 10 seconds or 100 mHz. When the input current drops to zero, frequencies as small as 500 μHz have been observed, at 25°C and also as warm as 35°C. Here is a wide-range data converter whose zero drift is *well* below 1 ppm per 10°C! (Rather more like 0.001 ppm per°C.) The usable dynamic range is better than 140 dB, with excellent accuracy at inputs between 100% and 1% and 0.01% and 0.0001% of full-scale.

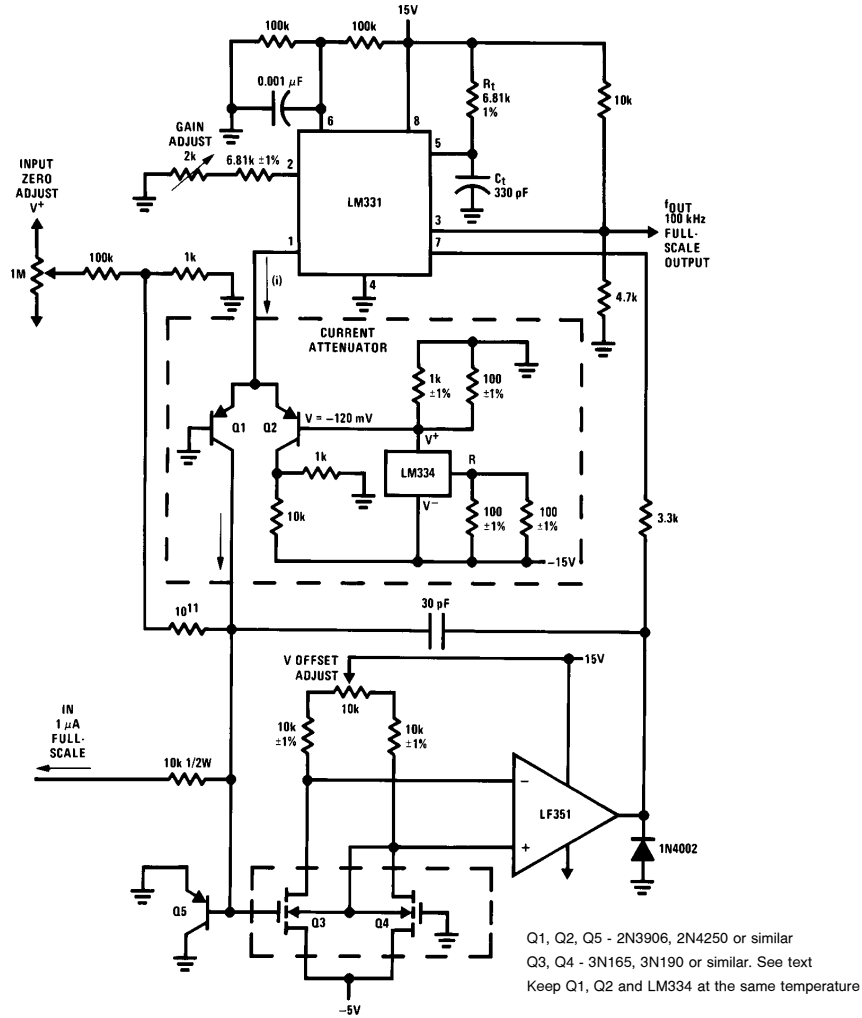


FIGURE 4. Picoampere-to-Frequency Converters

If a positive signal is of interest, the LM331 can be applied with a current reflector as in *Figure 5*. This current reflector has high output impedance, and low leakage. Its output can go directly to the summing point, or via a current attenuator made with NPN transistors, similar to the PNP circuit of *Figure 4*. This circuit has been observed to cover a wide (130 dB) range, with 0.1% of signal accuracy.

What is the significance of this wide-range current-to-frequency converter? In many industrial systems the question of using an inexpensive 8-bit converter instead of an expensive 12-bit data converter is a battle which is decided every day. But if the signal source is actually a current source, then you can use a V-to-F converter to make a cheap 14-bit converter or an inexpensive converter with 18 bits of dynamic range. The choice is yours.

Why use an I-to-F converter?

- It is a natural form of A-to-D conversion.
- It naturally facilitates integration, as well.
- There are many signals in the world, such as photospectrometer currents, which like to be digitized and integrated as a standard part of the analysis of the data.

- Similarly: photocurrents, dosimeters, ionization currents, are examples of currents which beg to be integrated in a current-to-frequency meter.

Other signal sources which provide output currents are:

- Phototransistors
- Photo diodes
- Photoresistors (with a fixed voltage bias)
- Photomultiplier tubes
- Some temperature sensors
- Some IC signal conditioners

Why have a fast frequency out?

- A 100 kHz output full-scale frequency instead of 10 kHz means that you have 10 times the resolution of the signal. For example, when I_{IN} is 0.01% of full-scale, the f will be 10 Hz. If you integrate or count that frequency for just 10 seconds, you can resolve the signal to within 1% — a factor of 10 better than if the full-scale frequency were slower.

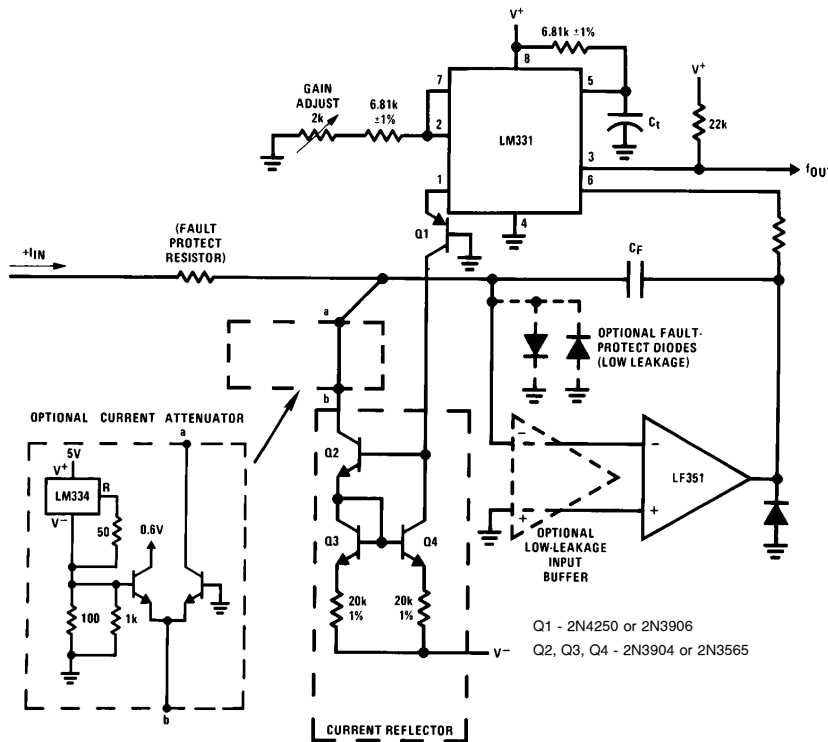


FIGURE 5. Current-to-Frequency Converter For Positive Signals

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