EDITED BY BRAD THOMPSON
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Chopper-stabilized amplifier cascade yields 160 to 10,240 programmable gain

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Certain medical and scientific instrumentation applications require amplification and measurement of microvolt-level signals. For example, accurately measuring the output of a thermopile-based microcalorimeter demands an amplifier that achieves high gain and exhibits excellent thermal stability and low noise.

Figure 1 illustrates how combining two amplifiers yields a programmable-gain amplifier that provides selectable gains of 160 to 10,240. The circuit also offers typical offset voltage of 5 μV, offset drift of 20 nV/°C, and equivalent input-noise voltage of 9 nV$\sqrt{\text{Hz}}$ at 0.1 Hz. IC_1, a Cirrus Logic (www.cirrus.com) CS3301 low-voltage, differential-input, differential-output, chopper-stabilized programmable-gain amplifier, serves as an input-amplifier stage and drives IC_2, a higher voltage INA114 instrumentation-amplifier output stage. The CS3301 provides seven programmable gains of one to 64, and the INA114 provides a fixed gain of 160. The combination achieves gains of 160 to 10,240. A thermopile produces a 1-mV signal, yielding 10.24V output from the INA114. To select other values of

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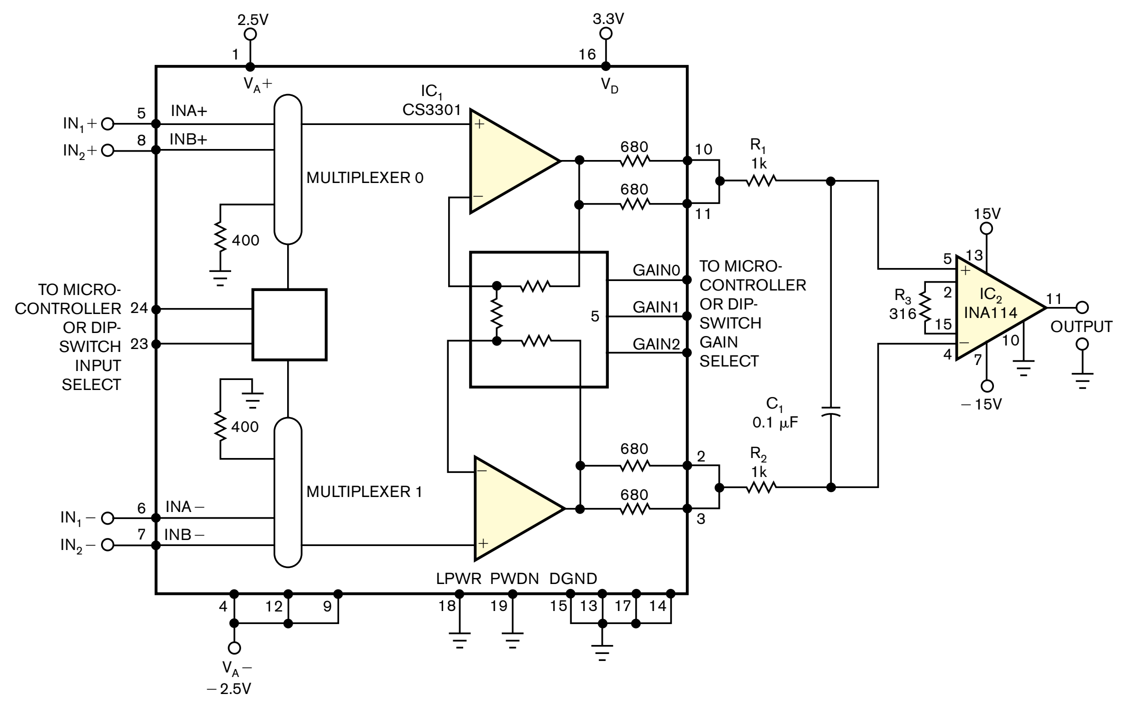

Figure 1 Combining a programmable-gain, chopper-stabilized amplifier with an instrumentation amplifier delivers high gain and low noise over a subaudible frequency range.

gain, change the value of the INA114's gain-setting resistor, R_3.

External DIP switches and pull-up resistors, which connect to the 3.3V supply (not shown), program the CS3301's gain- and multiplexer-control pins. A microcontroller that can drive 3.3V logic can also control these control inputs. Connecting the CS3301's outputs and the INA114's inputs, an RC lowpass filter composed of R_1, R_2, IC_1's output resistors, and C_1 limits noise above 500 Hz.

Figure 2 illustrates the combined amplifiers' measured input-referred noise performance at a gain of 10,000. With its 1/f noise corner at 0.08 Hz, the amplifier cascade achieves an equivalent input-noise voltage of about 9 $nV\sqrt{Hz}$ at 0.1 Hz. The noise-versus-frequency plot represents the results of FFT processing of more than 2 million output samples over an 18-hour period. For simplicity, the schematic doesn't show power supplies and bypass capacitors. Due to the circuit's extreme amplification factor, use construction techniques that maintain thermally balanced component placement and electrically balanced pc-trace lengths.**EDN**

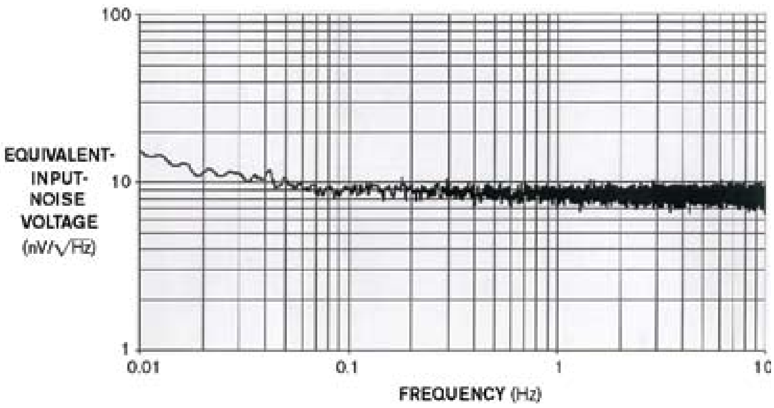

Figure 2 A three-octave plot displays the cascaded amplifiers' low equivalent-input-noise voltage versus frequency.

Current-mode instrumentation amplifier enhances piezoelectric accelerometer

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A typical piezoelectric sensor comprises a disk of PZT-5A ceramic material with metallized electrodes on its surfaces. Applying electrically conductive epoxy to the electrodes connects external wiring to the sensor. An insulating adhesive attaches the assembly to the structure under test and isolates the sensor from ground-referenced potentials. The disk faces the direction of the expected acceleration. When you mount the piezoelectric disk on a target structure, it serves as a simple force sensor and accelerometer by producing a voltage that's directly proportional to the force acting parallel to the disk's direction of polarization. A piezoelectric disk's capacitive impedance presents a large reactance at

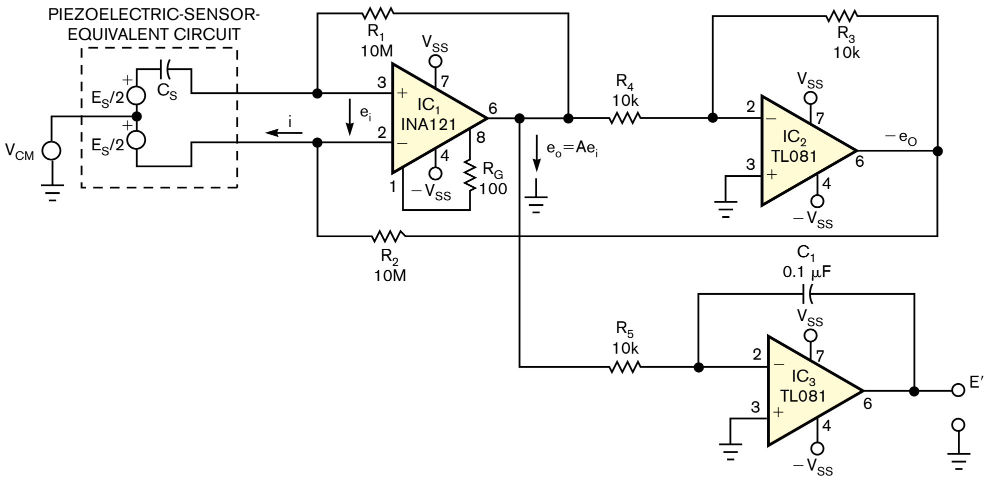

Figure 1 Three amplifiers and a handful of passive components suppress stray noise pickup on a piezoelectric accelerometer and its wiring.

low frequencies, making the disk and its wiring susceptible to interference that surrounding electrical equipment and power lines produce. Placing the sensor in a remote location requires shielded interconnecting cable, but even shielding is not entirely effective in removing common-mode signals because noise pickup can still occur at the disk's conductive surfaces.

One method of extracting the sensor's signal employs an instrumentation amplifier, which amplifies only the potential the sensor produces; the amplifier rejects common-mode-coupled noise potential that appears on each of the sensor's terminals.

A typical miniature piezoelectric-disk sensor that's 0.125 in. in diameter and 0.0075 in. thick presents a capacitance of approximately 500 pF. If the measurement application requires a dynamic response to force excitation frequencies of 10 Hz or below, the sensor's output reactance ranges into the tens of megohms. The circuit's pc-board insulating substrate and ambient humidity impose a practical limit of approximately 10 MΩ on the amplifier's input resistance.

You must carefully choose insulation and apply guarding potentials, and you must use an amplifier with picoampere input-bias currents. Otherwise, the sensor's capacitance and the amplifier's input-bias-current resistors impose a phase shift on the signal you apply to the instrumentation amplifier. To eliminate guarding and elaborate insulation requirements, the circuit in **Figure 1** uses an instrumentation amplifier with feedback to measure the sensor's short-circuit current and not its open-circuit voltage. V_{CM}, the common-mode voltage between the sensor and the signal ground, results from nearby noise sources resulting from stray capacitive coupling. The following **equation** relates the sensor's output current, i, and its open-circuit output voltage, E_S:

$$i=\left[\frac{2A+1}{\left(2R+\dfrac{(2A+1)}{j\omega C_S}\right)}\right]E_S,$$

where A represents IC_1's voltage gain, and $R=R_1=R_2$ in **Figure 1**. Resistors R_1 and R_2 provide feedback and input-bias-current-return paths for IC_1, an INA121 instrumentation amplifier, and resistor R_G sets the amplifier's gain. The INA121's input-bias-offset current of 0.5 pA produces 5 μV of voltage offset across its 10-MΩ feedback resistors. At an amplifier gain of 500, IC_1's output offset amounts to 2.5 mV. Amplifier IC_2, a TL081, provides unity-gain signal inversion.

If $2A+1>>2Rj\omega C_S$, then $i\cong j\omega C_S E_S$, and amplifier IC_1's input voltage, V_1, vanishes because the amplifier's input terminals act as a virtual short circuit across the sensor. Taking the sum of voltages around the loop comprising the instrumentation and inverting amplifiers' output, the two feedback resistors and the instrumentation amplifier's input terminals, whose potential difference is zero, yields $e_O=j\omega R_C E_S$, where e_O represents IC_1's output and also the negative value of IC_2's output.

An operational-amplifier-based integrator, IC_3, delivers the value for E_S at IC_3's output, E′ in the following **equation**.

$$E'=-\frac{RC_SE_S}{C(R_5)}.$$

For the component values in **Figure 1**, IC_1 provides a gain of 500. Resistors R_1 and R_2 are equal at 10 MΩ, and the piezoelectric sensor's capacitance measures 500 pF. For the highest frequency of interest, 10 Hz, the quantity $2R\omega C_S=0.6<<2A+1=501$ and the sensor's output, E_S, appear without phase error as E′. This circuit can measure quasistatic force changes; the circuit's ability to sustain a charge on C_1 imposes the ultimate limit on the circuit's frequency response. **EDN**

Low-cost RF sniffer finds 2.4-GHz sources

Vladimir Dvorkin, Linear Technology Corp, Milpitas, CA

Whether you measure or use RF circuits that operate in the popular 2.4-GHz ISM (industrial/scientific/medical) band, cordless telephones, Wi-Fi access points, Bluetooth devices, and microwave ovens can radiate RF signals, causing unwanted interference. A spectrum analyzer remains the instrument of choice for detecting and identifying interference sources, but analyzers are expensive, bulky, and sometimes not readily available.

The circuit in **Figure 1** shows an easily assembled, low-cost, and portable RF "sniffer" that provides a quick and reliable reading of the ambient-RF-signal level in the 2.4- to 2.5-GHz frequency band. At the circuit's heart, a Linear Technology (www.linear.com) general-purpose LT5534 RF-power detector, IC_1, measures RF-signal strengths from −55 to −5 dBm and provides an RSSI (received-signal-strength-indicator) dc-output voltage (**Reference 1**).

An antenna for this frequency band drives FL_1, a Toko (www.toko.com) filter (Part No. TDFU2A-2450T-10A), which restricts the circuit's passband to 2.4 to 2.5 GHz and limits out-of-band interference. The filter drives IC_1, whose internal circuitry comprises a cascade of RF detectors and limiters. The detectors' and limiters' summed outputs generate an accurate logarithmic-linear voltage proportional to the RF input in decibels. A single discrete transistor, Q_1, converts IC_1's RSSI output to a current that drives a low-current-LED signal-strength indicator. You can connect a digital voltmeter to IC_1's RSSI output to provide a digital readout of signal strength or rely on the lighted LED to visually indicate an RF signal. Two 1.5V alkaline batteries or three nickel-cadmium cells provide 3V power for the circuit.

The LT5534's frequency range of 50 MHz to 3 GHz covers the VHF, UHF, 800-MHz-cellular-telephone, 902- to 928-MHz-ISM, 2-GHz-PCS (personal-communications-system)/UMTS (Universal Mobile Telecommunications System), and 2.4-GHz-ISM bands. For the 2.4- to 2.5-GHz range, use a Laird Technologies (www.lairdtech.com) BlackChip antenna or a Toko dielectric antenna (Part No. DC2450CT1T). To build a sniffer for the 915-MHz band, replace the antenna with Part No. ANT-916-JJB-ST from Antenna Factor (www.antennafactor.com) and replace the input filter with a Toko 4DFA-915E-10 ceramic filter that provides 26 MHz of bandwidth centered on 915 MHz. **EDN**

REFERENCE

1 LT5534 data sheet, Linear Technology, www.linear.com.

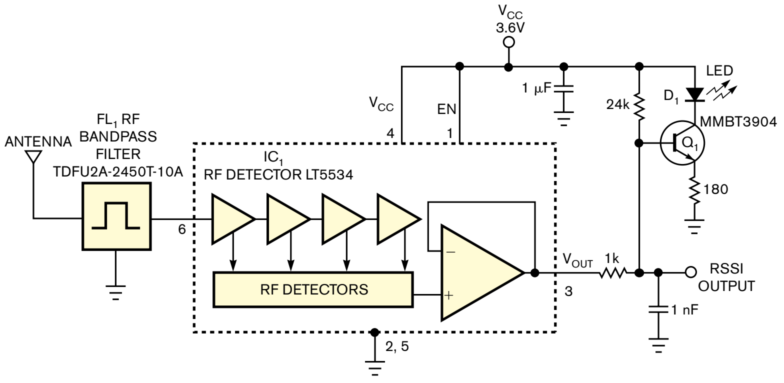

Figure 1 For best results, assemble this 2.5-GHz circuit on a double-sided pc-board layout according to the LT5534's data sheet and application notes.

Triangle waves drive simple frequency doubler

Jim McLucas, Longmont, CO

If you use a function generator, you may occasionally require a sine-wave output at a higher frequency than the generator can provide. If your function generator also produces a triangle-wave output, you can use a frequency doubler to extend the generator's available frequency by as much as a factor of two. A previously published Design Idea describes a triangle-wave-driven frequency-doubler circuit employing op amps that produce output frequencies limited to about 20 kHz (**Reference 1**).

This Design Idea describes a frequency doubler that provides a sine-wave output with a frequency of 4 to 6.7 MHz, with an output level that can range from 110 mV p-p to 1.30 V p-p into a 50Ω load. As **Reference 1** describes, applying a symmetrical triangle wave to a full-wave rectifier produces a triangle wave of twice the input frequency and offset by a dc level. Any asymmetry in the input waveform allows some of the input signal's fundamental frequency to pass through to the output. Also, the circuit's input transformer, T_1, may cause amplitude or phase imbalance, allowing some of the input signal to pass through to the output.

To construct a wideband transformer with good amplitude and phase balance, twist three AWG #30 enameled wires together at about 10 twists/in. Wind seven turns of the bundled wires onto a Fair-Rite (www.fair-rite.com) 2643002402 toroidal core. (Each pass through the core's central opening counts as one turn.) Connect the wires as shown in **Figure 1**. (Refer to **Reference 2** and **Figure 2** for additional information on this type of transformer.) This technique results in a wideband transformer with good amplitude and phase-balance characteristics.

To achieve maximum input-frequency attenuation, use a matched pair of Schottky diodes for D_1 and D_2. However, the prototype produced high-quality signals with unmatched Schottky diodes. In **Figure 1**, diode D_3 applies a small negative bias to D_1 and D_2 that allows operation at low signal levels. Capacitor C_1 passes the rectified and frequency-doubled triangle wave to the bases of a complementary emitter follower comprising Q_3, Q_4, and associated components. A simple, two-element lowpass filter at the follower's output removes higher frequency harmonics. Use any 1.6-µH inductor with a Q of 20 or greater for L_1. Although an inductor with a Q as low as 10 will not noticeably change the filter's frequency response, a value lower than 20 increases the inductor's insertion loss and decreases the maximum available output-signal amplitude.

A simple, two-element, lowpass output filter provides adequate performance for a symmetrical-triangle-wave input because the output's frequency components consist of the doubled input frequency signal and only the desired output signal's odd harmonics. For a 5-MHz output, the third harmonic occurs at 15 MHz with an amplitude of −19 dB relative to the 5-MHz signal. The lowpass filter imposes 15 dB more attenuation at 15 MHz, diminishing the 15-MHz signal to −34 dB relative to the 5-MHz output signal and attenuating higher order harmonics to even lower levels.

The complementary emitter follower's unfiltered output signal consists

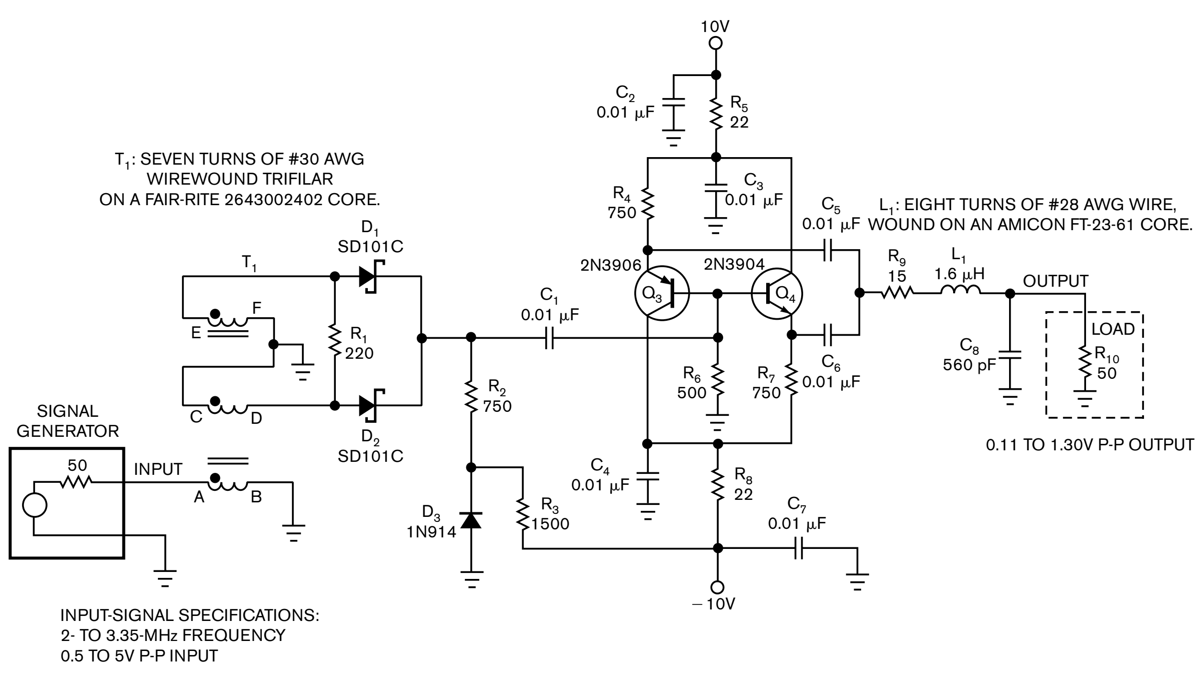

Figure 1 A full-wave rectifier, buffer, and lowpass filter produce a sine-wave output at twice the frequency of a triangular-wave input.

of a triangle wave of twice the input signal's frequency, plus odd harmonics of the doubled input frequency. For example, applying a 2.5-MHz triangle wave to the circuit's input produces a 5-MHz triangle-wave signal at the lowpass filter's input. For a nearly perfect triangle wave, the filter's input consists of a 5-MHz fundamental and only its odd harmonics. At −19 dB below the 5-MHz signal, the 15-MHz third harmonic represents the closest spurious signal and one that you can easily filter.

To use the circuit at higher frequencies, divide the values of output-filter components L_1 and C_8 by a factor of $F_{NEW}/5$, where F_{NEW} represents the desired output frequency in megahertz. For example, a nominal output frequency of 20 MHz requires division of the values of L_1 and C_8 by a factor of four, producing new values of 0.4 µH and 140 pF, respectively. Simulating the circuit with the revised filter in Spice shows adequate harmonic rejection over an output range of 16 to 26.8 MHz. Although designed for 5-MHz operation, the remainder of the circuit works well at 20 MHz without additional modifications. This frequency doubler also accepts a sine-wave input signal. However, the circuit's unfiltered output contains higher levels of the desired signal's even- and odd-order harmonics and requires additional filtering to produce a high-quality sine-wave output.**EDN**

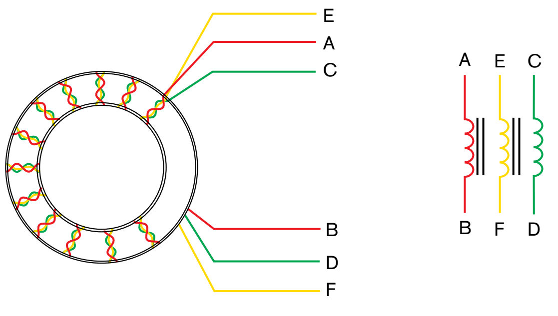

Figure 2 Transformer T_1 from Figure 1 consists of three windings on a toroidal ferrite core. For ease of assembly, twist three wires of different colors into a bundle to form the windings.

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1 Belousov, Alexander, "Frequency doubler operates on triangle waves," *EDN*, March 14, 1996, www.edn.com/archives/1996/031496/06di4.htm.

2 Demaw, MF "Doug," *Applying Toroidal Cores: Ferromagnetic-Core Design and Application Handbook*, ISBN: 0133140881, Prentice Hall, 1996, pg 97.