By Jim Williams and David Beebe, Linear Technology Corp

LOW-VOLTAGE SYSTEMS OFTEN NEED A LOCALLY GENERATED HIGH VOLTAGE. EVEN FOR AN APPLICATION AS NOISE-SENSITIVE AS VARACTOR-DIODE BIASING, A CAREFULLY PLANNED SWITCHING-REGULATOR-BASED DESIGN AND LAYOUT CAN PROVIDE THE NECESSARY BIAS VOLTAGE.

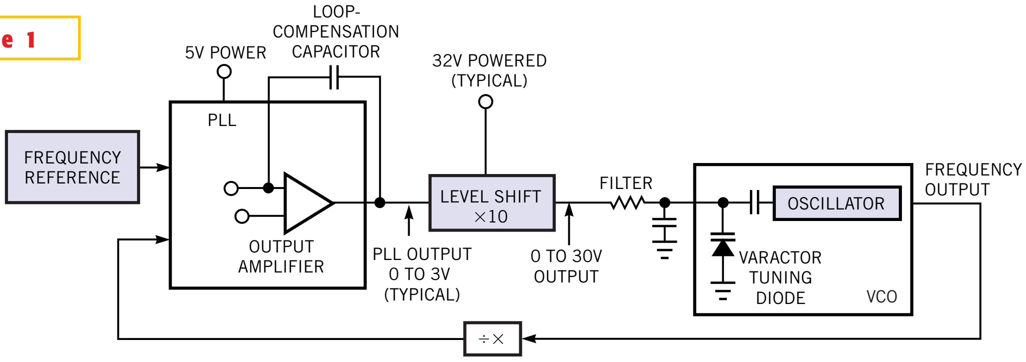
Switching-regulator supply provides low-noise biasing for varactor diodes

Telecommunication, satellite links, and set-top boxes require tuning of a high-frequency oscillator. The actual tuning element is a varactor diode, which is a two-terminal device that changes capacitance as a function of reverse-bias voltage (see **sidebar** "Variable-capacitance diodes"). The oscillator is part of a frequency-synthesizing loop (**Figure 1**). A PLL compares a divided-down representation of the oscillator with a frequency reference. The circuit level shifts the PLL's output to provide the high voltage necessary to bias the varactor, which closes a feedback loop by voltage tuning the oscillator. This loop forces the VCO (voltage-controlled oscillator) to operate at a frequency determined by the frequency reference and the divider's division ratio.

The high-voltage bias is necessary to achieve wide-range varactor operation. **Figure 2** shows varactor-capacitance versus reverse-voltage curves for a family of devices. A 10-to-1 capacitance shift is available, although a 0.1 to 30V swing is necessary. The curves in **Figure 2** are characteristic of typical hyperabrupt devices. Response modification is possible with compromises in performance, particularly with linearity and sensitivity.

Designers traditionally meet the bias-voltage requirement using the existing high-voltage rails. However, the current trend toward low-voltage-powered systems means that you must locally generate the high-voltage bias. Local generation of a high voltage implies the presence of some form of voltage-step-up switching regulator. You can use a step-up approach, but varactor-noise sensitivity complicates the design. In particular, the varactor responds to any form of amplitude variation of its bias,

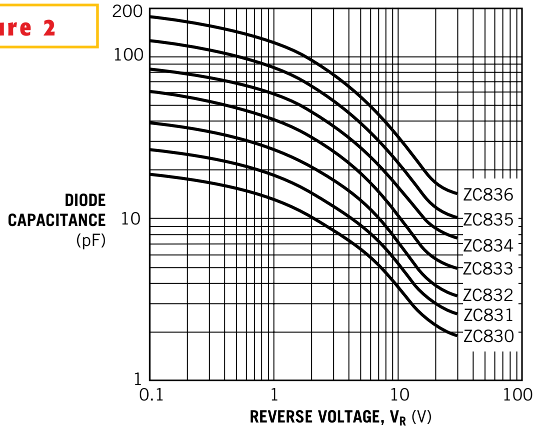
Figure 1



In this typical PLL-based frequency synthesizer, a level shift, which requires a 32V supply, furnishes a 0 to 30V bias for the VCO's varactor.

which results in an undesired capacitance shift. Such a shift causes VCO-frequency movement, resulting in spurious oscillator outputs. The PLL's loop action removes dc and low-frequency shifts, but activity outside the loop's passband causes undesired outputs. Most applications require that any spurious oscillator outputs, or spurs, are at least 80 dB below the nominal output frequency.

Figure 2



The most important characteristic of a varactor diode is the capacitance-voltage relationship. For the varactors and their associated curves in this figure, a 0.1 to 30V swing results in approximately a 10-times capacitance shift.

All of these requirements necessitate a low-noise, high-voltage supply and mandate caution in the switching-regulator design. Switching regulators are often associated with noisy operation, which makes a varactor-bias application seem hazardous. Careful preparation can eliminate this concern and allows for a practical switching-regulator-based approach to varactor biasing.

SIMPLE BOOST REGULATOR

In theory, a simple flyback regulator works for this application, but component choice and attention to layout are critical to achieving low noise. Additionally, component count, size, and cost are usually considerations in varactor-bias applications. **Figure 3a** shows a step-up switching regulator that, properly incarnated, permits low-noise varactor biasing. The circuit is a simple boost regulator. L_1, in conjunction with the SW pin's ground-referred switching, provides voltage step-up. D_1 and C_2 filter the output to dc. D_2 clips possible L_1 negative excursions. The feedback resistor ratio sets the loop servo point and, hence, the output voltage. C_3 tailors the loop's frequency response, minimizing switching-frequency ripple components at the output. C_1 and C_2 exhibit low-loss dynamic characteristics, and the 1.7-MHz switching frequency of the regulator IC allows miniature, small-value components. The relatively high switching frequency also means that ancillary downstream filtering is possible with similarly miniature, small-value components.

Layout is the most crucial design aspect for obtaining low noise. **Figure 3b** shows a suggested layout. The layout distributes ground, V_{IN}, and V_{OUT} in planes to minimize impedance. The IC's GND pin, pin 2, carries high-speed, switched current; this current's path to the circuit's power exit should be direct and highly conductive at all frequencies. R_2's return current should not mix with pin 2's large dynamic currents. The location of C_1 and C_2 should be close to pin 5 and D_1, respectively. The grounded ends of these capacitors should tie directly to the ground plane. L_1 has a low-impedance path to V_{IN}; the driven end of L_1 returns directly to pin 1 of the IC. D_1 and D_2 should have short, low-inductance runs to C_2 and pin 2, respectively. Also, the common connection of D_1 and D_2 should mate tightly with pin 1 and L_1. Pin 1 has a small area, which minimizes radiation. Note that planes operating at ac ground enclose pin 1, thereby forming a shield. The layout further shields the feedback node, pin 3, from switching radiation, preventing unwanted interaction. Finally, the layout should orient L_1

VARIABLE-CAPACITANCE DIODES

By Neil Chadderton, Zetex Inc

The varactor diode capitalizes on the properties of the depletion layer of a p-n diode. Under reverse bias, the carriers in each region—holes in the p type and electrons in the n type—move away from the junction, leaving an area that is depleted of carriers. Thus, reverse bias creates a region that is essentially an insulator and comparable to the classic parallel-plate-capacitor model. The effective width of this depletion region increases with reverse bias, and, consequently, the capacitance decreases. Thus, the depletion layer effectively creates a voltage-dependent-junction capacitance that can vary between the forward conduction region and the reverse breakdown voltage.

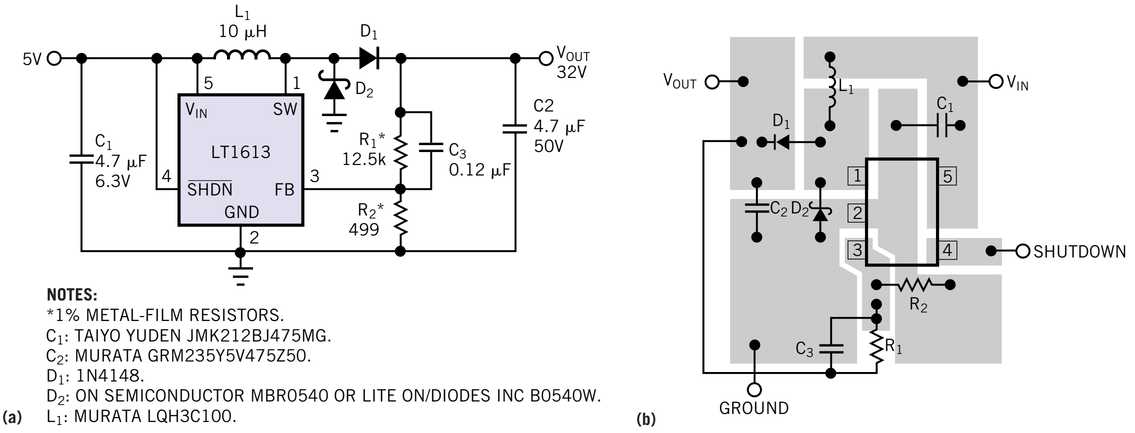
Manufacturers can produce varactor diodes with different junction profiles that exhibit different CV (capacitance-voltage) characteristics. Varactor types include those that exhibit a small range of capacitance to types that show a large change in capacitance for a relatively small change in bias voltage. This feature is particularly useful in battery-powered systems where the available bias voltage is limited.

When you choose a varactor diode, you should consider numerous device characteristics. The most important characteristic is the CV curve that summarizes the range of useful capacitance and also shows the shape of the CV relationship, which may be relevant when a specific response is necessary. Factors to consider include the circuit's operational frequency range and, hence, the appropriate capacitance range, the available bias voltage, and the required response. The quality factor, or Q, at a particular condition is a useful parameter in assessing the performance of a device in tuned circuits. With respect to stability, the temperature coefficient of capacitance as capacitance changes may also be relevant. The reverse breakdown voltage, V_{BR}, also has a bearing on device selection because this parameter limits the maximum reverse bias that you can use to achieve the minimum capacitance.

REFERENCE

1. Chadderton, Neil, "Zetex variable capacitance diodes," Application Note 9, Zetex plc, www.zetex.com.

Figure 3



NOTES:
*1% METAL-FILM RESISTORS.
C_1: TAIYO YUDEN JMK212BJ475MG.
C_2: MURATA GRM235Y5V475Z50.
D_1: 1N4148.
D_2: ON SEMICONDUCTOR MBR0540 OR LITE ON/DIODES INC B0540W.
L_1: MURATA LQH3C100.

A boost regulator with the appropriate components (a) and layout (b) has the necessary low-noise characteristics for varactor biasing. Proper layout requires attention to component placement and ground-current-flow management. A compact layout reduces parasitic inductance, radiation, and crosstalk. A good grounding scheme minimizes return-current mixing.

so that its radiation causes minimal circuit disruption.

The low-voltage PLL output in **Figure 1** requires an analog-level shift to bias the varactor. **Figure 4** shows some alternatives. In **Figure 4a**, the LT1613 regulator IC's 32V output powers the amplifier. The feedback ratio sets a gain of 10, resulting in a 0 to 30V output for a 0 to 3V

PREAMPLIFIER AND OSCILLOSCOPE SELECTION

The low-level measurements this article describes require some form of preamplification for the oscilloscope. Current oscilloscopes rarely have sensitivities greater than 2 mV/DIV, although older instruments offer more capability. **Table A** lists representative preamplifiers and oscilloscope plug-ins suitable for noise measurements. These units feature wideband, low-noise performance. It is particularly significant that many of these instruments are no longer in production in keeping with current instrumentation trends that emphasize digital-signal acquisition as opposed to analog-measurement capability.

The monitoring oscilloscope should have adequate bandwidth and exceptional trace clarity. High-quality analog oscilloscopes are unmatched in trace clarity. The exceptionally small spot size of these instruments is well-suited to low-level-noise measurement. In our work, we have found Tektronix's 454, 454A, 547, and 556 to be excellent choices. Their pristine trace presentation is ideal for discerning small signals of interest against a noise-floor-limited background. The digitizing uncertainties and raster-scan limitations of DSOs impose display-resolution penalties. Many DSO displays do not even register the small levels of switching-based noise.

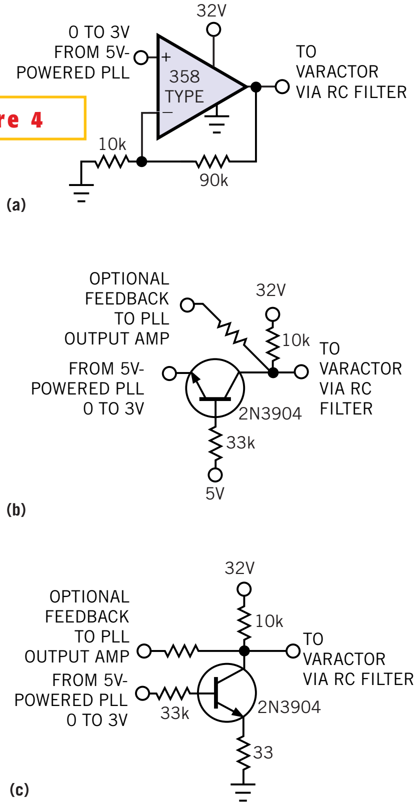
TABLE A–REPRESENTATIVE PREAMPLIFIERS AND OSCILLOSCOPE PLUG-INS

Instrument type	Manufacturer	Model	Bandwidth (MHz)	Maximum sensitivity/gain	Availability	Comments
Amplifier	Hewlett-Packard	461A	150	Gain=100	Secondary market	50Ω input, stand-alone
Differential amplifier	Preamble	1855	100	Gain=10	Current production	Stand-alone, settable band stops
Differential amplifier	Tektronix	1A7/1A7A	1	10 µV/DIV	Secondary market	Requires 500 series mainframe settable band stops
Differential amplifier	Tektronix	7A22	1	10 µV/DIV	Secondary market	Requires 7000 series mainframe settable band stops
Differential amplifier	Tektronix	5A22	1	10 µV/DIV	Secondary market	Requires 5000 series mainframe settable band stops
Differential amplifier	Tektronix	ADA-400A	1	10 µV/DIV	Current production	Stand-alone with optional power supply, settable band stops
Differential amplifier	Preamble	1822	10	Gain=1000	Current production	Stand-alone, settable band stops
Differential amplifier	Stanford Research Systems	SR-560	1	Gain=50,000	Current production	Stand-alone, settable band stops battery or line operation

input. **Figure 4b** is a noninverting common-base stage. The gain in this circuit is less well-controlled than in **Figure 4a**, but overall frequency-synthesizer loop action obviates this concern. **Figure 4c**'s common-emitter circuit is similar to **Figure 4b**'s except that it inverts the signal to the varactor.

Figure 5 combines the considerations mentioned above into a realistic test circuit. The 5V-powered design comprises the LT1613 regulator, an amplifier-based level shift, and a VCO operating in the gigahertz region. Using a filtered LT1004 reference and a gain of 10, the circuit biases the amplifier to a 12V output, which simulates a typical varactor-bias point. The regulator configuration's low-noise output receives additional filtering via the 100Ω, 0.1-µF network at the amplifier power pin and by the amplifier's PSRR (power-supply rejection ratio). The RC combination provides a theoretical, or unloaded, break below 20 kHz, and you can derive the amplifier's PSRR benefit from **Figure 6.** This graph shows PSRR versus frequency for a typical amplifier. There is a steep roll-off beyond 100 Hz, although almost 20 dB of attenuation is available in the megahertz region. This attenuation implies that the amplifier provides some beneficial filtering of the LT1613's residual 1.7-MHz switching components.

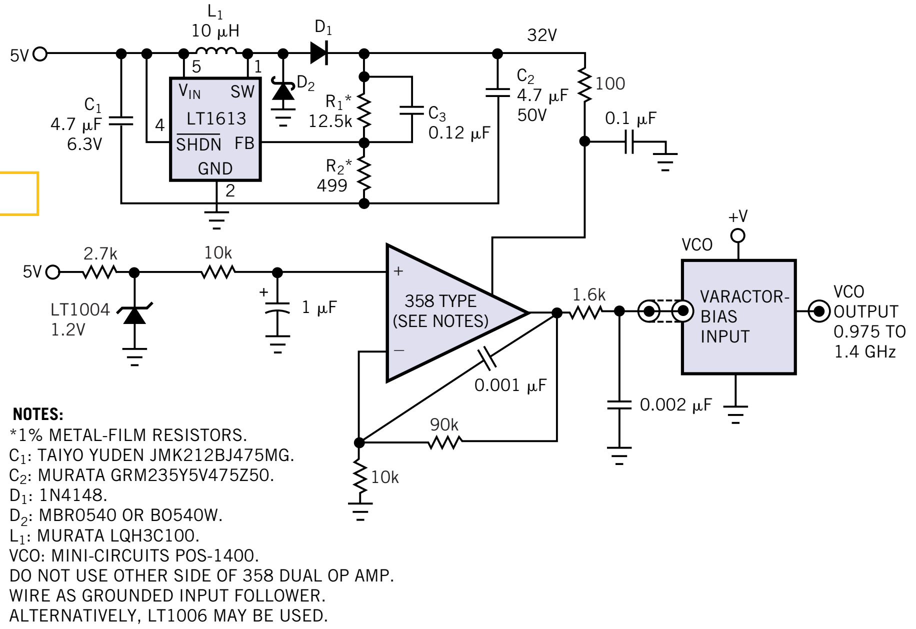
Figure 4



Level-shift options include an op amp (a), a noninverting common-base configuration (b), and an inverting common-emitter configuration (c). The op amp's operating point is inherently stable; the other options rely on PLL closed-loop action or optional feedback.

A final RC filter section sits directly at the VCO-varactor-bias input. Ideally, this filter's break frequency is far away from the 1.7-MHz switching rate for maximum ripple attenuation. In practice, the filter is within the PLL, which places restrictions on how much delay the filter can introduce. A PLL bandwidth of 5 kHz is usually desirable and dictates a filter point of about 50 kHz to ensure closed-loop stability. As such, the design sets the final RC filter—1.6 kΩ and 0.002 µF—at this frequency. It is worth noting that the varactor's input resistance is high—essentially that of a reverse-biased diode—and no filter buffering is necessary to drive it.

Figure 5



NOTES:

*1% METAL-FILM RESISTORS.
C_1: TAIYO YUDEN JMK212BJ475MG.
C_2: MURATA GRM235Y5V475Z50.
D_1: 1N4148.
D_2: MBR0540 OR B0540W.
L_1: MURATA LQH3C100.
VCO: MINI-CIRCUITS POS-1400.
DO NOT USE OTHER SIDE OF 358 DUAL OP AMP.
WIRE AS GROUNDED INPUT FOLLOWER.
ALTERNATIVELY, LT1006 MAY BE USED.

The noise-test circuit includes a step-up switching regulator with only one inductor, a biased-op-amp level shift, filtering elements, and a gigahertz-region VCO.

ANALYZING NOISE PERFORMANCE

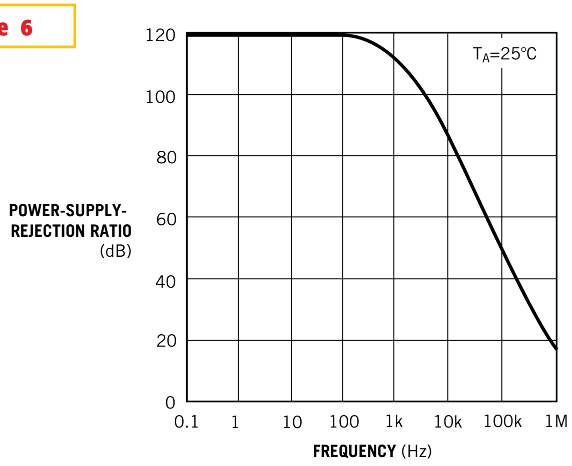
Careful measurements permit verification of circuit-noise performance (see **sidebar** "Preamplifier and oscilloscope selection"). **Figure 7a** shows ripple of approximately 2 mV at the LT1613's 32V output. Taken at the amplifier power pin, **Figure 7b** shows the effect of the 100Ω, 0.1-µF filter. Ripple and noise decrease to about 500 µV. **Figure 7c**, recorded at the amplifier output, shows the influence of amplifier PSRR. Ripple and noise further decrease to approximately 300 µV. The actual ripple component is approximately 100 µV. The final RC filter, located directly at the VCO varactor input, gives approximately 20 dB of further attenuation. **Figure 7d** shows ripple and noise inside 20 µV with a ripple component of about 10 µV.

The above results require good measurement technique and the use of a coaxial probing environment (**Reference 1**). Deviations from this regime produce misleading and pessimistic indications. For example, **Figure 8a** shows a 50% amplitude error over **Figure**

7a, even though the scope probe nominally monitors the same point. The difference between these two figures results from **Figure 8a**'s use of a 3-in. probe-ground lead instead of **Figure 7a**'s use of a coaxial ground-tip adapter. Similarly, the 500-mV measurement at **Figure 7b**'s amplifier power pin degrades to **Figure 8b**'s indicated 2-mV representation using the 3-in. probe-ground strap. The same ground strap causes error in **Figure 8c**'s apparent 2-mV amplifier output unlike **Figure 7c**'s correct 300-mV excursion. **Figure 8d** shows a 70-mV indication at the VCO varactor input using the 3-in. ground strap, which is different from **Figure 7d**'s 20-mV data taken with the coaxial ground-tip adapter. (If you don't think 70 mV is a long way from 20 mV, you should consider your reaction to a 3.5-times income-tax reduction.)

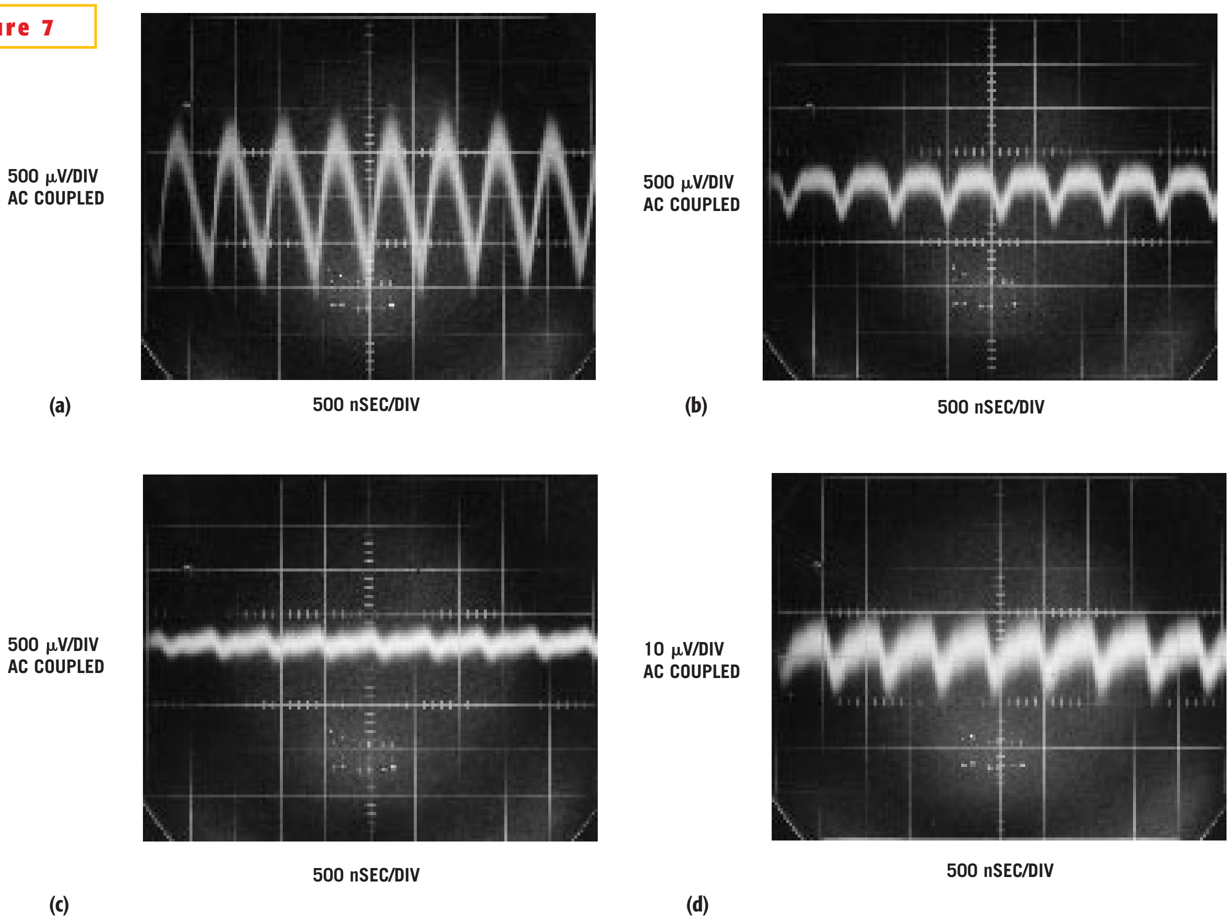
When using the coaxial ground-tip adapter (**Figure 8e**), the VCO varactor input shows a blizzard of noise, compared with **Figure 7d**'s orderly trace, because a 12-in. voltmeter lead connects to the input point. Pickup and stray RF act against the node's finite output impedance, corrupting the measurement. **Figure 8f**, also tak-

Figure 6



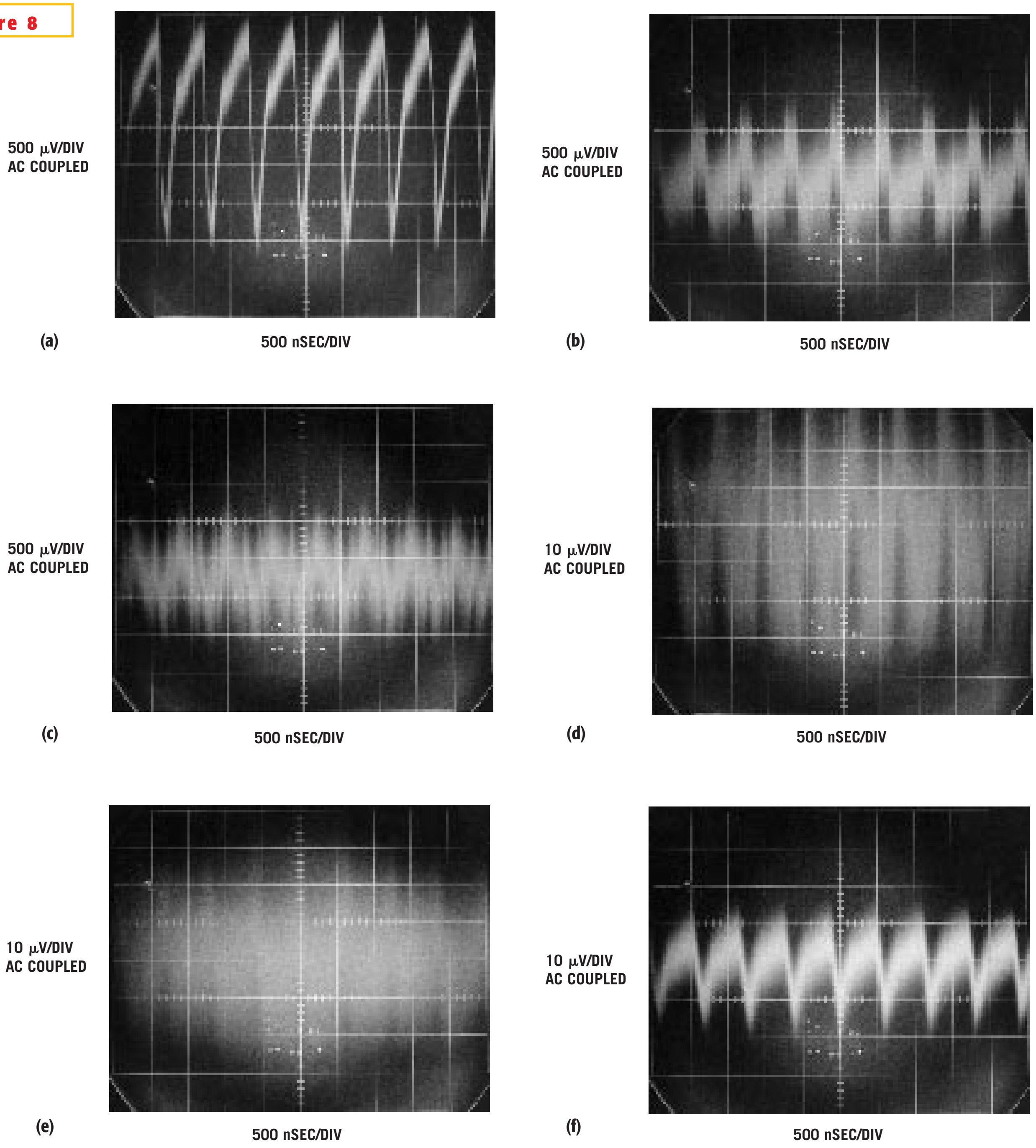
The typical op amp's PSRR degrades with frequency, although nearly 20 dB is available in the LT1613's megahertz switching range.

Figure 7



The regulator's output shows ripple and noise of 2 mV p-p (a). The RC filter at the amplifier's power-input pin reduces ripple and noise to 500 µV p-p (b). The amplifier output shows additional filtering due to the amplifier's PSRR; any aberrations are inside 300 µV (c). The result is the VCO varactor-bias input, which displays less than 20 µV of ripple and noise after the 50-kHz RC filter (d).

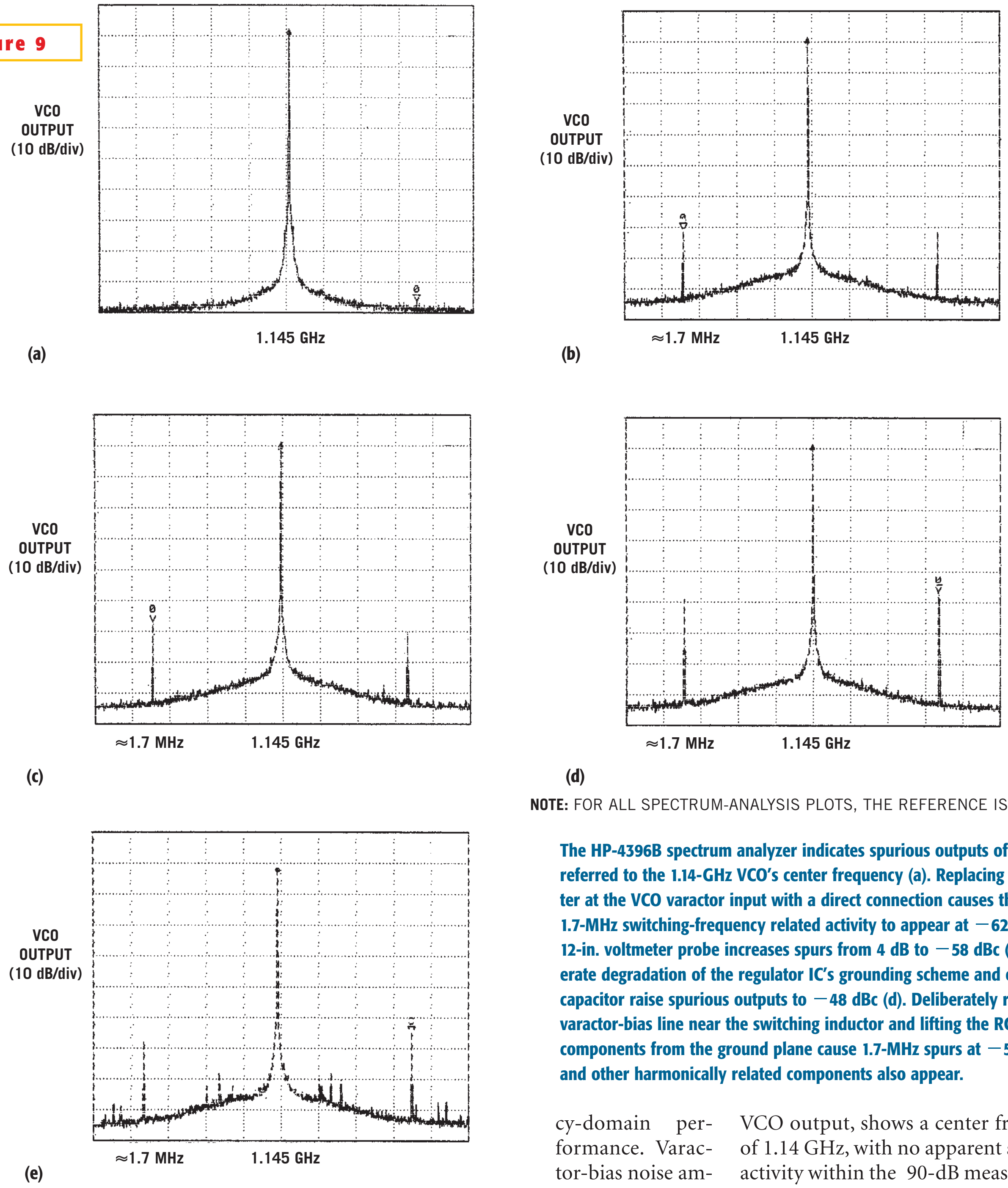
Figure 8



Improper probing technique leads to erroneous results. A 3-in. ground lead causes a 50% display error versus Figure 7a's purely coaxial measurement (a). A 3-in. ground lead degrades Figure 7b's 500-µV reading to 2 mV (b). A probe-ground strap causes an erroneous 2-mV indication compared with the actual value of Figure 7c's 300-µV reading (c). A probe-ground strap causes 3.5-times readout error versus Figure 7d's correctly measured 20 µV (d). A 12-in. voltmeter probe introduces a 2.5-times measurement error to Figure 7d's results (e). An oscilloscope trigger-channel probe also causes a 50% measurement error (f).

en at the VCO input, is clearer than **Figure 8e** but still shows greater than 50% error. The culprit is a second probe, which on the LT1613 VSW pin and triggers the oscilloscope. Even with coaxial techniques in use at both probe points, the trigger probe dumps transient currents into the ground plane. This current introduces small common-mode volt-

Figure 9



NOTE: FOR ALL SPECTRUM-ANALYSIS PLOTS, THE REFERENCE IS 15 dBm.

The HP-4396B spectrum analyzer indicates spurious outputs of −90 dBc referred to the 1.14-GHz VCO's center frequency (a). Replacing the RC filter at the VCO varactor input with a direct connection causes the LT1613's 1.7-MHz switching-frequency related activity to appear at −62 dBc (b). A 12-in. voltmeter probe increases spurs from 4 dB to −58 dBc (c). Deliberate degradation of the regulator IC's grounding scheme and output capacitor raise spurious outputs to −48 dBc (d). Deliberately routing the varactor-bias line near the switching inductor and lifting the RC filter components from the ground plane cause 1.7-MHz spurs at −54 dBc (e), and other harmonically related components also appear.

ages, resulting in a noise increase. One approach is to trigger the oscilloscope with a noninvasive probe (**Reference 1**).

CHECKING RESULTS

Although the varactor-bias noise-amplitude measurements are critical, it is difficult to correlate them with frequency-domain performance. Varactor-bias noise amplitude translates into spurious VCO outputs, which is the measurement of ultimate concern. Although it is possible to view the gigahertz-region VCO on an oscilloscope, a time-domain measurement lacks adequate sensitivity to detect spurious activity. You should use a spectrum analyzer. **Figure 9a**, a spectral plot of the VCO output, shows a center frequency of 1.14 GHz, with no apparent spurious activity within the 90-dB measurement noise floor. The marker at 1.7 MHz (3.5 divisions from center), corresponds to the LT1613's switching frequency. No distinguishable activity is apparent at approximately −90 dBc. Succeeding figures "sanity-check" this performance by systematically degrading the circuit and noting results. In **Figure 9b**, a direct connection replaces the VCO varactor input's RC filter. The 1.7-MHz spurious outputs are clearer at approximately −62 dBc. Connecting a 12-in. voltmeter lead to the measurement point results in a 4-dB degradation to approximately −58 dBc (**Figure 9c**). **Figure 9d** shows effects due to poor LT1613 layout. (A power-ground pin is routed circuitously, rather than directly, back to input common.) The **figure** also shows poor component choice, such as a lossy capacitor for C_2. In this case, spurious activity jumps to −48 dBc. Even with the proper layout and components, you can see problems in **Figure 9e** when you move the varactor-bias line close to switching inductor L_1. The bias line and RC-filter components are also farther away from the ground plane in **Figure 9e** than in the previous plots. The resultant electromagnetic pickup and increase in bias-line effective inductance cause 1.7-MHz spurs at −54 dBc. Additional harmonically related activity, although less severe, is also apparent. When you restore the bias line and RC filter to their proper orientation, the resultant plot is essentially identical to **Figure 9a**.

In sum, layout and measurement practices are at least as important as circuit design. As always, "the hidden schematic dominates performance," which is a favorite quotation of Charly Gullett of Intel Corp.□

AUTHORS' BIOGRAPHIES

Jim Williams, staff scientist at Linear Technology Corp (Milpitas, CA), has been writing technical articles for EDN *for 25 years (see pg 45). He specializes in analog-circuit and -instrumentation design. He has served in similar capacities at National Semiconductor, Arthur D Little, and the Instrumentation Laboratory at the Massachusetts Institute of Technology (Cambridge, MA). A former student at Wayne State University (Detroit), Williams enjoys art, collecting antique scientific instruments, and restoring old Tektronix oscilloscopes.*

David Beebe is associate design engineer at Linear Technology Corp (Milpitas, CA), where he has worked for five years. In his current position, he helped develop a line of bipolar, low-power, and micropower switching power supplies. He attended the College of San Mateo (San Mateo, CA), Mission College (Santa Clara, CA), and Community College of the Air Force (Montgomery, AL). Spare-time interests include acting as a mechanic and pit-crew member for Cliff Blackwell's No. 27B Sprint Car in Northern California.

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