THE JIM WILLIAMS PAPERS

Filters and oscillators

Filters get rid of a signal's unwanted frequency components. Oscillators create signals at predictable frequencies. As you might imagine, the two types of circuits have more than a little in common.

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Filters and oscillators share a common point of view—they deal with signals in the frequency domain. You can define a filter's function as rejecting frequencies you don't want (the job of a band-reject filter, for example) or including only the frequencies you want (what a bandpass filter does). If you reorient your thinking slightly, though, you realize that all filters reject unwanted frequencies. (The bandpass filter rejects frequencies outside the band of interest.) When you view filters in this way, you see that any filter's function is the inverse of an oscillator's; oscillators synthesize individual frequencies or ranges of frequencies. Although there are more kinds of filters and oscillators than any magazine article of reasonable length can hope to touch on, herein are a few types of circuits that can meet a range of needs.

Fig 1a shows a highly selective bandpass filter using a resonant ceramic element and a single amplifier. Except at its resonant frequency, (in this case, 400 kHz) the ceramic element looks like a high impedance. For off-resonance inputs, IC_1 produces no output; it acts as a follower whose input is grounded. At resonance, the ceramic element has a low impedance, and IC_1 behaves as an inverter with gain. The 100Ω resistor isolates IC_1's summing point from the ceramic element's capacitance. This capacitance is quite substantial and limits the circuit's out-of-band rejection. Fig 1b, curve A shows this effect. The plot shows very steep rejection, with IC_1's output down about 20 dB at 300 kHz and 40 dB at 425 kHz. Unfortunately, parasitic capacitance causes the gentle rise in output at higher frequencies and also sets the −20-dB floor at 300 kHz.

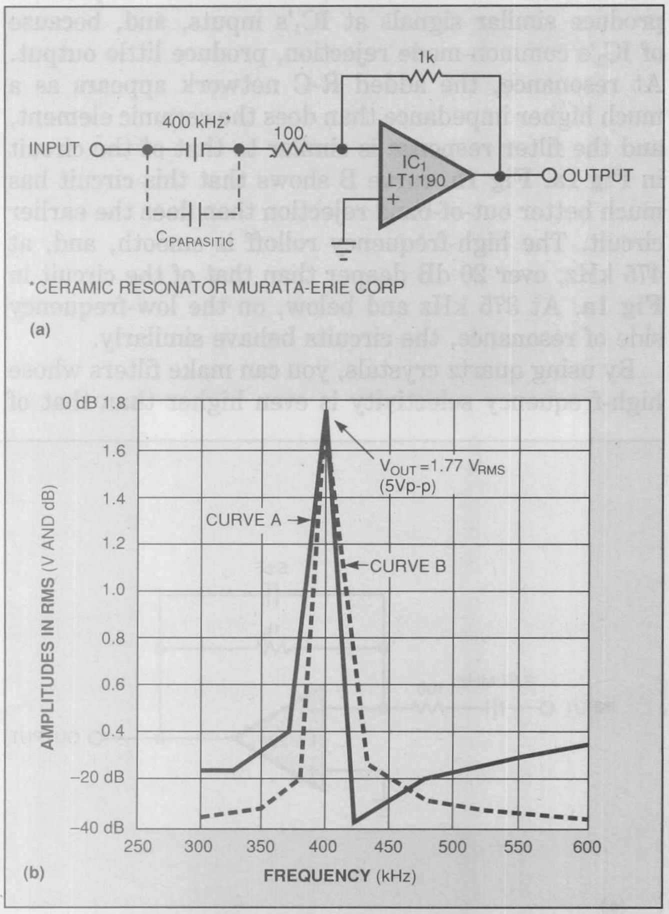

***Fig 1—One amplifier and a ceramic resonator** create a bandpass filter (a). The solid curve of **b** shows the filter's frequency response. Note the dip to −40 dB on the high side of resonance. The dip is the result of the resonator's parasitic capacitance.*

the ceramic element has a low impedance, and IC_1 behaves as an inverter with gain. The 100Ω resistor isolates IC_1's summing point from the ceramic element's capacitance. This capacitance is quite substantial and limits the circuit's out-of-band rejection. **Fig 1b**, curve A shows this effect. This plot shows very steep rejection, with IC_1's output down almost 20 dB at 300 kHz and 40 dB at 425 kHz. The device's stray parasitic capacitance causes the gentle rise in the output at higher frequencies and also sets the −20-dB floor at 300 kHz.

Fig 2 shows how to use a nulling technique to partially correct problems caused by the ceramic element's parasitic capacitance. This circuit is similar to the previous one, except that a portion of the input goes to IC_1's positive input. The R-C network at that input has an impedance close to the ceramic resonator's off-null impedance. Therefore, out-of-band components produce similar signals at IC_1's inputs, and, because of IC_1's common-mode rejection, produce little output. At resonance, the added R-C network appears as a much higher impedance than does the ceramic element, and the filter response is similar to that of the circuit in **Fig 1a**. **Fig 1b**, curve B shows that this circuit has much better out-of-band rejection than does the earlier circuit. The high-frequency rolloff is smooth, and, at 475 kHz, over 20 dB deeper than that of the circuit in **Fig 1a**. At 375 kHz and below, on the low-frequency side of resonance, the circuits behave similarly.

By using quartz crystals, you can make filters whose high-frequency selectivity is even higher than that of filters based on ceramic resonators. **Fig 3a** replaces **Fig 1a**'s ceramic element with a 3.57-MHz quartz crystal. **Fig 3b** shows almost 30 dB of attenuation only a few kHz on either side of resonance! The differential nulling technique used with the ceramic elements is less effective with quartz crystals. Crystals have significantly lower parasitic capacitance, making the cancellation less effective.

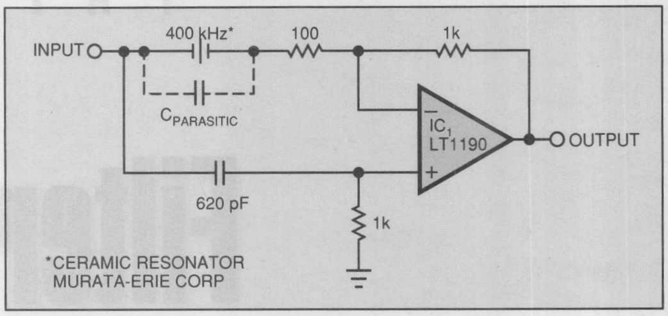

Fig 2—A slight modification *of the circuit in **Fig 1a** allows you to cancel out the effects of the resonator's parasitic capacitance. The dashed curve of **Fig 1b** shows the effects on the filter response. Below resonance, the modified circuit attenuates by an extra 20 dB. Above approximately 525 kHz, the improvement is even more dramatic.*

Oscillators use crystals and resonators

The circuit in **Fig 4** places a crystal within the amplifier's feedback path, creating an oscillator. With the crystal removed, the circuit is a familiar noninverting amplifier with a grounded input. The impedance ratio of the elements associated with IC_1's negative input sets the gain. Inserting the crystal closes a positive

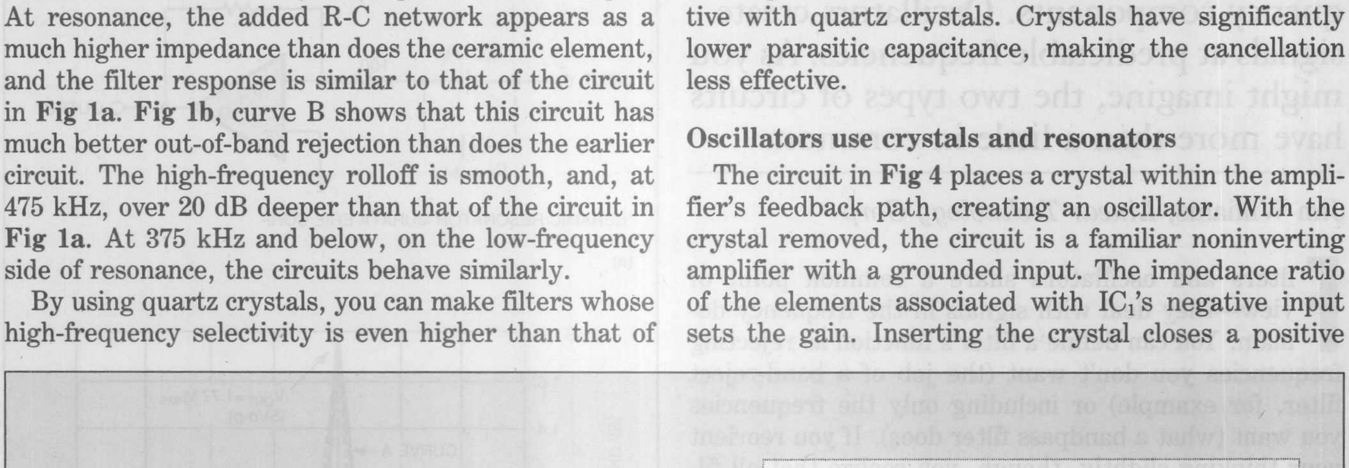

Fig 3—Replacing the ceramic resonator *of **Fig 1a** with a 3.57-MHz crystal is the most significant change that leads to this crystal filter **(a)**. You can see the crystal filter's response in **b**.*

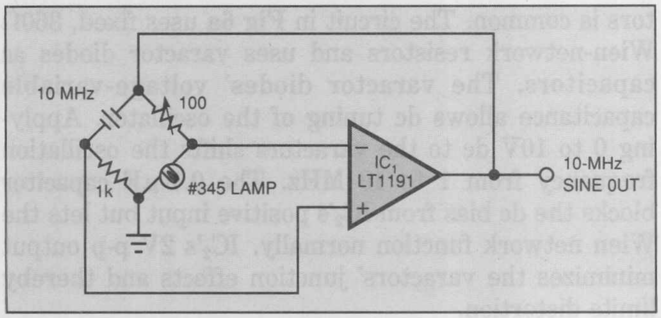

*Fig 4—**An incandescent lamp's** current-dependent resistance stabilizes the oscillation amplitude of this 10-MHz crystal oscillator.*

feedback path at the crystal's resonant frequency, and oscillations commence.

In any oscillator, you must control the gain as well as the phase shift at the frequency of interest. If the gain is too low, oscillation will not occur. Conversely, too much gain produces saturation limiting. In this circuit, gain control comes from the positive temperature coefficient of the lamp at IC_1's negative input. When you first apply power, the lamp's resistance is low, the gain is high, and the oscillation amplitude increases. As the amplitude builds, the lamp current increases and causes heating, which raises the lamp resistance. The increased resistance reduces the amplifier gain and the circuit finds a stable operating point. This circuit's sine-wave output has all of the stability advantages associated with quartz crystals. Although shown with a 10-MHz crystal, the circuit works well with a variety of crystal types from 100 kHz to 20 MHz. Using a lamp to control the amplifier gain is a classic technique, first described by Meacham in 1938. Electronic gain control, though more complex, offers more precise control of amplitude.

Fig 5a's quartz stabilized oscillator replaces the lamp with an electronic amplitude-stabilization loop. IC_2 compares the IC_1 oscillator's positive output peaks with a dc reference. The diode in the dc-reference path compensates for the rectifier diode's temperature dependence. IC_2 biases Q_1, controlling the FET's channel resistance and influencing the loop gain. The amplitude of the oscillator's output is a reflection of the loop gain. Loop closure around IC_1 stabilizes the amplitude of the oscillator's output; the 1-µF capacitor compensates the gain-control loop.

The dc-reference network provides optimum temperature compensation for the rectifier diode, which sees IC_1's 2V p-p, 20-MHz output waveform. IC_1's small output swing minimizes the distortion attributable to channel-resistance modulation in Q_1. To use this circuit, adjust the 50Ω trimmer until 2V p-p oscillations appear at IC_1's output.

Fig 5b is a spectrum analysis of the oscillator's output. The fundamental is at 20 MHz; the second harmonic, at 40 MHz, is 47 dB down. The third harmonic,

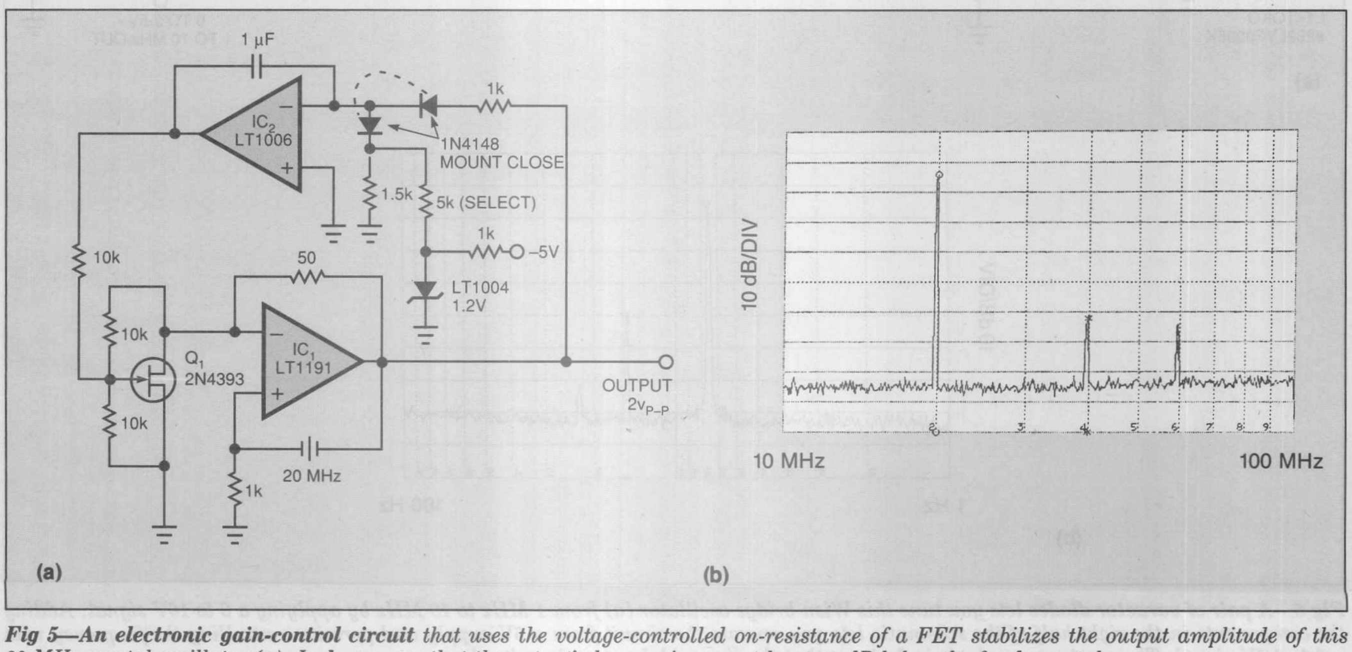

*Fig 5—**An electronic gain-control circuit** that uses the voltage-controlled on-resistance of a FET stabilizes the output amplitude of this 20-MHz crystal oscillator **(a)**. In **b**, you see that the output's harmonics are at least 47 dB below the fundamental.*

50 dB down, occurs at 60 MHz. Resolution bandwidth for the spectrum analysis is 1 kHz.

The circuit in **Fig 6a** replaces the quartz crystal with a Wien network at IC_2's positive input. IC_1 controls Q_1 to stabilize the amplitude of IC_2's oscillations. The operation is identical to that of the circuit in the previous figure. Although the Wien network is not nearly as stable as a quartz crystal, it has the advantage of a variable-frequency output. Normally, you vary the frequency by varying either R or C or both. The use of manually adjustable elements, such as dual potentiometers and 2-section variable capacitors is common. The circuit in **Fig 6a** uses fixed, 360Ω Wien-network resistors and uses varactor diodes as capacitors. The varactor diodes' voltage-variable capacitance allows dc tuning of the oscillator. Applying 0 to 10V dc to the varactors shifts the oscillation frequency from 1 to 10 MHz. The 0.1-µF capacitor blocks the dc bias from IC_2's positive input but lets the Wien network function normally. IC_2's 2V p-p output minimizes the varactors' junction effects and thereby limits distortion.

This 5V-powered circuit requires a voltage step-up to develop adequate varactor drive. IC_3 and the

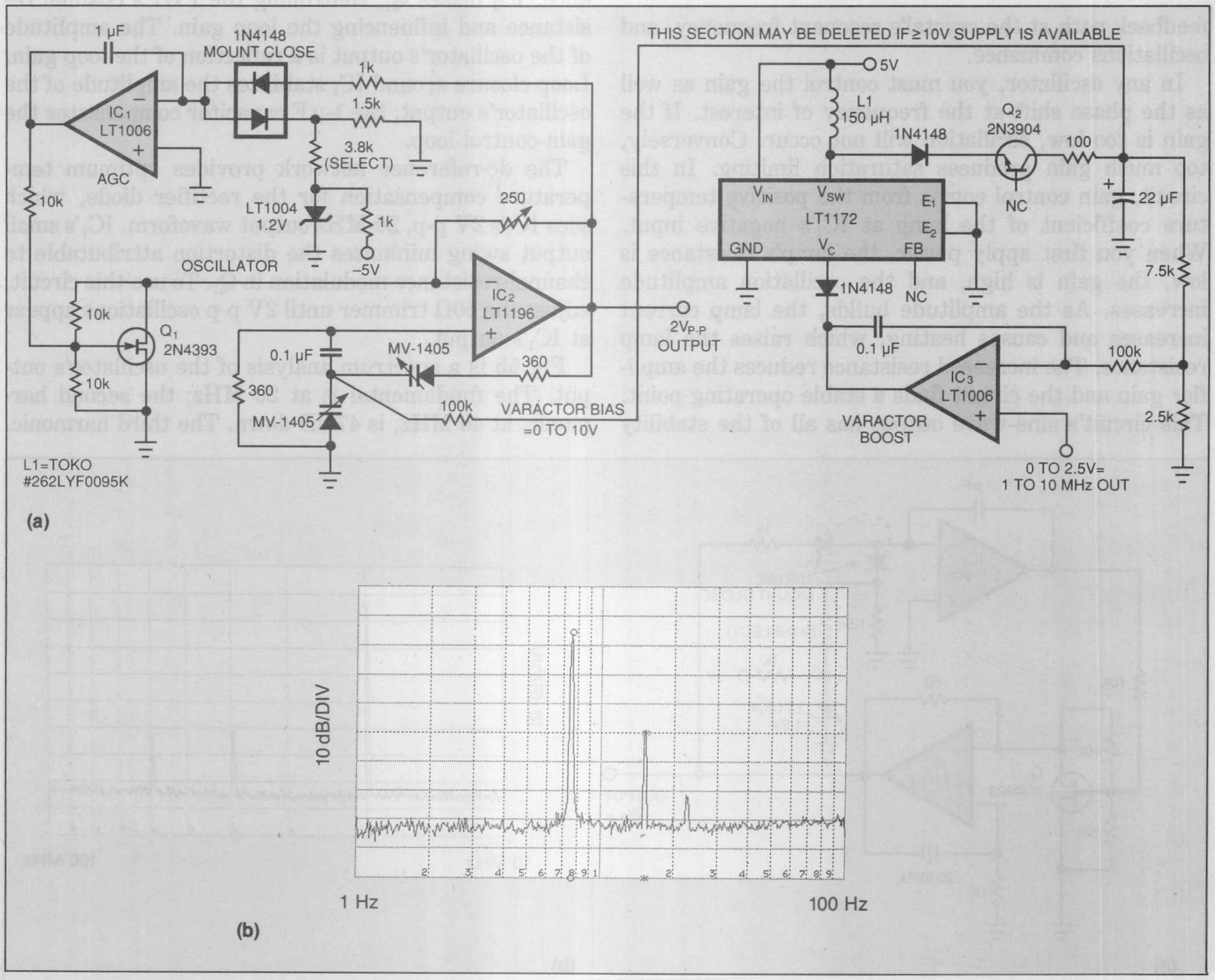

*Fig 6—**A pair of varactor diodes** lets you tune this Wien-bridge oscillator (**a**) from 1 MHz to 10 MHz by applying a 0 to 10V signal. Adding the components in the right half of the schematic lets you operate the circuit from a 5V supply and permits controlling the frequency with a 0 to 2.5V signal. The spectrum analysis in **b** shows that the sinusoidal output is quite clean.*

LT1172 switching regulator form a simple voltage step-up regulator. IC_3 controls the LT1172 to produce whatever output voltage is required to close a loop at IC_3's negative input. The 22-µF output capacitor stores L_1's high-voltage inductive-flyback pulses after they have been rectified by the diode-and-zener-connected Q_2. The 7.5-kΩ/2.5-kΩ divider closes the loop by providing a sample of the output value to IC_3's negative input. The 0.1-µF capacitor stabilizes this feedback action. IC_2's zener drop allows the circuit to produce controlled outputs at voltages as small as zero. This arrangement permits a 0 to 2.5V input at IC_3 to produce a corresponding 0 to 10V varactor bias. **Fig 6b**, a spectral plot of the circuit running at 7.6 MHz, shows the second harmonic down 35 dB and the third harmonic down almost 60 dB. The resolution bandwidth is 3 kHz.

Fig 7a shows the schematic of an AM radio station—complete from microphone to antenna, but lacking a Federal Communications Commission license. IC_1, set up as a quartz-stabilized oscillator similar to the one in **Fig 4**, generates the carrier. IC_1's output feeds IC_2, which functions as a modulated RF power-output stage. The bias applied to offset pins 1 and 8 restricts IC_2's input-signal range. (See the LT1194 data sheet for details.) IC_3, a microphone amplifier, supplies bias to the offset pins, resulting in an amplitude-modulated RF carrier at IC_2's output. The dc voltage summed with the microphone output biases IC_3's output to the appropriate level for good quality modulation characteristics. Calibrating this circuit involves trimming the 100Ω potentiometer in the oscillator for a stable 1V p-p 1-MHz output from IC_1.

Fig 7a does not show on-air personalities—or, in keeping with current trends in AM radio—a means of providing any kind of program other than a talk show. There is no phonograph pickup or connection to the output of a compact-disc player. Nevertheless, you can connect such a music source to the microphone input. **Fig 7b** shows a typical AM carrier output at the antenna. In a throw-back to the days when top-40 formats reigned on the AM band, the modulating signal is Mr Chuck Berry singing the rock-'n'-roll classic "Johnny B. Goode."

Start with a triangle; end up with a sine

The oscillators presented to this point have limited tuning-frequency range. Although the circuit in **Fig 8a** is not a true oscillator, it produces a synthesized sine-wave output over a wide dynamic range. Many applications such as audio, shaker-table driving, and automatic test equipment require voltage-controlled oscillators (VCOs) that have sine-wave outputs. This circuit meets this need, spanning a range of 1 Hz to 1 MHz (equal to 6 decades or 120 dB) for a 0 to 10V input. The circuit maintains 0.25% frequency linearity and 0.40% distortion.

To understand the circuit, assume Q_5 is on and its collector (**Fig 8b**, trace A,) is at −15V, cutting off Q_1. IC_3, which inverts the positive input voltage and biases the summing node of integrator IC_1 through the 3.6-kΩ

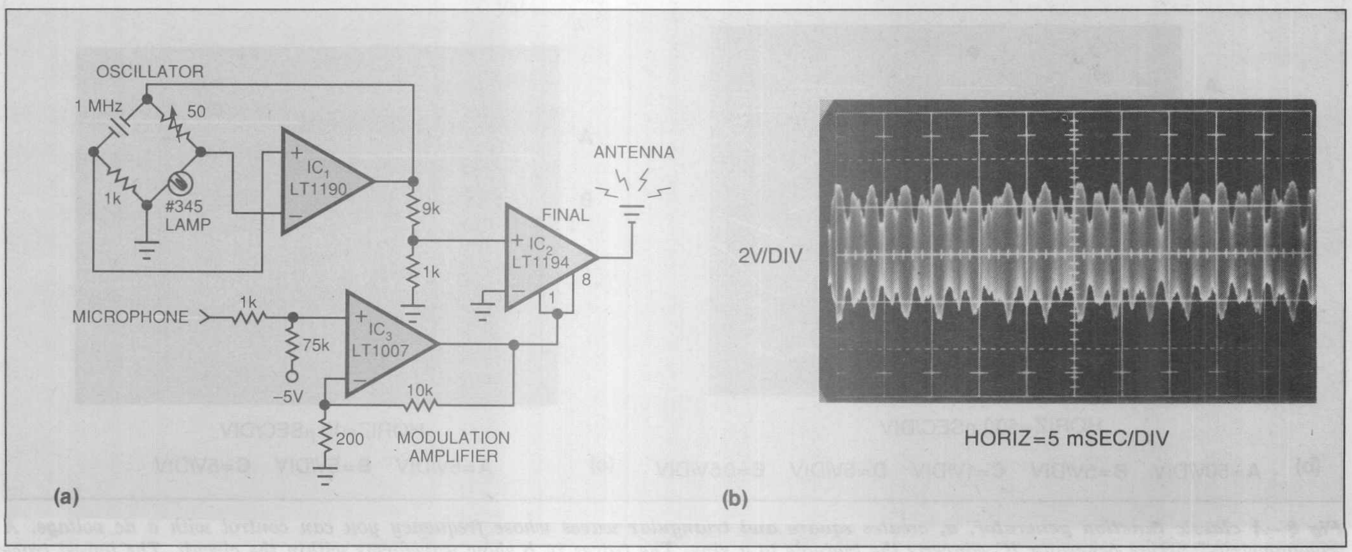

*Fig 7—**Though perhaps not worthy of Wolfman Jack** or Dick Biondi, the circuit of **a** is still a complete AM radio station. When Chuck Berry picks his guitar and belts out "Johnny B. Goode," the modulated output looks like what you see in **b**.*

resistor and the self-biased FET's, pulls a current, $-I$, from the summing point. IC_2, a precision op amp, provides dc stabilization of IC_1. IC_1's output, (trace B,) ramps positive until IC_5's input, (trace C,) crosses zero and causes IC_5's inverting output to go negative. The Q_4/Q_5 level shifter then turns off, and Q_5's collector goes to +15V, allowing Q_1 to come on. The values of the resistors in Q_1's path result in a current, +2I, exactly twice the absolute magnitude of the current, $-I$, that flows out of the summing node. As a result, the net current into the junction becomes +I, and IC_1 integrates negatively at the same rate it did during its positive-going excursion.

When IC_1 integrates far enough in the negative di-

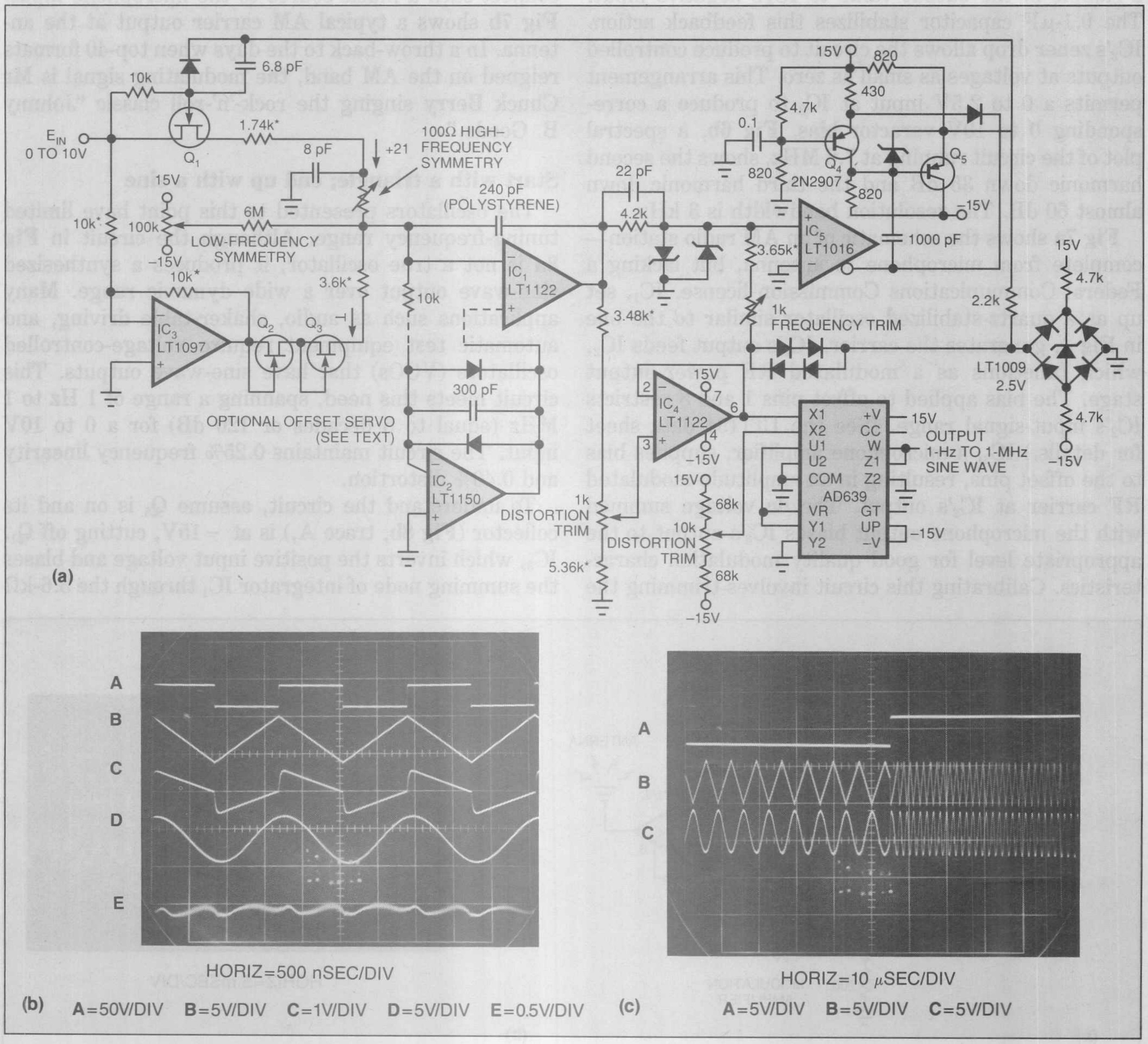

***Fig 8—A classic function generator, a**, creates square and triangular waves whose frequency you can control with a dc voltage. A trigonometric-function generator IC converts the triangle to a sine. The traces in **b** show waveforms within the circuit. The lowest trace shows the residual distortion after you remove the output's fundamental-frequency component. In **c**, you see the circuit's quick and clean response to a command to change frequency.*

rection, IC_5's + input crosses zero and the circuit's two outputs change state. The state change switches the Q_4/Q_5 level shifter's state, causing Q_1 to go off and the entire cycle to repeat. The result is a triangular waveform at IC_1's output. The frequency of this triangle depends on the circuit's input voltage and varies from 1 Hz to 1 MHz with a 0 to 10V input. The LT1009 diode bridge and the series-parallel diodes provide a stable bipolar reference that always opposes the sign of IC_1's output ramp. The Schottky diodes bound IC_5's + input, ensuring its clean recovery from overdrive.

Sine of the times

The AD639 trigonometric function generator, biased via IC_4, converts IC_1's triangular output into a sine wave, (trace D). To avoid output distortion, you must supply the AD639 with a triangular wave that does not vary in amplitude. At higher frequencies, delays in the IC_1-integrator switching loop result in late turn-on and turn-off of Q_1. Unless you minimize these delays, the triangle amplitude will increase with frequency and cause the distortion level to increase. IC_5, the Q_4/Q_5 level shifter, and Q_1 generate a total delay of 14 nsec. This small delay, combined with the 22-pF feed-forward network at IC_5's input, keeps distortion to just 0.40% over the entire 1-MHz range. At 100 kHz, the distortion is typically less than 0.2%. The 8-pF capacitor in Q_1's source line minimizes the effects of gate-source charge transfer, which occurs whenever Q_1 switches. Without this capacitor, a sharp spike would occur at the triangle peaks, increasing distortion. FETs Q_2 and Q_3 compensate for the temperature-dependent on-resistance of Q_1 and keep the +2I/−I relationship constant with temperature.

This circuit responds very rapidly to input changes—something most sine-wave generators cannot do. **Fig 8c** shows what happens when the input switches between two levels, (trace A). IC_1's triangle output (trace B), shifts frequency immediately, with no glitches or poor dynamics. The sine output, (trace C), reflecting this action, is similarly clean. To adjust this circuit, apply 10.00V and trim the 100Ω potentiometer for a symmetrical triangle output at IC_1. Next, apply 100 μV and trim the 100-kΩ potentiometer for triangle symmetry. Then, apply 10.00V again and trim the 1-kΩ frequency-trim adjustment for a 1-MHz output frequency. Finally, adjust the distortion-trim potentiometers for minimum distortion as measured on a distortion analyzer (**Fig 8b**, trace E). You may have to readjust the other potentiometers slightly to achieve the lowest possible distortion. If you won't operate the circuit below 100 Hz, you can delete the IC_2-based dc-stabilization stage. If you make this change, you should ground IC_1's positive input.

Many of the filter and oscillator circuits presented here are simple as well as useful. Their simplicity shows that clever circuit designers often take a minimalist approach. When you speak or write, you are more likely to get your point across if you use short words that are familiar to your audience. So it is with circuits. The simplest design that does the job usually costs the least and operates more reliably than complex alternatives. EDN

Author's biography

For more information on this article's author, turn to pg 163 in the October 10, 1991, issue.

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