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PIEZOCERAMIC TRANSFORMERS HAVE MANY FEATURES, INCLUDING SMALL FORM FACTOR, THAT MAKE THEM INHERENTLY WELL-SUITED TO CCFL-BACKLIGHT INVERTERS.

A svelte beast cuts high voltage down to size

LCDs ARE IN USE EVERYWHERE, from PCs of all sizes to point-of-sale terminals to instruments, autos, and medical apparatus. LCDs use a cold-cathode fluorescent lamp (CCFL) as a light source to backlight the display. The CCFL requires a high-voltage ac supply for operation. Typically, more than 1000V rms are necessary to initiate lamp operation, with sustaining voltages of 200 to 800V ac.

To date, designers have used magnetic transformers in the high-voltage section of backlight "inverters," which convert a dc voltage to high-voltage ac. Designers have spent much effort on magnetic transformers for CCFL inverters, and much written material exists about these designs (**references 1**, **2**, and **3**).

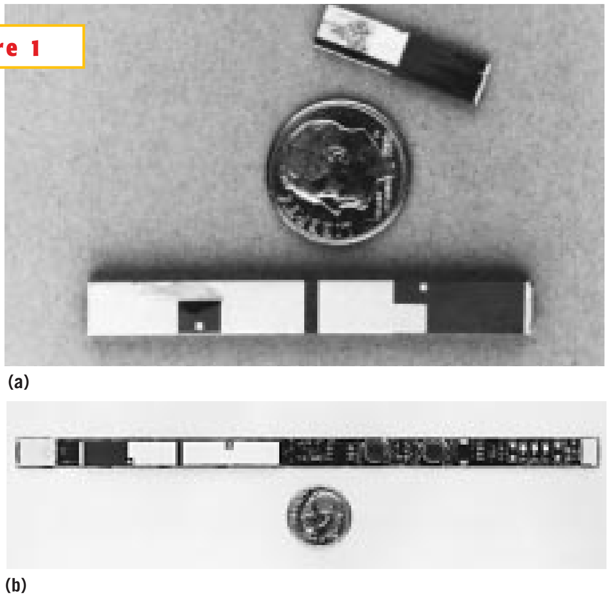
However, the piezoceramic (PZT, for the lead-zirconate-lead-titanate material it comprises) transformer, an arcane and little-known technology, now presents a new approach to this high-voltage generation (see "How it works," pg 54). PZT transformers have many compelling characteristics, including small size, safety, and the ability to work with different displays without recalibration. The size and width of these transformers provide an ideal form factor for constructing space-efficient CCFL-backlight inverters (**Figure 1**).

MAGNETIC CCFL TRANSFORMERS

The PZT transformer is an important design alternative because magnetic-transformer-based approaches are running into difficulties as pc-board space shrinks. In particular, laptop computers with large-area screens have little room for the backlight-inverter board. In many cases, so little space is available that building the inverter function inside the LCD panel has become attractive although, to date, impractical. Thus, construction and high-voltage-breakdown characteristics of magnetic transformers present barriers to implementing them in these forthcoming space-intensive designs.

Additionally, as refined as magnetic technology is, other inverter problems associated with this technology exist, including the necessity to optimize and

Figure 1

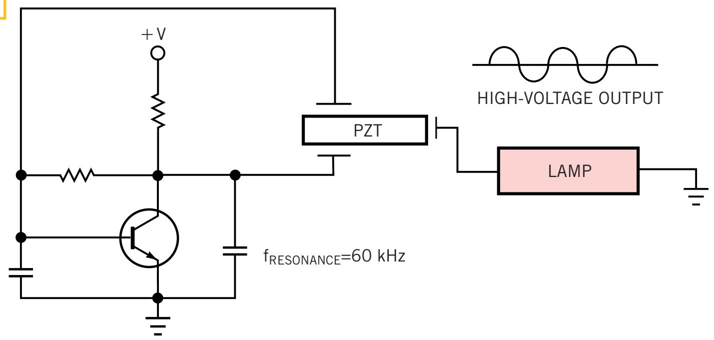

(a)

(b)

Piezoceramic transformers—in this case, 1.5 (upper) and 10W (lower) devices—are much smaller and narrower than magnetic transformers (a). A complete LCD-backlight inverter fits onto a much thinner board (b).

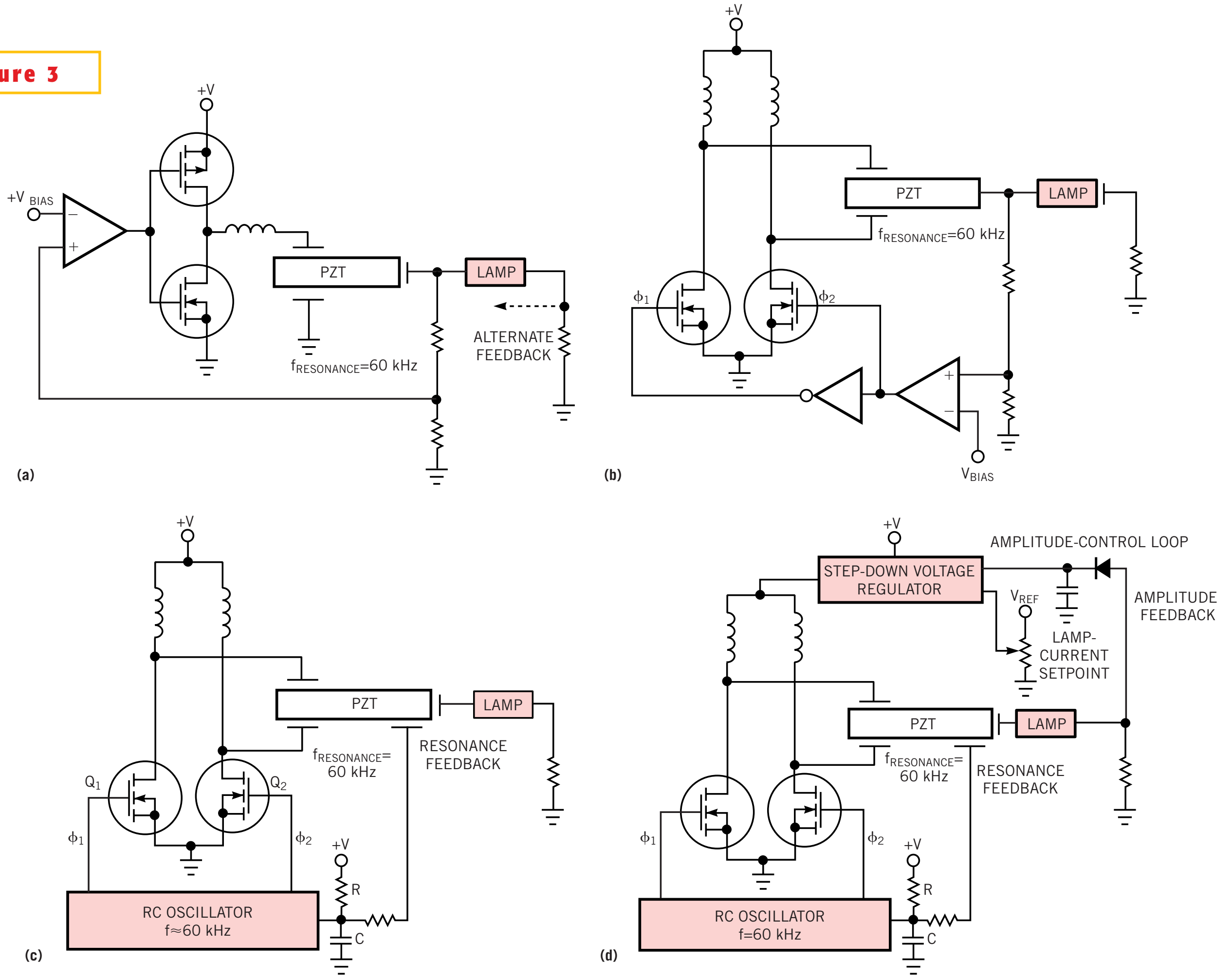
calibrate the inverter for best performance with a given display type. Practically, this requirement means that the manufacturer must adjust inverter parameters, via either hardware or software, to achieve optimum performance with a given display type. Commensurate adjustments in inverter characteristics must accompany changes in the display type. Another problem is fail-safe protection due to self-destructive transformer malfunctions. Finally, the magnetic field that conventional transformers provide can interfere with the operation of adjacent circuitry. With the exception of size, you can address all of these problems, but the solutions in-

Figure 2



A Pierce-type circuit sustains resonance but cannot efficiently deliver power. The circuit also "mode-hops" due to the transformer's parasitic resonances.

Figure 3



A feedback-based oscillator has an efficient drive stage, but poorly defined transformer-phase characteristics cause spurious modes with line and load variations (a). A push-pull version of the circuit in (a) retains efficiency and permits simple all-n-channel drive. Poor phase characteristics still preclude stable loop operation (b). A feedback tap on the PZT transformer synchronizes the RC oscillator, providing stable phase characteristics (c). Adding an amplitude-control loop with current sensing stabilizes the lamp's intensity (d).

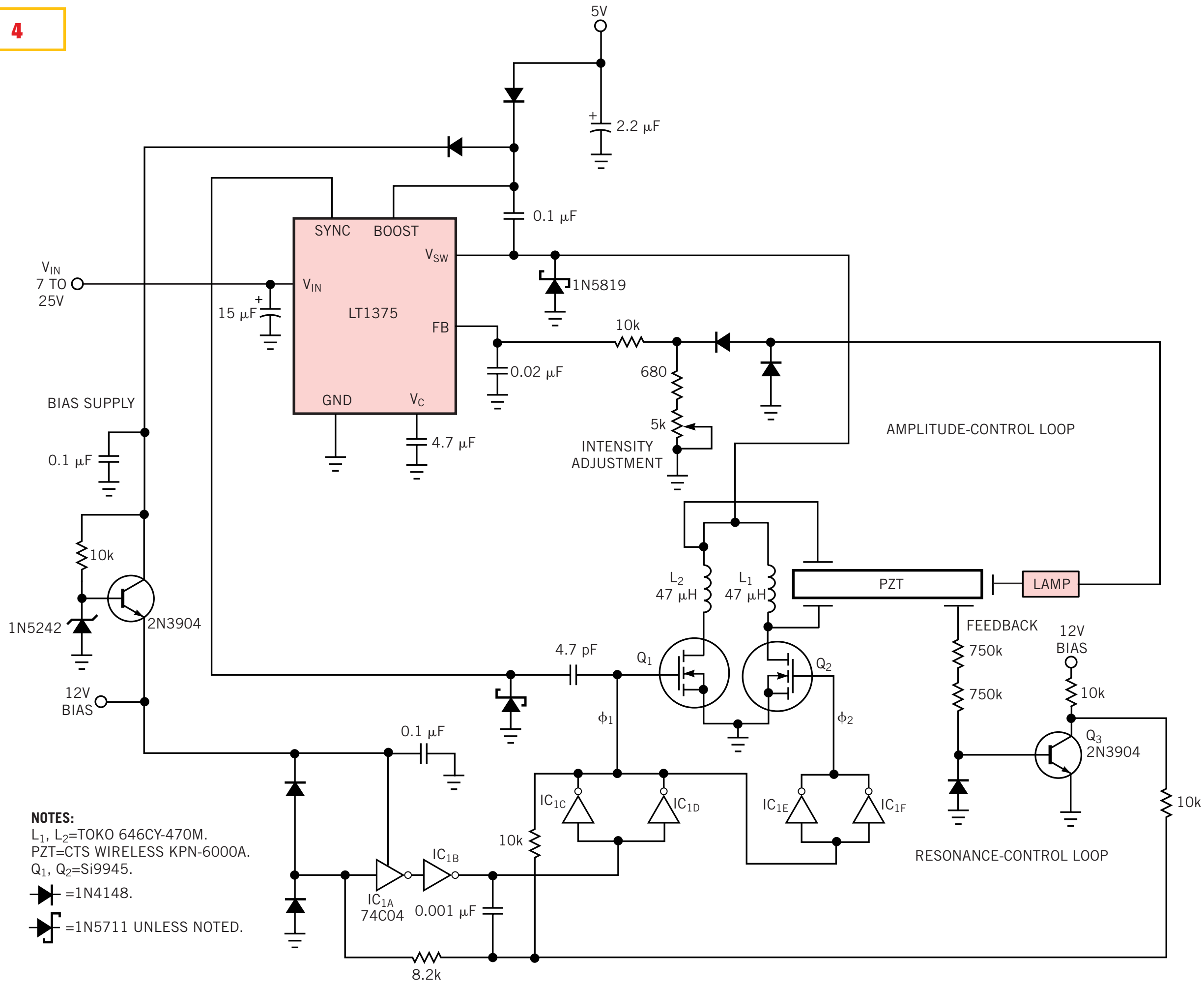
cur economic and circuit/system penalties, as **references 1**, **2**, and **3** discuss.

PZT TRANSFORMERS CONVERT ENERGY

Like magnetic devices, PZT transformers are basically energy converters. A magnetic transformer operates by converting an electrical input to magnetic energy and then reconverting the magnetic energy back to an electrical output. A PZT transformer has an analogous operating mechanism: A PZT transformer converts an electrical input into mechanical energy and subsequently reconverts this mechanical energy back to an electrical output. The mechanical transport causes the PZT transformer to vibrate, similar to quartz-crystal operation, but at acoustic frequencies. The resonance associated with this acoustic activity is extraordinarily high; Q factors greater than 1000 are typical. This transformer action results from using properties of certain ceramic materials and structures. The physical configuration and number of layers in its construction set a PZT transformer's voltage gain. This structure is obviously different from a magnetic transformer, although some very rough magnetic analogs are turns ratio and core configuration. Also different, and central to any serious drive-scheme attempt, is that a PZT transformer has a large input capacitance, as opposed to a magnetic transformer's input inductance.

Piezoelectric-transformer technology is not new and currently exists in various products (**references 4**, **5**, and **6**). More familiar examples of piezoelectric devices are barbecue-grill igniters, for which a direct mechanical input to the PZT transformer produces an electrical discharge, and marine sonar transducers, for which an electrical input produces a pronounced sonic output. You can also find piezoelectric devices in speakers (tweeters), medical ultrasound transducers, mechanical actuators, and fans. Various designs have attempted to use piezoelectric-based backlight inverters, but previous transformer and circuit approaches could not provide power, efficiency, and wide dynamic range of operation. These designs had restricted transformer operating regions and complex and ill-performing electronic-con-

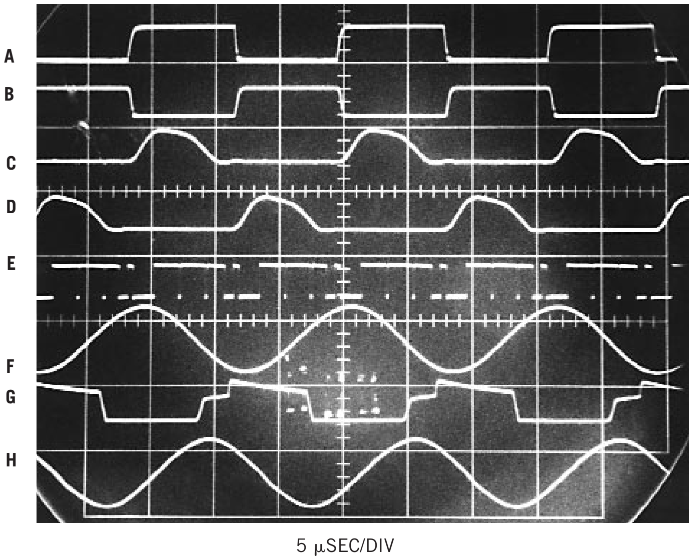
Figure 4



The design in Figure 3d provides the basis for a complete PZT-based backlight inverter. The PZT transformer's resonant feedback synchronizes the RC oscillator via Q_3. The amplitude-control loop powers the transformer via the LT1375 switching regulator.

trol schemes. Additionally, the PZT-transformer-mounting schemes enlarged the overall size, negating the size advantage.

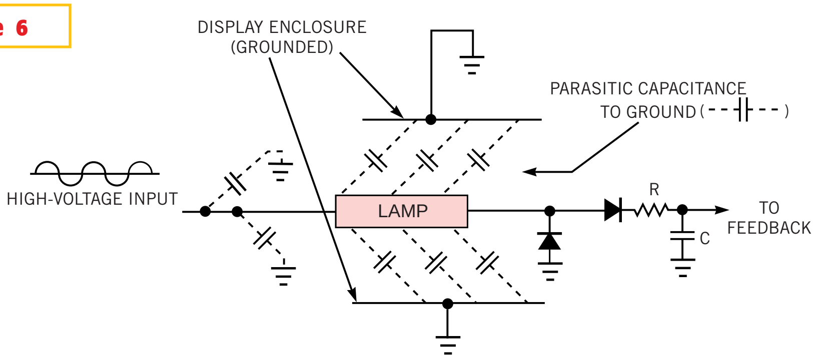
Figure 5



TRACE	VERTICAL SCALE	DESCRIPTION
A	20V/DIV	Q_2 GATE DRIVE
B	20V/DIV	Q_1 GATE DRIVE
C	50V/DIV	Q_1 DRAIN RESPONSE
D	50V/DIV	Q_2 DRAIN RESPONSE
E	20V/DIV	L_1-L_2 JUNCTION
F	500V/DIV	PZT FEEDBACK TAP
G	20V/DIV	Q_3 COLLECTOR
H	2000V/DIV	PZT HIGH-VOLTAGE OUTPUT

Waveforms for the circuit in Figure 4 show the PZT's high-voltage output (Trace H). The PZT transformer acts as a mechanical filter, producing low-distortion sine waves.

Figure 6



All displays introduce some amount of parasitic capacitance between the lamp, its leads, and other electrically conductive elements.

DEVELOP A CONTROL SCHEME

Constructing a practical circuit requires a few design iterations. The circuit in **Figure 2** treats the PZT transformer like a quartz crystal, using it in a Pierce-type oscillator. Self-resonance occurs, and a sinusoidal ac high voltage drives the lamp. This circuit has a number of unpleasant features. Little power is available due to the circuit's high output impedance. Additionally, the PZT transformer has a number of other spurious modes besides its desired 60-kHz fundamental. Changes in drive level or load characteristics induce "mode-hopping," manifested by the transformer's resonance jumping to subharmonic or harmonic frequencies. Sometimes, several modes occur simultaneously. Operation in these modes results in low efficiency and instability. Practically, this circuit was never a serious candidate, only as an exploratory exercise. Its contribution is demonstrating that the PZT transformer's self-resonance is a potentially viable path.

The circuit in **Figure 3a**, a feedback oscillator, addresses the high-output-impedance problem with a totem-style pair. This circuit is partially successful, although efficient totem drive devoid of simultaneous conduction requires care. The mode-hopping problem persists, and, in this case, the long acoustic transit time through the transformer and the wideband-feedback path aggravates the problem. This acoustic transit time, or transit time at the speed of sound, produces enormous feedback phase error. Even worse, this phase error varies with line and load conditions. The alternate feedback in **Figure 3a** senses current as opposed to voltage. This scheme eliminates the voltage-divider-induced loading but does nothing to address the phase uncertainties and mode-hopping. A final problem, which is common to all resonant oscillators, concerns start-up. Gently tapping the transformer at the low-voltage end usually starts a reticent circuit, but this fact is hardly reassuring. The circuit in **Figure 3b** is similar but uses a ground-referred push-pull power stage, simplifying the drive scheme. This approach is a better one, but phase error and mode-hopping and start-up problems are as before.

The circuit in **Figure 3c** retains the drive scheme and solves the remaining problems. Central to this circuit's operation is a new resonance-feedback terminal at the PZT transformer. This connection, precisely positioned on the transformer, provides constant-phase resonance information regardless of operating conditions. At power-up, the RC oscillator drives Q_1 and Q_2 at a frequency outside resonance. The transformer, excited off-resonance, at first responds inefficiently, although voltage-amplified resonant waveforms appear at the feedback and output terminals. The resonant information at the feedback terminal injection-locks the RC oscillator, pulling it to the transformer's resonance. At this point, the circuit supplies the transformer with on-resonance drive, and efficient operation commences. Note that this type of operation is the heart and soul of a bootstrapped start-up circuit. The circuit maintains the feedback terminal's constant-phase characteristic over all line and load conditions, and the loop enforces resonance.

The circuit in **Figure 3d** retains the resonance loop and adds an amplitude-control loop to stabilize lamp intensity. The circuit feeds back sensed lamp current to a voltage regulator to control the transformer's drive power. The regulator's reference point is variable, permitting a lamp-intensity setting at any desired level. The amplitude and resonance loops operate simultaneously but fully independently of each other. This two-loop operation is the key to high-power, wide-range, and reliable control.

Figure 4 is a detailed schematic of **Figure 3d**'s concept. The resonance loop comprises Q_3 and the CMOS-inverter-based oscillator. The amplitude loop centers on the LT1375 switching regulator. **Figure 5** shows circuit waveforms. Traces A and B show Q_2 and Q_1 gate drives, respectively, and traces C and D are the resultant Q_1 and Q_2 drain responses. The LT1375 step-down switching regulator, responding to the rectified and averaged lamp current, closes the amplitude loop by driving the L_1-L_2 junction (Trace E). The 4.7-μF capacitor at the V_C pin stabilizes the loop. The PZT transformer's acoustic transport speed furnishes an almost-pure delay in the loop, making compensation an interesting exercise (see additional information for this article at www.ednmag.com). Note that the design in **Figure 4** includes no filtering; the raw LT1375 500-kHz PWM output directly drives the L_1-L_2-PZT network. This direct drive is permissible because the PZT transformer's Q factor is so high that it responds only at resonance, as the half-sine waves of traces C and D indicate.

The feedback tap (Trace F) supplies phase-coherent information and looks like a current source to Q_3 under all conditions (note Trace F's vertical-scale factor). The 750-kΩ resistors in series minimize parasitic capacitance at the transformer feedback terminal. Q_3's collector (Trace G) clamps this information to a lower voltage and injection-locks the CMOS-inverter-based oscillator, which closes the resonance loop. The oscillator ensures start-up, just as in **Figure 3c**, and effectively filters the already-narrowband resonant feedback, further ensuring resonance-loop fidelity under all conditions. Trace H is the PZT transformer's high-voltage output delivered to the lamp. This example uses a potentiometer to set the dimming, although simple current summing to the LT1375 feedback pin also allows electronic control (**Reference 1**).

ADDITIONAL CONSIDERATIONS AND BENEFITS

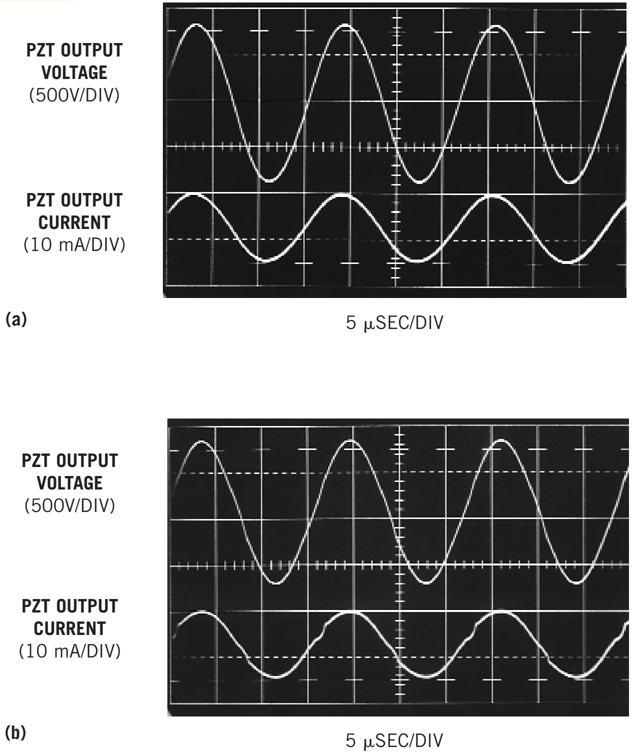
As mentioned, the PZT transformer has other benefits besides size. One of these benefits is safety. A PZT transformer cannot fail due to output shorts or opens. Short circuits knock the PZT transformer off-resonance, and it simply stops, absorbing no energy. Open circuits do not cause arc-induced PZT failures because arcing between turns, as in a magnetic transformer, can't occur. However, it is always wise to sense and arrest an overvoltage condition. Despite their size, PZT transformers are capable of large outputs. With a 10V supply, an uncontrolled PZT transformer can easily produce 3000V rms. This ability mandates some form of overvoltage protection in a production circuit.

Another significant attribute is that the amplitude-control loop's scale factor is almost completely independent of load, including parasitic capacitance. The practical advantage is that you can use the same PZT-based inverter circuit with a range of displays with no recalibration of any kind. This feature is a distinct advantage over magnetically based inverters, which all require some form of scale-factor recalibration, either hardware- or software-based, when you change the display. Understanding this feature requires some study.

Almost all displays introduce some parasitic capacitance between the lamp, its leads, and electrically conductive elements within the display. Such elements may include the display enclosure, the lamp reflector, or both (**Figure 6**). The parasitic capacitance to ground has two major impacts. The capacitance absorbs energy, causing lost power. This power loss raises overall inverter input power because the inverter must supply both parasitic and intended load paths. Some techniques can minimize the effects of parasitic capacitance, but the compensation is never complete (**Reference 1**).

A second effect of parasitic capacitance, manifested in magnetically based inverters, is much subtler. A magnetically based inverter has a finite source impedance at frequency, which corrupts the produced sinusoid. The amount of parasitic capacitance influences the degree of corruption. Displays have varying amounts of parasitic capacitance, resulting in varying degrees of waveform distortion. The RC-averaging time-constant circuit of the magnetic and PZT-based inverters is not an rms-to-dc converter and produces different outputs as distortion content in its input waveform changes. The amplitude loop acts on the dc output of the RC-averaging circuit, and you generally assume that the input-waveform-distortion content is constant. In a well-designed magnetically based inverter, this fact is essentially true, even as operating conditions vary. The averaging circuit's output error is consistent, and you can "calibrate away" the error using scale-factor adjustments. However, changing the display type subjects the averaging circuit to a differently distorted waveform, and new scale-factor adjustments are necessary. Thus, some calibration-constant adjustment is necessary for each display type, complicating production and inventory requirements.

Figure 7



When a PZT inverter drives a low-parasitic-capacitance display, the resulting waveforms are nearly ideal sinusoids (a). A display with higher capacitive loss causes minor distortion, but the lamp's rms current changes by only 0.5% (b).

PZT-based inverters are largely immune to this problem because of their extraordinarily high Q factor, which is typically greater than 1000. The PZT transformer forces the output waveform to have a consistent amount of distortion, nominally zero. The PZT transformer's resonant mechanical filtering produces an almost-pure sinusoidal output, even with widely varying parasitic and intended loads. **Figure 7a** shows PZT output voltage (Trace A) and current (Trace B) with a low-parasitic-loss display. The waveshapes are essentially ideal sinusoids. **Figure 7b** shows the same waveforms with a much higher parasitic-loss display. Minor waveform distortion, particularly in the current trace, is evident, although minimal. The RC-averaging circuit produces little error compared with that in **Figure 7a**, and less than 0.5% lamp-current difference exists between the two cases. In contrast, a magnetically based inverter can easily suffer 10 to 15% lamp-current differences, which impact display luminosity and lamp lifetime.□

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AUTHORS' BIOGRAPHIES

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