

LINEAR TECHNOLOGY

JUNE 1992

VOLUME II NUMBER 2

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Introducing the LT1227: A Video Amplifier for All Seasons

by William H. Gross

Introduction

The LT1227 is the best low-cost, current-feedback amplifier for video applications. The amplifier is unsurpassed for use in professional studio equipment, security systems, personal-computer display adapters, and workstations. The LT1227 is LTC's fastest amplifier; its bandwidth is over 140MHz and its slew rate is over 1100V/ μ s. The LT1227 operates on all supplies from +5V to \pm 15V. It comes in 8-pin DIPs and 8-pin SOs and uses the industry standard pin-out, with offset adjust and a shutdown pin for multiplexing several amplifiers' outputs.

Types of Video

There are many different video formats and standards, but they all belong to one of two groups: RGB or composite. RGB stands for red, green, and blue; these are the three primary colors in a color picture tube. All colors from black (no R, G, or B) to white (maximum R, G, and B) can be produced from various combinations of these three components. The RGB format requires three signals that represent the amplitudes of the respective primary colors plus timing signals (sync) that are sometimes combined with the green component. Composite video refers to a single signal that contains all of the color and timing information described above. Composite video modulates the RF signal that your TV receives.

Video-Amplifier Requirements

In order to better understand the design of the LT1227, we will briefly review the requirements of video systems. Video signals typically swing about 1V positive and 400mV negative; they have information spread over a wide frequency range, from near DC to several MHz. To preserve the low frequency information, most video amplifiers are DC coupled, if possible. However, DC offset is not a very important parameter for video amplifiers. This is because the information needed to restore or clamp the DC zero level is in the video signal. The DC level is usually restored at the inputs of monitors and test equipment, and at the inputs of A-to-D converters. Therefore, the DC offset of a video amplifier needs only to be low enough to prevent distortion of the output signal. Large supplies make this easier, and today most video systems operate on \pm 12V supplies, although a growing number of systems operate on \pm 5V.

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Another Lonely Day at the Word Processor

by Richard Markell

This issue is one of our most diverse yet. We have articles on the design of new integrated circuits, such as the LT1227 Video Amplifier, we have an article applying the LTC1047 to a "real world" instrumentation amplifier problem, and we have application articles on cold-cathode fluorescent lighting circuits, palm-top pager circuits and the SwitcherCAD design software. A diverse group of articles all in all.

Linear Technology Corporation continues to offer highly cost-effective solutions to an ever increasing variety of linear circuit problems. Our integrated-circuit design group has become increasingly involved in the

design of power-supply solutions for all types of 5 Volt and 3.3 Volt computers and hand-held devices such as palm-top computers, pagers, cellular phones, and bar-code readers. Our new high-speed line of operational amplifiers provide solutions for a plethora of RF, analog, and digital video applications. These amplifiers provide cost-effective solutions for the growing world of Multimedia, DVI, CD-I and CD-V applications.

Another area that LTC is involved in is power control. We are developing circuits for driving power MOSFETs, including Motor Control IC's, solid-

state circuit breakers, switching regulators, and related devices.

Linear Technology is also involved in a variety of products that defy easy classification. These include CCFL displays, portable FAX's, palm top computers, pen computers, LANs and other networking schemes, and geopositioning devices.

We at LTC continue to offer whatever design and application assistance is required to support our integrated circuits. Do not hesitate to call us to discuss your circuit, your application or how we can help you do the best, most cost effective job on your design.

Issue Highlights

Bill Gross leads off this issue with his article on the LT1227 Video Amplifier. The LT1227 is LTC's fastest amplifier, with a bandwidth of over 140MHz and a slew rate greater than 1100 Volts/microsecond. This is Bill's second article for *LT*. He is the design manager for the High Speed Amplifier Product Group at Linear Technology Corp. Bill has been designing integrated circuits in the semiconductor industry for over 20 years. He is married and is the father of two teenaged sons, whose sports activities keep him glued to the playing field.

Nello Sevastopoulos describes another innovation in filter technology, the LTC1063. This is the lowest-offset switched capacitor filter currently available anywhere. Nello has worked in the semiconductor industry for 20 years, eight years as an applications manager and twelve years as an IC designer. Nello designed the MF10, the MF4, the MF8, the LTC1060, the LTC1064, and the entire line of Linear Technology's switched-capacitor filters. His outside interests include his family, travel, and Harley Davidsons (his particular mid-life crisis). He and the editor, and many other designers, look

forward to the first crop of tomatoes, olives, and feta cheese to celebrate the mid-summer tomato season.

Dennis O'Neill has been with LTC for eight years. Before that he worked at another famous brand name where he toiled for Carl Nelson. At LTC he has designed many of our bread-and-butter voltage regulators, including the LT1083, LT1084, LT1085, LT1086, and LT1054. He also designed the LT1241 series of PWM controllers, the LT1123, and the new LT1121. Dennis' interests include bicycling, photography, cooking, and the infinite remodeling of his house.

Brian Huffman has been an Applications Engineer at LTC for five years. Before that he designed a ground-fault interrupter and did device modeling for another company. Brian has been completely immersed in the SwitcherCAD software for the past year. He may be able to recite spreadsheet equations in his sleep. His outside interests include country western dancing and being a "thrill junkie." It's not unusual to find Brian at "The Saddle Rack" on Tuesdays or climbing inside caves (spelunking) on weekends.

Jim Williams needs no introduction to these pages. He has been by far the most significant author of LTC Application Notes, Design Notes and articles. Jim has been with LTC for eight years. His article on backlights is "enlightening" both from a technical perspective and for the reason that this is a hot topic these days. Jim's outside interests include his son, whose outgrown shoes continue to accumulate in Williams' office, and antique scientific instruments (what a combo!).

Dave Dwelley, the baby of the Integrated Circuit Design Group, worked in sonar for two years before being hired by Linear Technology as a Field Applications Engineer. Dave actually got a close up view of a relative of the giant squid that Captain Nemo saw (in *20,000 Leagues Under the Sea*) when he got to ride in a submarine to test his circuits. Dave has been designing CMOS zero-offset amplifiers since he moved from being an FAE to being an IC designer. His outside interests include a 1959 Chevy (not Chebyshev) Impala that he is restoring, famous writers school, mountain bike riding, and preparing to restore his very own house. **LT**

Illumination Circuitry for Liquid Crystal Displays

by Jim Williams

Current-generation portable computers and instruments employ back-lit liquid crystal displays (LCDs). Cold-cathode fluorescent lamps (CCFLs) provide the highest available efficiency for backlighting the display. These lamps operate on high-voltage AC and therefore require efficient high-voltage DC-AC converters. In addition to providing high efficiency, converters used with CCFLs should deliver the lamp drive in the form of a sine wave. This is desirable to minimize RF emissions, which can cause interference with other devices and degrade overall operating efficiency. The circuit should also permit lamp-intensity control from zero to full brightness with no hysteresis or "pop-on."

The LCD also requires a bias supply for contrast control. The supply's negative output should be regulated and should be variable over a considerable range.

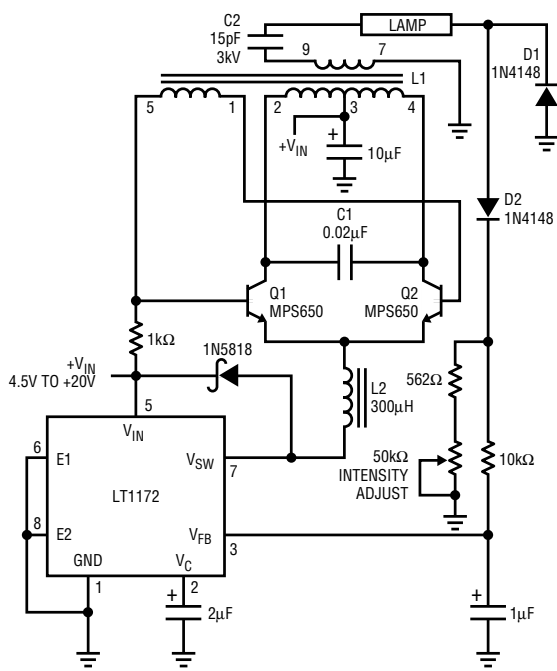
Because of their small size and battery-powered operation, LCD-equipped devices require low component count and high efficiency. Size constraints place severe limitations on circuit architecture, and long battery life is usually a priority. Laptop and hand-held portable computers are excellent examples. In these applications, the CCFL and its power supply are responsible for almost 50% of the battery drain. Additionally, these components, including the PC board and all hardware, must usually fit within the LCD enclosure, with a height restriction of 0.25".

CCFL Power Supplies

Any discussion of CCFL power supplies must consider lamp characteristics. These lamps are difficult loads to drive, particularly for a switching regulator. They have a "negative resistance" characteristic; the starting voltage is significantly higher than the operating voltage. Typically, the starting voltage is about 600 volts, although higher and lower voltage bulbs are common. Operating voltage is usually 300-400 volts, although other bulbs may require different potentials. Bulb size or length does not necessarily correlate to break-down voltage. The bulbs will operate from DC, but migration effects within the bulb will quickly damage it. Hence, the waveform must be AC with no DC content.

Bulb operating frequencies are typically 20 to 100kHz, and a sine-like waveform is preferred. The sine-like drive has low harmonic content, which minimizes RF emissions that can cause interference and efficiency degradation.

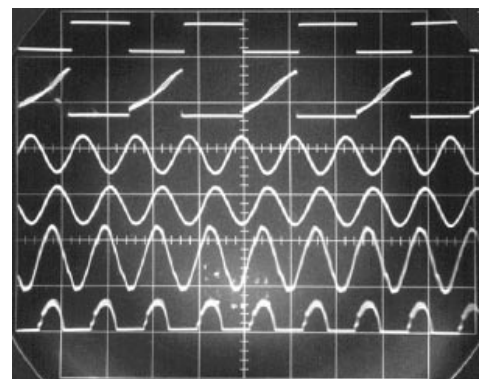
Figure 1's circuit meets CCFL-drive requirements. Efficiency can be as high as 78% with an input voltage range of 4.5V-20V. 82% efficiency is possible if the LT1172 is driven from a low voltage (3-5V) source. Additionally, lamp intensity is continuously and smoothly variable from zero to full



C1 = MUST BE A LOW LOSS CAPACITOR. METALIZED POLYCARB WIMA FKP2 (GERMAN) RECOMMENDED.
 L1 = SUMIDA-6345-020 OR COILTRONICS-CTX110092-1. PIN NUMBERS SHOWN FOR COILTRONICS UNIT
 L2 = COILTRONICS-CTX300-4
 Q1, Q2 = AS SHOWN OR BCP 56 (PHILIPS SO PACKAGE)
DO NOT SUBSTITUTE COMPONENTS
 SUMIDA (708) 956-0666
 COILTRONICS (305) 781-8900

Figure 1. Cold-cathode fluorescent lamp power supply

A = 20V/DIV
 B = 0.4V/DIV
 C = 20V/DIV
 D = 20V/DIV
 E = 1000V/DIV
 F = 5V/DIV



A AND B HORIZ = 10μs/DIV
 C THRU F HORIZ = 20μs/DIV
 TRIGGERS FULLY INDEPENDENT

Figure 2. CCFL power supply waveforms

intensity. When power is applied, the LT1172 switching regulator's feedback pin is below the device's internal 1.23V reference, resulting in full duty-cycle modulation at the V_{SW} pin (trace A, Figure 2). L2 conducts current (trace B), which flows from L1's center tap, through the transistors, into L2. L2's current is deposited in switched fashion to ground by the regulator's action.

L1 and the transistors comprise a current-driven, Royer-class converter, which oscillates at a frequency determined primarily by L1's characteristics (including its load) and the 0.02 μ F capacitor. LT1172 driven L2 sets the magnitude of the Q1-Q2 tail current, and hence L1's drive level. The 1N5818 diode maintains L2's current flow when the LT1172 is off. The LT1172's 100kHz clock rate is asynchronous with respect to the push-pull converter's (60kHz) rate, accounting for trace B's waveform thickening.

The 0.02 μ F capacitor combines with L1's characteristics to produce sine wave voltage drive at the Q1 and Q2 collectors (traces C and D, respectively). L1 furnishes voltage step-up, and about 1400V_{P-P} appears at its secondary (trace E). Current flows through the 15pF capacitor into the

lamp. On negative waveform cycles, the lamp's current is steered to ground via D1. Positive waveform cycles are directed, via D2, to the ground referred 562 Ω -50k Ω potentiometer chain. The positive half-sine appearing across these resistors (trace F) represents 1/2 the lamp current. This signal is filtered by the 10k Ω -1 μ F pair and presented to the LT1172's feedback pin. This connection closes a control loop which regulates lamp current. The 2 μ F capacitor at the LT1172's V_C pin provides stable loop compensation. The loop forces the LT1172 to switch-mode modulate L2's average current to whatever value is required to maintain a constant current in the lamp. The constant current's value, and hence lamp intensity, can be varied with the potentiometer. The constant current drive allows full 0-100% intensity control with no lamp dead zones or "pop-on" at low intensities. Additionally, lamp life is enhanced because current cannot increase as the lamp ages.

Several points should be kept in mind when observing this circuit's operation. L1's high-voltage secondary can only be monitored with a wide-band, high voltage probe fully specified for this type of measurement. The vast

A Related Circuit: Helium Neon Laser Driver

The high-voltage-compliance current-loop approach of the CCFL power supply is suitable for other applications as well. Current sensing permits precise, high-efficiency control of a wide variety of difficult loads. A HeNe laser is such a load. Lasers are negative impedances operating at very high voltages. Typically, they require from 6 to 10kV to start, with an operating voltage in the 1 to 3kV range. Simple high-voltage drive does not provide this. The circuit in Figure A1 adapts the CCFL circuitry to control a laser. Both tube-current stability and electrical efficiency are improved over the more conventional voltage-mode drive.

Q1 and Q2 combine with L2 to form a self-oscillating DC-DC converter. No resonating capacitor is used in this design. The DC-DC converter operates in square-wave mode, although resonant operation could be used to minimize harmonics. The converter's high-voltage output is multiplied by the D1-D2 voltage doubler and applied to the laser via the 50k Ω ballast resistor. This resistor is required to isolate the laser from the 0.1 μ F output capacitor. Laser current flow is converted to a voltage by the 340 Ω shunt and is fed back to the LT1074 step-down switching regulator. D3, L1, and C1 smooth the LT1074's pulsed output to DC and drive the DC-DC converter. This completes a loop that controls the laser current. The components at the LT1074's V_C pin stabilize the loop. The frequency compensation is arranged so transients (e.g., turn-on) will not cause a brief lowering of the tube current. Such an event will cause laser impedance to rise dramatically, extinguishing the laser.

L2 and the voltage doubler supply a maximum of about 3.5kV, not enough to start laser conduction. A1, L3, and associated components provide a high voltage start-up.

continued on page 7

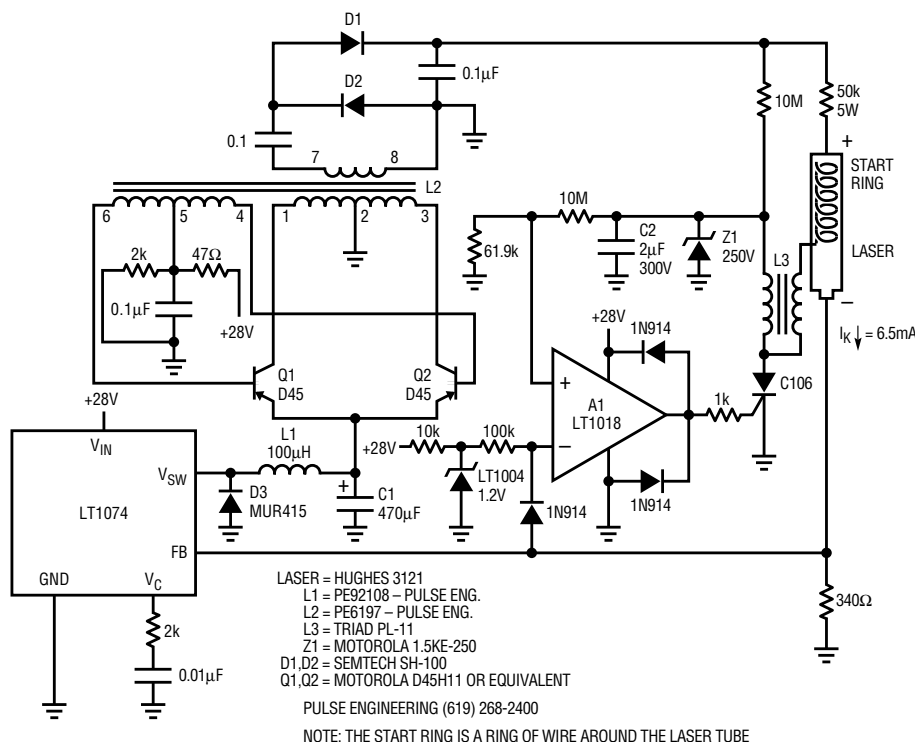


Figure A1. Laser-driver power supply

majority of oscilloscope probes will break down and fail if used for this measurement.¹ Tektronix type P-6009 (acceptable) or types P6013A and P6015 (preferred) probes must be used to read L1's output.

Another consideration involves observing waveforms. The LT1172's switching frequency is completely asynchronous from the Q1-Q2 Royer converter's switching. As such, most oscilloscopes cannot simultaneously trigger and display all the circuit's waveforms. Figure 2 was obtained using a dual-beam oscilloscope (Tektronix 556). LT1172-related traces A and B are triggered on one beam, while the remaining traces are triggered on the other beam. Single-beam instruments with alternate sweep and trigger switching (e.g., Tektronix 547) can also be used, but are less versatile and are restricted to four traces.

Obtaining and verifying high efficiency requires some diligence.² The optimum efficiency values given for C1 and C2 are typical, and will vary for specific types of lamps. C1 sets the circuit's resonance point, which varies to some extent with the lamp's characteristic. C2 ballasts the lamp, effectively buffering its negative-resistance characteristic. Small values of C2 provide the most load isolation, but require relatively large transformer output voltage for loop closure. Large C2 values minimize transformer output voltage, but degrade load buffering. Also, C1's "best" value depends somewhat on the type of lamp used. Both C1 and C2 must be selected for given lamp types. Some interaction occurs, but general guidelines are possible.

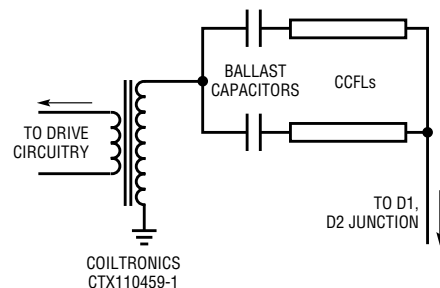


Figure 3. Separate ballast capacitors allow one transformer to drive two tubes

Typical values for C1 are 0.01 to 0.047μF. C2 usually ends up in the 10pF-47pF range. C1 must be a low-loss capacitor; substitution for the WIMA device is not recommended. A poor-quality dielectric for C1 can easily degrade efficiency by 10%. C1 and C2 are selected by trying different values for each and iterating towards minimum supply input current. During this procedure, ensure that loop closure is maintained by monitoring the LT1172's feedback pin, which should be at 1.23 volts. Several trials usually produce the optimum C1 and C2 values. Note that the highest efficiencies are not necessarily associated with the most aesthetically pleasing waveshapes, particularly at Q1, Q2, and the output.

Other issues influencing efficiency include bulb wire length and energy leakage from the bulb. The high-voltage side of the bulb should have the smallest practical lead length. Excessive length results in radiative losses, which can easily reach 3% for a three-inch wire. Similarly, no metal should contact or be in close proximity to the bulb. This prevents energy leakage, which can exceed 10%. (These considerations should be made with knowledge of other LCD issues. See Appendix B of AN49, "Mechanical Design Considerations for Liquid Crystal Displays.")

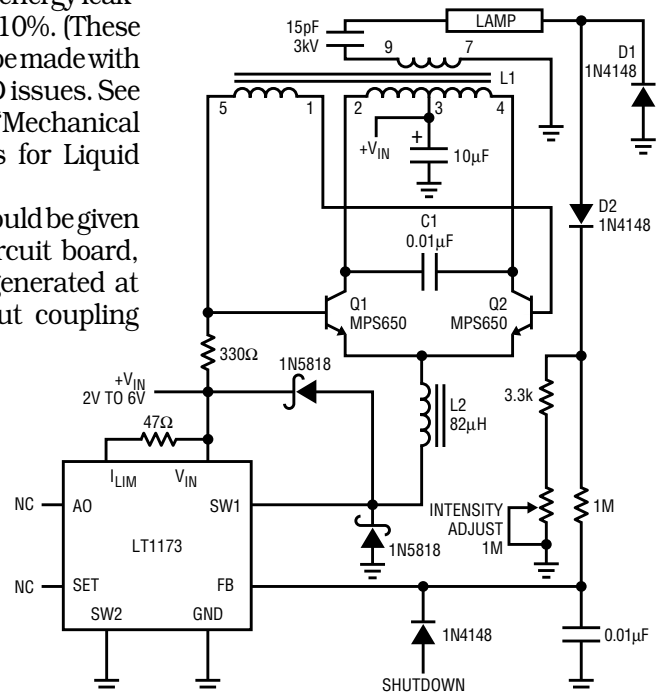
Special attention should be given to the layout of the circuit board, since high voltage is generated at the output. The output coupling capacitor must be carefully located to minimize leakage paths on the circuit board. A slot in the board will further minimize leakage. Such leakage can permit current flow outside the feedback loop, wasting power. In the worst case, long term contamination build-up can increase leakage inside the loop, resulting in starved lamp drive or

destructive arcing. To minimize leakage, it is good practice to break the silk-screen line which outlines transformer T1. This prevents leakage from the high voltage secondary to the primary. Another technique for minimizing leakage is to evaluate and specify the silk-screen ink for its ability to withstand high voltages.

Once these procedures have been followed, efficiency can be measured. Efficiency may be measured by determining bulb current and voltage. Measuring current involves measuring RMS voltage across the 562Ω resistor (short the potentiometer). The bulb current is

$$I_{BULB} = (E/R) \times 2$$

Multiplication by two is necessary because the diode steering dumps the current to ground on negative cycles. Bulb RMS voltage is measured at the bulb with a properly compensated high-voltage probe. Multiplying these two results gives power in watts, which may be compared to the DC-input-supply E x I product. In practice, the lamp's current and voltage contain



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- PIN NUMBERS SHOWN FOR COILTRONICS UNIT
- L2 = TOKO 262LYF-0091K
- DO NOT SUBSTITUTE COMPONENTS

Figure 4. Low-current CCFL power supply

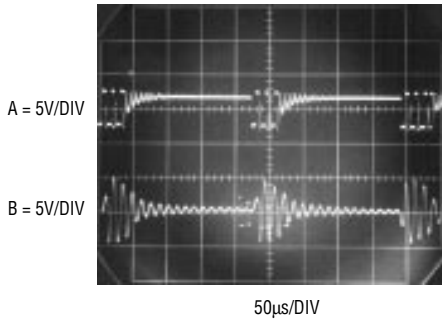


Figure 5. Low-current CCFL power-supply waveforms

small out-of-phase components, but their error contribution is negligible.

Both the current and voltage measurements require a wide-band true-RMS voltmeter. The meter must employ a thermal-type RMS converter—the more common logarithmic-computing type instruments are inappropriate because their bandwidths are too low. (See AN49 for a discussion of the operational theory and limitations of various AC voltmeters.)

The previously recommended high voltage probes are designed to see a 1MΩ, 15–22pF oscilloscope input. The RMS voltmeters have a 10MΩ input. This difference necessitates an impedance matching network between the probe and the voltmeter. Details of this and other efficiency measurement issues appear in Appendix C of

AN49, “Achieving Meaningful Efficiency Measurements.”

Two-Tube Designs

Some displays require two tubes instead of the more popular single-tube approach. These two-tube designs usually require more power. Accommodating two tubes involves separate ballast capacitors (see Figure 3), but circuit operation is similar. Higher power may require a different transformer rating. Figure 1’s transformer can supply 7.5mA, although more current is possible with appropriate transformer types. For reference, an 11mA-capability transformer appears in Figure 3.

Low-Power CCFL Supply

Figure 4 represents the other extreme. This design is optimized for single-tube operation at very low currents. Figure 1’s circuit typically drives 5mA maximum, but this design tops out at 1mA. This circuit maintains control down to tube currents of 1µA, a very dim light. It is intended for applications where the longest possible battery life is desired. Maintaining high efficiency at low tube currents requires modifying the basic design.

Achieving high efficiency at low operating currents requires lowering Figure 1’s quiescent power drain. To do this, the LT1172, a pulse-width-modulator-based device, is replaced

with an LT1173. The LT1173 is a burst-mode-type regulator. When this device’s feedback pin is too low, it delivers a burst of output current pulses, putting energy into the transformer and restoring the feedback point. The regulator maintains control by appropriately modulating the burst duty cycle. The ground-referred diode at the SW1 pin prevents substrate turn-on due to excessive L2 undershoot. During the off periods, the regulator is essentially shut down. This type of operation limits available output power, but cuts quiescent current losses. In contrast, Figure 1’s LT1172 pulse-width-modulator-type regulator maintains “housekeeping” current between cycles. This results in more available output power but higher quiescent currents. Figure 5 shows operating waveforms for the circuit in Figure 4. When the regulator comes on (trace A) it delivers bursts of output current to the L1–Q1–Q2 high-voltage converter. The converter responds with bursts of ringing at its resonant frequency. The circuit’s loop operation is similar to that of Figure 1.³

LCD Bias Supplies

LCDs also require a bias supply for contrast control. The supply’s variable negative output permits adjustment of display contrast. Relatively little power is involved, easing RF radiation and efficiency requirements. The logic sections of display drivers operate from single 5V supplies, but the actual driver outputs swing between +5V and a negative bias potential. Varying this bias varies the contrast of the display.

An LCD bias generator, developed by Steve Pietkiewicz of LTC, is shown in Figure 6. In this circuit U1 is an LT1173 micropower DC-DC converter. The 3V input is converted to +24V by U1’s switch, L1, D1, and C1. The switch pin (SW1) then drives a charge pump composed of C2, C3, D2, and D3 to generate -24V. Line regulation is less than 0.2% from 3.3V to 2.0V inputs. Although load regulation suffers somewhat because the -24V output is not directly regulated, it still measures 2% from a 1mA to 7mA load.

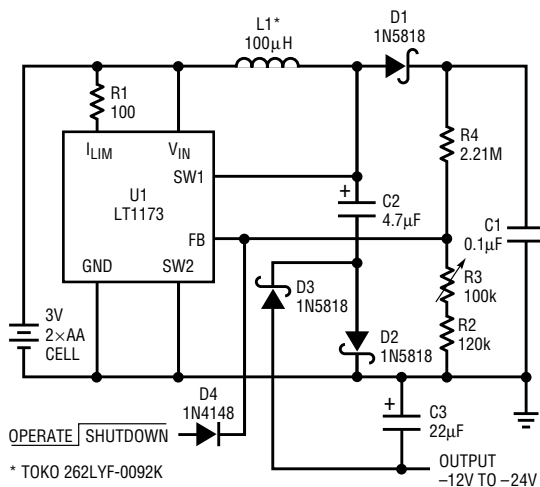


Figure 6. LCD bias generator (3V to -12 to -24V)

The circuit will deliver 7mA from a 2.0V input at 75% efficiency.

If greater output power is required, Figure 6's circuit can be driven from a +5V source. R1 should be changed to 47Ω and C3 to 47μF. With a 5V input, 40mA is available at 75% efficiency. Shutdown is accomplished by bringing the anode of D4 to a logic high, forcing the feedback pin of U1 to go above the internal 1.25V reference voltage. Shutdown current is 110μA from the input source and 36μA from the shutdown signal.

Another interesting modification of a boost converter that can provide negative bias from a 5V supply is shown in Figure 7. The converter, developed by Jon Dutra of LTC, is half switcher and half charge pump. The charge pump (C1, C2, D2, and D3) is driven by the flying node at V_{SW} . The output is variable from -10 to -30V, providing contrast control for the display.

On low-voltage supplies (6V or less) V_{IN} and V_{BATT} can be tied together. With higher battery voltages, high efficiency is obtained by running the LT1172 V_{IN} pin from 5V. Shutting off the 5V supply will automatically turn off the LT1172. The maximum value for V_{BATT} is equal to the negative output plus 1V. Also, the difference between V_{BATT} and V_{IN} must not exceed 16V. R1, R2, and R3 are made large to minimize battery drain in shutdown, since they are permanently connected to the battery via L1 and D1. Efficiency is about 80% at $I_{OUT} = 25mA$.

Laser Driver, continued from page 4

When power is applied, laser current is zero and A1's output goes to ground. The high-voltage converter supplies full output (3.5kV), but the laser does not start. Under these conditions, the C106 SCR is off and C2 charges. A divided-down portion of C2's voltage biases A1's positive input. When C2 reaches about 200V, A1's output goes high, triggering the SCR. This dumps C2's charge through L3 to ground. L3's output, a very-high-voltage spike, ionizes the

laser, driving it into conduction. Laser impedance drops and the main current control loop begins behaving as described above. The presence of voltage across the 340Ω shunt causes A1's output to go low, preventing further SCR conduction. Zener clamp Z1 limits C2's voltage under these conditions. If the laser fails to start, the cycle will repeat until start-up occurs. Electrical efficiency for this circuit is about 75% for inputs from 22 to 35V.

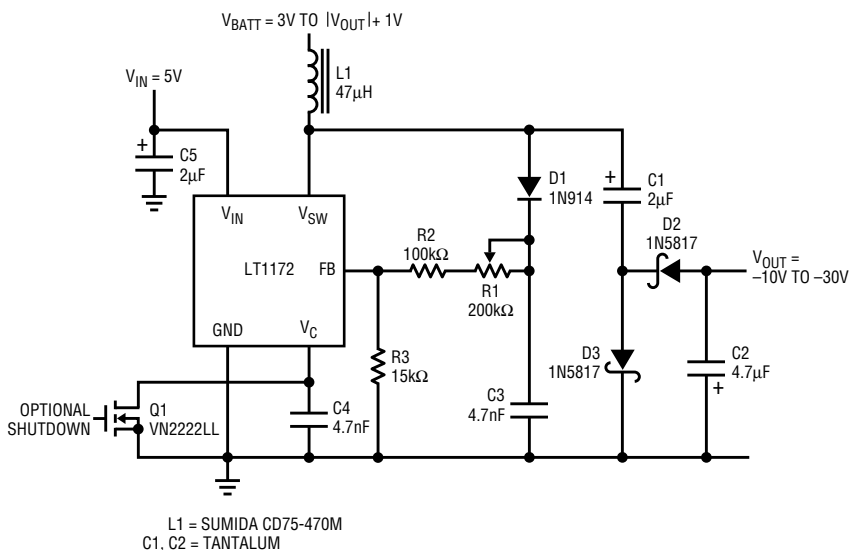


Figure 7. 5V LCD bias generator (5V to -10 to -30V)

This article was extracted from LTC Application Note 49 available in August. For more details, and additional information, please request AN49 on the response card or call the 800 number listed on the last page of this magazine.

¹ Don't say we didn't warn you!

² The term "efficiency" as used here refers to electrical efficiency. In fact, the ultimate concern centers around the efficient conversion of power-supply energy into light. Unfortunately, lamp types show considerable variation in their current-to-light conversion efficiency. Similarly, the emitted light for a given current varies over the life of any particular lamp. Hence, this article treats "efficiency" on an electrical basis: as the ratio of power removed from the primary supply to the power delivered to the lamp. When a lamp has been selected, this ratio can be measured with a photometer.

³ The discontinuous energy delivery to the loop causes substantial jitter in the burst-repetition rate, although the high-voltage section maintains resonance. Unfortunately, circuit operation is in the "chop" region of most oscilloscopes, precluding a detailed display. "Alternate" operation causes waveform-phasing errors, also producing an inaccurate display. Hence, waveform observation requires special techniques. Figure 5 was taken with a dual-beam instrument (Tektronix 556) with both beams slaved to one time base. Single-sweep triggering eliminated jitter artifacts. Most 'scopes, whether analog or digital, will have trouble reproducing this display.

The LTC1153 Electronic Circuit Breaker

by Tim Skovmand

The LTC1153 electronic circuit breaker is designed to work with a low-cost, N-channel power MOSFET to interrupt power to a sensitive electronic load in the event of an over-current condition. Under normal operating conditions, the voltage drop across the switch is extremely low, limited primarily by the $R_{DS(ON)}$ of the MOSFET switch. The breaker is tripped by an over-current condition and remains tripped for a period of time programmed by an external timing capacitor, C_T . The switch is then automatically reset and the load momentarily retried. If the load current is still too high, the switch is shutdown again. This cycle continues until the over-current condition is removed, thereby protecting the sensitive load and the power MOSFET.

The gate voltage for the high-side MOSFET N-channel switch is generated completely on-chip by a high-frequency charge pump. No external charge-pump components are required. Further, the charge-pump circuitry is designed for maximum efficiency with an operating supply current of only $85\mu A$ when powered from a 5V supply. Supply current drops to $8\mu A$ when the circuit is switched to the standby mode (input low).

Programmable Timing

The trip current, trip-delay time, and auto-reset period are programmable over a wide range to accommodate a variety of load impedances. Figure 1 demonstrates how the LTC1153 is used in a typical circuit-breaker application. The DC trip current is set by a small-valued resistor, R_{SEN} , in series with the drain lead, which drops 100mV when the current limit is reached. In the circuit of Figure 1, the DC trip current is set at 1A ($R_{SEN} = 0.1\Omega$).

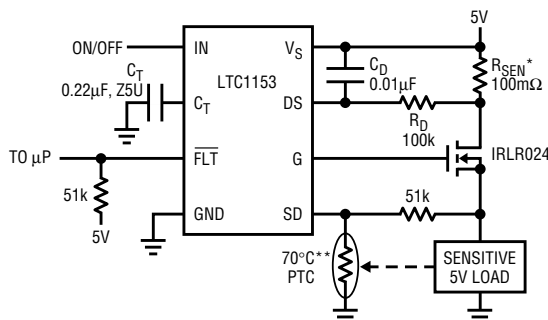
The trip-delay time is set by the two delay components, R_D and C_D , which establish an RC time constant in series with the drain sense resistor, producing a trip delay which is shorter for increasing breaker current (similar to that of a mechanical circuit breaker). Figure 2 is a graph of the trip-delay time versus the circuit-breaker current for a 1ms RC time constant. Note that the trip time is 0.63ms at 2A, but falls to $55\mu s$ at 20A. This characteristic ensures that the load and the MOSFET switch are protected against a wide range of overload conditions.

Auto-Reset Function

The auto-reset time is typically set in the range of 10s of milliseconds to a few seconds by selecting the timing capacitor, C_T . The auto-reset period for the circuit in Figure 1 is 200ms, i.e., the circuit breaker is automatically reset (retried) every 200ms until the overload condition is removed. The switch then returns to normal operation and continues to power the load until another fault condition is encountered.

An open-drain fault output is provided to warn the host microprocessor whenever the circuit breaker has been tripped. The microprocessor can either wait for the auto-reset function to reset the load, or shut the switch OFF after a fixed number of retries.

The shutdown input interfaces directly with a PTC thermistor to sense over-temperature conditions and trip the circuit breaker whenever the load temperature or the MOSFET-switch temperature exceeds a safe level. The thermistor shown in Figure 1 trips the circuit breaker when the load temperature exceeds approximately $70^\circ C$. The breaker is then automatically reset when the load temperature falls back to a safe level. A small amount of



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Figure 1. LTC1153 5V/1A circuit breaker with thermal shutdown

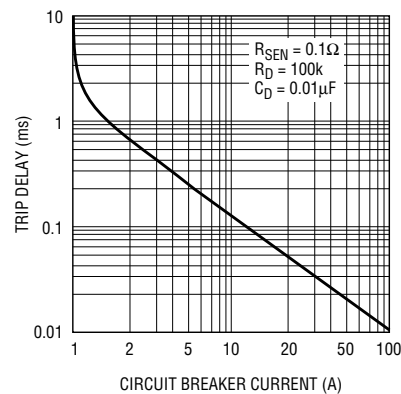


Figure 2. Trip-delay time versus circuit-breaker current (1ms RC time constant) for circuit of Figure 1

hysteresis is provided to ensure clean switching. Standby efficiency is maintained by powering the PTC thermistor from the switch output, as shown in Figure 1.

Surface-Mount Packaging

All the components shown in Figure 1, including the LTC1153 and the drain sense resistor, are available in surface-mount packaging and, therefore, consume a very small amount of printed circuit board space. The total power dissipation of this circuit is less than 100mW when powering a nominal 5V, 0.5A load. This efficiency is due in part to the extremely low drop across the MOSFET switch and the drain-sense resistor (50mV each), and by the extremely low quiescent current required by the LTC1153 charge pump and protection circuitry.

Additionally, power dissipation does not rise appreciably during a current overload condition. This is because the switch is only engaged for a very short period of time (<50µs) every 200ms, i.e., an extremely low duty cycle. This ensures that the MOSFET is never required to operate in a high

dissipative mode, even with the output shorted.

Figure 3 is a timing diagram with some typical waveforms generated by the circuit breaker in the normal operating mode, the overload mode, and the shutdown mode. Note that the timing capacitor, C_T , is held low until a fault condition is encountered and then charged by a small internal current source until the threshold is reached and the switch turned back ON. This cycle continues until the overload is removed and the switch returns to normal operation.

SCSI Termination Power

The termination power for a SCSI interface is protected to avoid damaging the drivers, the connectors, and the printed circuit board in the event of the connector or the interconnecting cable being shorted. This protection is provided by the circuit breaker circuit shown in Figure 4. With the component values shown, the DC current is limited to 1A with a trip-delay time constant of 10ms. The breaker will trip if the cable or connector is accidentally shorted and will retry every second until the short

circuit is removed. The termination power will then return to normal and the interface will be reconnected. The microprocessor can continuously monitor the status of the termination power via the fault flag output of the LTC1153 and can take further action if the fault condition persists.

DC Motor Protection

A 5V DC motor can be powered and protected using the circuit shown in Figure 5. The DC current delivered to the motor is limited to 5A and a rather long trip delay is used to ensure that the motor starts properly. The motor temperature is also continuously monitored and the breaker is tripped if the motor temperature exceeds 70°C. The fault output of the LTC1153 informs the host microprocessor whenever the breaker is tripped. The microprocessor can disable the motor if a set number of faults occur or it can initiate a retry after a much longer period of time has elapsed. A rectifier diode across the motor returns the motor current to ground and restricts the output of the switch to less than 1V below ground. \blacktriangleleft

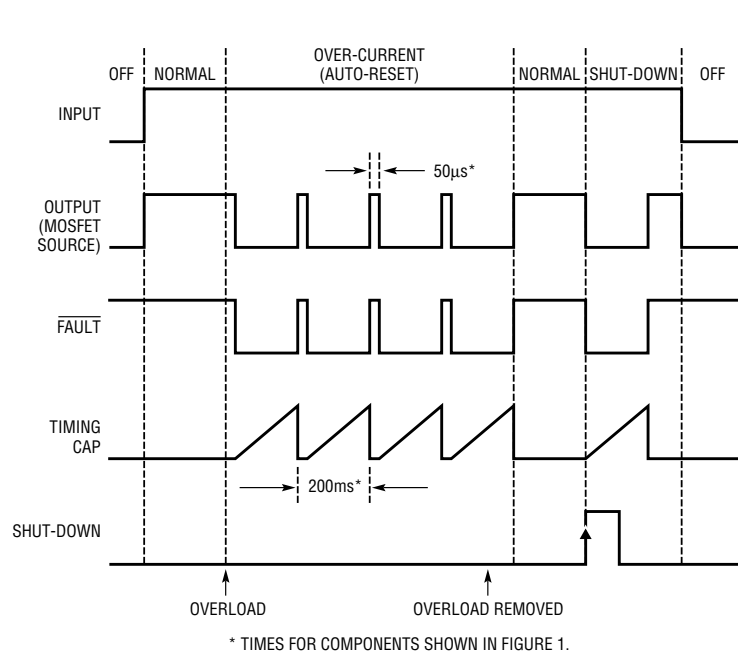


Figure 3. LTC1153 typical timing diagram

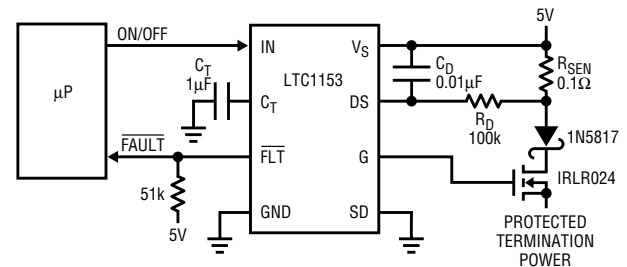


Figure 4. SCSI termination power circuitry

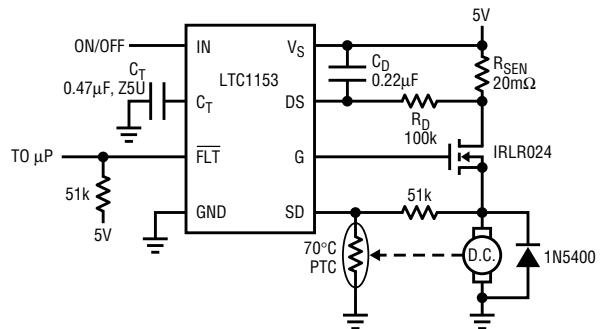


Figure 5. DC motor driver with over-current and over-temperature protection

The LTC1063 Low-Offset, Clock Tunable, Fifth-Order Butterworth Lowpass Filter

by Nello Sevastopoulos

The LTC1063 is the first monolithic lowpass filter simultaneously offering outstanding DC and AC characteristics, internal or external clock tunability, cutoff frequencies to 50kHz, 1 millivolt typical output DC offset, and a dynamic range in excess of twelve bits over a decade of input-voltage range. The LTC1063 approximates a five-pole Butterworth polynomial. A five-pole linear phase version of this filter will be offered soon.

AC Capabilities

The unique internal architecture of the filter allows outstanding amplitude matching from device to device. Typical matching ranges from 0.01dB at 25% of the filter passband to 0.05dB at 50% of the filter passband. This capability is important for multi-channel data-acquisition systems, where channel-to-channel matching is critical.

An external or internal clock programs the filter's cutoff frequency. The clock-to-filter cutoff-frequency ratio is set to 100:1. In the absence of an external clock, the LTC1063's internal precision oscillator can be used. An external resistor and capacitor set the LTC1063's internal clock frequency (Figure 1). Note that unlike the popular DC-accurate LTC1062 Butterworth filter, the internal clock frequency tolerance of the LTC1063 does not affect

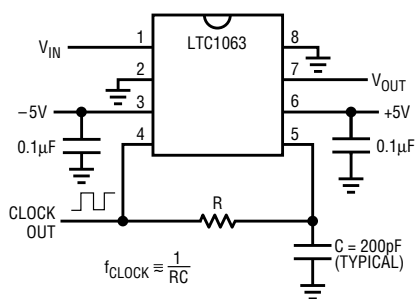


Figure 1. Setting the LTC1063 internal clock with an external R,C

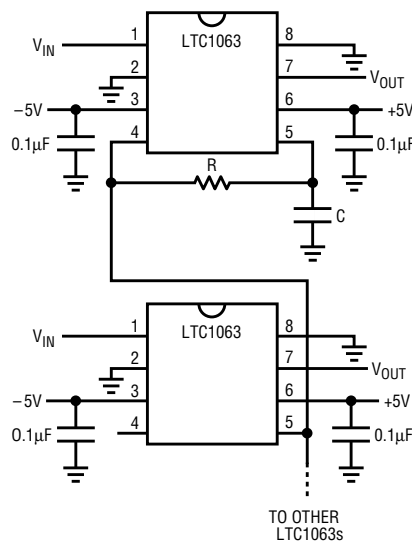


Figure 2. Synchronizing multiple LTC1063s

the flatness of its passband. The internal oscillator output is brought out at pin 4 so that it can be used as a synchronized master clock to drive other LTC1063s. Ten or more LTC1063s may be locked together to a single LTC1063 clock output (see Figure 2).

The LTC1063 has both low noise and very low clock feedthrough. The wide-band noise and clock feedthrough are both measured with the input of the filter grounded, as illustrated in Figure 3. The wide-band noise is the integral of the noise spectral density; it is usually expressed in μV_{RMS} . The wide-band noise is virtually independent of filter cutoff frequency. The LTC1063 has an excellent noise specification of $90\mu V_{RMS}$. This number is clock-frequency and power-supply independent.

Some users prefer to describe wide-band noise in $dBV/(Hz)^{1/2}$. These designers limit their measurements to noise in the filter's passband. In this case the filter's cutoff frequency must be known. The method for cal-

culating noise in $dBV/(Hz)^{1/2}$ is illustrated in Figure 4. Remember that the area in the rectangle is an approximation of the measured noise contribution and must be treated as such. Also note that an output buffer is not necessary when measuring noise and clock feedthrough, but it is good practice to use it when evaluating the filter's dynamic range.

Dynamic range

The LTC1063's AC design is based on optimum dynamic range rather than just wide-band noise. Dynamic-range measurements take into account the device's total harmonic distortion. Figure 5a shows the typical connection for dynamic range measurement. An inverting buffer is preferred over a unity gain follower. Large-input common-mode signals can severely degrade the distortion performance of a non-inverting buffer. It is also important to make sure the undistorted op-amp swing is equal to or better than that of the filter. Figure 5b shows the device's operating distortion plus noise versus input-signal amplitude measured with a standard 1kHz pure sine wave input. The performance improves with increased power supply voltage. This improved performance at higher power supply

The LTC1063's Unique Features

- Trivial to use
- Precision internal clock
- S/N ratio ≥ 90 dB at 0.02% THD level
- Better than 80dB noise+THD, $0.5V_{RMS} < V_{IN} < 2.5V_{RMS}$
- $V_{OS} \leq 1$ millivolt (typical)
- Clock tunable without V_{OS} change
- Excellent low-frequency amplitude matching ± 0.01 dB at $f_{IN} = 0.2f_C$

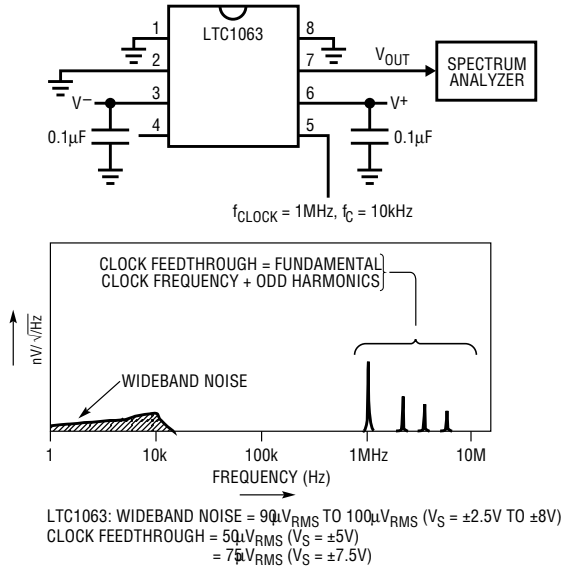


Figure 3. Measuring LTC1063 noise and spurious signals

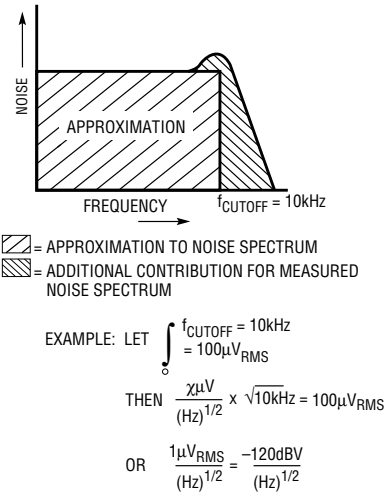


Figure 4. Calculating wideband noise in dBV/(Hz)^{1/2}

voltages is possible because the LTC1063's noise does not increase with higher supply voltages.

Figure 5b illustrates how the filter can handle inputs to $4V_{RMS}$ ($11.2V_{P-P}$) with less than 0.02% THD. At this input level, the dynamic range is only limited by distortion and not by wideband noise. The signal-to-noise ratio at $4V_{RMS}$ input is 93dB. Optimum signal-to-noise plus distortion according to Figure 5b is 83dB, yet a com-

fortable 80dB (0.01%) is achieved for input levels between $1V_{RMS}$ and $2.4V_{RMS}$.

DC Performance

The LTC1063's output DC offset voltage is optimized for $\pm 5V$ supply applications. Output offset is low enough to compete with discrete-type R,C active filters using low-offset op amps. These discrete filters can provide only one cutoff frequency.

Power-supply decoupling and PC-board layout are extremely critical to achieve a constant output offset over a wide range of clock frequencies. Ideally the power-supply pins should be decoupled with good quality ceramic capacitors exhibiting low AC impedance over a wide range of frequencies. If a single capacitor cannot be used, two or more capacitors of different values should be connected in parallel.

continued on page 17

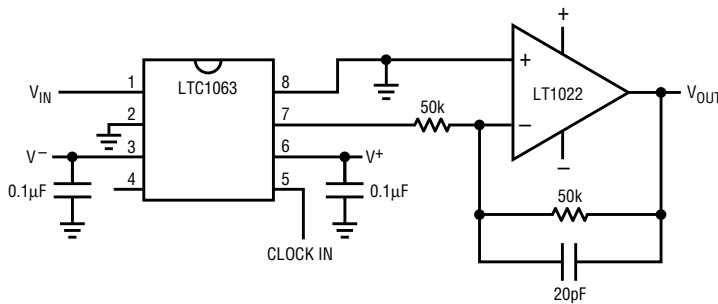


Figure 5a. Typical connection for measuring Distortion + Noise and Signal to THD + Noise ratio

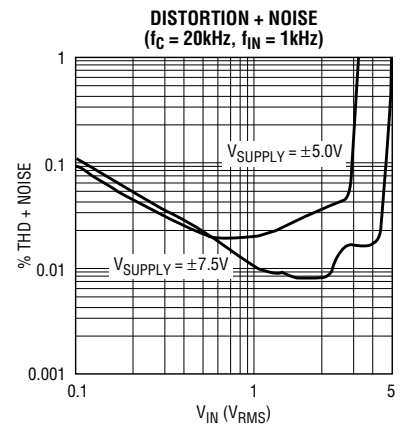


Figure 5b. Plot of Distortion + Noise vs V_{IN}

The LTC1047: New Dual Micropower Zero-Drift Op Amp

by Dave "wish I wrote movie scripts" Dwelley

It's 8:00 am at ACME Instrumentation and Handgun, Inc. I'm sittin' here, feet up, suckin' on a cup of java, tryin' to chase away the excesses of last night. Gotta stop hanging out with Johnny... But enough moaning. Let's talk about me. I'm Rex Linear, manager of analog design. You can call me Mr. Linear. Nice digs, eh? These corner offices give you a real panoramic view of the parking lot. Let me tell you how I got here...

Big Trouble in Silicon Valley

It was a dark and stormy night. I was holed up in the lab, trying to tune an 8th-order elliptic filter made from OP27s and old chewing gum. I'd just got the first notch to stop oscillating when the boss came in. Apparently we're competing with Very Large Corporation for a new contract from Smoking Gun Security, Inc. He handed me a strange looking transducer with a differential output. He tells me it can sense body heat at 100 yards, but it needs a high-input-impedance instrumentation amplifier with 16-bit DC performance. Not only that, but the whole ball o' wax has to run on batteries. The goons at Very Large Corp. say they've already perpetrated a working prototype, so I'd better get right on it or he'll have me scrubbing toilets until I retire. Sixteen bits DC? Running on batteries? I often wonder how he got to be the boss; maybe it's his sparkling interpersonal skills...

LTC Mag Saves the Day

Now, normally, I would have started reading up on porcelain cleaners, but that night I was up late reading the new issue of the LTC mag with my pal, Johnny. Johnny Walker Black Label. That's Mr. Walker to you, pal. I was looking for the latest Jim Williams article when I stumbled across this story: "LTC1047: New Dual Micropower

Zero-Drift Op Amp" by some guy named Dooley. As I glanced through it, the visions of endless plumbing fixtures started to fade from my fogged brain. I was just getting to the good part when Johnny hit me in the head. Still hurts...

Between aspirins the next day, I did a little checking around, and found out some more about this part they call LTC1047. It's a zero-drift (all right, chopper-stabilized) dual op amp, based on the same architecture as the popular LTC1050/51 parts. It uses internal sample-and-hold capacitors, unlike some competing chopper amps which require external capacitors. Because the 1047 requires no external parts, it fits the standard dual op-amp pinout, and comes in a standard 8-pin plastic DIP or a 16-pin 300mil SO package (those caps make the die way too big for the SO8). It's optimized for low supply current by squeezing each internal section until it starts to scream, then backing off a little. The result is 10 μ V V_{OS} with 50nV/ $^{\circ}$ C drift, 105dB minimum CMRR and PSRR, 120dB minimum DC gain, and 200kHz gain-bandwidth product, all at 60 μ A/side, typical. The only trade-offs are front end noise and output drive, both parameters that depend heavily on supply current. Noise is 3.5 μ V_{P-P}, roughly twice that of the LTC1050. The 1047's output will sink 5mA and source 1mA, three times less than the 1050; it will swing to within 5mV of either rail with a 100k load.

LTC1047 Architecture

Internally, the 1047 uses the same architecture as the rest of the LTC chopper line, with a wide-band amplifier in parallel with a nulling amplifier (see Figure 1, over there next to the coffee stain). The nulling amp alternately zeros its own output, then corrects the wide-band amplifier. The wide-band amplifier is always actively

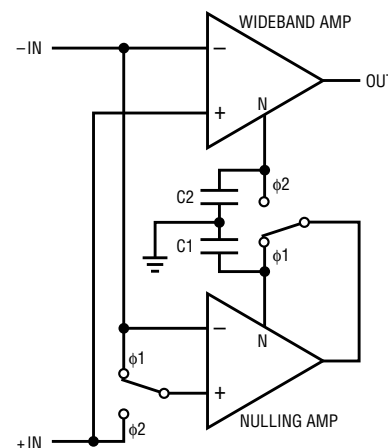


Figure 1. LTC1047 Block diagram

connected to the output and has substantial bandwidth at the internal clock frequency, allowing its feedback loop to correct most of the clock-feedthrough and aliasing errors caused by the nulling amp. As a result, the 1047 has output-clock and feedthrough levels far better than those of traditional choppers, micropower or not.

Soldering Iron Memories and Micropower Applications

I called up my bookie and put \$10 on "Starlight Lounge" to show. Then I called up the rep and had him bring by a couple of these LTC1047s, scratched out a circuit on the back of an overdue bill (Figure 2a), and gave it to my sidekick Rachel. Rachel... I remember the day when our paths first crossed. I was in the lab, sweating over a particularly nasty switching-regulator breadboard. I'd just sent another power MOSFET to the great semiconductor in the sky, and was considering calling my old pals, Smith & Wesson, to really fix this breadboard. The stench of burning rosin was thick in the air when out of nowhere she appeared, packing a 15W Radio Shack iron. She tacked a 0.22 μ F

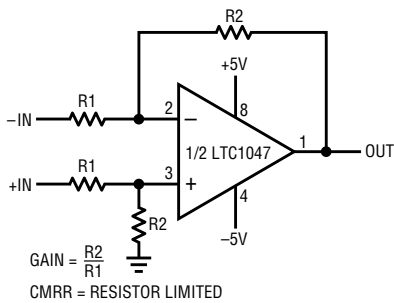


Figure 2a. Rex's IA circuit

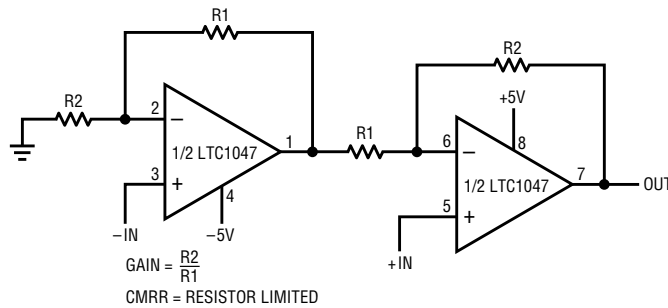


Figure 2b. Rachael's IA circuit

cap across the snubber network, and had that circuit singing like a parole violator in no time. I offered her a new Weller soldering station as a token of gratitude, but she turned me down, mumbling something like "all in a day's work." The world needs more women like her...

Anyhow, I figured she'd be either fighting noise or loading the transducer with those input resistors, but she came up with this slick IA circuit whose inputs eat only the pA-level bias current of the 1047 (Figure 2b). Not only that, it eats 50% less current than the three-amplifier configuration, and only uses one 8-pin DIP per transducer. I should pay her more...

Sampling IA—Better Specs, Less Juice

That next week, I was drinking lunch with the local distributor and my old nemesis Rocco, the government inspector. The disti-shark was telling me about an improvement to the LTC1043 switched-capacitor building block; said he's got samples of a new lower power mask set. He slipped me one when Rocco wasn't looking. I thought about it for a minute, and the lightbulb was just lighting up over my head when the waitress showed up. I ordered a screwdriver (hold the OJ) and started scratching on the napkin. Now, if I combine this 1043 with a 1047, throw in a resistor or two here... let's see... Ohm's law is $I = ZV$, no, $E = I/V$, no, that's not right...

When I got back to the office, I threw out the napkin (couldn't read it anyhow after the Rocco spilled his drink on it), and sat down at the computer. Let's see... just hook up pin 3 to node 5

and...what's this? "Unable to find bias point for transient analysis?" Damn these simulations! Gonna have to breadboard this thing.

Sampling IA Performance

I put Rachel on the case. She whipped up a breadboard that would make a Linear Technology technician jealous, and came back with the numbers (Figure 3). Numbers like 120dB CMRR at 60Hz, 10 μ V total system V_{OS} , only 60 μ A supply current for two channels with a single 5V supply, and Pittsburgh down by six in the third quarter. I took these numbers and made a couple of calls. Then I started thinking about circuits. This one uses the 1043 switched-capacitor block to create a sampling front end that gives exceptional AC common-mode rejection, as well as rail-to-rail input common mode range. The 1047 buffers the 1043's output, providing gain with minimum DC error. The 1047 also

provides rail-to-rail output swing into the system's A/D input, allowing the guys doing the digital design to use all of the A/D's bits. All this performance with less current draw than the self-discharge of the battery pack—this should earn me a few points with the guys upstairs.

The Happy Ending

Anyhow, the sensor was a big success; we beat Very Large Corporation to the market by seven months, ended up selling millions of those things, and Pittsburgh pulled it out to win in the fourth, 21-20. The boss took all the glory for that 1047 design, really rode it for a while until one of those 1047s caught him sneaking in the back door of the Pussycat Club downtown. Now I'm the boss, and Rachel's designing circuits that make those college grads at Very Large Corp. look bad. So, let me tell you about the time Johnny and me went fishing...

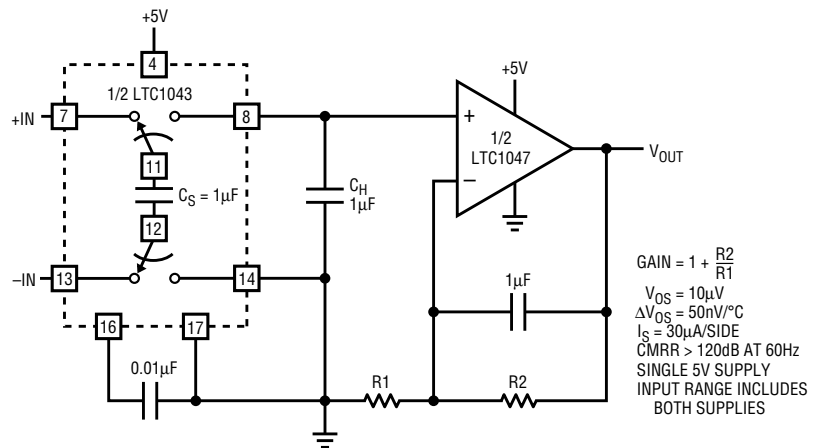


Figure 3. The final IA circuit

The LT1121 Low-Dropout Regulator

by Dennis O'Neill

Introduction

An ideal low-dropout regulator should have zero dropout voltage, zero quiescent current, and a stable, regulated output voltage for a wide range of loads. The previous architecture of choice was the PNP-transistor type low-dropout regulator supplied by many manufacturers. This architecture has many deficiencies when applied to micropower operation, ranging from minor inconveniences to major system problems. These problems include large increases in ground-pin current when the regulator approaches its dropout voltage, and the requirement of large output capacitors for frequency compensation.

A new micropower low-dropout regulator, the LT1121, provides over 150 milliamps of output current, yet operates with less than 30 microamps of quiescent current (no load). Dropout at high output currents (150mA) is only 0.4 volts. (Dropout voltage versus output current is shown in Figure 1.) Quiescent current does not rise appreciably when the device enters the dropout region. The LT1121 is available in fixed output voltages of 5V and 3.3V. The device is designed to be stable with output capacitors as low as 0.33 μ F.

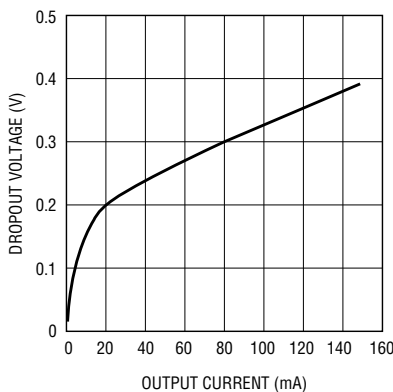


Figure 1. Dropout voltage versus output current for the LT1121

New Features

An important feature unavailable until now in low-dropout regulators is the ability to reverse or decrease the input voltage below the output without reverse current flow. This is important in battery powered circuits, which are becoming increasingly popular. The new LT1121 regulator operates as if an ideal diode were connected in series with its input. The dropout voltage is equal to the collector-

The LT1121's ability to operate with small-value output capacitors is a big advantage in systems where transient output currents are small and space is limited, as in many battery operated circuits.

to-emitter saturation voltage of the PNP output transistor, but there is no reverse current flow from output to input. The output voltage may be held high, perhaps by a battery-backup power system, while the input is pulled to ground or is even reversed. There will be no current flow from the output pin back to the input. The output stage of the LT1121 draws only 15 μ A under these conditions. If used in this type of application, currently available regulators draw large reverse currents and quickly drain the backup battery.

The control circuit of the LT1121 allows the device to operate with only 30 μ A quiescent current (no load) while supplying up to 150mA of output current. Figure 2 shows the quiescent current versus input voltage characteristics of the device. The LT1121 incorporates anti-saturation circuitry that controls the drive current of the output transistor. This prevents the increase in quiescent current as the

device enters the dropout region which is exhibited by other PNP-type low-dropout regulators. This feature extends the useful life of the battery, a most important consideration in today's battery-powered world.

The design of low-dropout regulators requires a capacitor on the output of the regulator for frequency compensation. Careful design of the AC performance characteristics of the LT1121 allows the use of output capacitors as low as 0.33 μ F in comparison to tens of microfarads on older regulators. Figure 3 shows the basic LT1121 circuit. The output capacitor does not need to have extremely low effective series resistance (ESR). Transient response will, of course, suffer somewhat with smaller output capacitors. This is because the overall feedback loop is relatively slow and the output capacitor is required to provide current into transient loads for several microseconds until the loop responds. The LT1121's ability to operate with small-value output capacitors is a big advantage in systems where transient output currents are small and space is limited, as in many battery operated circuits.

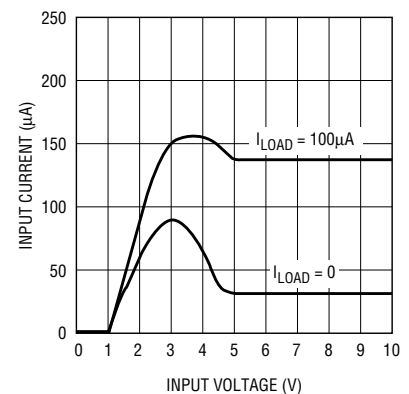


Figure 2. Quiescent current versus input voltage for the LT1121

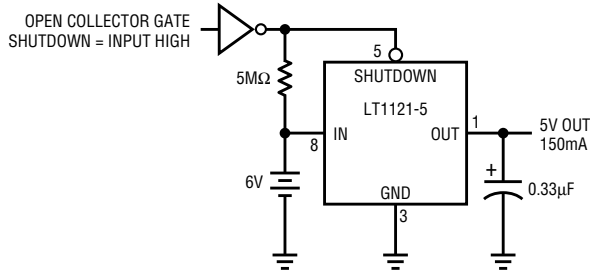


Figure 3. LT1121 basic circuit

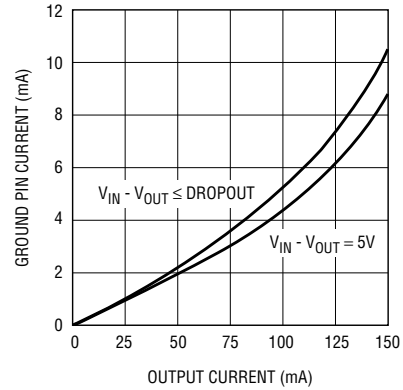


Figure 4. Ground-pin current versus output current for the LT1121

The LT1121 exhibits only a small increase in the ground-pin current when the device nears its dropout voltage. This is a major improvement over other PNP low-dropout regulators. This is graphically illustrated in Figure 4.

Architecture and Packages

The basic architecture of the LT1121 is shown in Figure 5. The output voltage is sampled by the circuitry shown in box A. The output of

box A drives transistor Q1, which drives the base of the output PNP transistor Q2. This architecture allows either the input or the output to be held high or subjected to reverse voltage without excessive current flow or reverse current flow through the output transistor.

The LT1121 is available in three-lead TO-92 and SOT-223(surface mount) packages, 8-lead SO (surface mount) and mini dip packages. In 8-pin packages, a shutdown pin is

provided, allowing logic control of system power. Pulling the shutdown pin to ground turns off the output stage of the regulator and reduces the supply current to 16μA, including the shutdown-pin bias current. The output pin may still be held high without reverse current flowing. As shown in Figure 6, the output of the device draws only 15μA when it is held high and the input is at zero volts.

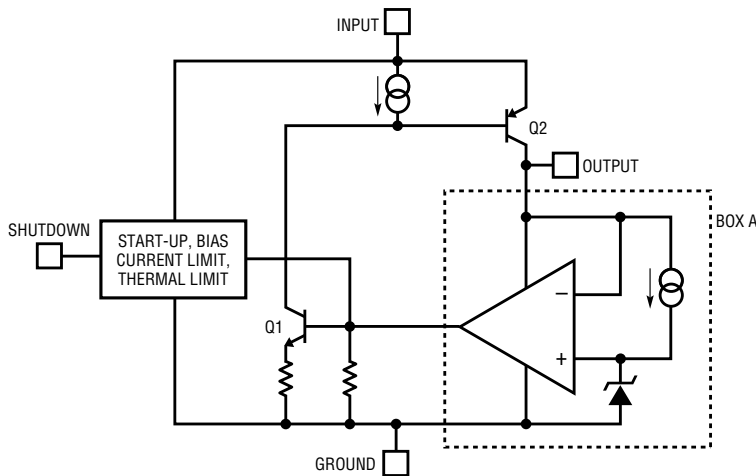


Figure 5. LT1121 Basic architecture

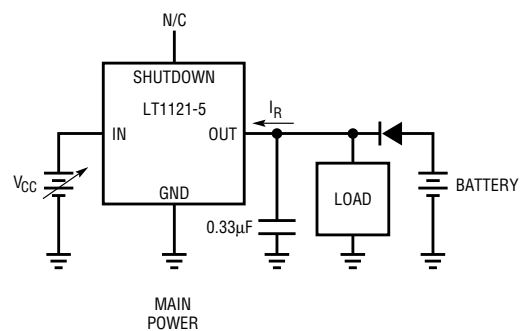


Figure 6. Power supply with battery backup. Reverse output current (I_R) with $V_{CC} = 0V$ is only 15μA

Table 1. Bandwidths of popular video formats

Composite Video	Flat BW	-3dB BW
Monochrome Composite	1MHz @ 1dB	3MHz
Color Composite (home use)	3MHz @ 1dB	5MHz
Color Composite (professional)	5MHz @ 0.05dB	50MHz
HDTV (professional)	30MHz @ 0.1dB	120MHz

RGB Video	Pixel Width	-3dB BW
VGA, 640 x 480	40ns	35MHz
SVGA, 800 x 600	30ns	50MHz
Workstation, 1024 x 768	15ns	90MHz
Workstation, 1200 x 900	9ns	150MHz

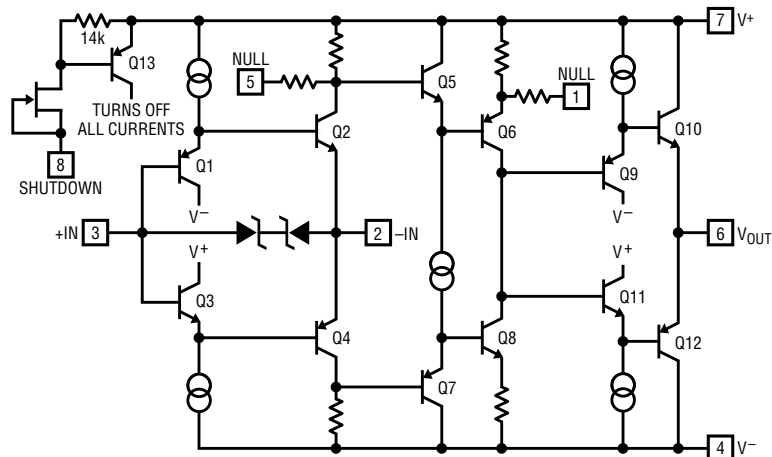


Figure 1. Video amplifier simplified schematic

LT1227, continued from page 1

In most video circuits, the impedance levels are quite low, in order to maximize frequency response. Typical feedback resistors are less than 2k and the most common load is a 75Ω cable. For this reason, video amplifiers must deliver high output currents. Video amplifiers should be specified when driving one or more 150Ω loads (the equivalent of driving one properly terminated 75Ω cable) as well as driving higher values such as 1kΩ.

What Amplifier Parameters Affect Video Performance?

When selecting a video amplifier, the first consideration is bandwidth. Table 1 lists several video formats and the approximate bandwidth each requires. If there is more than one amplifier in the signal path, each will need more bandwidth than is indicated in the table.

The next parameter to look at is output-drive capability. If the amplifier is driving internal circuitry, the load is unlikely to be a problem. Cable-driving applications require more current than traditional op amps can deliver; be sure the amplifier can deliver enough current. Also, check to see how much the amplifier slows down when driving a heavy load.

Heavy loads do more than just slow down amplifiers. Because the output impedance of real amplifiers is neither zero nor constant, the open-loop characteristics change with output current. For video amplifiers, the main

concern is bandwidth changing with the output DC level. For RGB video this is not too important, since the changes in bandwidth are usually small and impossible to detect, but color composite video is very sensitive to this. Small changes in bandwidth affect the gain and phase of the color subcarrier, causing changes in tint and color intensity. The specifications that describe these changes in the color subcarrier are "differential gain" and "differential phase." Most television sets have about 2 to 4% differential gain and 2 to 4 degrees of differential phase. Professional equipment has to be much better because the signal may pass through several pieces of equipment and the errors can accumulate.

The LT1227 Video Amplifier

The LT1227 is a current-feedback amplifier optimized for speed and AC linearity. The excellent performance of the LT1227 is due to simple circuitry and a very fast complementary process. This LTC proprietary process combines 36V low-capacitance, 600MHz PNPs and NPNs on one chip. The excellent DC matching of the transistors allows the signal path to be very simple and very fast. The simplified schematic in Figure 1 shows that the input stage consists of just four transistors: Q1-Q4. For maximum speed, only two transistors make up each current mirror (Q5 & Q6 and Q7 & Q8). The output buffer (Q9-Q12) is as

simple as the input stage. Another advantage of simple circuits is that they operate on low supply voltages as well as on standard higher-voltage supplies.

The LT1227's output is capable of driving over 60mA at 25°C. Current limiting reduces this with increasing temperature in order to limit power dissipation during fault conditions. The current-limit transistors are not shown in Figure 1.

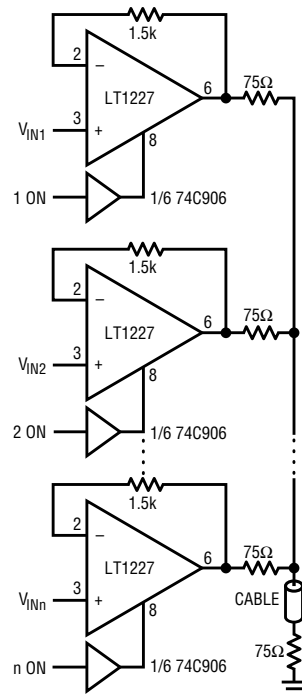


Figure 2. Many-input video MUX cable driver

The amplifier has offset-adjust pins, so a single potentiometer can vary the gain of one of the current mirrors. This changes the inverting-input bias current to null the output-offset voltage. Driving these pins with another amplifier will adjust the output offset automatically.

Pulling pin 8 of the LT1227 low turns off the amplifier. The easiest way to drive pin 8 is with an open-collector or open-drain logic gate. The amplifier operates normally when pin 8 is open or at V_{CC} . Pulling pin 8 more than 4V below V_{CC} guarantees shutdown. There is no need for a current-limiting resistor in series with pin 8 because an internal FET limits the current to 100 μ A. The amplifier is shut down by turning off all the bias currents, and the total supply current drops to 120 μ A, including the current pulled from pin 8. The input stage is off and the output impedance rises to over 200k in parallel with 12pF. The feedback resistors are still there, so for minimum loading by the out-put when the amplifier is shutdown, operate the LT1227 at unity

gain. In typical cable driving applications, the input-to-output isolation is 70dB at 10MHz. The input will isolate signals up to 10V peak-to-peak; larger signals will feed through the zener clamp across the input stage. The zener clamp protects the input transistors from excessive voltage during faults such as electrostatic discharge.

Figure 2 shows how simple it is to configure a video MUX using the LT1227.

LT1227 Performance

Table 2 lists the major performance specifications of the LT1227 on $\pm 5V$ and $\pm 15V$ supplies. Performance on $\pm 12V$ is essentially the same as on $\pm 15V$.

Table 2. LT1227 performance characteristics

Parameter	Gain	Load	$V_S = \pm 15V$	$V_S = \pm 5V$
Bandwidth	$A_V = +1$	$R_L = 150\Omega$	275MHz	200MHz
Bandwidth	$A_V = +2$	$R_L = 150\Omega$	140MHz	85MHz
Bandwidth	$A_V = -1$	$R_L = 150\Omega$	77MHz	70MHz
Bandwidth	$A_V = +4$	$R_L = 150\Omega$	90MHz	70MHz
Bandwidth	$A_V = +10$	$R_L = 150\Omega$	65MHz	50MHz
Differential Gain	$A_V = +2$	$R_L = 150\Omega$	0.014%	0.02%
Differential Phase	$A_V = +2$	$R_L = 150\Omega$	0.01°	0.14°
Output Slew Rate	$A_V = +10$	$R_L = 400\Omega$	1100V/ μ s	600V/ μ s
Input Slew Rate	$A_V = +1$		150V/ μ s	100V/ μ s
Minimum Output Current			30mA	30mA
Maximum Input Offset Voltage			10mV	10mV
Maximum Inverting Input Current			60 μ A	60 μ A
Input Noise Voltage	$A_V = +10$		3nV/ \sqrt{Hz}	3nV/ \sqrt{Hz}
Maximum Quiescent Supply Current			15mA	13mA

1063, continued from page 11

filter exhibiting no more than 200 μ V of total output-offset variation over four decades of cutoff frequency. A combination of a WIMA ceramic capacitor and a solid tantalum capacitor is used for power-supply decoupling. The LTC1063 was tested using a well thought out and carefully designed PC board.

Conclusions

Sampled-data filter technology has evolved considerably over the past several years. The output offset of the LTC1063 has been lowered by over two order of magnitudes in comparison to the first switched-capacitor filters. At the same time the AC performance of the device is at the lead-

ing edge of filter technology. The LTC1063 has nothing to envy from its active R,C active counterparts. Future switched-capacitor filters will challenge the active R,C filter in all performance criteria, including output offset voltage, maximum cutoff frequency, and dynamic range.

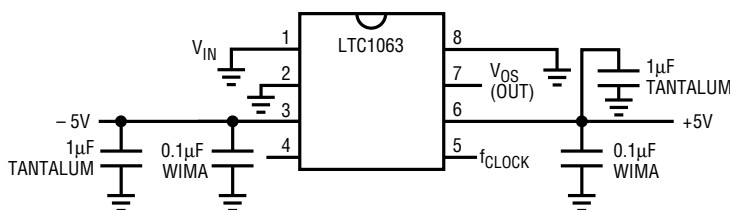


Figure 6a. LTC1063 operating as a clock-sweepable lowpass filter

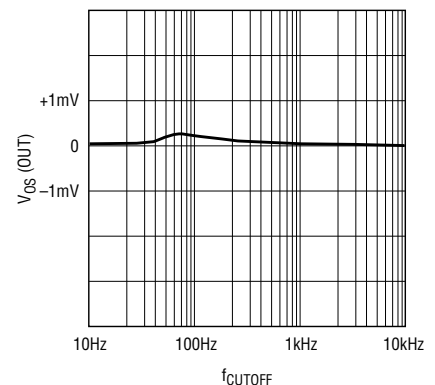


Figure 6b. Output offset vs f_{CUTOFF} for Figure 6a's circuit

Cascaded 8th-Order Butterworth Filters Provide Steep Roll-Off Lowpass Filter

by Philip Karantzalis and Richard Markell

Sometimes a design requires a filter that exceeds the specifications of the standard “dash-number” filter. In this case, the requirement was a low-distortion (–70dB) filter with roll-off faster than that of an 8th-order Butterworth. An elliptic filter was ruled out because its distortion specifications are too high. Two low-power LTC1164-5s were wired in cascade to

investigate the specifications that could be achieved with this architecture. The LTC1164-5 is a low-power (4 milliamperes with ±5 volt supplies), clock-tunable, 8th-order filter, which can be configured for a Butterworth or Bessel response by strapping a pin. Figure 1 shows the schematic diagram of the two-filter system. The frequency response is

shown in Figure 2, where it can be seen that the filter's attenuation is 80dB at 2.3 times the cutoff frequency. The distortion, as shown in Figure 3, is nothing less than spectacular. From 100Hz to 1kHz, the two filters have less than –74dB distortion specifications. At the standard measurement frequency of 1kHz, the specification is –78dB. **LT**

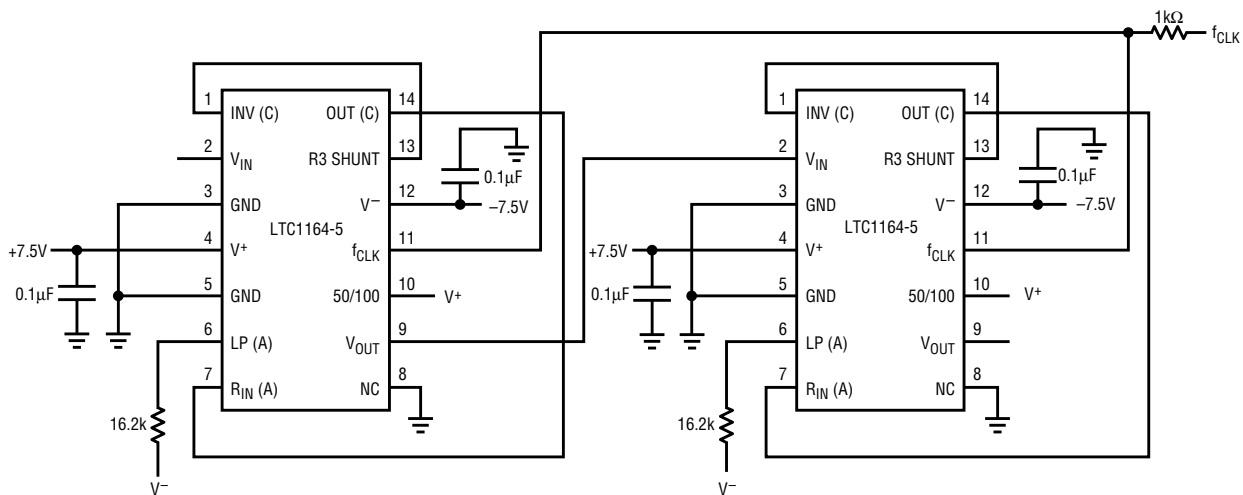


Figure 1. Schematic diagram: low-power, 16th-order lowpass filter (two 8th-order butterworths cascaded)

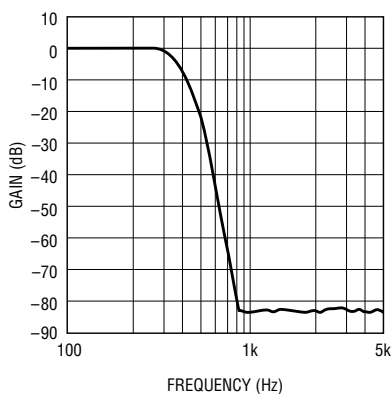


Figure 2. Frequency response for $f_{CLK} = 20kHz$

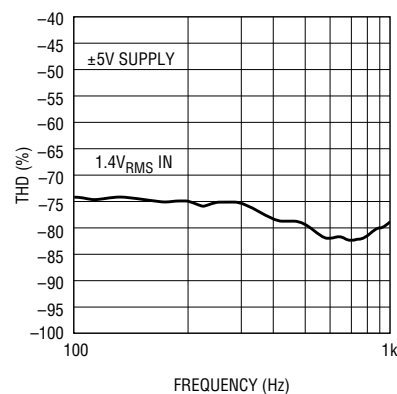


Figure 3. Distortion performance: two LTC1164-5s, $f_{CLK} = 60kHz$ (57:1) pin 10 connected to V^+

LT1110 Supplies 6 Volts at 550mA from 2 AA NiCad Cells

by Steve Pietkiewicz

The LT1110 micropower DC-DC converter can provide 5V at 150mA when operating from two AA alkaline cells. The internal switch $V_{CE(sat)}$ sets this power limit. Even with an external low-drop switch, more power is not realistically possible. The internal impedance (typically 200m Ω fresh and 500m Ω at end-of-life) of alkaline AA cells limits peak obtainable battery power. Conversely, nickel-cadmium cells have a constant internal impedance (35-50m Ω) for AA size) that increases only when the cell is completely discharged. This allows power to be drawn from the cell at a far greater rate. The circuit in Figure 1 uses two AA NiCad cells to supply 6 volts at 550mA. The circuit, developed for pagers with transmit capability, runs at full output current for 15 minutes with two Gates Millennium AA NiCad cells. With a 250mA load, the circuit runs for 36 minutes. Less heat is generated with a reduced load, resulting in the watt-hour difference observable above.

The circuit uses a micropower LT1110 switching-regulator IC as a controller. The internal switch of the LT1110 furnishes base drive to Q1 through the 220 Ω resistors. Q1, in turn, supplies base drive to the power switch Q2. The Zetex ZTX849 NPN device is rated at 5 amps current and comes in a TO-92 package. For surface-mount fans, the FZT-849, also from Zetex, provides the same performance in an SOT-223 package. The 16 Ω resistor provides a turn-off path for Q2's stored charge. When Q2 is on, current builds in L1. As Q2 turns off, its collector flies positive until D1 turns on. L1's built-up current discharges through D1 into C2 and the load. The voltage at V_{OUT} is divided by R4 and R3 and fed back into the FB pin of the LT1110, which controls Q2's cycling action. Switch-current limit, which is necessary to ensure saturation over supply variations, is implemented by Q3-Q5. Q3, C1, R2, and the auxiliary gain block inside the LT1110, form a 220mV reference point at the LT1110's

SET pin. Transistors Q4 and Q5 form a common-base differential amplifier. Q5's emitter monitors the voltage across 50m Ω resistor R1. When the voltage across R1 exceeds 220mV, Q4 turns on hard, pulling current through R5. When the voltage at the I_{LIM} pin of the LT1110 reaches a diode drop below the V_{IN} pin, the internal switch turns off. Thus, maximum switch current is maintained at 220mV/50m Ω , or 4.4A, over input variations and manufacturing spread in the LT1110's on time and frequency.

The circuit's output ripple measures 200mVp-p, and efficiency is 78% at full load with a 2.4V input. Output power can be scaled down for less demanding requirements. To reduce peak current, increase the value of R1. A 100m Ω resistor will limit current to 2.2A. L1 should be increased in value linearly as current is reduced. For a current limit of 2.2A, L1 should be 10 μ H. Base drive for Q2 can also be reduced by increasing the value of the 10 Ω resistor. These lower peak currents are much easier on alkaline cells and will dramatically increase alkaline battery life. \blacktriangleleft

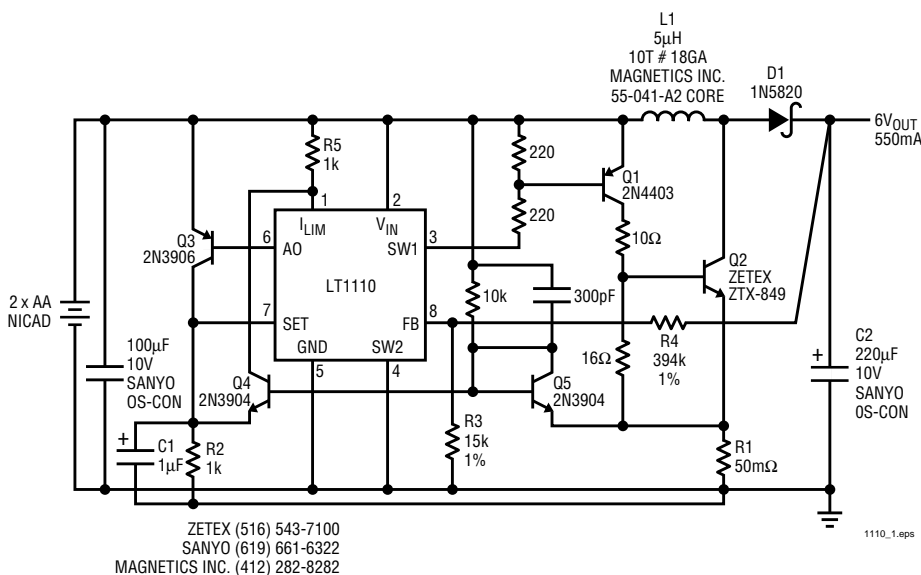


Figure 1. Schematic diagram, 2 AA NiCad to +6 volt converter

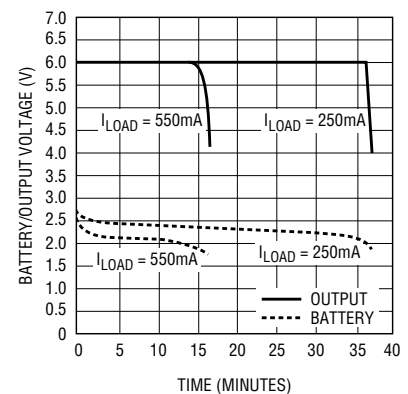


Figure 2. Operating time at $I_{LOAD} = 550mA$ and $250mA$

SwitcherCAD Release Slated for August

by Brian Huffman

Linear Technology will release a new design software program called SwitcherCAD in August. SwitcherCAD is a menu-driven DC-DC converter design-aid program that runs on IBM-PCs and compatibles. The program selects the appropriate DC-DC converter architecture and Linear Technology switching-regulator IC for a given design specification. In addition, it selects the other essential components for the converter, including the input and output capacitors, inductor, catch diode, and output filter, and calculates the operating conditions for these components. SwitcherCAD can cut days off the design cycle by eliminating the necessity of searching through multiple data sheets, application notes, and magazine cookbook articles for the answer to a design problem.

SwitcherCAD was designed to be used by the novice and expert designer alike. SwitcherCAD is organized around several different windows or screens. First, you enter your design requirements in the Design Specification Screen, shown in Figure 1. The Design Specification screen assumes that the design requirements, including input-voltage range, output voltage and current, output ripple, and maximum ambient temperature, are well defined. Once this screen is

completed, advance to the Topology and Device Selection Screen, shown in Figure 2.

In the Topology and Device Selection Screen, SwitcherCAD determines which DC-DC converter topologies and which Linear Technology IC's will satisfy the design requirements. There may be several architectures to choose from. Trade-offs between efficiency and circuit complexity will influence the final selection. SwitcherCAD supports several topologies, including step-up, step-down, inverting, and flyback converters.

SwitcherCAD selects the optimum Linear Technology switching regulator ICs based upon topology, input-voltage range, output voltage, and current requirements. The user can select any part listed in the parts column to compare designs based on different parts or topologies. The user also has a choice of several package styles, although not all of the listed packages are available for all LTC parts. SwitcherCAD displays the approximate peak switch current of the selected part along with other electrical and thermal characteristics.

Switcher Design Spec.

Output Voltage (V): Nom

Input Voltage (V): Min Nom Max

Load Current (A): Min Nom Max

Allowed Output Ripple Voltage mV(p-p):

Output #2 and #3 are for Multiple Output Switcher Only:

	Vout(V)	IoutMin(A)	IoutMax(A)	Ripple(mV)
Output #2:	<input type="text" value="0"/>	<input type="text" value="0"/>	<input type="text" value="0"/>	<input type="text" value="0"/>
Output #3:	<input type="text" value="0"/>	<input type="text" value="0"/>	<input type="text" value="0"/>	<input type="text" value="0"/>

Max Temperature (°C): Ambient IC Diode

Fully Isolated Output: No Yes

Figure 1. SwitcherCAD Design Specification Screen

Select from allowed Topology & Device lists

Allowed topologies	Parts	Packages	
Positive Boost	LT1171	TO-220-5	<input type="button" value="Schematic"/>
Flyback	LT1170	TO-3	<input type="button" value="Novice Mode"/>
-----	LT1071	TO-220-11	<input type="button" value="Expert Mode"/>
	LT1070	J-8	<input type="button" value="Close"/>
	LT1270	N-8	
	LT1270A	CS-8	
	LT1271		

Part	PeakIsw	I _m	Freq	ThetaJA	ThetaJC
LT1170	1.797A	5.00A	100kHz	50.0	2.0

Figure 2. SwitcherCAD Topology and Device Selection Screen

Positive Boost Operating Condition & Parts List

Operating Conditions:

C1	Nichicon x1 UPL1A151MPH	150µF	10V	ESR=0.350Ω	Irms= 0.265A
C2	United Chemi-Con x1 LXF16VB181M6X15LL	180µF	16V	ESR=0.220Ω	
C3	Nichicon x1 UPL1A151MPH	150µF	10V	ESR=0.350Ω	Irms=0.265A
L1	Gowanda 050AT1002	10µH	DCR=0.010Ω		
L2	Hurricane HL-8015	3µH	IpK=3A		
D1	Motorola Schottky MBR115P	If=1A	Vr=15V	Trr=0nS	
R1	4.74kΩ	1%			
R2	1.24kΩ	1%			
Rc	Suggested Value: 1.0kΩ				
Cc	Suggested Value: 1.0µF				
U1	LT1170	Im=5.0A	Vs=0.0V	Rsw=0.20Ω	f=100kHz
1	Vout=6V	VinMin=5V	VinNom=5V	VinMax=5V	
2	IoMin=0.5A	IoNom=0.08A	IoMax=1A		
3	Ripple=120mV	TaMax=60°C	TjMax=100°C	TjDMax=100°C	

<input type="radio"/>	Operating Mode at Full Load Current	=	_Cont_
<input type="radio"/>	Duty Cycle	=	25.5 %
<input type="radio"/>	Maximum Rated Switch Current at this DC	=	5.000 A


Close

Print

Figure 3. SwitcherCAD Novice Mode Screen

allows the user to view up to three selected variables without having to scroll through the spreadsheet. This feature is particularly useful for finding worst-case operating condition for the various components. For example, input-capacitor RMS ripple current, output-capacitor RMS ripple current, and IC power dissipation can be monitored simultaneously as the input voltage is changed.

As with any CAD program, SwitcherCAD performs computer *aided* design, not computer *generated* design. At the core of SwitcherCAD are up to 300 design equations for each topology. The equations quantify the operating point for each circuit component, but they cannot guarantee that, once assembled, the circuit will meet the user's every expectation. It is the responsibility of the user to verify SwitcherCAD's work by building the circuit and evaluating its performance by measuring component stresses under all expected operating conditions.

SwitcherCAD will be available in August from your local LTC sales office, or by calling the 800 number listed on the last page of this magazine. 

containing diodes, inductors and capacitors. Electrical characteristics of the components are extracted from the database when operating characteristics are computed. The program provides enough information about the selected components to allow the user to make substitutions.

SwitcherCAD calculates all operating conditions and selects components based on a minimum input voltage and maximum output current. To vary the input conditions to simulate worst-case conditions for each component, the user should advance to Expert Mode.

Expert Mode

The Expert Mode screen, shown in Figure 4, displays a "spreadsheet" containing a detailed view of a converter design and its operating conditions. More important, this screen allows the user to modify selected component values and operating conditions and view the results on the screen or print them in a report. This is useful for performing "worst case" analysis and for playing "what if" with component values and operating conditions.

An on-line help feature provides quick information about operating conditions and component selections. Help provides detailed information on the significance of the highlighted parameter or value, how it is calculated, and

its role in determining other values and parameters. Understanding how and why a particular component is selected is essential in designing a reliable switching regulator circuit.

Because only a small portion of the spreadsheet can be displayed on the screen at one time, SwitcherCAD is equipped with a "Watch List" at the bottom of the screen. This window

Positive Boost [LT1170]

I Output Voltage	=	6.0	V
I Min Input Voltage	=	5.0	V
I Nom Input Voltage	=	5.0	V
I Max Input Voltage	=	5.0	V
I Min Load Current	=	0.050	A
I Nom Load Current	=	0.080	A
I Max Load Current	=	1.000	A
I Output Ripple Voltage	=	120.0	mV p-p
I Max Ambient Temperature	=	60	°C
IC Characteristics			
I Maximum Rated Switch Voltage	=	65.0	V
I Rated Switch Current	=	2.500	A
I Switch On Resistance	=	0.400	Ω
I Switch Offset Voltage Loss	=	0.0	V

I Min Input Voltage	5.0	<<Input
----------------------------	------------	---------

Variable Watch List:

<input type="radio"/>	Power Dissipated in IC	=	0.32	W
<input type="radio"/>	Output Capacitor RMS Ripple Current	=	0.670	A RMS
<input type="radio"/>	Input Capacitor RMS Ripple Current	=	0.342	A RMS

Print

Help

Close

Watch

Figure 4. SwitcherCAD Expert Mode Screen

New Device Cameos

by LTC Marketing

LT1225, LT1226: New Ultra-High-Speed Op Amps for Fast Data-Acquisition Systems

The new LT1225 and LT1226 are ultra-high-speed operational amplifiers with excellent DC performance. The output currents of the LT1225 and LT1226 are typically 24mA minimum, making them capable of driving a 500Ω load to ±12V with ±15V supplies and a 150Ω load to ±3V with ±5V supplies. The unique output stages of these devices allow them to remain stable while driving any amount of capacitive load, which makes them useful in buffer or cable-driving applications. The LT1225 is compensated to be stable for gains of five or more and provides a 150MHz gain-bandwidth product, 400V/μs slew rate, 90 nanosecond settling time to 0.1% with a 10V step, and 20V/mVDC gain. The LT1225 consumes only 7mA of supply current. A key feature of the LT1225 is its precision offset voltage. The LT1225 provides a 1mV maximum offset voltage, typically 0.5mV. The LT1226 is a low-noise, ultra-high-speed operational amplifier with excellent DC performance. The device is stable for gains of 25 or more and provides a 1GHz gain-bandwidth product, 400V/μs slew rate, 50V/mV minimum large-signal voltage gain, and 100 nanoseconds settling time to 0.1% with a 10V step. Key features of the LT1226 include a maximum offset voltage of 1mV and a mere 2.6 nanovolts/(Hz)^{1/2} of noise. Applications include high-speed data-acquisition systems, cable driving, RF amplifiers, and high-speed sample-and-hold circuits. Additional applications include input buffers for A/D converters, output buffers for D/A converters, and video-imaging circuitry.

8-Pin 12-Bit Complete Data-Acquisition System

The LTC1291 is the latest 12-Bit A/D converter to join Linear Technology's growing list of data-acquisition prod-

ucts. This device is a complete data-acquisition system packaged in an 8-pin DIP. It includes a serial-I/O, successive-approximation A/D that uses switched-capacitor technology to perform 12-bit unipolar conversions. The analog front end has a two-channel multiplexer and a sample-and-hold. The multiplexer can be configured for single-ended or differential inputs. With the sample-and-hold, fast-moving signals with bandwidths of up to 27kHz can be digitized. An external reference is not required because the LTC1291 takes its reference from the power supply pin (V_{CC}). When the device is not being used, it can be put into a power-shutdown mode that reduces the supply current to 5μA. The serial I/O allows the LTC1291 to be easily interfaced to most processors with as few as three wires. Ease of use, small package, and low power consumption make this device well suited for remote-sensing applications and portable, hand-held instruments.

New LT1137A Advanced, Low-Power 5V RS232 Transceiver with Small Capacitors

The LT1137A is a three-driver, five-receiver RS232 transceiver that is pin compatible with the industry-standard LT1137, and offers performance improvements that permit operation with small (0.1 microfarad) storage capacitors. The LT1137A's charge pump is designed for extended compliance and can deliver over 40 milliamps of load current. Additional load-drive capability is important for driving external peripherals such as mice. Supply current is typically 12 milliamps, which is competitive with similar CMOS devices. An advanced driver output stage operates to 120kbaud while driving heavy capacitive loads.

The LT1137A is fully compliant with all EIA-RS232 specifications. Special bipolar construction techniques protect the drivers and receivers beyond the fault conditions stipulated for

RS232. Driver outputs and receiver inputs can be shorted to ±30V without damaging the device or the power-supply generator. In addition, the RS232 I/O lines are resilient to multiple 5kV ESD strikes.

The transceiver has two shutdown modes. One mode disables the drivers and charge pump, while the other shuts down all circuitry. While shut down, the drivers and receivers assume high impedance output states.

The new LT1137A is specified for temperature ranges from military (MJ) to commercial (CN and CJ) and is also available in a 28-pin surface-mountable package.

New LT1112 Dual Microvolt-Offset, Picoamp-Input-Current Op Amp In SO8 Package

The new LT1112 is a dual, internally compensated, universal precision operational amplifier. This part has the lowest offset voltage of any dual non-chopped op amp. The lowest grade has a guaranteed offset of 75 microvolts. The LT1112 combines picoampere bias currents, microvolt offset voltage, low voltage and current noise and low power dissipation. The LT1112 achieves precision operation on two NiCad batteries with 1.6mW of power dissipation. The part also achieves very high CMRR and PSRR specifications, almost non-existent warm-up drift, and the ability to deliver 5 milliamps load current.

The LT1112 is available in the industry-standard dual SO8 operational-amplifier pinout. The dual amplifiers have a full set of matching specifications. These matching specifications make it easy to use the amplifiers in applications that require amplifier matching, such as two- and three-amplifier instrumentation amplifiers. The quad version of the LT1112 is known as the LT1114. The LT1114 features four operational amplifiers in a single package, with the same guaranteed specifications as the LT1112.

Another set of specifications are furnished at $\pm 1V$ supply. These specifications, plus the low 290- μA -per-amplifier supply current, allow the LT1112/LT1114 to be powered by two nearly discharged AA cells.

The LT1109A Micropower Step-up DC-DC Converter

The LT1109A is the newest member of LTC's growing micropower DC-DC converter family. Housed in a space-saving 8-pin DIP or SO package, the LT1109A-12 delivers 12 volts at over 250mA from a 5 volt supply. Up to four flash-memory chips can be programmed simultaneously using the LT1109A for V_{pp} generation. Like its little brother the LT1109, the "A" version has a logic-level shutdown input and high-speed 120kHz operation. A 1.5A switch, on-chip switch-current limit, and a 65% duty cycle provide over twice the output power of the LT1109. The LT1109A operates over a 2-to-9-volt input range and consumes just 300 μA quiescent current under no-load or shutdown conditions. Five-volt and adjustable versions are also available.

Surface Mount Power Devices in DD Packages

LTC will soon have available several power devices in a new surface mount power package, generically referred to as the DD package. This package has been specially designed to allow voltage regulators to be surface mounted. Ever since LTC began offering the SO package for surface mount applications, customers have been asking for linear and switching regulators in surface mount packages. Believe it or not, otherwise sane and intelligent engineers will call up and ask for "an LT1084 in an SO package." What was required was a surface-mountable package designed especially to dissipate power. Now it's here.

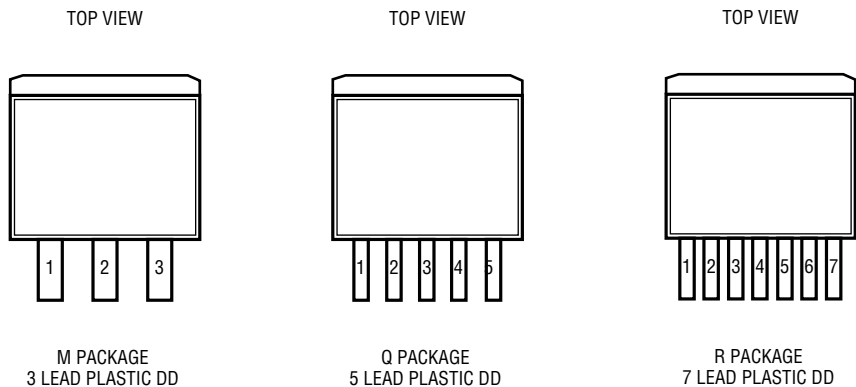


Figure 1. DD packages

In the past, when designs employing surface mount technology (SMT) required high-current voltage regulators, one was forced to either use standard packages with the leads formed for surface mounting or to have holes drilled on an otherwise SMT board. Neither choice is ideal from cost and manufacturability viewpoints. The DD package is the solution. The DD package is available in 3, 5, and 7 lead versions and will allow LTC to offer everything from simple 3-terminal regulators to full-featured switching regulators. The package suffix designators are as follows: 3-Lead: M, 5-Lead: Q, 7-Lead: R.

An example of a typical part number is "LT1171CQ"

The three package types are shown in Figure 1.

Mechanical and Thermal Details The DD package resembles a TO-220 with the tab cut off and the leads clipped and formed for surface mounting. Measurements verify about 2°C/W junction-to-case thermal resistance. With a surface-mounted device, most heat sinking is done through the board, so layout and copper pad size will contribute to the overall thermal resistance number. It is unlikely that a linear regulator operating at 3 amps

at high input/output voltage differential will be a candidate for surface mounting, but the DD package will allow many high-current switching regulation tasks to be performed.

Part Types to be Offered The following is a list of our initial product offering in the DD package:

- LT1171CQ 3A 100kHz switching regulator
- LT1271CQ 4A high-efficiency switching regulator
- LT1076CR-5 5V, 2A step-down switching regulator



For further information on any devices mentioned in this issue of Linear Technology, use the reader service card or call the LTC literature service number: (800) 637-5545. Ask for the pertinent data sheets and application notes.

Information furnished by Linear Technology Corporation is believed to be accurate and reliable. However, no responsibility is assumed for its use. Linear Technology makes no representation that the circuits described herein will not infringe on existing patent rights.

DESIGN TOOLS

Applications on Disk

NOISE DISK

This IBM-PC (or compatible) program allows the user to calculate circuit noise using LTC op amps, determine the best LTC op amp for a low noise application, display the noise data for LTC op amps, calculate resistor noise, and calculate noise using specs for any op amp.

Available at no charge.

SPICE MACROMODEL DISK

This IBM-PC (or compatible) high density diskette contains the library of LTC op amp SPICE macromodels. The models can be used with any version of SPICE for general analog circuit simulations. The diskette also contains working circuit examples using the models, and a demonstration copy of PSPICE™ by MicroSim.

Available at no charge.

Technical Books

Linear Databook — This 1,400 page collection of data sheets covers op amps, voltage regulators, references, comparators, filters, PWMs, data conversion and interface products (bipolar and CMOS), in both commercial and military grades. The catalog features well over 300 devices. \$10.00

Linear Applications Handbook — 928 pages chock full of application ideas covered in-depth through 40 Application Notes and 33 Design Notes. This catalog covers a broad range of "real world" linear circuitry. In addition to detailed, systems-oriented circuits, this handbook contains broad tutorial content together with liberal use of schematics and scope photography. A special feature in this edition includes a 22-page section on SPICE macromodels. \$20.00

Monolithic Filter Handbook — This 232 page book comes with a disk which runs on PCs. Together, the book and disk assist in the selection, design and implementation of the right switched capacitor filter circuit. The disk contains standard filter responses as well as a custom mode. The handbook contains over 20 data sheets, Design Notes and Application Notes. \$40.00

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