High-powered booster circuits enhance op-amp output

Although modern IC op amps simplify linear-circuit design, their output power is limited. Well-designed booster stages can solve this problem without sacrificing amplifier performance.

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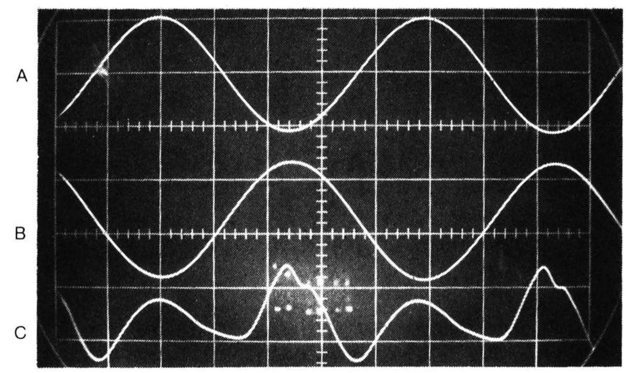
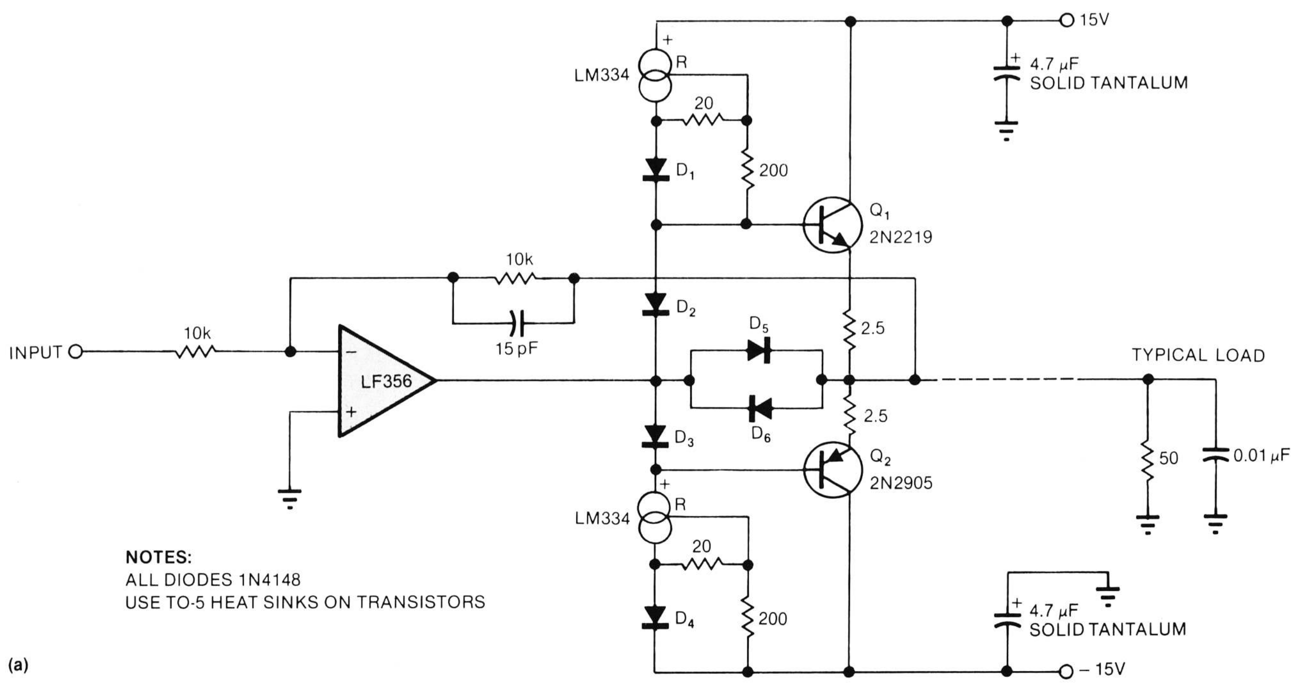
You can use the circuits presented here to substantially increase an IC amplifier's voltage and/or current output drive. Although the circuits were developed to solve specific problems, they are general enough to satisfy a variety of applications.

A booster is a gain stage with its own inherent ac characteristics. Therefore, in applying these circuits, you can't ignore such parameters as phase shift, oscillation and frequency response if you want the booster and amplifier to work well together. Designing booster stages that maintain good dynamic performance is a difficult challenge, especially because the booster circuitry changes with the application.



TRACE	VERTICAL
A	10V/DIV
B	10V/DIV

(b)



(a)

Fig 1—Complete with short-circuit protection *and fully temperature compensated, a booster circuit* ***(a)*** *develops a ±200-mA output current. Even with a heavy load (50Ω in parallel with 10,000 pF), response is quick and clean* ***(b); overall circuit distortion*** *measures less than 0.05% (trace C).*

Feedforward design technique increases current-booster speed

Start with some current-gain stages

The circuit shown in **Fig 1a** boosts the output-current level of an LF356 (a unity-gain inverting amplifier) to ±200 mA while maintaining a full ±12V output swing. In it, LM334 current sources, set for a 3.5-mA output by the 20Ω resistors, bias the complementary emitter followers, which provide drive and sink functions for the LF356 output. The RC feedback network creates a gain roll-off above 2 MHz.

The circuit's diodes satisfy several needs. D_1 and D_4, along with their associated 200Ω resistors, temperature-compensate the current sources. D_2 and D_3 eliminate crossover distortion in the output stage, while D_5 and D_6 provide short-circuit protection by shunting the drive to Q_1 and Q_2 when the output current exceeds 275 mA. For best results, thermally couple D_2 and D_3 to the transistors' heat sinks.

Circuit response **(Fig 1b)** is quick and clean. When you drive a 20V p-p sine wave into a heavy load (50Ω in parallel with 0.01 μF), output distortion measures less than 0.05%.

The circuit depicted in **Fig 2** accommodates higher current applications; it drives 3A (±25V pk) into an 8Ω load. As in **Fig 1a**'s design, the booster network—LM391-80 driver and associated power transistors—lies within the op amp's feedback loop. Booster-network bandwidth, set by the 5-pF capacitor at pin 3 of the LM391-80, is greater than 250 kHz.

Feedback resistors set the loop gain at 10, with the 100-pF capacitor introducing a roll-off at 100 kHz to ensure stability for the amplifier/booster combination. The output RC network, along with the 4-μH inductor, prevents circuit oscillations. You set the output-stage quiescent current at 25 mA by monitoring the voltage drop across the 0.22Ω resistors while adjusting the 10-kΩ pot at pins 6 and 7 of the 391.

How to increase speed

These first two circuit designs stress stability at the expense of speed. For example, **Fig 1a**'s booster network has a much wider bandwidth than the LF356 op amp. Unfortunately, the network's presence within the amplifier's feedback loop means that the LF356 dictates overall circuit response time.

However, there are ways to accentuate speed. In **Fig 3a**, for example, a feedforward network lets ac signals bypass the LM308 op amp and directly drive a very-high-bandwidth 200-mA current-boost stage. And because the LM308 provides the signal path for dc and low frequencies, the circuit achieves fast response with no sacrifice in overall dc stability.

Current sources Q_1 and Q_2 bias the complementary emitter followers (Q_3/Q_6 and Q_4/Q_7). Because this output stage introduces signal inversion, circuit output feeds back to the LM308's noninverting input. The 10-kΩ/15-

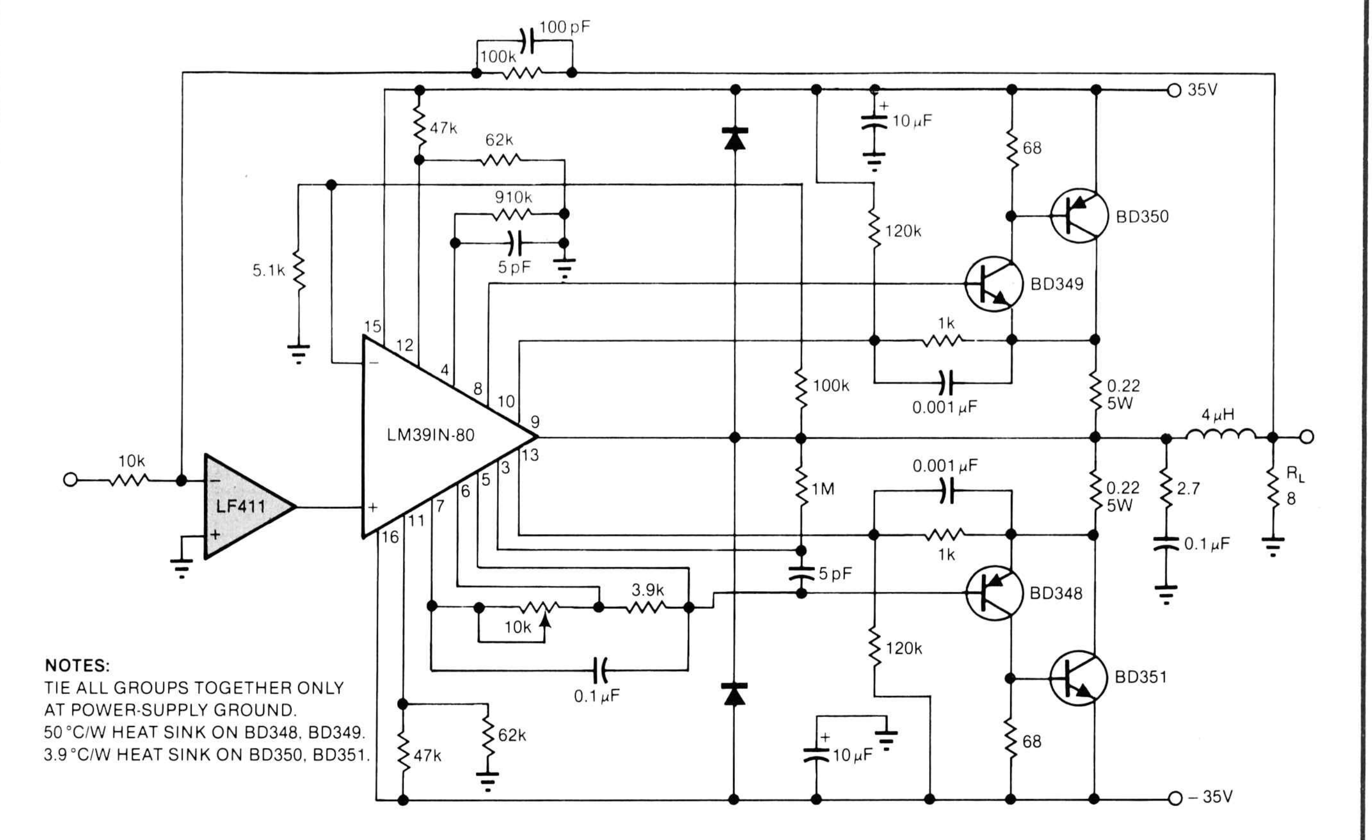
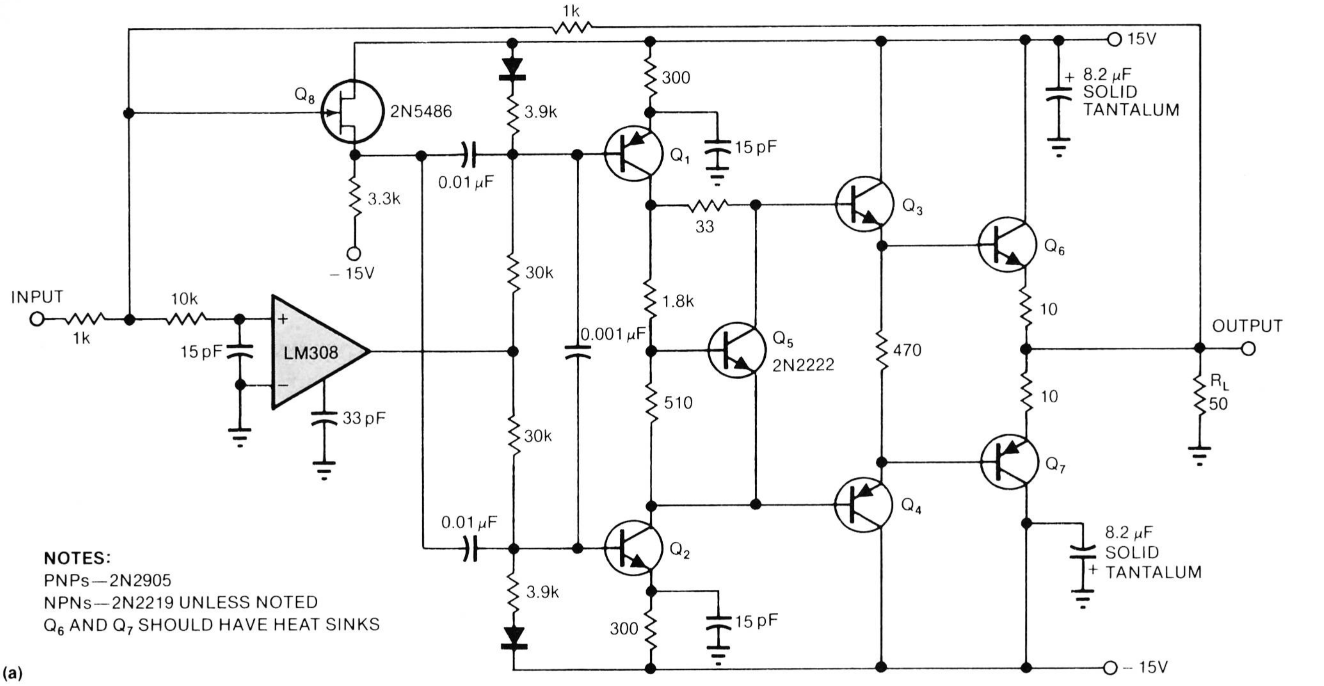
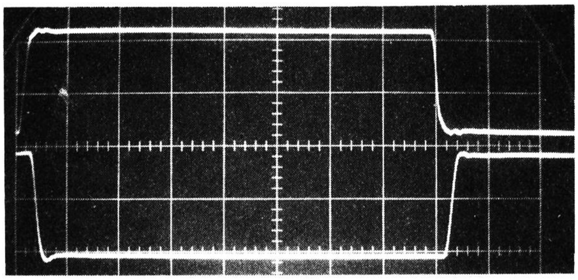


Fig 2—Designed to satisfy high-current needs, *this booster network drives 3A into an 8Ω load. The output RCL network prevents circuit oscillations, and the 10-kΩ pot sets output-stage quiescent current.*



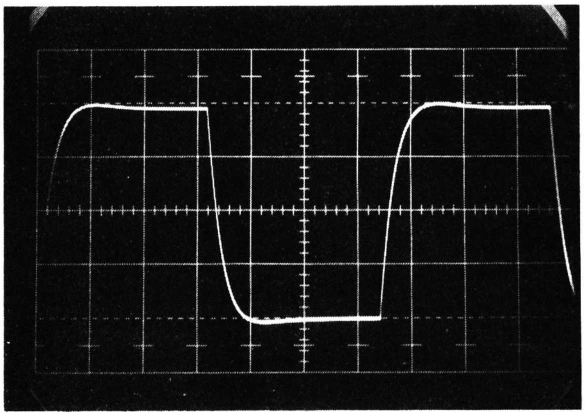
(a)



TRACE	VERTICAL	HORIZONTAL
A	5V/DIV	100 nSEC/DIV
B	5V/DIV	100 nSEC/DIV

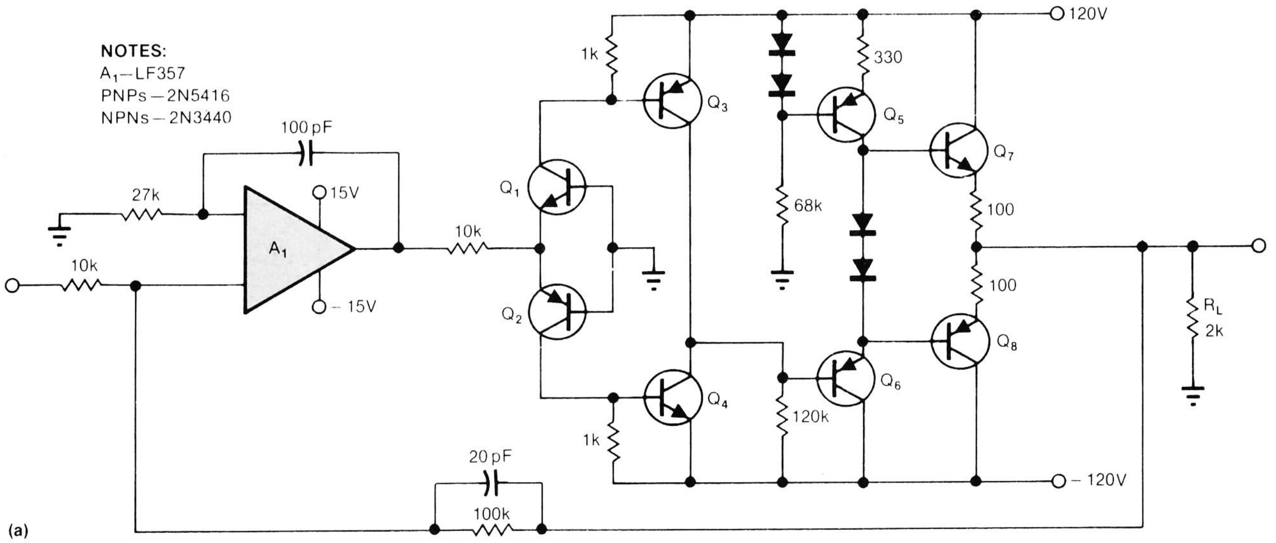
(b)

Fig 3—To increase speed, *a booster circuit* ***(a)*** *employs a feedforward network that allows ac signals to bypass the op amp and directly drive the high-bandwidth current-boost stage. Driving a 10V pulse into 50Ω, the booster evidences clean settling characteristics* ***(b);*** *rise and fall times measure less than 15 nsec.*



VERTICAL	HORIZONTAL
50V/DIV	5 μSEC/DIV

(b)



(a)

Fig 4—If you need extra voltage, *a booster design* ***(a)*** *develops ±100V across a 2-kΩ load. And it readily accommodates 30-kHz signals* ***(b).***

Stacking amplifier outputs effectively doubles voltage swing

pF RC network at the op amp's input shunts the 308's high-frequency inputs. These inputs go directly to the output stage via source follower Q_8.

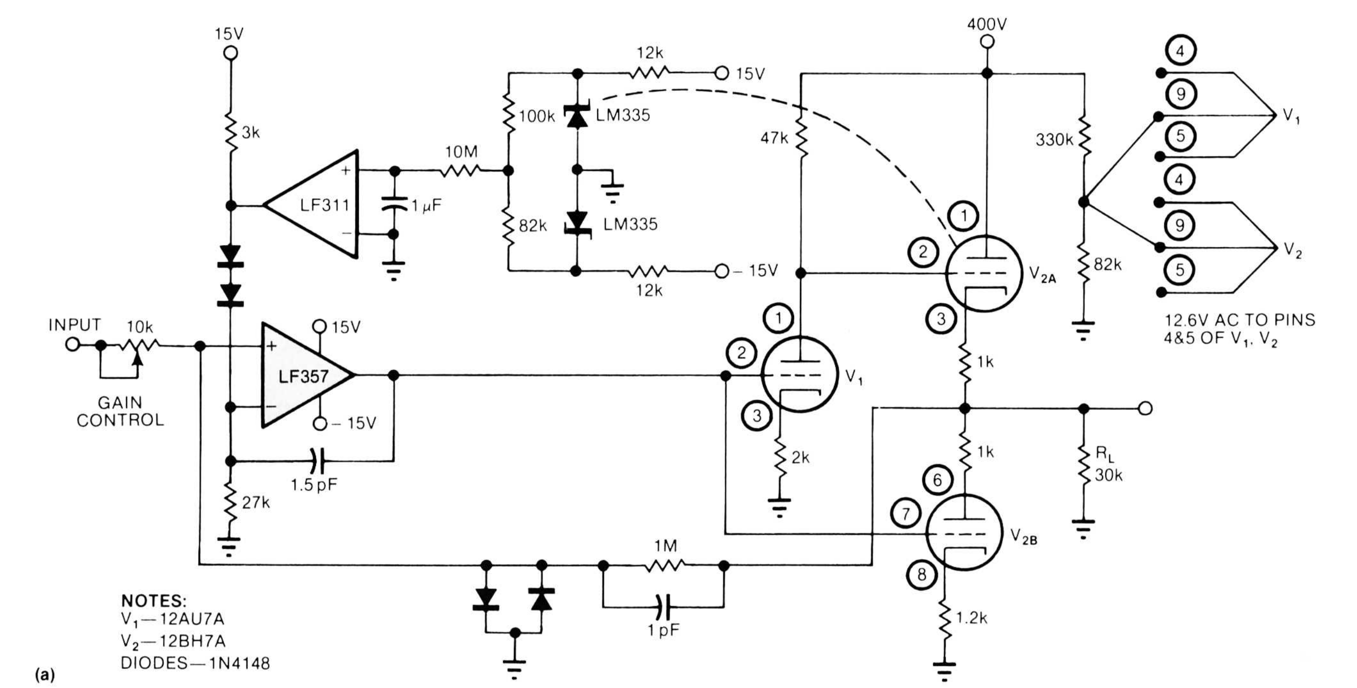
Despite the added complexity, performance is impressive **(Fig 3b)**. The boosted amplifier features a 750V/μsec slew rate, full-power (±12V, 200 mA) bandwidth greater than 6 MHz and a 3-dB point beyond 11 MHz.

Voltage boosting presents no problems

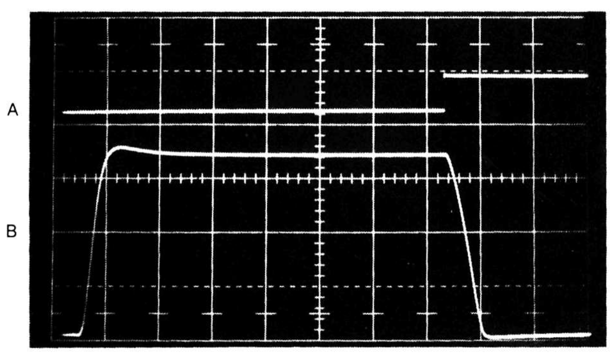
Turn now to voltage-boosting designs. Thanks to the gain provided by the Q_1/Q_2 complementary common-base stage, the circuit shown in **Fig 4a** drives ±100V into a 2000Ω load. Q_3 and Q_4 furnish additional gain to the Q_7/Q_8 output stage, with Q_5/Q_6 providing the bias. The diodes attached to Q_5's collector minimize crossover distortion.

The circuit employs two feedback loops. Overall output-to-input feedback (returned to the LF357's noninverting input to allow for the Q_3/Q_4 inverting stage) sets A_1's gain at 10 to ensure specified output for ±10V input signals. And local ac feedback around A_1 adds dynamic stability.

With a ±50-mA output level, the circuit also provides some current gain. If your application doesn't require that capability, though, you can eliminate transistors Q_5 through Q_8 (along with their associated components) and close the feedback loop from the Q_3/Q_4 collector line. However, to prevent crossover distortion, make sure



(a)



TRACE	VERTICAL	HORIZONTAL
A	20V/DIV	2 μSEC/DIV
B	100V/DIV	2 μSEC/DIV

(b)

Fig 5—Virtually immune to load shorts and reverse voltages, *a positive-output-only booster* ***(a)*** *drives 350V into a 30-kΩ load. With a 15V input pulse, the output rises in 1 μsec and settles in less than 5 μsec* ***(b)****. The falling edge slews just as rapidly and settles within 4 μsec.*

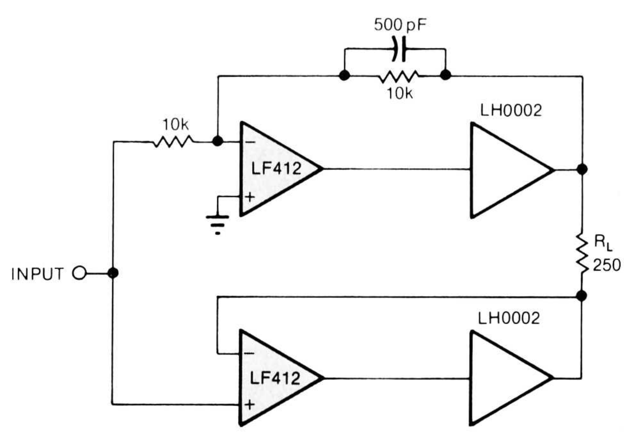


Fig 6—Effectively double the voltage swing *across a load by stacking or bridging amplifier outputs. Although this booster-circuit design is simple and requires no high-voltage supplies, you do have to float the load with respect to ground.*

that resistive output loading doesn't exceed 1 MΩ.

Fig 4b shows the boosted amplifier driving a ±100V square wave into a 200Ω load at 30 kHz. A second high-voltage booster circuit (**Fig 5a**) drives 350V into a 30-kΩ load and is virtually immune to load shorts and reverse voltages. And although the circuit has a 350V limit, tubes with higher plate-voltage ratings can extend the output capacity to several kilovolts.

In **Fig 5a,** the tubes are arranged in a common-cathode (V_{2B}), loaded-cathode-follower (V_{2A}) output configuration driven from a common-cathode (V_1) gain stage. Booster output feeds back to the LF357's noninverting input, with the 1-pF capacitor rolling off loop gain at 1 MHz. Local feedback stabilizes the LF357. The diodes at the summing junction protect the amplifier against high voltages during circuit start-up and slew-rate limiting. **Fig 5b** shows the booster's response at a gain of approximately 25.

In general, tubes are much more tolerant of load shorts and reverse voltages than transistors and are much easier to protect. In this circuit, one of the two LM335 temperature sensors is in contact with V_2, and its output gets compared with that of the second LM335, which monitors ambient temperature.

Under normal operating conditions, V_2 runs about 45°C above ambient temperature, generating a −100-mV signal at the LF311's noninverting input and forcing its output low. When a load fault occurs, V_2's plate dissipation increases causing its associated sensor's output to rise. This action in turn forces the LF311 output high, drives the LF357 output low and shuts down the output stage. V_2's thermal time constant, along with the 10-MΩ/1-μF delay network in the LF311's input line, provides adequate hysteresis.

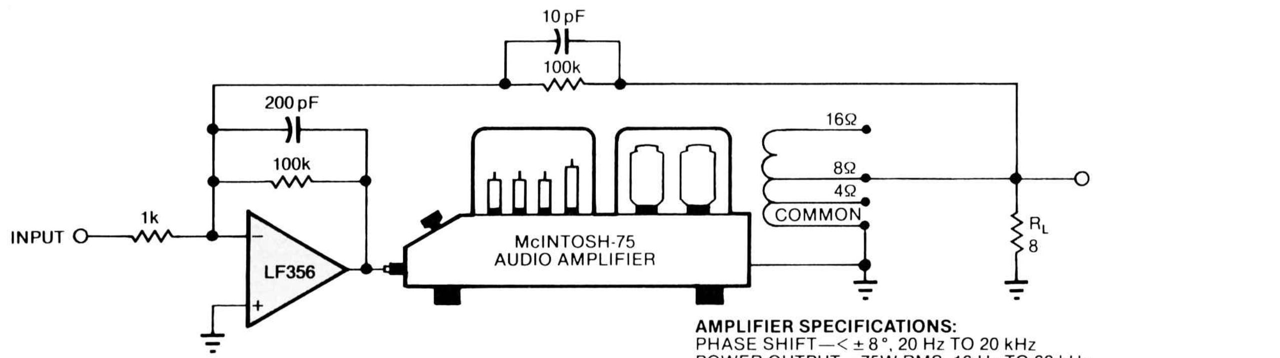


Fig 7—Voltage and current boosting are a snap *when you use a high-quality audio amplifier. For loads in the 4 to 16Ω range, this circuit produces 75W.*

BOOSTER-CIRCUIT PERFORMANCE

FIGURE	VOLTAGE GAIN	CURRENT GAIN	BANDWIDTH	COMMENTS
1	NO	YES (200-mA OUTPUT)	DEPENDS ON OP AMP: 1 MHz TYP.	FULL ± OUTPUT SWING. STABLE INTO 50Ω/10,000-pF LOAD. INVERTING AND NONINVERTING OPERATION. SIMPLE.
2	YES (±30V OUTPUT)	YES (3A OUTPUT)	50 kHz	FULL ± OUTPUT SWING. ALLOWS INVERTING OR NONINVERTING OPERATION.
3	NO	YES (200-mA OUTPUT)	FULL OUTPUT TO 6 MHz, −3-dB POINT AT 11 MHz.	ULTRAFAST, 750V/μSEC. FULL BIPOLAR OUTPUT. INVERTING OPERATION ONLY.
4	YES (100V OUTPUT)	YES (50-mA OUTPUT)	50 kHz	FULL ± OUTPUT SWING. ALLOWS INVERTING OR NONINVERTING OPERATION. CAN BE SIMPLIFIED TO DRIVE CRT DEFLECTION PLATE.
5	YES (350V OUTPUT)	NO	500 kHz	OUTPUT VERY RUGGED. GOOD SPEED. POSITIVE OUTPUTS ONLY.
6	YES (24V OUTPUT)	NO	DEPENDS ON OP AMP	REQUIRES THAT THE LOAD FLOAT ABOVE GROUND.
7	YES (70V OUTPUT)	YES (3A OUTPUT)	100 kHz	OUTPUT EXTREMELY RUGGED. WELL SUITED FOR DRIVING DIFFICULT LOADS IN LAB SETUPS. FULL BIPOLAR OUTPUT. AC ONLY.
8	YES (1000V OUTPUT)	YES (300-mA OUTPUT)	50 Hz	HIGH VOLTAGE AT HIGH CURRENT. SWITCHED-MODE OPERATION ALLOWS USE OF ±15V SUPPLIES. GOOD EFFICIENCY. LIMITED BANDWIDTH WITH ASYMETRICAL SLEWING. POSITIVE OUTPUTS ONLY.

Designs boost current and voltage simultaneously

Multifunction boosting's also possible

Three additional circuit designs all provide combined current- and voltage-output boosting. **Fig 6,** for example, depicts a simple way to effectively double the voltage swing across a load by stacking or bridging amplifier outputs. Each LF412 output feeds an LH0002 amplifier to provide current-drive capability. Because only one of the LF412s inverts, though, the combination produces 24V across the 250Ω load (±12V swings from each leg).

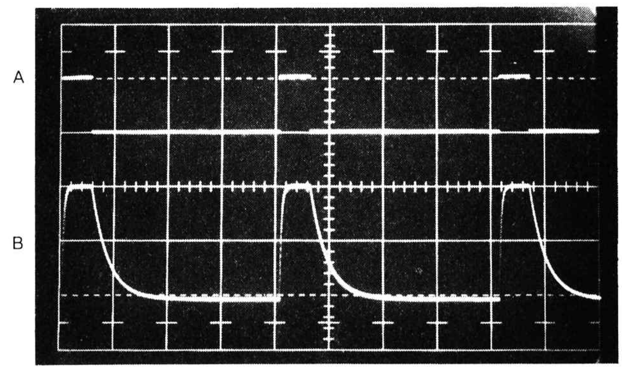
The circuit is simple and requires no high-voltage supplies. However, you must float the load with respect to ground.

Fig 7's circuit uses a high-quality audio amplifier as a current-voltage booster for ac signals. (The McIntosh-75, with its transformer-isolated output and clean response, is a venerable favorite in research labs.) The LF356 op amp's loop is closed locally at a dc gain of 100 and rolled off at 50 kHz by the 200-pF capacitor. Booster output from the audio amplifier feeds back via a 100-kΩ resistor to set overall ac gain at 100.

This design is an excellent choice for laboratory applications because the vacuum-tube-driven, transformer-isolated output is extremely forgiving and almost indestructible. You can use this booster to power ac variable-frequency supplies and shaker-table, motor and gyro drives, as well as other difficult-to-handle inductive and active loads. Power output into 4 to 16Ω loads equals 75W; you can drive 1Ω loads at reduced power output levels.

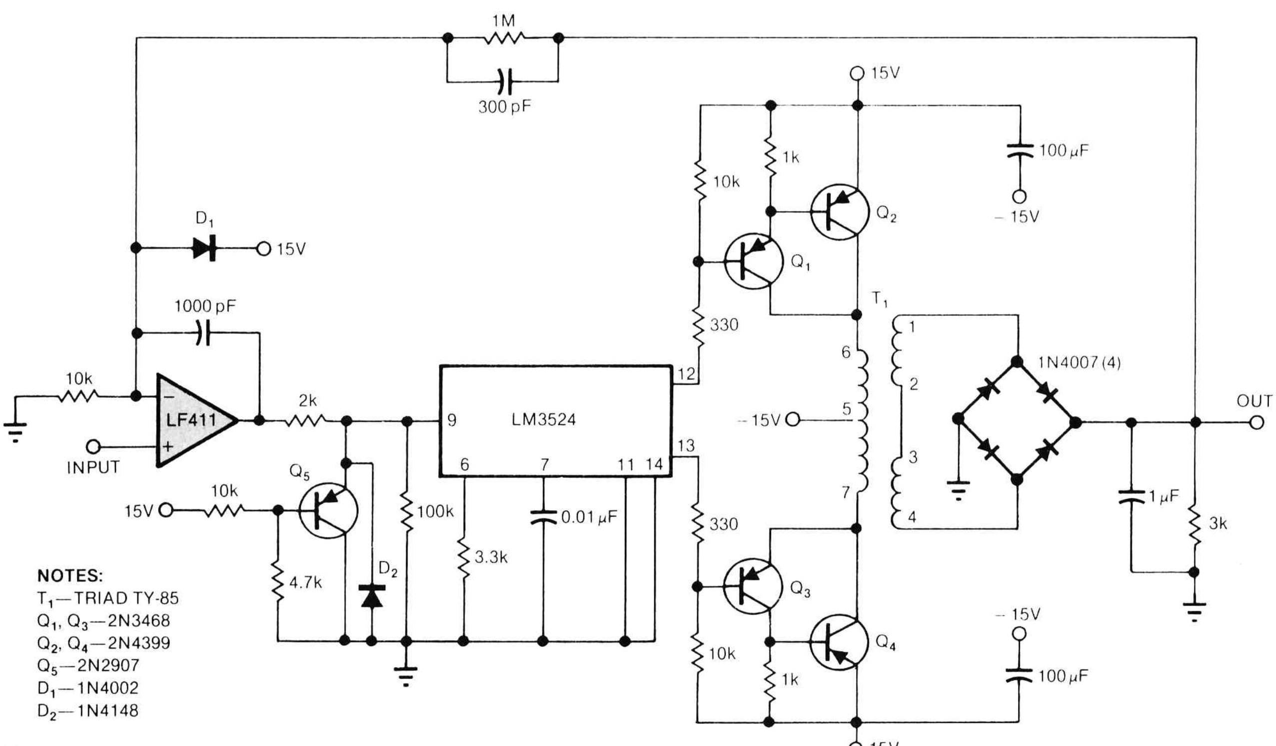
In **Fig 8a,** the LF411 op amp controls as much as 300W for positive outputs ranging to 1000V. The booster achieves this performance without sacrificing efficiency because it operates in switching mode. Additionally, it requires only ±15V supplies to develop its high-potential outputs.

An integral dc/dc converter directly generates the required high output voltage. The LM3524 regulator chip pulse-width-modulates transistors Q_1 through Q_4 to provide switched 20-kHz drive to the stepup transform-



TRACE	VERTICAL	HORIZONTAL
A	10V/DIV	10 mSEC/DIV
B	500V/DIV	10 mSEC/DIV

(b)



(a)

Fig 8—Operating in switching mode, *a high-power booster design* ***(a)*** *features 300W (1000V/300 mA) output capability. Performance is impressive* ***(b):*** *Output rise time equals 1 msec, while fall time measures about 10 msec (due to capacitor discharge time). Slew-rate limiting comes into play during output-pulse rise time—toroid switching action is barely visible on the output pulse's leading edge.* ***(Caution: Output levels are lethal!)***

Watch out for lethal voltage levels

er. The transformer output, rectified and filtered, feeds back to the LF411, which controls the LM3524 input. Therefore, op-amp feedback action has the same stabilizing effect found in the previous circuit designs.

Two protection networks are provided. The Q_5/diode combination clamps the LF411 output to prevent LM3524 damage during circuit start-up. And the diode at the LF411's summing junction prevents high-voltage transients coupling through the feedback capacitor from destroying the amplifier.

For the component values shown, the circuit exhibits a full-power sine-wave output frequency of 55 Hz. Resistor feedback sets amplifier gain at 100, so a 10V input produces a 1000V output. Although the 20-kHz switching rate sets the upper limit on loop information-transmission speed, the 1-μF capacitor at the output restricts circuit bandwidth. **Fig 8b** shows the LF411's boosted response with a 10V pulse applied to the circuit input.

A word of caution: Approach the construction, testing and applicaton of this circuit *with extreme care*. The output potentials developed are far above lethal levels.

As a design aid, the **table** summarizes pertinent points discussed in this article. Using it can greatly simplify the task of matching a booster circuit to your application. **EDN**

References

1. Gussow, S, 'Vacuum-tube amplifiers,'' Massachusetts Institute of Technology, private communication.
2. Dobkin, R C, ''Feedforward amplifiers,'' National Semiconductor Corp, private communication.

Author's biography

Jim Williams, manager of National Semiconductor Corp's Linear Applications Group (Santa Clara, CA), has made a specialty of analog-circuit design and instrumentation development. Before joining National, he was a consultant with Arthur D Little Inc in analog systems and circuits. From 1968 to 1977, Jim directed the Instrumentation Development Lab at the Massachusetts Institute of Technology, where in addition to designing experimental biomedical instruments, he was active in course development and teaching. A former student of psychology at Wayne State University, he lists tennis, art and collecting antique scientific instruments as his leisure interests.