Thermal Issues Count in High-Power Amp Design

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Designers can make sound decisions for dissipating the heat by choosing devices, heatsinks and circuits that will realize the smallest, best-performing design.

Designing a high-speed, high-current amplifier able to deliver at least 50 V_{RMS} is no simple task. For whatever the amplifier will be driving—a magnetic coil in an MRI-type application, a metal detector or an ultrasonic welder—there are many issues to be resolved. The challenge then is to transform what otherwise might be a hit-or-miss puzzle into a rigorous and systematic design sequence—while avoiding some common pitfalls.

The design example in this article examines the thermal requirements when three Apex MP108 open-frame power amplifier modules are connected in parallel to drive a piezoelectric device, often used in industrial ultrasonic nondestructive test equipment (see "Reaping the Benefits of Open-Frame Modules" on page 47). This power amplifier module is capable of high-voltage operation, a fast slew rate and a wide power bandwidth, making it well suited for such an application (**Fig. 1**).

As will be shown in this article, an off-the-shelf open-frame amplifier is the smallest, best-performing approach for medium-production volume applications. What's more, a tight schedule for design completion and the delivery of the engineering package will be met simply because paralleling three operational amplifiers is far easier than assembling an array of discrete devices. This solution is also smaller and less expensive than using a single hybrid power amplifier. Central to the design task will be thermal management techniques that remove the heat from the MOSFET junctions in the modules, so that they operate at safe temperatures, thereby assuring maximum reliability.

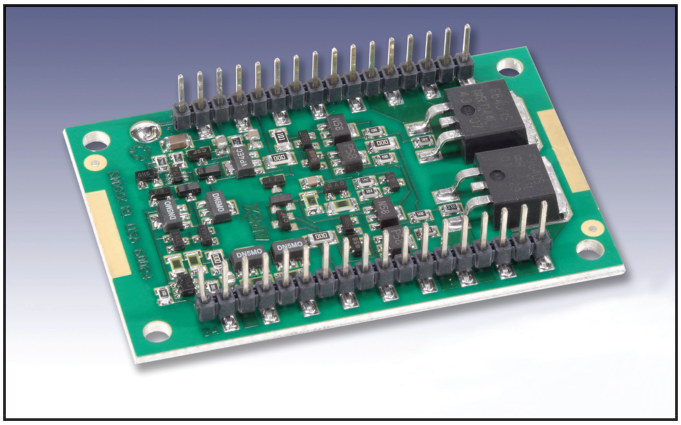


Fig. 1. *An open-frame power module, the Apex MP-108 handles high power and exhibits a fast slew rate and a wide power bandwidth.*

Start at the Load

The best place to begin this design is with the load, for it will play the commanding role in governing how the design develops.

In this example (**Fig. 2**), assume that the load can be represented by a 50-nF capacitor and will be driven by a 50-V_{RMS} source at 50 kHz. A ±90-V supply voltage was chosen because having these potentials on each rail enables peak voltage swings of approximately 76 V. Since a 50-V_{RMS} voltage has a peak value of 70.7 V, this provides a 5.3-V ceiling so that the swing—positive and negative—does not reach the rail voltage.

The issue as to how much voltage the power supply should deliver is fairly simple: In this case, the power supply has to deliver ±90 V. The Common Mode Range (CMR) indicates that signals must be at least 15 V from the supplies. So, planning on a supply that delivers ±90 V makes good sense.

The load impedance of the piezoelectric cartridge is given by this expression:

$$\frac{1}{j\omega C} = \frac{1}{j2\pi\ (50 \times 10^{3})(50 \times 10^{-9})} = -j64\ \Omega \qquad \text{(Eq. 1)}$$

With both the supply-voltage value (V_S) of ± 90 V and the impedance value of 64 Ω known, it can be determined how much power will be dissipated.

The key to determining the required power dissipation begins with knowing the phase difference between V and I in the load. In this case, it is quite simple because the load is modeled as a pure capacitor. Therefore, the phase angle is 90 degrees. The formula for determining the maximum power dissipated in the case of a reactive load for a phase angle greater than 40 degrees is given by:

$$P_D(\max)=\frac{V_S^2}{2Z_L}\left(\frac{4}{\pi}-\cos\Phi\right) \qquad \text{(Eq. 2)}$$

where V_S is the magnitude of each supply and Z_L is the magnitude of the load impedance.

In this case, Eq. 2 can be simplified because the phase angle equals 90 degrees, so the equation becomes:

$$P_D(\max)=\frac{2V_S^2}{\pi Z_L} \qquad \text{(Eq. 3)}$$

Therefore,

$$P_D(\max)=\frac{2(90)^2}{\pi(64)}=80.5\text{ W}$$

Since the load is totally reactive, all of the 80.5 W is dissipated by the three amplifier modules and none by the load. Therefore, each of the modules dissipates one-third of the total or 26.8 W. In this example, assume that operation is continuous rather than burst, which might be the case in an ultrasonic welder or other burst-type operation.

Getting the Heat Out

One of the reasons to design with three open-frame power modules in parallel rather than with a single hybrid amplifier is the benefit realized in ridding the power amplifier of heat. It is easier to conduct heat away from three distinct devices than from one. Additionally, these three modules can utilize a single heatsink, each individually dissipating one-third of the total heat. As a result, the overall surface area will be smaller than it would be if each amplifier employed its own heatsink. Thus, the interface between the heatsink and the air is spread over a relatively small surface area while reducing the thermal flux density.

But, as anticipated with almost any benefit, there is a tradeoff from the electric standpoint: achieving success at driving each of the independent devices so they behave as a single power amplifier. For if any one of the three modules begins drawing excessive current, a runaway effect might occur, which if not curbed, will lead the amplifier trio toward self-destruction. However, a compensation technique can be employed so that each module always carries an equal part of the drive burden.

For the heatsink, we chose an aluminum, extrusion-type Model E3093 manufactured by Thermaflo of Plano, Texas (**Figs. 3a** and **3b**). Aluminum is a popular heatsink material because it is relatively inexpensive and exhibits good thermal performance. Given that this heatsink is smaller and lighter than what is required for a single hybrid amplifier, and that the cost of three MP108s is less than a solo hybrid device, we had an overall cost and weight savings.

To confirm that the junction temperatures of the MOSFET devices in the MP108 modules will not exceed a safe value, use the familiar thermal resistance equation:

$$P \times \theta_{JA} = T_J - T_A \qquad \text{(Eq. 4)}$$

$$P \times (\theta_{JC} + \theta_{CA}) = T_J - T_A$$

We can modify equation 4 by substituting the thermal resistance of the heatsink θ_{HS} for θ_{CA}:

$$P \times (\theta_{JC} + \theta_{HS}) = T_J - T_A \qquad \text{(Eq. 5)}$$

Solving Eq. 5 for T_J to confirm that we will not exceed the maximum junction temperature and rearranging the terms:

$$T_J = P \times (\theta_{JC} + \theta_{HS}) + T_A \qquad \text{(Eq. 6)}$$

In this case, the power per device is 26.8 W and the θ_{JC} is 1°C/W, according to the MP108 data sheet. The θ_{HS} for the heatsink is 0.7°C/W, as determined from **Fig. 3a**, and the rise in temperature above the ambient is 24°C, as determined from **Fig. 3b**.

So, the maximum junction temperature will be:

$$T_J = P \times (\theta_{JC} + \theta_{HS}) + T_A = 26.8 \times (1 + 0.7) + 25°C = 45.56°C + 25°C = 70.56°C$$

Thus, the actual T_J will never rise above 70.56°C, which is far below the maximum permissible value of 150°C specified in the MP108 data sheet.

Determining the Safe Operating Area

A "safe operating area (SOA) curve" depicts the limitations on the power handling capability of each MP108 module. As shown in **Fig. 4**, the horizontal axis on the SOA curve, $V_S - V_O$, defines the voltage stress across the output device in each of the MP108s. It is the range of the instantaneous voltage $(V_S - V_O)$ that is applied to each of the two MOSFETs in an MP108 module. The vertical axis (**Fig. 4**) represents the current that the amplifier is sourcing or sinking through the output pin (V_O). At any instant, each MOSFET is either sourcing or sinking current, as depicted in **Figs. 5a** and **5b**, respectively.

In **Fig. 4**, the blue horizontal line along the top, which is the 20-A line, represents the limit on the output current imposed by current-density constraints in the wire bonds, the die junction area and the conductors in the MOSFETs.

Using a dc equation to estimate the peak power dissipation, it would assume zero current-to-voltage phase shift. But in this case with a purely reactive load, the peak power dissipation is substantially more than the case in which the voltage and current are in phase. Because the load is not resistive, the peak current does not necessarily occur at the point of peak power dissipation; nor does the peak voltage occur at peak

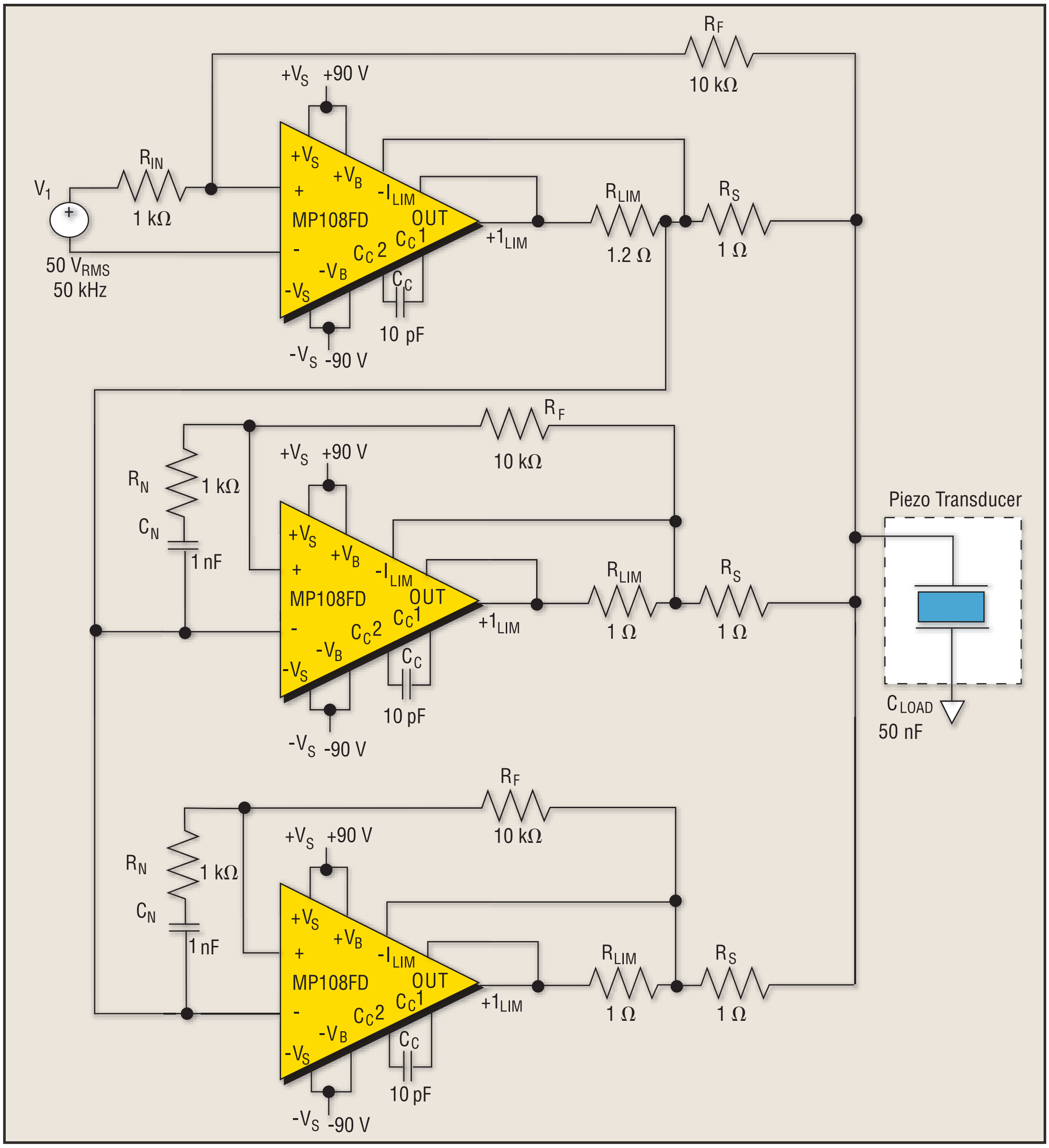


Fig. 2. *Three open-frame, parallel power modules with the master at top, drives the two slaves below. However, the outputs of all three modules drive the load.*

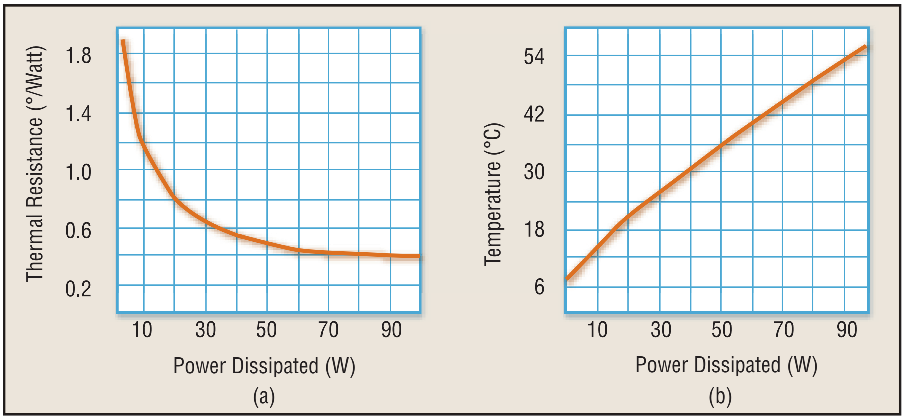


Fig. 3. *The Thermaflo E3093 heatsink thermal resistance as a function of power dissipated (a) and the temperature rise at the interface with the power module (b).*

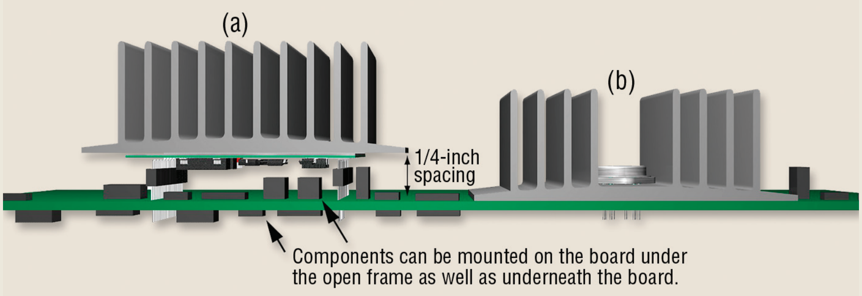
power dissipation. Using the Power Design spreadsheet[2], we can plot a curve that provides the instantaneous current and voltage over the full V_S-V_O range[2]. The peak power dissipation occurs when the power dissipation is closest to the SOA at the "X" in **Fig. 4**.

The peak dissipation is then the voltage difference (V_S-V_O) that develops across each MP108 module multiplied by the current at the highest point. This turns out to be 0.343 A at 116 V, which has been plotted by the black "X" in **Fig. 4** .

Reaping the Benefits of Open-Frame Modules

For more than 30 years, design techniques that employed hybrid power devices were the only approach to designing analog power amplifier solutions. But when decreasing overall system costs and time-to-market are paramount, the relatively new, open-frame products deserve serious consideration. Not just confined to power amplifiers, open-frame modules are being introduced by a number of manufacturers. The open-frame products deliver the power and thermal performance of a hybrid, but at a cost that is significantly less.

Although its footprint can be slightly larger than a hybrid design, an open-frame amplifier module allows a designer to create a smaller and less costly system. The open-frame design incorporates the pins and circuitry on the same side of the substrate. When the open frame is mounted on a printed-circuit board, at a height of 0.25 in. above the board, as shown at the left side of the illustration below, the space created between the amplifier and the board enables bypass capacitors to be placed very close to the amplifier's power supply pins while freeing-up valuable board space. This arrangement also makes room for other necessary system components.



By mounting the heatsink above the power module, an open-frame architecture (left), frees up more space on the board for components.

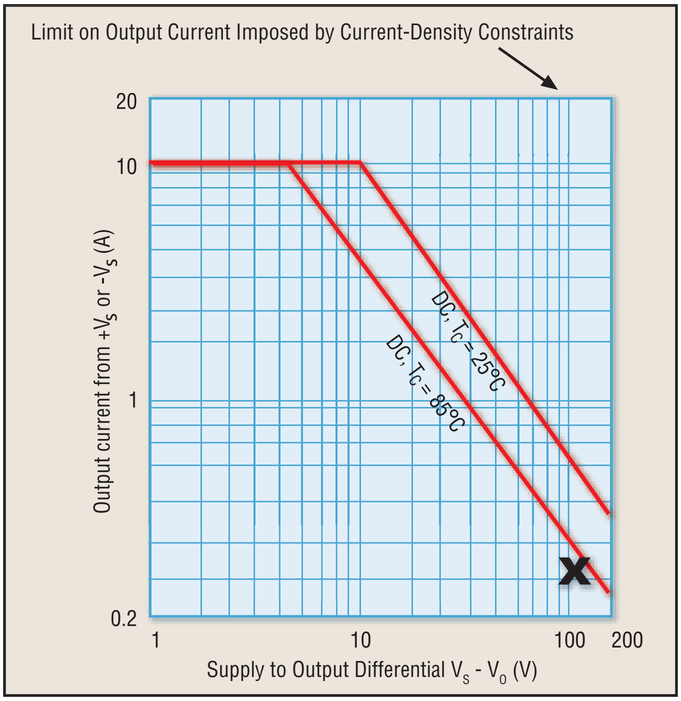


Fig. 4. *Safe operating area (SOA) curves for the MP108 show that the modules will operate well within their safe operating region (X in the figure).*

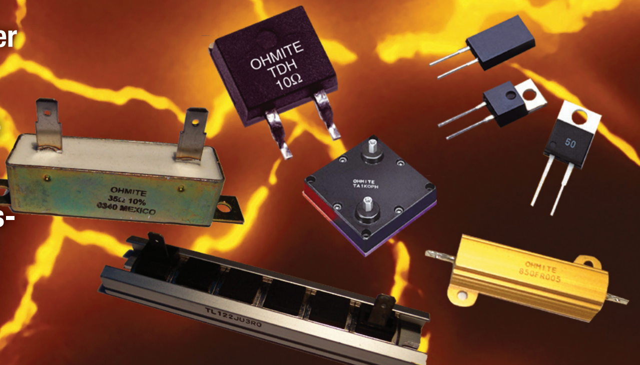
With a dissipated power of 26.8 W, the case temperature for the heatsink will rise 24°C degrees, as can be determined from **Fig. 3b**. This is the temperature rise at the interface between the heatsink and the MP108. Assuming the ambient is 25°C, the case temperature at the heatsink interface will actually be 49°C.

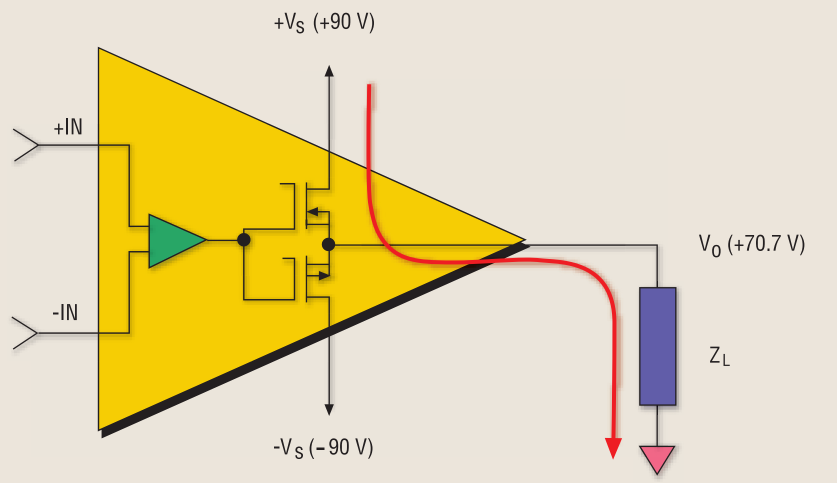
Since the maximum instantaneous power designated by the black "X" in **Fig. 4** is below the 85°C line, then it is certainly below the 49°C line and is therefore in a safe operating region, with regard to operating temperature.

Current Limiting Is a Must

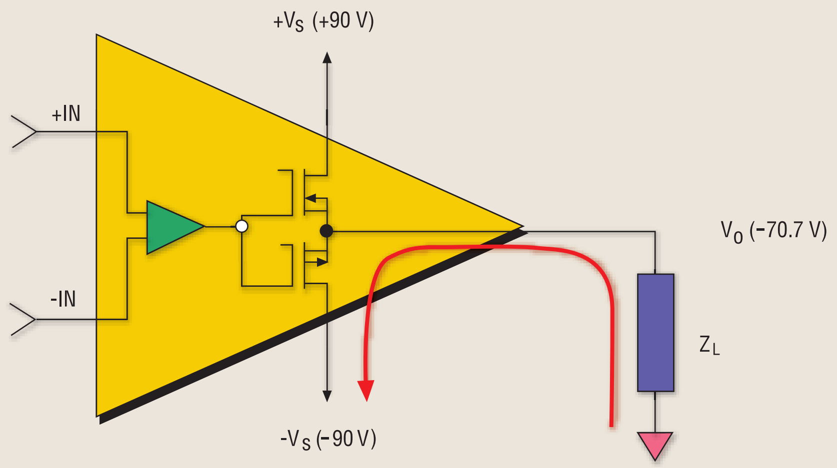
Use the 1.2-Ω resistor for R_{LIM} in the master module and the 1-Ω value for the R_{LIM} resistors in the two slaves, as shown in **Fig. 2**. This will ensure that the master begins to current-limit first. These values of resistance will still allow the normal, instantaneous maximum peak current required by the load, but will limit the short-circuit current, should one occur, to 0.54 A at 25°C and 0.4 A at 85°C. (Note that the effect of these current limiting resistors does depend on the temperature.)

The components R_n and C_n relate to the 10-pF compensation capacitors (C_c) that are employed in all three of the amplifier modules. These compensation





(a) Sourcing Current



(b) Sinking Current

Fig. 5. *Each MOSFET in the MP108 module is either sourcing current (a) or sinking current (b) at any point in time.*

capacitors are chosen for stability reasons and depend on the gain. Normally, we would have a master with a C_c of 10 pF, which is fast, and slaves with a C_c of 33 pF, which would be slower. However, if this were to occur, the frequency performance of the three would not be the same, which would cause a number of problems.

So that we can use the same C_C values for all three amplifiers, we employ "noise gain compensation"[3]. At higher frequencies, C_n approaches a short circuit so that with R_{IN} equal to 1 kΩ and R_F equal to 10 kΩ, the noise gain is 10. But this occurs far beyond the necessary bandwidth for our 50-kHz driving signal. This ensures the signal is not affected, but instead "tricks" the amplifier into believing it has a gain of 10. We then can use the same value (10 pF) for the compensation capacitors (C_C) for all three amplifiers so that they will all exhibit the identical slew rate, bandwidth and overall performance[3].

We still have a limitation on bandwidth in this configuration because there will be a phase difference between the outputs of the master and the slave. The different output voltages will create circulating currents in the 1-Ω sharing resistors (**Fig. 2**). Higher signal frequencies will create more phase difference and will eventually create unacceptable circulating currents. In this configuration, the phase difference will be less than 5 degrees at 50 kHz, creating a voltage difference of about 0.33 V.

Summing Up

Although designing with discretes might make sense for high-volume production at quantities well above 100,000 units, low-to-medium volume applications can benefit from selecting an off-the-shelf open-frame amplifier solution because thermal management issues can be more easily addressed. And at these volumes, nonrecurring engineering charges are a significant component of cost. In short, if you choose to design from the ground up with discretes, you are often looking at design times on the order of four to five weeks, given that you are an experienced power analog designer. But by choosing an open-frame power module approach, you are likely to reduce the basic design time to as little as two days, even with moderate experience and a little outside technical help.

Open-frame products save still more board space by allowing the heatsink to be mounted on top of the device, as shown in the illustration in "Reaping the Benefits of Open-Frame Modules" on page 47. This is in sharp contrast to a hybrid design that requires through-hole mounting of the hybrid and the heatsink. The latter places the heatsink on the board, thus occupying valuable board space close to the amplifier. **PETech**

References

1. Apex Microtechnology Corp. Application Note 24, *General Operating Considerations.* www.apexmicrotech.com.

2. Apex Microtechnology Corp. Application Note 37, *Using the Power Design Tool.* www.apexmicrotech.com.

3. Apex Microtechnology Corp. Application Note 25, *Driving Capacitive Loads.* www.apexmicrotech.com.