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Figure 2 Nuventix cooling devices consist of a diaphragm mounted in a cavity. An electromagnetic driver vibrates the diaphragm 100 to 200 times per second, forcing tiny jets of air out through openings in the cavity. These devices are virtually silent compared with conventional fans.

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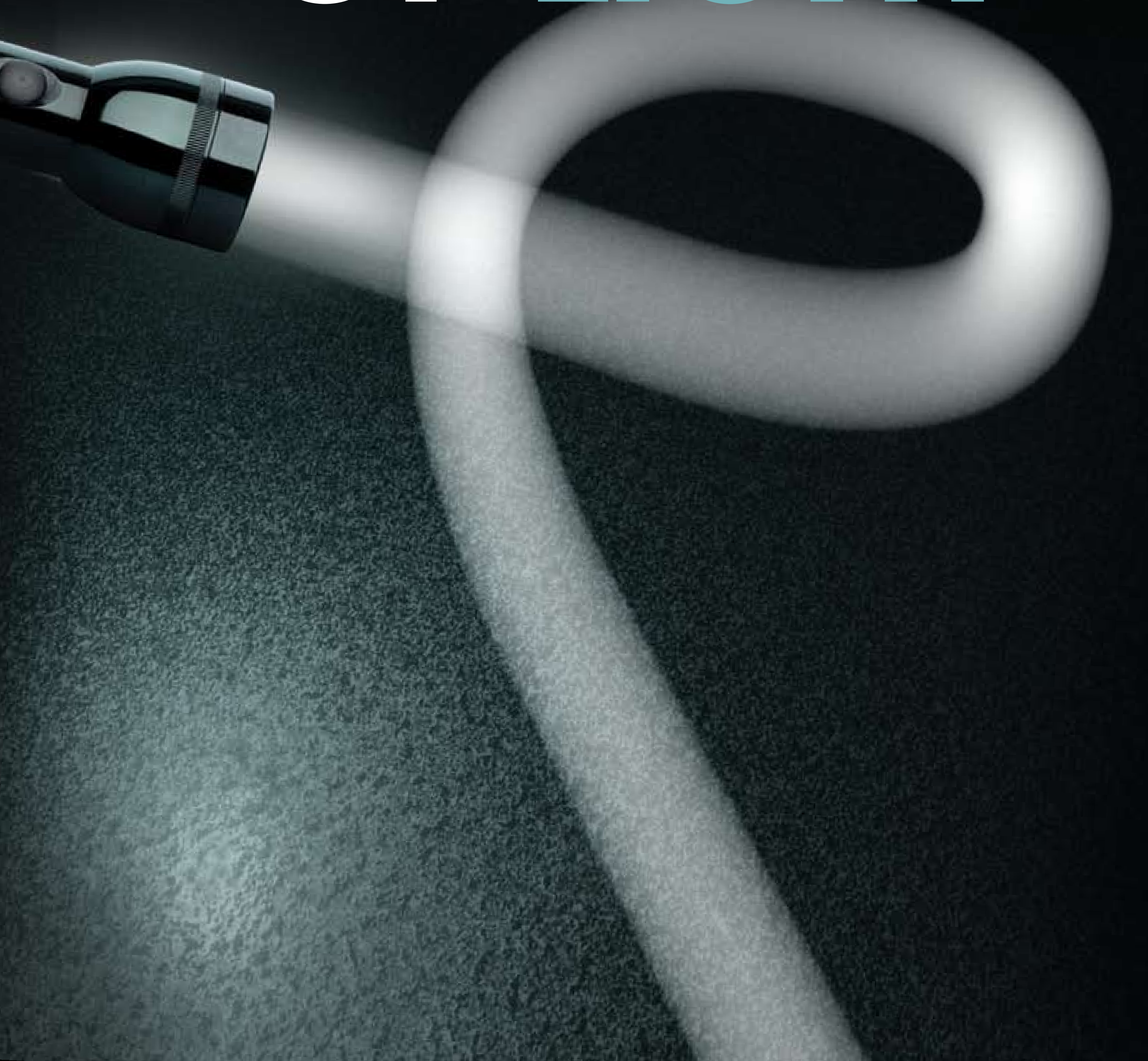
BY MARGERY CONNER • TECHNICAL EDITOR

Electronic and thermal improvements bring advances to lighting technologies

THE DIRECTION OF LIGHT



The desire to cut costs and reduce energy use has led both consumers and businesses to explore more efficient lighting options. By 2012, the United States will begin to implement the first phases of the efficiency standards mandated by the EISA (Energy Independence and Security Act) of 2007 and will begin to phase out the use of incandescent bulbs (**Reference 1**). In the short term, CFL (compact-fluorescent-light) bulbs will be the most common replacements for incandescents, and halogen bulbs will be a distant second. Manufacturers have also begun to deploy SSL (solid-state lighting) employing HB LEDs (high-brightness light-emitting diodes) in applications that can trade off SSL's premium price in exchange for efficiency and ruggedness.

RESIDENTIAL AND COMMERCIAL LIGHTING CURRENTLY ACCOUNTS FOR 20% OF THE ELECTRICITY USED IN THE UNITED STATES. ALTHOUGH CFLs ARE THE BEST OPTIONS FOR INCREASING EFFICIENCY AND DECREASING POWER NEEDS, HB-LED TECHNOLOGY IS ALSO MAKING ADVANCES. BOTH TECHNOLOGIES HAVE DRAWBACKS, HOWEVER, AND STAND TO BENEFIT FROM IMPROVEMENTS IN ELECTRONICS, MANUFACTURING, AND THERMAL MANAGEMENT.

Both CFLs and SSL have drawbacks, however. CFLs had an early history of premature failures, and you must still carefully match them to your application, including on-time and bulb orientation. In addition, some users have concerns about the bulbs' use of mercury, its impact on the environment, and the bulbs' potential for hazardous breakages. The HB LEDs in SSL, on the other hand, struggle with thermal-management challenges and an overall hefty price tag. Fortunately, the two lighting sources can benefit from new circuits, chips, and thermal devices, as well as advancements in manufacturing.

Cost-conscious consumers have recently turned to CFLs to reduce their energy bills. CFLs now account for 20% of light bulbs that users purchase for residential use, and that number will continue to grow because of minimum-lighting-efficiency standards that the EISA set. A common misconception about the EISA is that it bans the sale of incandescent bulbs after 2012. "The [EISA] does not expressly ban incandescent bulbs. … It lays out performance thresholds," explains Alex Baker, lighting-program manager for Energy Star. "If you can make an incandescent bulb that meets those performance thresholds, then you can continue to sell [those] bulbs."

Baker lays out the phase-in schedule for more efficient lights: In 2012, EISA will require an increase of approximately 25% in lumens per watt for 100W incandescent bulbs. In 2013, that requirement will also apply to 75W bulbs and, in 2014, to 60W bulbs.

These restrictions apply only to the traditional Edison-type light bulbs with midsized screw bases. The EISA does not limit the sale of many other bulbs, such as incandescent bulbs with candelabra-type bases; globe-shaped bulbs, such as those that find use in bathroom-vanity fixtures; general-service light bulbs; or modified-spectrum lights, such as GE's Reveal series. "There's still going to be plenty of incandescents out there for many years to come," says Baker.

After the United States passed the EISA in 2007, GE vowed to develop an HEI (high-efficiency-incandescent) bulb that met the standards. However, in November 2008, the company announced that it had suspended the development of HEI bulbs to focus on LED and OLED (organic-LED) lighting because of the two technologies' potential to surpass other energy-efficient technologies, such as fluorescent, with the additional benefits of long life and durability **(Reference 2)**.

Despite its commitment to LED and OLED lighting, GE still sees a strong future for CFLs, as the introduction of its Energy Smart CFL line demonstrates (**Figure 1**). CFLs have an overwhelming advantage in that they are inexpensive and available. However, CFLs have their detractors, who tend to fall into two broad categories: those who object to the CFLs because they contain small amounts of mercury and those who object to the devices' performance.

The mercury problem is complex. A CFL uses a tube filled with pressurized mercury vapor. The CFL's internal ballast transforms the ac-line voltage to create an electrical arc through the mercury vapor, creating UV (ultraviolet) emissions, which strike the phosphor coating on the inside of the tube. The phosphor converts the UV light into visible "white" light. Early CFLs had relatively large amounts of mercury, often exceeding 10 mg per bulb. The dosing method that introduced the elemental mercury into the tube was relatively crude: Energy Star's Baker likens it to using a medicine dropper to add liquid. The process was difficult to control, and manufacturers tended to err on the side of too much rather than too little mercury. In addition, over time, the mercury vapor tended to bond with the phosphor powder that coated the inside of the tube, and the mercury must be in vapor form to emit UV light.

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CFL manufacturers have reduced the amount of mercury the bulbs require by developing a pelletized method of dosing the tubes, allowing for more precise control of the added mercury. They have also developed phosphor coatings that resist mercury bonding. According to Baker, some CFL manufacturers have stated that 1.5 mg of mercury approaches the theoretical minimum. Energy Star standards now cap the maximum mercury amount for CFLs at 5 mg.

European lighting manufacturer Megaman claims that the mercury in its "mercury-liquid-free" line of CFLs remains in an amalgam until it reaches 100°C atmospheric pressure. Normally, because the tube is pressurized, the mercury is a vapor at room temperature. Megaman claims that the amalgam does not pollute water or landfills.

No formal definition of how much mercury is toxic is available. Researchers perform most work on methyl mercury, which is a form of mercury that ends up in the water and eventually in fish. Because a fetus's developing central nervous system is especially susceptible to mercury, the FDA (Food and Drug Administration) and EPA (Environmental Protection Agency) have issued warnings for pregnant women about limiting their consumption of certain kinds of fish from specific waters. Even these amounts are open to debate, however: Because of supposed general-health benefits that eating fish confers, the FDA recently relaxed its stance on how much fish a pregnant woman should eat. Opponents claim that the FDA yielded to pressure from the agricultural industries. These differences in opinion underline the fact that no hard and fast rules exist for methyl mercury, elemental mercury, or mercury vapor. Energy Star's Web site provides detailed guidelines on cleaning up after CFL breakage for anyone who is concerned about mercury's danger (**Reference 3**).

AT A GLANCE

- CFL (compact-fluorescent-light) bulbs had an early history of premature failures, and you must still carefully match them to your application.
- Some users have concerns about CFL bulbs' use of mercury, its impact on the environment, and the bulbs' potential for hazardous breakages.
- CFL manufacturers have reduced the amount of mercury the bulbs require by developing a pelletized method of dosing the tubes, allowing for more precise control of the added mercury. They have also developed phosphor coatings that resist mercury bonding.
- HB LEDs (high-brightness light-emitting diodes) in SSL (solid-state lighting) struggle with thermal-management challenges and an overall hefty price tag.
- Incandescent light bulbs will still remain in use for a long time to come.
- DORS (dim-on-random switching) allows light to dim with every rapid on/off action in seconds, adjusting from 100% brightness to 66% to 33% and, finally, to 5%. The technology exemplifies the migration of control intelligence from building infrastructures to light bulbs.

Can using CFLs actually reduce the amount of mercury released into the environment? Maybe. Coal is the source of much of the electrical power that the United States and many other countries generate; coal-fired power generation releases mercury into the atmosphere. Powering an incandescent bulb over its lifetime releases 10 mg of mercury, compared with a maximum of 4 mg for a CFL. Some areas, such as California, rely on hydroelectricity and natural gas, so switching to CFLs in California would not necessarily reduce mercury emissions. On the other hand, when California's demand exceeds its capacity, the state gets its energy from a number of out-of-state sources, including coal,

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through the North American power grid. The savings in energy due to CFLs' greater efficiency remains: CFL users can save \$15 to more than \$60 over the life of a CFL, assuming a 10,000-hour life and electricity costs of 13 cents per hour. The \$15 savings assumes a lifetime of only 2000 hours.

Despite that advantage, however, detractors of the technology usually complain about the lights' failure to meet advertised lifetimes and about the "cold" fluorescent color the bulbs produce. CFLs burn out prematurely primarily because of application mismatches. The ideal long-life application for a CFL is in a table lamp whose bulb points straight up so that the electronics in the base are out of the path of rising heat, the bulb is unenclosed so that heat doesn't build up, and the lamp is on for several minutes at a time. In a harsher application, a bulb could reside in an enclosed light fixture on the ceiling of a closet; in this scenario, users briefly turn the light on and then off. In response to complaints about the short lifetimes of CFLs, Energy Star created a bulb-finder guide to assist users in finding the right bulbs for their applications (**Reference 4**).

Standard CFLs are poor candidates for dimmer-switch-controlled lights in homes because these switches typically

SPACE CONSTRAINTS ARE INHERENT IN HOME AND OFFICE LIGHTING, LEAVING HEAT REMOVAL AS THE DOMINANT ISSUE IN SSL.

use triac-based phase-cutting dimmer circuits. Triac-based wall dimmers work well with resistive loads, such as incandescent bulbs, but perform poorly with capacitive loads, such as CFLs. Using a generic CFL with a triac-based dimmer switch causes the bulb to die immediately or drastically shortens the bulb's life. Most major CFL manufacturers now offer a specialty version of a dimmable CFL bulb.

International Rectifier's DIM8 ballast-control half-bridge driver reduces the component count for the CFL-dimming control circuits, which must fit into the base of the CFL bulb, where space is at a premium. With the addition of a microcontroller, the DIM8, whose prices start at \$1.09 (10,000), can serve as a dimming controller inside the CFL. It allows a user to dim the light simply by switching a standard light switch on and off with no additional wiring or wiring changes. This scheme, DORS (dim-on-random switching), allows light to dim with every rapid on/off action in seconds, adjusting from 100% brightness to 66% to 33% and, finally, to 5%. You reset the light to full brightness by switching off the lamp for more than 3 seconds and then switching it on again. DORS exemplifies the migration of control intelligence from building infrastructures to light bulbs.

The combination of cost savings, government regulations, and improvements in CFL technology has convinced purchasers of lights for both residential and office use to make the move to the more efficient lighting. CFLs are not the only efficient light sources, however. SSL using HB LEDs can be as efficient as CFLs; has the potential for unlimited variation in colors, lifetime, and packag-

ing; and has begun to move into lighting applications in offices, theaters, homes, and city streets.

Standard low- and medium-power LEDs serve as indicators: They create just enough light to draw attention to a system's state and typically draw approximately 20 to 40 mA. HB LEDs typically draw 350 mA to 1.5A. For example, Cree's XLamp XP-E cool-white HB LEDs provide 114 to 122 lumens at 350 mA. SSL HB LEDs have lifetimes in excess of 25,000 hours or 22 years when they remain lit for three hours a day. They are good choices for applications requiring ruggedness or in which it is difficult or expensive to change a light bulb, such as streetlights. Cities such as Austin, TX; Juneau, AK; and Raleigh, NC, have moved to LED streetlights to save on energy bills and maintenance costs.

SSL units include several components—the HB LED; the ac/dc- and dc/dc-power-conversion electronics, which can reduce efficiency by 10 to 15%; and the cooling components—that all play a part in reducing the light efficiency, or efficacy, measured in lumens per watt. In an application in which space is not at a premium, such as a streetlight, you could put an HB-LED die on a huge chunk of aluminum and passively radiate all of the heat the die generates. Space constraints are inherent in home and office lighting, however, leaving heat removal as the dominant issue in SSL.

Figure 3 Cool Innovations' flared-pin fin heat sinks feature an array of sparsely configured round pins that slant outward, a configuration that can cool the HB-LED die in SSL in natural-convection environments.

The combination of an electron and a hole inside an LED produces both radiative and nonradiative recombination. Radiative recombination generates a photon with the energy of the hole-electron-pair bandgap. Instead of producing light, nonradiative recombinations just vibrate the LED-crystal lattice, resulting in heat.

Although LED manufacturers are constantly refining their manufacturing processes to minimize impurities and the resulting nonradiative recombinations, impurities will always be a significant heat generator for LEDs, especially as HB LEDs' die size increases; the probability of defects increases with the larger die. Unlike incandescent bulbs, LEDs cannot radiate heat as infrared energy. The exception is IR (infrared) LEDs, which are comparatively efficient. Adding to the problem, sockets for conventional incandescent bulbs act as insulators rather than heat radiators.

In addition, as an LED's temperature increases, its lumens per amp and its overall power efficiency decrease. Chronically running an HB LED at an elevated temperature results in decreased efficiency, at least a slight color shift, and an overall decrease in life expectancy. Using small electromechanical fans is one way to actively remove heat from HB LEDs, but they require additional power, reduce lighting efficiency, introduce audible noise, and suffer from the decreased reliability to which mechanical moving parts are susceptible. The ideal cooling product for an HB LED must be small, efficient, quiet, and highly reliable.

One approach is the synthetic-jet design Nuventix uses in its SynJet fanless coolers. The SynJet requires much less current than a motor and operates from a 5V power supply. The coolers use an electromagnetically coupled diaphragm that pulses high-velocity jets of air through tiny nozzles. Once the air leaves the nozzle, it entraps the sur-

+ For more on new applications and standards for high-brightness LEDs, go to www.edn.com/article/CA6512150.

+ For more on control ICs in dimming circuits for energy-efficient CFLs, go to www.edn.com/article/CA6614726.

+ For another look at CFLs and their applications, visit www.edn.com/article/CA6607201.

+ Find out how to operate an LED "bulb" from a dimmer switch at www.edn.com/blog/1470000147/post/380022638.html.

+ For *EDN*'s coverage of Nuventix's SynJet technology when it was still an R&D project at the Georgia Institute of Technology, go to www.edn.com/article/CA376646.

rounding air, pulling that air along with it, in much the same way that a tornado gathers mass by pulling in surrounding air.

Nuventix offers standard SynJet products for HB-LED fixtures. One is an MR-16 configuration; the other resembles a PAR-38-style lamp base. The MR-16 and PAR-style configurations can dissipate as much as approximately 20 and 50W, respectively. A self-contained HB LED with a luminous efficacy of 80 lumens/W can deliver several thousand lumens, according to Cary Eskow, director of Lightspeed, the SSL and LED business unit of Avnet Electronics Marketing. Prices for SynJet start at approximately $15 in low volume (**Figure 2**).

Passive heat sinks are also seeing some innovation. Cool Innovations' flared-pin, finned heat sinks outperform equivalent straight-pin heat sinks (**Reference 5**). A 1.5-in.-tall, 1-in.^{2} straight-pin, finned aluminum heat sink has a thermal resistance of 16.14°C/W, whereas its flared-pin equivalent has a thermal resistance of 12.65°/W, an improvement of 22%. A 2-in.-tall, 5-in.^{2} straight-pin heat sink has a thermal resistance of 0.74°C/W, compared with a flared-pin version of 0.64°C/W, an improvement of 14% (**Figure 3**).

It would be a formidable challenge for SSL to replace the venerable incandescent bulb and, in the longer run, the CFL. The task is so difficult that the Department of Energy last May instituted the L Prize (www.lightingprize.org) for the development of an SSL that "must perform similarly to the incandescent lamps they are intended to replace in … color appearance, light output, light distribution, and lamp shape, size, form factor, appearance, and operating environment. They must be reliable, available through normal market channels, and competitively priced." Industry observers currently forecast the prize to be worth $10 million. EDN

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