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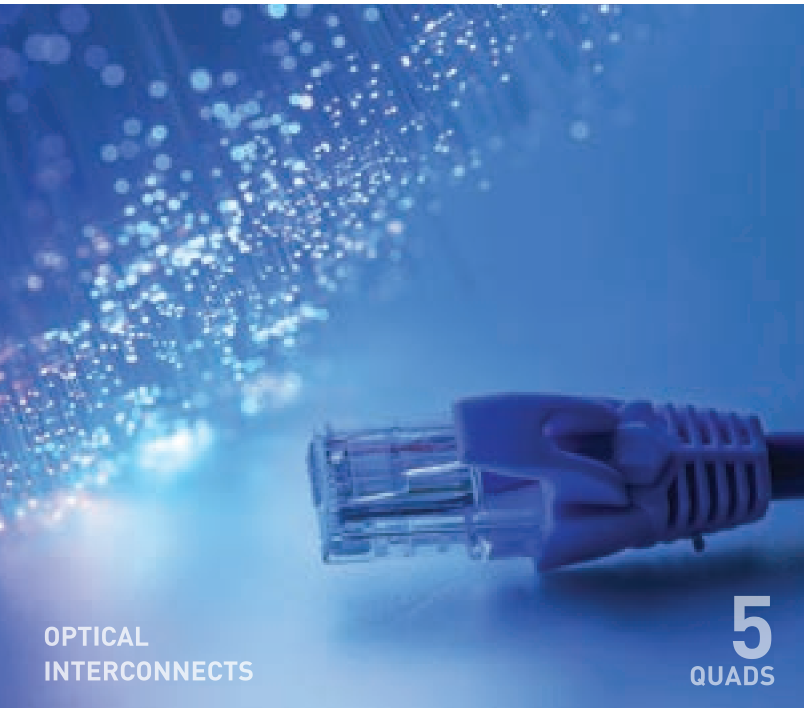
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Negawatts

Optics, Photonics and Energy Savings

Edited by Keith Goossen

Five scientists survey the potential energy savings that could flow from selected optical technologies, ranging from optical data interconnects to photonic gas sensors.

When thinking about optics, photonics and energy, one usually thinks of photovoltaics. But other optics and photonics technologies can also have a huge energy impact—not in generating energy, but in saving it. One need look no further than the global long-distance fiber communication system; by one calculation, powering today's Internet using electrical links, rather than long-haul optical fiber, would burn more energy than is currently consumed for *all* purposes worldwide.

The pages that follow survey the potential energy impact of six technologies in optics and photonics—flat-panel displays, solid-state lighting, optical interconnects, infrared CO_2 sensors, optical building envelope technology, and industrial lasers. Together, these six areas could realize power savings—"negawatts," in the theoretical energy-avoidance units proposed by Amory Lovins—of as much as 65 quads per year. (A quad is equivalent to 10^{15} Btu, or 1.055 exajoules.) That amounts to some 12 percent of global energy consumption. While the calculations that follow rest on a variety of assumptions, they provide a glimpse of the enormous energy efficiency potential of optics and photonics. —*Keith Goossen*

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References and resources can be found online at www.osa-opn.org/negawatts/references.

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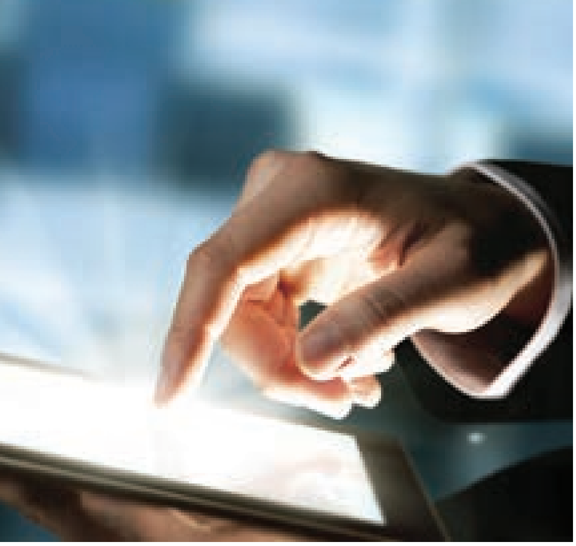


FLAT-PANEL DISPLAYS

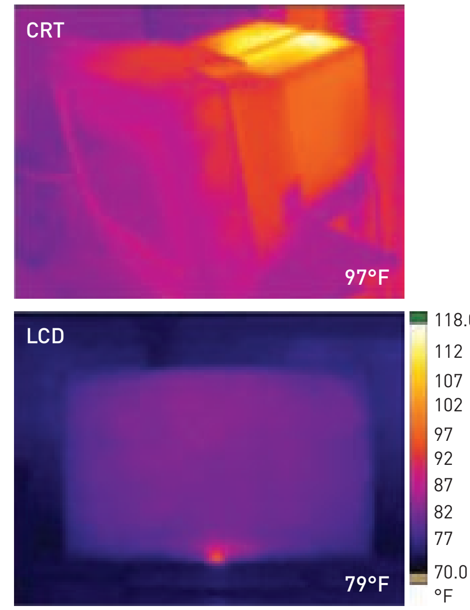
The transition in the past decade from cathode ray tubes (CRTs) to liquid crystal displays (LCDs) has resulted in energy savings of up to 75 percent per unit screen area. LCD technology, utilizing the electro-optic properties of liquid crystals combined with backlighting from cold-cathode fluorescent lamp (CCFL) and, later, more efficient LEDs, has superseded the inefficient electron gun and phosphor cathodoluminescence (CL) of CRTs. And another 30 percent inherent per-area energy saving is expected from the further transition to organic LEDs (OLEDs).

The efficiency gain of LCDs over CRTs stems mainly from the power requirements for generating and scanning the CRT electron beams. A 19-inch CRT display consumes about 100 W. Thermal electrons are generated by an oxide-coated cathode (4 W), collimated via electron guns (27 W), and accelerated toward a phosphor screen by electrically charged anodes (39 W). The conversion efficiency of CL slightly lags that of LEDs or fluorescent, due to energy loss during the migration, to transfer of excitation energy, and to the minimum energy requirement to create electron-hole pairs, which causes non-radiative energy losses of incident electrons. Primary-color phosphors range in conversion efficiencies from 11 to 25 percent.

The transition in the past decade from cathode ray tubes (CRTs) to liquid crystal displays (LCDs) has resulted in energy savings of up to 75 percent per unit screen area.

Energy consumption of an equivalent LCD can be as low as 25 W with LED backlighting. The electrical-to-optical efficiency of CCFLs can reach about 20 percent in such systems, and the overall efficiency of systems using phosphor-converted LEDs can reach 30 percent, equivalent to more than 100 lumens/W. OLED displays are inherently 30 percent more efficient than LCDs, because an LCD pixel spends, on average, 30 percent of the time blocking the light, whereas there is no light blocking in OLED displays. In 2013, Panasonic announced it had developed a high-efficiency white OLED with a luminous efficacy of 114 lumens/W; estimates from another vendor, Samsung, suggest that a power consumption of only 20 W for 40-inch high-definition OLED displays may be coming in several years.

How do these numbers translate into overall energy savings? The Super-efficient Equipment and Appliance Deployment (SEAD) group estimates annual global energy consumption due to computer monitors at 30 to 40 terawatt-hours (TW-h) per year, and the International Energy Agency (IEA) has identified worldwide annual television energy consumption at 275 TW-h. On a per-area basis, LCDs consume 25 percent of the energy of CRTs, and OLEDs 18 percent—but, of course, displays have been getting bigger over the same period, which represents an added complexity.



Infrared images of traditional CRT (top) and LCD display (bottom) show lower heat emission and higher efficiency of the LCD, with most of the CRT's inefficient heat generation located not on the phosphor screen but in the electron beam generation.

Image taken by Daniel Wolfe, using Fluke TI110 infrared camera

Assuming that CRTs would have increased in area at the same rate as has been seen in the past several years for flat-panel displays, however, a rough calculation of annual energy savings would 0.82 × (35 + 275) TW-h—that is, energy savings of around 82 percent from LCD and OLED technology, multiplied by worldwide monitor and television energy consumption—or a total savings of 254 TW-h. Assuming an electric power plant efficiency of 0.3, that equates to 2.9 quads/year of primary energy. OPN

Daniel Wolfe, University of Delaware, Newark, Del., USA

SOLID-STATE LIGHTING

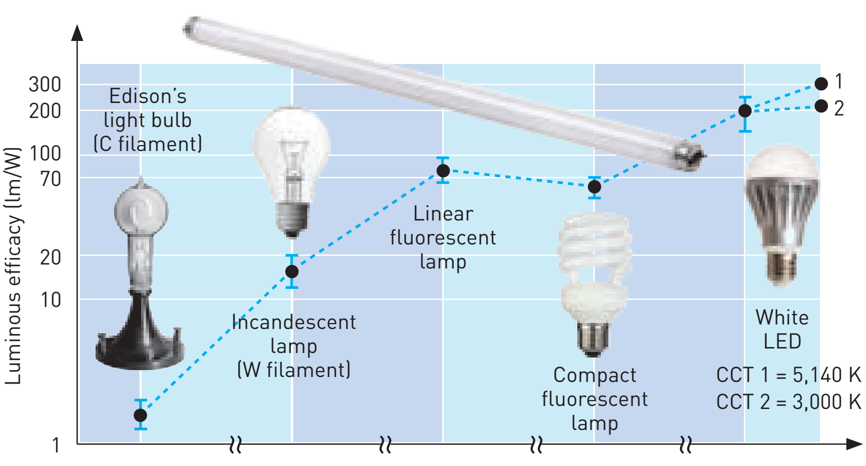
Solid-state lighting devices emitting white light of a wide range of color temperatures have attained a remarkable efficiency. Luminous source efficacies (the ratio of luminous flux to power) for solid-state lighting have reached more than twice those of the best conventional sources. And there is room for these values to grow.

At present, commercially available solid-state light sources have luminous efficacies of 50 to 100 lumens/W. The theoretical maximum of LED efficacy is about 300 to 350 lumens/W, with the exact value depending on the color temperature, the specifics of the LED chip (e.g., blue or violet) and the specifics of the wavelength-converting phosphor (e.g., yellow or green-plus-red). Company research labs have recently reported efficacies in the range of 200 to 300 lumens/W.

These record efficiencies are typically attained at low current densities, where the LED chip efficiency is highest. LED chips in lamps available to the consumer, by contrast, are driven at high current densities, to minimize the number of LED chips. Notwithstanding this, the efficacies of commercially available sources can be expected to increase to values higher than 100 lumens/W in coming years. Given this excellent recent performance, solid-state light sources can realistically be expected to achieve, on average, efficiencies a factor of two higher than those of conventional incandescent and fluorescent light sources—an expectation that would have seemed optimistic only a few years ago.

Therefore, if conventional light sources were fully replaced by solid-state sources, power consumption attributable to lighting, on average, could be reduced to half of its current value. There's every reason to be confident that these savings can be achieved via a complete retrofit of society's lighting with LED-based systems, in view of the transition away from conventional lighting and toward LEDs that's already under way. But the timing of the savings depends upon the commercial adoption of LED lighting. The fraction of LED lighting purchased in 2010 was near zero. In 2014, the U.S. Department of Energy has estimated the LED purchase fraction at around 5 percent (a likely underestimate for MR 16 lamps, but an overestimate for regular light bulbs or A-lamps). Based on the current rate of adoption, we expect that the fraction could increase to virtually 100 percent by 2025.

Luminous source efficacies for solid-state lighting have reached more than twice those of the best conventional sources. And there is room for growth.



Evolution of luminous efficacy, from Edison to LED. White LED device performance is shown for correlated color temperature (CCT) of 5,140 K and 3,000 K.

Adapted from Fred Schubert/CCT Source: Cree Company, 2014;Osram Company, 2014

The global energy savings of LED lighting can be estimated based on figures from the International Energy Agency (IEA) and the U.S. Energy Information Administration (EIA). IEA estimates that lighting accounts for 20 percent of global electricity use. EIA, meanwhile, pegs total U.S. 2014 electricity consumption at 4,100 TW-h, and worldwide annual electricity consumption at 20,000 TW-h. A reduction of lighting consumption by half due to conversion to LED lighting, then, could, result in potential long-term annual savings of some 2,000 TW-h—or, using an electric power plant efficiency of 0.3, a reduction in primary energy of 23 quads/year. OPN

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OPTICAL INTERCONNECTS

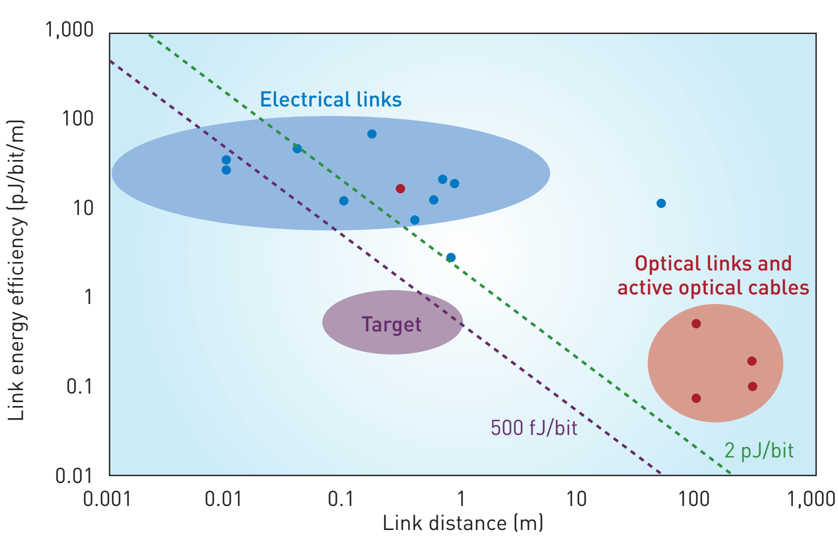
When fiber optics first emerged as a viable communication technology, coaxial and other electrical waveguides were increasingly deployed around the globe, and horn-antenna-based microwave relays were in widespread use. Coaxial RF communication systems achieved an efficiency of 10^{-5} J/bit/1,000 km, whereas optical systems have achieved 10^{-9} J/bit/1,000 km—an energy saving of four orders of magnitude. Perhaps more significant, commercial optical systems today have a bandwidth–distance product of 10^{7} Gb/s-km, versus 10^{-2} Gb/s-km for state-of-the-art electrical transmission lines. By this metric, realizing today's Internet without optics could, hypothetically, have required nine orders of magnitude more electronic hardware and associated manufacturing, maintenance and support infrastructure.

The Global e-Sustainability Initiative (GeSI) has estimated the carbon footprint of fiber optic communications in 2011 at about 0.2 percent of the total global carbon footprint, mostly from operating energy use. Thus, if fiber optic communication technology had not emerged, and electrical links rather than optical fiber had been used to realize today's Internet, several times the total current worldwide carbon footprint (and energy use) would be required for the transmission equipment alone.

Obviously, the Internet that would exist without optical fiber would differ greatly from the current version and would operate at much lower bandwidth (remember dial-up?). But it would almost certainly use as much energy as the economics would allow, resulting in significantly higher global energy use and carbon footprint. And while the Internet has spurred increased worldwide economic growth—and energy use correlates strongly with economic growth—since the beginning of the widespread use of the fiber-based Internet in the United States, around 2000, U.S. energy use per capita has declined, and energy use per gross domestic product dollar has continued on its already established downward trend.

By these indications, the transition to a fiber-based Internet economy has not resulted in greater energy use. Indeed, some studies have indicated that Internet technologies can lead to deep energy savings far beyond communications alone, through techniques that include dematerialization, telecommuting and so-called smart technologies such as automobile traffic controls, smart electrical power grid controls and in-home power monitoring. In total, according to GeSI, information and communication technologies are anticipated to offset more than seven times their own carbon footprint by 2020. If done right, energy spending on the Internet can be a case of spending a quad to save seven.

Going forward, additional energy savings could come as optical fiber communication penetrates the distance scale below 100 m, reaching to 1 mm. In such short links or interconnects, an optical system can outperform electronic systems in terms of energy/bit/meter by one to two orders of magnitude. The anticipated global energy savings of displacing electrical with optical interconnects can thus be estimated assuming that (1) in coming years servers, routers, switches, and other devices convertible from an electrical to optical backplane or network will consume a few percent of the world's energy, and (2) the interconnects consume 10 to 30 percent of that share. By that calculation, development of optical interconnects covering 1 mm to 100 m could conceivably result in additional energy savings of approximately 1 percent of the world's energy consumption, or around 5 quads/year. OPN



Energy efficiency of electrical and optical links, including active optical cables.

A. Krishnamoorthy et al., IEEE J. Sel. Top. Quantum Electron. **17**, 357 (2011)

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NON-DISPERSIVE INFRARED (NDIR) CO_2 SENSORS

The lowly NDIR gas sensor is a simple photonic device—with an enormous potential impact on energy efficiency through ventilation control. A typical design consists of an incandescent source guided through a gas chamber to a detector that uses a band-pass filter centered at the gas absorption line to measure gas concentrations. Advanced designs with infrared LEDs, under development, will provide faster initialization time, longevity of greater than 15 years and lower power consumption and cost.

Maintaining a building's "air quality" can have many meanings, but in most cases, particularly in commercial buildings, it means keeping CO_2 below acceptable values, usually considered to be 1,000 ppm (a level set not based on health effects but to minimize CO_2–related odors). The U.S. Department of Energy has estimated that in 96 percent of commercial facilities, ventilation to maintain air quality is uncontrolled, which often results in overventilation (primarily due to variable building occupancy) and the associated energy penalty of heating or cooling the intake air and of excessive fan energy. Case studies have indicated that with CO_2 control, ventilation can be reduced 10 to 40 percent in office buildings and 30 to 60 percent in retail buildings.

Mapping this ventilation control to total energy savings requires an estimate of total current ventilation. An estimated 370 billion ft^2 of commercial floor space exists globally; assuming an average ceiling height of 9 feet, that suggests 3.3 trillion ft^3 of commercial space. Air change rates are 3 to 4 changes per hour for office spaces and 6 to 30 per hour for retail; using an average of 8 changes per hour, global commercial ventilation is 440 billion cubic feet per minute (cfm) when occupied, or on average 180 billion cfm assuming the building is occupied 40 percent of the time.

Assuming an average six-month heating season and an inside-outside temperature differential of 20°F, the average annual global heat expelled due to ventilation would be 19.6 quads. If all building heat were natural gas with an average combustion efficiency of 80 percent, the annual winter heating energy consumption due to ventilation would be 24.5 quads. In summer, the energy load due to ventilation is commonly 20 percent of the winter load, and air conditioning typically has a coefficient of performance of 2.5, so the summer electrical cooling energy caused by ventilation is 1.6 quads, or 5.3 quads of primary energy assuming an electrical generation efficiency of 0.3. Fan energy depends upon many factors, but global annual fan energy for ventilation can be estimated at 590 TW-h, or a primary energy of 6.7 quads (again assuming an electric power plant efficiency of 0.3).

Thus, a rough estimate of the global energy cost of ventilation of commercial spaces is 36.5 quads, or about 6.6 percent of total energy consumption. If, as stated above, CO_2 sensor control can reduce ventilation by an average of around 35 percent, the heating and cooling savings would be proportional, and fan energy savings would be proportionally higher or lower depending on the specific configuraiton. On average, this suggests that approximately 12.8 quads of primary energy could be saved globally each year from this optical technology. OPN

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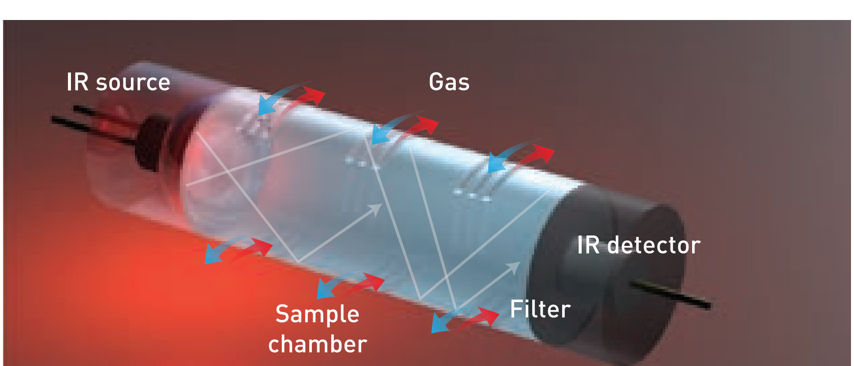

A typical commercial non-dispersive infrared (NDIR) gas sensor.
Phil Saunders/spacechannel.org, adapted with permission of International Light Technologies Inc.

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OPTICAL BUILDING-ENVELOPE TECHNOLOGIES

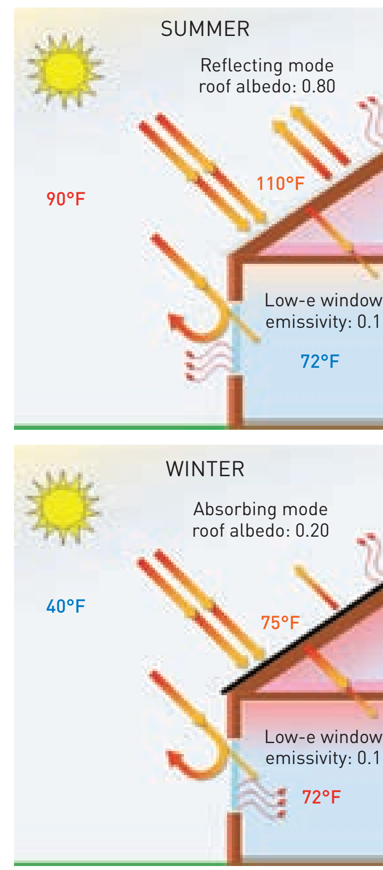
Optical thin films and reflective coatings can promote significant energy savings by tailoring solar loads on exterior building envelopes, while facilitating desired thermal performance. Low emissivity (low-e) window coatings, formed by chemical vapor deposition (CVD) or magnetron sputtered vapor deposition (MSVD), minimize the amount of ultraviolet and infrared light passing through without compromising visible transmittance. Similarly, "cool" roof membranes and reflective paints composed of metallic elements, thermoplastic polyolefin (TPO) or polyvinyl chloride (PVC) can reflect 55 to 90 percent of incident solar radiation.

Applying low-e films on multiple glazings allows for interior longwave radiation to be reflected back inside during cold winter months and radiated to the external environment during hot summer months. Standard double-pane glass windows with a fixed wood/vinyl frame have a U-factor of about 0.5 Btu/ft^2/hour/°F and a solar heat gain coefficient (SHGC) of 0.8; the same metrics for a triple glazed, double coated, low-e window with ½-inch argon spaces can be as low as low as 0.23 Btu/ft^2/hour/°F and 0.4, respectively. The Lawrence Berkeley National Laboratory (LBNL) has calculated that a home with low-e windows, in most climates, consumes 5 to 10 million Btu less energy per year (8 to 15 percent less total household energy use) for heating and cooling than homes equipped with standard double-pane windows.

Optical thin films and reflective coatings can promote significant energy savings by tailoring solar loads on exterior building envelopes.

Reflective roofing materials—single-ply thermosets (EPDM, Hypalon), single-ply thermoplastics (TPO, PVC) and various other coatings—can be applied to existing surfaces or new construction to decrease solar absorbance and temperature gain. But a reflective roof can, in some locales, actually hinder energy savings by requiring increased winter heating. An optical building envelope capable of modulating reflected solar radiation can produce energy savings independent of temperature or season. Changing the albedo of an optical roof from 0.8 in the summer to 0.2 in the winter allows for the solar load to be tailored for maximum energy saving in heating, ventilation and air conditioning (HVAC). In the aggregate, increasing the solar reflectance of a typical residential roof by 0.65 yields an average reduction in cooling of 8 to 48 kW-h/m^2 (or 19 to 65 percent cooling-load savings), depending on the local climate.

Global annual energy consumption in the residential and commercial sectors is 80.9 quads, with approximately 40 percent (32.4 quads) attributed to HVAC consumption. Assuming that 60 percent (19.4 quads) of this energy is used for heating and 40 percent (13 quads) for cooling, it is possible to estimate global energy savings of implementing low-e windows and reflective roofs. As suggested above, low-e windows can save approximately 12 percent of household energy annually, which implies 3.9 quads of global heating and cooling energy savings. Using an average savings of 42 percent for reflective roofs, meanwhile, such roofs have the potential to save 5.5 quads/year globally, or 6.1 quads if controllable-reflectance roofing is incorporated. OPN



Roof and window reflectivity significantly affect HVAC costs. White roofs are clearly better for hot climates, and black roofs for cold climates; research in modulated-reflectivity roofing can control solar load irrespective of seasonal variability.
Daniel Wolfe

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ULTRAFAST LASER MICROMACHINING

Other sections in this feature have discussed optics or photonics technologies that save energy compared with predecessor technologies. Ultrafast (picosecond to femtosecond) laser micromachining, by contrast, saves energy by producing components with such precision that they enable higher energy efficiency. In particular, ultrafast laser micromachining can fashion fuel injectors for engines that, because of their small size and precise shape, allow far greater efficiency of conversion of combustion into force. The result is higher vehicle fuel efficiency—as much as 20 to 30 percent more miles per gallon for automotive vehicles with these laser-machined injectors, according to the industrial-laser manufacturer Raydiance Inc.

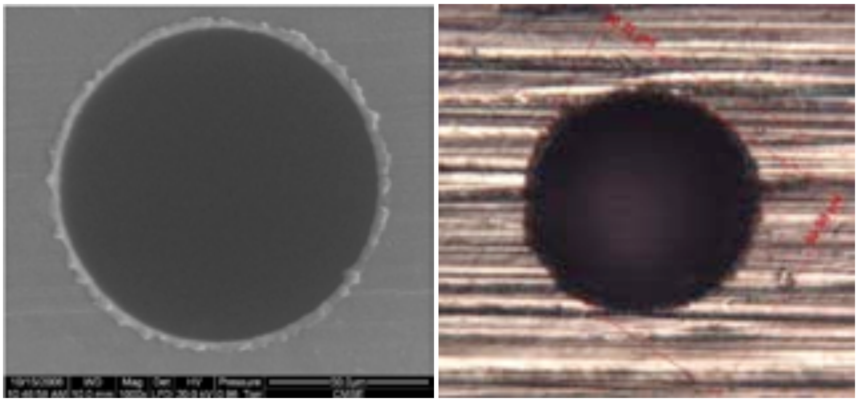
Precision hole drilling at the micron level, such as that required for fuel injectors, has previously been slow and costly. The legacy technology of choice, electronic discharge machining (EDM), uses a charged electrode to bore into metal, but as the drilling takes place, the electrode wears out and changes shape slightly, resulting in high part variability. Ultrafast laser drilling operates three times faster than the EDM process, with 60 percent less variation, through the phenomenon of cold ablation.

All materials have an ablation threshold—that is, an optical intensity at which the material is directly vaporized. The threshold energy per unit area for ablation decreases with pulse width, flattening out at a value of about 1 J/cm^2 below 10 picoseconds. This low ablation fluence means that only moderate pulse energy is required. Most of the optical energy goes into exciting electrons that quickly ablate the surrounding material within a distance less than a micron from the pulse. There is almost no melting, resulting in a hole with submicron precision.

Commercialization of ultrafast lasers for drilling, as well for as other applications (particularly medical ones), has been enabled mainly by advances in diode-pumped solid-state lasers and by the semiconductor saturable absorbing laser mirror (SESAM), which allows passive pulse mode-locking. Current diode-pumped solid-state systems provide femtosecond pulse energies into the hundreds of microjoules at a wavelength of 1,064 nm. The average power of these systems is scalable up into the range of hundreds of watts, allowing for very high speed micromachining.

Ultrafast laser micromachining saves energy by producing components with such precision that they enable higher energy efficiency.

As noted above, in principle, fuel injectors built via ultrafast laser micromachining can result in fuel efficiency approximately 25 percent higher than for conventional EDM, for all gasoline engines on the road. With global gasoline consumption at approximately 23 million barrels/day, or 44 quads/year, the potential energy savings of ultrafast laser technology in this application alone could be as high as 11 quads/year. OPN



The hole drilled in steel using EDM (left) shows evidence of a melt zone, whereas the one using ultrafast laser drilling (right) does not, a demonstration of the higher precision offered by laser micromachining.

Courtesy of Makino Inc. (left)/A. Oehler, JDSU Ultrafast Lasers (right)

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