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E. Fred Schubert and Jong Kyu Kim

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REVIEW

Solid-State Light Sources Getting Smart

E. Fred Schubert and Jong Kyu Kim

More than a century after the introduction of incandescent lighting and half a century after the introduction of fluorescent lighting, solid-state light sources are revolutionizing an increasing number of applications. Whereas the efficiency of conventional incandescent and fluorescent lights is limited by fundamental factors that cannot be overcome, the efficiency of solid-state sources is limited only by human creativity and imagination. The high efficiency of solid-state sources already provides energy savings and environmental benefits in a number of applications. However, solid-state sources also offer controllability of their spectral power distribution, spatial distribution, color temperature, temporal modulation, and polarization properties. Such "smart" light sources can adjust to specific environments and requirements, a property that could result in tremendous benefits in lighting, automobiles, transportation, communication, imaging, agriculture, and medicine.

The history of lighting has taken several rapid and often unexpected turns (*1*). The first commercial technology for lighting was based on natural gas that served thousands of streets, offices, and homes at the end of the 19th century. As a result of the competition from Edison's incandescent lamp, gaslights were strongly improved by the use of mantles soaked with the rare-earth compound thorium oxide, which converted the gas flame's heat energy and ultraviolet (UV) radiation into visible radiation. Ultimately, however, the gaslights shown in Fig. 1 were displaced by incandescent light bulbs first demonstrated in 1879. Fluorescent tubes and compact fluorescent lamps became widely available in the 1950s and early 1990s, respectively. Along with high-intensity discharge lamps, they offer a longer life and lower power consumption than incandescent sources, and have become the mainstream lighting technology in homes, offices, and public places.

The efficiency of fluorescent lamps based on mercury vapor sources is limited to about 90 lm/W by a fundamental factor: the loss of energy incurred when converting a 250-nm UV photon to a photon of the visible spectrum. The efficiency of incandescent lamps is limited to about 17 lm/W by the filament temperature that has a maximum of about 3000 K, which results, as predicted by blackbody radiation theory, in the utter dominance of invisible infrared emission. In contrast, the present efficiency of solid-state light sources is not limited by fundamental factors but rather by the imagination and creativity of engineers and scientists who, in a worldwide concerted effort, are longing to create the most efficient light source possible.

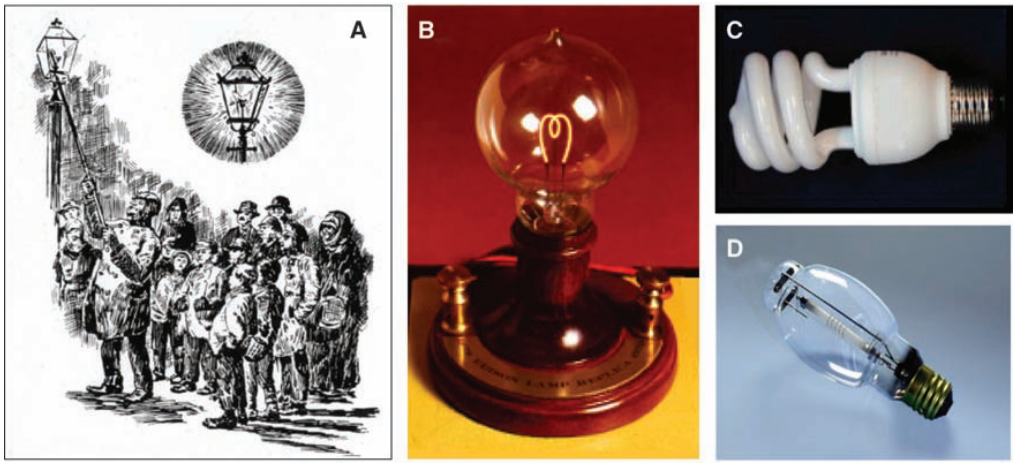

Fig. 1. (**A**) 1880s illustration of the nightly illumination of a gaslight with a thorium oxide–soaked mantle. (**B**) Replica of Edison's lamp. (**C**) Contemporary compact fluorescent lamp. (**D**) High-pressure sodium lamp.

Bergh *et al.* (*2*) discussed the huge potential benefits of solid-state light sources, in particular reduced energy consumption, dependence on foreign oil, emission of greenhouse gases (CO_2), emission of acid rain–causing SO_2, and mercury pollution. Solid-state lighting could cut the electricity used for lighting, currently at 22%, in half. Although tremendous energy savings have already materialized [e.g., traffic lights that use light-emitting diodes (LEDs) consume only one-tenth the power of incandescent ones], there is a sobering possibility that energy savings may be offset by increased energy consumption: More wasteful usage patterns, abundant use of displays, and an increase in accent and artistic lighting may keep the use of electricity for lighting at its current level [11% in private homes, 25% in commercial use, and 22% overall (*3*)].

Several promising strategies to create white light with the use of inorganic sources, organic sources, and phosphors are shown in Fig. 2, including di-, tri-, and tetrachromatic approaches. These approaches differ in terms of their luminous efficiency (luminous flux or visible light output power per unit electrical input power), color stability, and color rendering capability (i.e., the ability of a light source to show or "render" the true colors of an object). It is well known that there is a fundamental tradeoff between color rendering and luminous efficacy of radiation (luminous flux per unit optical power). For optimized wavelength selection, dichromatic sources have the highest possible luminous efficacy of radiation, as high as 425 lm/W, but they

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poorly render the colors of objects when illuminated by the dichromatic source. Tetrachromatic sources have excellent color rendering capabilities but have a lower luminous efficacy than dichromatic or trichromatic sources. Trichromatic sources can have both good color rendering properties and high luminous efficacies (>300 lm/W).

Figure 2 also shows several phosphor-based white light sources. Such sources use optically active rare-earth atoms embedded in an inorganic matrix. Cesium-doped yttrium-aluminum-garnet (YAG) is a common yellow phosphor. However, phosphor-based white light sources suffer from an unavoidable Stokes energy loss due to the conversion of short-wavelength photons to long-wavelength photons. This energy loss can reduce by 10 to 30% the overall efficiency of systems based on phosphors optically excited by LEDs. Such loss is not incurred by white light sources based exclusively on semiconductor LEDs. Furthermore, phosphor-based sources do not allow for the extensive tunability afforded by LED-based sources, particularly in terms of spectral composition and temporal modulation (YAG phosphorescence radiative lifetime is in the millisecond range).

The luminous efficiency of a light source is a key metric for energy savings considerations. It gives the luminous flux in lumens (light power as perceived by the human eye) per unit of electrical input power. Luminous efficiencies of 425 lm/W and 320 lm/W could potentially be achieved with dichromatic and trichromatic sources, respectively, if solid-state sources with perfect characteristics could be fabricated. Perfect materials and devices would allow us to generate the optical flux of a 60-W incandescent bulb with an electrical input power of 3 W.

Besides luminous efficiency, color rendering is an essential figure of merit for a light source used in illumination applications. It is a very common misconception that the color of an object depends only on the properties of the object. However, as George Palmer first found in 1777, the perceived color of an object equally strongly depends on the illumination source [for Palmer's original paper, see (*4*)]. Illuminating colored test samples with different light sources, he found that "red appears orange" and, more strikingly, "blue appears green." Thus, the "true color" of an object requires that we have a certain reference illuminant in mind. Today, a procedure similar to Palmer's is used: The apparent color of a set of sample objects is assessed (quantitatively in terms of chromaticity coordinates, no longer just qualitatively as Palmer did) under illumination by the test light source and then by the reference light source. The color differences of a set of eight standardized color samples are added. The sum, weighted by a prefactor, is then subtracted from 100. This gives the color rendering index (CRI), a key metric for light sources. A high CRI value indicates that a light source will accurately render the colors of an object.

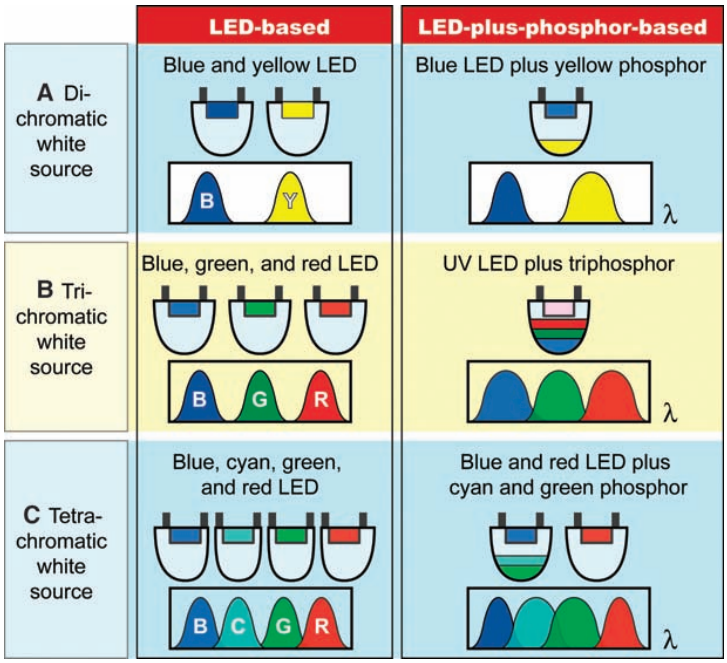

Fig. 2. LED-based and LED-plus-phosphor–based approaches for white light sources implemented as di-, tri-, and tetrachromatic sources. Highest luminous source efficiency and best color rendering are obtained with dichromatic and tetrachromatic approaches, respectively. Trichromatic approaches can provide very good color rendering and luminous source efficiency.

Although trichromatic sources already give very good CRI values, tetrachromatic sources give excellent CRI values suitable for essentially any application. The emission spectrum, luminous efficacy, and color rendering properties of a tetrachromatic white LED-based source with color temperature of 6500 K are shown in Fig. 3. Color temperature may appear to be a somewhat surprising quantity, as color and temperature would not seem to have a direct relationship with each other. However, the relationship is derived from Planck's blackbody radiator; at increasing temperatures it glows in the red, orange, yellowish white, white, and ultimately bluish white. The color temperature is the temperature of a blackbody radiator that has the same chromaticity as the white light source considered. Figure 3 shows that a favorable wavelength combination is λ = 450, 510, 560, and 620 nm, giving a luminous efficacy of 300 lm/W and a CRI of 95. Such a CRI makes tetrachromatic light sources suitable for practically any application.

However, the emission power, peak wavelength, and spectral width of inorganic LEDs vary with temperature, a major difference from conventional lighting sources. LED emission powers decrease exponentially with temperature; low-gap red LEDs are particularly sensitive to ambient temperature. As a result, the chromaticity point, correlated color temperature, CRI, and efficiency of LED-based light sources drift as the ambient temperature of the device increases. An example of the change in chromaticity point with junction temperature is shown in Fig. 4 for a trichromatic LED-based light source (*5*); the chromaticity changes by about 0.02 units, thereby exceeding the 0.01-unit limit that is considered the maximum tolerable change by the lighting industry. Furthermore, the CRI changes from 84 to 72. To avoid this change, corrective action must be taken by tuning the relative electrical input powers of the LEDs. Energy-efficient adaptive drive electronics with integrated temperature compensation are already under development. White sources that use phosphor, particularly UV-pumped phosphor sources, have great color stability and do not suffer from the strong change in chromaticity and color rendering. This is because the intra–rare-earth atomic transitions occurring in phosphors do not depend on temperature.

Technological Challenges

What specific advances will be required to move solid-state light sources from their current performance closer to their fundamental limits? What are the "bottlenecks" that will need to be overcome to enable specific types of control for smart lighting systems? The major technical challenges in solid-state lighting can be categorized into three groups:

- Epitaxial and bulk crystal growth; materials including nanomaterials and substrates; phosphors

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• Device physics; device design and architecture; low-cost processing and fabrication technologies

• Packaging; integration of components into lamps and luminaires; smart lighting systems

We next discuss several important technical issues involved in meeting these challenges. Additional challenges and a roadmap with specific goals were presented by Tsao (*6*) and Rohwer and Srivastava (*7*). Here, we emphasize inorganic materials and devices, which at this time are more advanced in terms of luminance and reliability than organic devices.

Internal efficiency. The development of efficient UV emitters (<390 nm), green emitters (515 to 540 nm), yellow-green emitters (540 to 570 nm), and yellow emitters (570 to 600 nm) is a major challenge. The internal quantum efficiency (photons created per electron injected) of some of these emitters, particularly in the deep UV, can be below 1%. A better understanding of the materials physics—in particular, defects, dislocations, and impurities—will be required to attain efficient emitters in this wavelength range. Novel epitaxial growth approaches, including growth on pseudo-matched substrates and growth on nano-structured substrates (*8*, *9*), will be required to overcome these limitations.

Phosphors. Hundreds of phosphors are available for excitation at 250 nm, the dominant emission band of Hg lamps. In solid-state lighting, however, the excitation wavelength is much longer, typically in the range 380 to 480 nm. New high-efficiency phosphors, which can be efficiently excited at these wavelengths, are now being developed. Whereas high-efficiency yellow phosphors are readily available (e.g., cesium-doped YAG phosphors), the efficiency of red phosphors still lags.

Extraction efficiency. The efficient extraction of light out of the LED chip and the package is complicated because this light tends to be generated near metallic ohmic contacts that have low reflectivity and are partially absorbing. Either totally reflective or totally transparent structures are desirable. This insight has driven the replacement of absorbing GaAs substrates with transparent GaP substrates, and it has also spurred the development of new omnidirectional reflectors with angle-integrated transverse electric–transverse magnetic (TE-TM) averaged mirror losses that are 1% those of metal reflectors. Sophisticated chip shapes and photonic crystal structures are becoming commonplace. Another fruitful strategy is to reduce deterministic optical modes trapped in the chip and the package by introducing indeterministic optical elements such as diffuse reflective and transmissive surfaces.

Chip and lamp power. Although substantial progress has been achieved in LED optical output power, an order of magnitude increase in power per package is still required. Several strategies are being pursued simultaneously, including (i) scaling up the chip area, (ii) scaling up the current density, and (iii) increasing the maximum allowable operating temperature.

Scaling of the chip area is particularly interesting because it reminds us of the scaling in Si microelectronics technology that for decades has been governed by Moore's law. Whereas feature sizes are shrinking in Si technology, die sizes are growing in solid-state lighting devices. However, the increase in chip area is frequently accompanied by a reduced efficiency (scaling losses) due to absorption losses of waveguided modes propagating sideways within the semiconductor. New scalable geometries and high-reflectivity omnidirectional reflectors are being developed by several research groups. Surface-emitting devices are generally more scalable, as they do not suffer from waveguide losses. Surface emission can be accomplished by micromirrors that redirect waveguided modes toward the surface-normal direction of the chip.

The scaling of the current density requires strong confinement of carriers to the active region. Such confinement reduces carrier escape out of the active region and carrier overflow. Changes in device design will be required, including the use of electron and hole blocking layers that prevent carriers from escaping from the active region.

Semiconductors with band gap energies corresponding to the visible spectral range, in particular wide-gap III-V nitrides, exhibit great temperature stability. However, common epoxy encapsulants limit the maximum temperature of operation to about 120°C. Silicone, mostly known as a common household glue, offers mechanical flexibility (reducing stress) and great stability up to temperatures of about 190°C.

Thermal issues. In conventional packages, LED chips driven at high currents quickly heat up. This is because the thermal resistance of "5-mm packages," which have been around for decades, is greater than 200 K/W. Active cooling (with a fan or thermoelectric device) is not an option for most applications, as such cooling reduces the power efficiency. Advanced packaging methods use a direct thermal path: a metallic slug that extends from the LED chip through the package to a larger heat sink (such as a printed circuit board) that spreads the heat. Such packages will have thermal resistances < 5 K/W, nearly two orders of magnitude lower than conventional packages.

Polarization control. Polarization control would be useful for a number of applications. For example, a backlighting power saving of up to 50% in liquid crystal display applications would result from the ability to

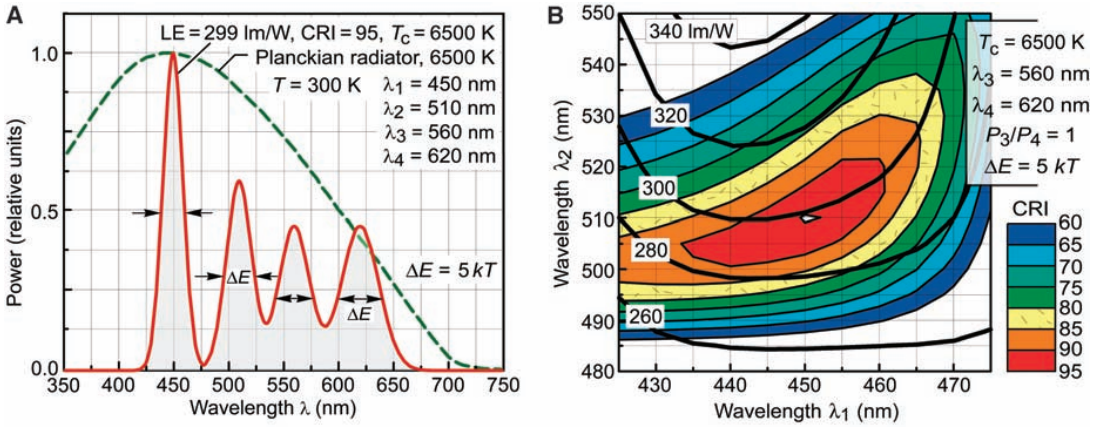

Fig. 3. Spectrum (**A**) and contour plot (**B**) showing luminous efficiency of radiation and CRI of tetrachromatic LED-based white light source with peak emission wavelength λ_1, λ_2, λ_3, and λ_4 and a spectral width of $\Delta E = 5\ kT$ (~125 meV), as is typical for light-emitting active regions consisting of ternary alloy semiconductors. The power ratio is chosen to obtain a chromaticity location on the Planckian locus with a color temperature of 6500 K.

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control polarization. Photonic crystal structures, which can have a photonic gap for only one polarization, offer a unique capability for achieving this goal. Superluminescent structures offer an alternative way to enhance one polarization.

High-luminance/high-radiance devices and control of far field. Flexible optical designs require high-luminance devices with small, very bright surfaces (high luminance and radiance). Such high-radiance point sources can be imaged with greater precision and enable flexible optical designs with precise steering of beams. LEDs emitting through all side surfaces and the top surface are not well suited for point-source applications. New structures that completely lack side emission will need to be developed for such applications; photonic band gap structures and the use of reflectors will be required. Furthermore, specific arrangements of phosphors will allow for chromatically dispersive emission patterns (i.e., patterns that exhibit a correlation between emission color and direction).

Cost. Although cost is a *conditio sine qua non* from a point of view that focuses on the replacement of conventional sources, it is of lesser importance for smart lighting applications. The benefits of smart lighting add another dimension to the economics of lighting, as these benefits derive from the possibility of temporal, spatial, spectral, and polarization control, a feature that conventional lighting technologies are unable to offer. Whereas the "cost of ownership," which includes the cost of lamp purchase and cost of electricity to operate the lamp, would appear most relevant, the lamp purchase price, measured in "$ per lumen," is the cost that prominently appears on the price tag to the consumer. A high lamp purchase price is a barrier for the broad adoption of solid-state lighting.

Substantial cost reductions are to be expected mostly through scaling of LED chips, lamps, and packages. In silicon technology, scaling of integrated circuits has reduced the cost of a logic gate by more than six orders of magnitude. Similarly, the scaling up of the LED chip size (analogous to geometric scaling in Si integrated circuits) and of the current density (analogous to current-density scaling in Si integrated circuits) will enable substantial cost reductions that, in the years to come, will bring LEDs into offices, homes, and maybe even the chandeliers of dining rooms.

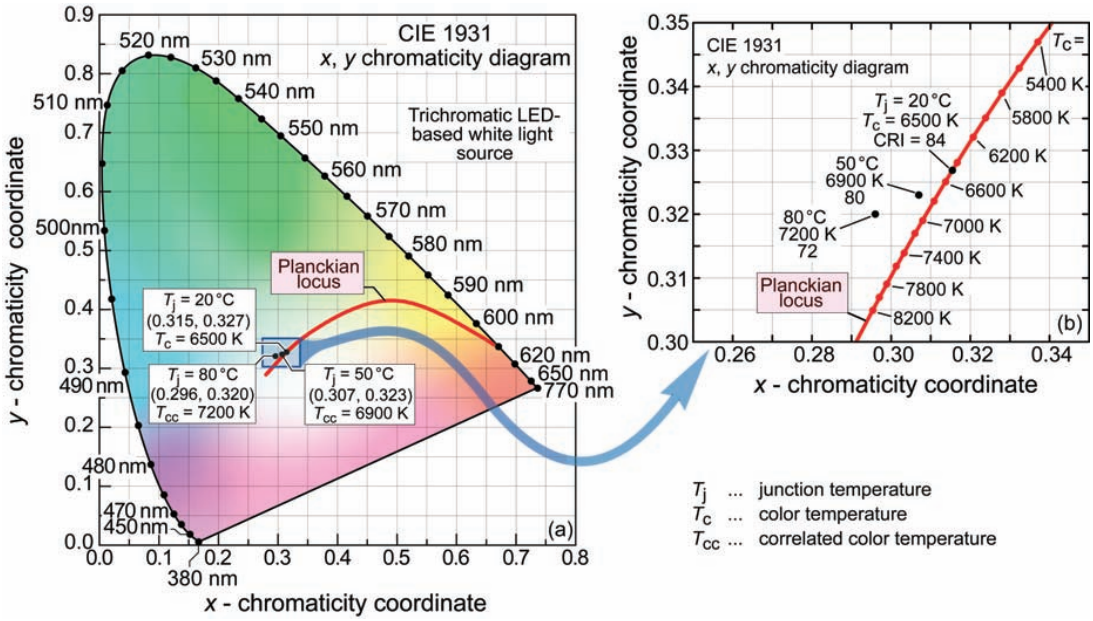

Fig. 4. Change in chromaticity coordinate, correlated color temperature, and CRI of trichromatic LED light source for junction temperatures of T_j = 20°, 50°, and 80°C represented in the (*x*, *y*) chromaticity diagram.

Smart Lighting

In addition to the energy savings and positive environmental effects promised by solid-state lighting, solid-state sources—in particular, LED-based sources—offer what was inconceivable with conventional sources: controllability of their spectral, spatial, temporal, and polarization properties as well as their color temperature. Technologies currently emerging are expected to enable tremendous benefits in lighting, automobiles, transportation, communication, imaging, agriculture, and medicine.

Recently, a remarkable discovery was made: A fifth type of photoreceptor had first been postulated and then identified in the retina of the human eye, more than 150 years after the discovery of the rod cells and the red-, green-, and blue-sensitive cone cells (*10–12*). The fifth type of photoreceptor, the ganglion cell, had been believed to be merely a nerve interconnection and transmitter cell. Such cells are now believed to be instrumental in the regulation of the human circadian (wake-sleep) rhythm. Because ganglion cells are most sensitive in the blue spectral range (460 to 500 nm, Fig. 5), they act as a "blue-sky receptor," that is, as a high-color-temperature receptor. Indeed, during midday periods natural daylight has color temperatures ranging from 6000 K under overcast conditions to as high as 20,000 K under clear blue-sky conditions. However, in the evening hours, the color temperature of the Sun decreases to only 2000 K. This periodic variation of the color temperature of natural light synchronizes the human circadian rhythm. Figure 5 shows that the circadian and visual efficacies are vastly different (orders of magnitude), particularly in the red spectral range.

Inappropriate lighting conditions were shown in mammals to upset the body chemistry and to lead to deleterious health effects, including cancer (*13*). Thus, circadian light sources with tunability of color temperature would be beneficial to human health, well-being, and productivity. Furthermore, such circadian lights could lead to a reduced dependence on sleep-inducing pharmaceuticals. For this reason, sources replicating the Sun's high color temperature during the midday period and low color temperatures during early morning and at night would be a wonderful illumination

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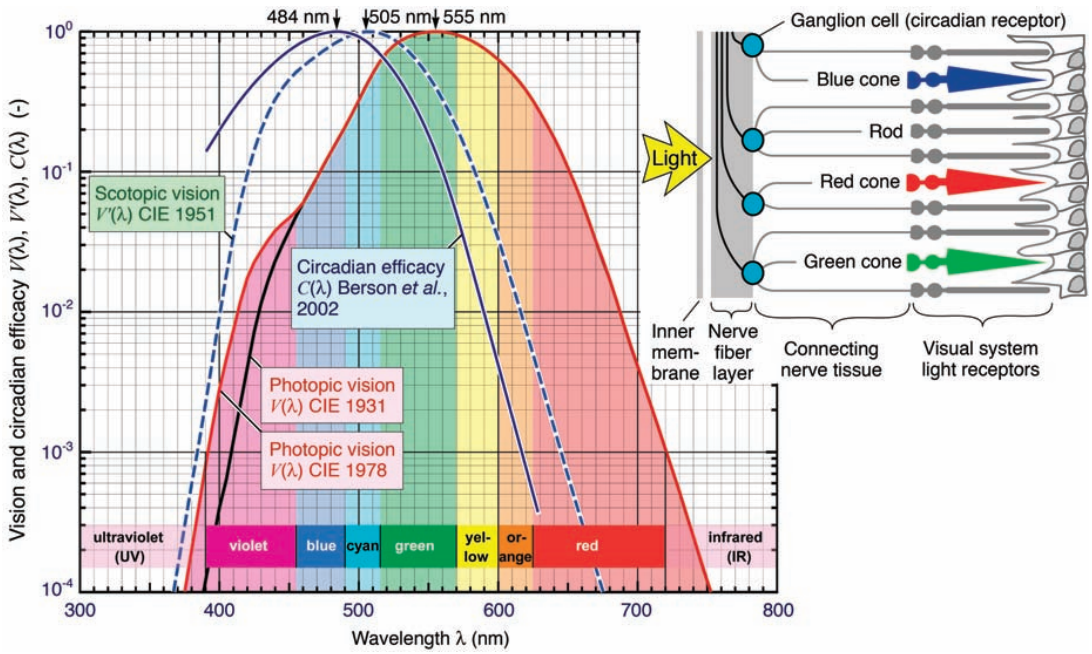

Fig. 5. CIE eye sensitivity function $V(\lambda)$ for the photopic vision regime mediated by retinal cone and rod cells. Also shown is the eye sensitivity function for the scotopic vision regime, $V'(\lambda)$, that applies to low ambient light levels, and the circadian efficacy curve $C(\lambda)$ derived from retinal ganglion cell photoresponse.

source, given that we humans adapted to such a circadian source during evolution. Alternatively, we may want to influence and manipulate the human circadian rhythm: If circadian lights (e.g., blue automotive dashboard lights) could reduce driver fatigue, the number of traffic accidents and fatalities caused by this condition could be reduced as well.

Another potential benefit of smart lighting originates in the ability to rapidly modulate the output power of LED-based light sources, thereby enabling communication features. New modes of communication based on room-light sources would help to reduce the overcrowding of the radio frequency bands. Of course, the visual appearance of such communicative light sources would be indistinguishable from conventional sources. In automotive communication applications, brake lights could communicate an emergency braking maneuver to a following car. Headlights could inform a red traffic light of an approaching car while fully maintaining their normal function as headlights. Smart road signs could flash warnings specifically to drivers that approach a dangerous curve with excessive speed. Room lights could broadcast messages, alarms, and other types of information, without any noticeable change in the illumination quality. Modulation rates in the megahertz range are possible, with the limiting factor being the device resistance and capacitance (RC time) of high-power devices. The large-area junction capacitance means that such devices would be limited by RC time rather than by spontaneous lifetime.

Smart lighting could be used in headlights that are spectrally and spatially dispersive, with peripheral regions having a spectrum different from that of the center. It is well known that the spectral sensitivity of the cone cell–rich central vision region of the retina is different from the rod cell–rich peripheral vision region of the retina. It is also well known that human vision has a photopic (daytime vision) regime with peak sensitivity at 555 nm and a scotopic (nighttime vision) regime with peak sensitivity at 505 nm. Although it is too early to guess at the magnitude of safety enhancements, advances in automotive lighting enabled by solid-state sources would certainly reduce accidents.

Plant growth in northern countries and during non-native seasons is already supported by artificial illumination. However, spectral distributions are not yet optimized. Smart lighting would allow one to select the most efficacious spectral composition, thereby enabling plant growth in the most energy-efficient way.

In microscopy applications, smart lighting with infrared, visible-spectrum, and UV illumination sources with specific spectral compositions, polarizations, and color temperatures (for white illumination) could render microscopic objects more clearly than a conventional light bulb could. Smart sources could enable real-time identification, counting, and sorting of biological cells. During surgical procedures, the real-time enhanced rendering of specific cells, tissues, and organs could be very helpful.

Other applications are awaiting the arrival of smart sources for imaging, microscopy, and visualization. For television sets, computer monitors, and outdoor displays, smart light sources promise a huge color gamut, brilliant colors, and again, large energy savings. Solid-state light sources are already the type of source manufactured in the greatest numbers. They have enjoyed double-digit growth rates for more than a decade. The opportunities discussed above will ensure that this trend will be sustained for years to come.

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