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Since its inception, the term “photonics” has been applied to increasingly wide realms of application, with connotations that distinguish it from the broader-brush terms “optics” or “the science of light.” The briefest glance at the topics covered in these volumes shows that such applications now extend well beyond an obvious usage of the term to signify phenomena or mechanistic descriptions involving photons. Those who first coined the word partly intended it to convey an aspiration that new areas of science and technology, based on microscale optical elements, would one day develop into a comprehensive range of commercial applications as familiar and distinctive as electronics. The fulfilment of that hope is amply showcased in the four present volumes, whose purpose is to capture the range and extent of photonics science and technology.

It is interesting to reflect that in the early 1960s, the very first lasers were usually bench-top devices whose only function was to emit light. In the period of growth that followed, most technical effort was initially devoted to increasing laser stability and output levels, often with scant regard for possibilities that might be presented by truly photon-based processes at lower intensities. The first nonlinear optical processes were observed within a couple of years of the first laser development, while quantum optics at first grew slowly in the background, then began to flourish more spectacularly several years later. A case can be made that the term “photonics” itself first came into real prominence in 1982, when the trade publication that had previously been entitled Optical Spectra changed its name to Photonics Spectra. At that time the term still had an exotic and somewhat contrived ring to it, but it acquired a new respectability and wider acceptance with the publication of Bahaa Saleh and Malvin Teich’s definitive treatise, Fundamentals of Photonics, in 1991. With the passage of time, the increasing pace of development has been characterized by the striking
progress in miniaturization and integration of optical components, paving the way for fulfilment of the early promise. As the laser industry has evolved, parallel growth in the optical fiber industry has helped spur the continued push toward the long-sought goal of total integration in optical devices.

Throughout the commissioning, compiling, and editing that have led to the publication of these new volumes, it has been my delight and privilege to work with many of the world’s top scientists. The quality of the product attests to their commitment and willingness to devote precious time to writing chapters that glow with authoritative expertise. I also owe personal thanks to the ever-professional and dependable staff of Wiley, without whose support this project would never have come to fruition. It seems fitting that the culmination of all this work is a sequence of books published at the very dawning of the UNESCO International Year of Light. Photonics is shaping the world in which we live, more day by day, and is now ready to take its place alongside electronics, reshaping modern society as never before.

David L. Andrews

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SOLID-STATE LIGHTING: TOWARD SMART AND ULTRAEFFICIENT MATERIALS, DEVICES, LAMPS, AND SYSTEMS

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1.1 A BRIEF HISTORY OF SSL [1]

We start this section with a brief history of solid-state lighting (SSL): key materials and device breakthroughs (illustrated in Fig. 1.1); the current state-of-the-art device and lamp architectures that those breakthroughs have enabled; and the current dominant system applications that those device and lamp architectures have enabled.

1.1.1 Stepping Stones: Red and Blue LEDs

Semiconductor electroluminescence was first reported by H. J. Round in 1907, and the first light-emitting diode (LED) was reported by O. V. Losev in 1927 [3]. Not until the birth of semiconductor physics in the 1940s and 1950s, however, was scientific development of technologies for light emission possible.
For SSL, the use of semiconductor electroluminescence to produce visible light for illumination, the seminal advances were first, the demonstration of red light emission by N. Holonyak in 1962 [4] and, second, the demonstration of a bright blue LED by S. Nakamura in 1993 [5], along with earlier material advances by I. Akasaki and H. Amano [6, 7]. In Sections 1.1.1.1 and 1.1.1.2, we briefly discuss these two advances and their subsequent evolution.

1.1.1.1 Red LEDs: Ever Increasing Efficiencies and Powers  As mentioned earlier, the first seminal advance in visible light emission was in the red, and this is the LED color that dominated the early history of LEDs. The first commercial LED lamps were introduced in 1968: indicator lamps by Monsanto and electronic displays by Hewlett-Packard. The initial performance of these products was poor, around 1 mIlm at 20 mA, in part because the only color available was deep red, where the human eye is relatively insensitive. Since then, steady, even spectacular, progress has been made in efficiency, lumens per package, and cost per lumen.

As illustrated in Figure 1.1 (top panel), progress in efficiency was largely an outcome of the exploration and development of new semiconductor materials: first

![Figure 1.1](image-url)

**FIGURE 1.1** (a) Historical evolution of the performance (lm W⁻¹) for commercial red, green, blue, and phosphor-converted white LEDs. Data for Part (a) were compiled from Reference 2 and Philips Lumileds datasheets. (b) Historical evolution of the performance (lumen per package) and cost ($ per lumen) for commercially available red and phosphor-converted (PC) white LEDs. Part (b) was adapted from Reference 1. (*For a color version of this figure, see the color plate section.*)
GaP and GaAsP, then AlGaAs, then, finally, AlInGaP. Luminous efficacies improved by more than three orders of magnitude: from about 0.02 lm W$^{-1}$ in the 1970s from GaP and GaAsP LEDs to 10 lm W$^{-1}$ in 1990 from AlGaAs LEDs (for the first time exceeding that of equivalent red-filtered incandescent lamps) to the current state-of-the-art of >150 lm W$^{-1}$ from AlInGaP LEDs.\(^1\)

Also, as illustrated in Figure 1.1 (bottom Haitz' Law panel), progress in efficiency (as well as progress in high-power packaging) then enabled tremendous progress in lumens per package and cost per lumen. In 1968, red LEDs were viewable only if competing with dim indoor lights; by 1985, they were viewable in bright ambient light, even in sunlight. Nevertheless, red LEDs at that time were still limited to small-signal indicators and display applications requiring less than 100 mlm per indicator function or display pixel. Then, around 1985, red LEDs stepped beyond those small-signal applications and entered the medium-flux power signaling market with flux requirements of 1–100 lm, beginning with the newly required center high-mount stop light (CHMSL) in automobiles. At this point in time, red LEDs are well into the >100 lm high-flux domain associated with lighting-class applications.

Of course, it was not just that increasingly higher efficiency enabled these increasingly higher flux applications; the needs of these higher flux applications also drove the quest for higher efficiency. In other words, there was a coevolution of higher efficiency (technology push) and power-signaling applications (market pull) that could make use of higher efficiency. Solutions based on large numbers of small-signal lamps were too expensive, thus demanding the development of higher-efficiency, higher-power LEDs. The development of higher-efficiency, higher-power LEDs, in turn, opened up additional stepping-stone markets. The result is the Haitz' law evolution illustrated in the bottom panel of Figure 1.1. In a Moore's-law-like fashion, flux per lamp has been increasing 20× per decade while cost per lumen (the price charged by LED suppliers to original equipment manufacturers, or OEMs) has been decreasing 10× per decade.

1.1.1.2 Blue LEDs: Enabling White Light  As mentioned earlier, the second seminal advance in visible LEDs was the blue LED, and this is the color that came to dominate the subsequent history of LEDs. The initial breakthroughs came in the late 1980s and early 1990s, with the discoveries by I. Akasaki and H. Amano that a previously recalcitrant wide-bandgap semiconductor, GaN, could be p-type doped [7] and grown with reasonable quality on lattice-mismatched sapphire [6]. Building on these discoveries, in 1993 S. Nakamura at Nichia Chemical Corporation demonstrated a bright blue LED [5]. As illustrated in the top panel of Figure 1.1,

\(^{1}\)Osram Opto Semiconductors GmbH of Regensburg, Germany, recently announced research results with a record efficiency of 61% for a red high-power LED. The 1 mm² chip, housed in a laboratory package, emits at a dominant wavelength of 609 nm with a luminous efficiency of 201 lm W$^{-1}$ at an operating current of 40 mA. At a typical operating current of 350 mA its luminous efficacy is still 168 lm W$^{-1}$, so even at this high wattage more than half of the electrical energy is converted into light.
efficiency improvements followed quickly, to the point where today’s state-of-the-art blue LEDs, at least at low-power densities, have power-conversion efficiencies exceeding 80% [8].

Most importantly, because blue is at the short-wavelength (high-energy) end of the visible spectrum, it proved possible to “downconvert” blue light into green, yellow, and even red light using passive phosphorescent and fluorescent materials [9]. The visible spectrum could thus be filled out, white light could be produced, and general illumination applications became a possibility. Indeed, as illustrated in the bottom panel of Figure 1.1, Haitz’ Law, developed originally for red LEDs, is continuing for white LEDs. There is now virtually no question that SSL will eventually displace all conventional technologies in general illumination applications, and indeed in virtually every application in which visible light is needed [10].

1.1.2 State-of-the-Art SSL Device Architecture: InGaN Blue LED + Green/Red Phosphors

At this point in time, the state-of-the-art SSL architecture is based on blue LEDs combined with green, yellow, and/or red phosphors, the so-called PC-LED (phosphor-converted LED) architecture illustrated in Figure 1.2. As indicated, the
sub-efficiencies of this PC-LED are blue LED (40%), phosphor + package (70%), and spectral match to the human eye response (80%). Taken together, the overall wall-plug efficiency is 22% ($\approx 0.4 \times 0.7 \times 0.8$).

The reasons this architecture has prevailed, as opposed to a color-mixing architecture in which light from multiple LEDs with different colors is mixed (and which would potentially eliminate the inefficiencies stemming from the phosphor and spectral mismatch), are fourfold.

First, improvements in the efficiency of direct electroluminescence have been uneven across the visible spectrum [11]. As illustrated in Figure 1.3 [12], the wall-plug efficiencies of blue and red LEDs at the wavelengths (460 and 614 nm, respectively) desirable for general illumination are now over 40% and 30%, respectively. However, the efficiency of green and yellow LEDs at the wavelengths (535 and 573 nm, respectively) desirable for general illumination is of the order 20% or less. Thus, at least for green and yellow light, it is more efficient to produce these colors from LED-pumped phosphors than directly from LEDs.

Second, progress in power package development has been rapid, and, despite the relatively low overall wall-plug efficiency of $\sim 22\%$, has enabled useful, 1 klm amounts of light to be produced from single-PC-LED lamps. In particular, a blue-pumped, cool-white LED lamp with a 2 mm $\times$ 2 mm chip can now be operated at 10 W with a luminous efficacy of 100 lm W$^{-1}$, giving a flux of 1 klm and an operating life of 50 kh. For applications requiring only a 3 kh life, this lamp can be operated at 25 W, delivering 2 klm of flux.

Third, color stability has proved to be important. The human visual system is extremely sensitive to the exact chromaticity of white light. Because LEDs of
different colors have different operating-temperature-dependent lumen outputs, multiple independently controlled feedback loops and current drivers are necessary to achieve an operating-temperature-independent color point. In contrast, blue LEDs and conversion phosphors are far less temperature dependent, allowing open loop (no feedback) operation for many lighting applications.

Fourth, high-temperature operation has also proved to be quite important, enabling devices to be driven at higher input powers to achieve higher output powers. However, the efficiencies of green and yellow LEDs decrease much faster than those of blue LEDs with increasing temperature [13].

Note, however, that a hybrid architecture is now emerging, in which blue and red LEDs are combined with a blue-pumped green-and-yellow-light-emitting phosphor. We discuss this architecture in Section 1.4.1, and consider it to be an important step beyond the current state-of-the-art and toward the smart, ultraefficient SSL that is the central theme of this chapter.

1.1.3 State-of-the-Art SSL Lamp Architectures

Based on the PC-LED (blue LED and green + yellow + red phosphor) device architecture just discussed in Section 1.1.2, there are two broad classes of lamp architectures, depending on whether the white light originates from a point source or a distributed source. There are also intermediate architectures, but for our purpose here we focus on these two extremes.

1.1.3.1 Point-Source Lamps In a point-source lamp, the white light originates from a very small area, and hence, can be relatively precisely imaged and directed with downstream optics. A simple example of such a lamp is one in which phosphors are “locally” placed directly on a blue LED with a small (say, 1 mm²) footprint; a more complex example of such a lamp would be one in which a blue laser is focused onto a phosphor. In both examples, some of the blue light is scattered and some is phosphor converted and reemitted as green, yellow, and/or red light, resulting in white light originating from a near-point source with relatively uniform chromaticity over its angular divergence.

Such point-source lamps are, however, difficult to achieve when “useful” amounts of light for general illumination are desired. Since all the blue light must come from a single small-area LED or laser, achieving useful amounts of light then requires high input power densities. If the LED or laser has only moderate efficiencies, heat management can be difficult and temperature rise substantial; high temperatures decrease the efficiency and reliability of both LEDs and lasers as well as of the proximal phosphors.²

But when such point-source lamps can be achieved [14] they are the most flexible and desirable. As illustrated in the left panel of Figure 1.4, they have the flexibility,

²Note that phosphor cooling can be especially problematic, though progress is being made with higher thermal conductivity conformal phosphor coatings, so that the phosphor can be cooled reasonably effectively through the LED die.
A BRIEF HISTORY OF SSL

FIGURE 1.4  Point-source lamps can be used to provide non-diffuse, directed beams, such as in the laser headlights on the left (courtesy of Frank Wienstroth, BMW Group), or to provide diffuse, non-directed light, such as in the LED-coupled waveguide luminaire on the right (courtesy of John K. Langevin, Rambus, Inc.).

using downstream optics, to serve non-diffuse lighting applications requiring focused or directed beams. Flashlights (among the earliest of the “power” LED applications) and automotive headlights [15] (among the most recent) are good examples. As illustrated in the right panel of Figure 1.4, they also have the flexibility, using waveguides and light pipes, to serve diffuse lighting applications. For example, point-source lamps may be used to illuminate a waveguide with surface light-extraction features, thereby effectively creating distributed light sources. This is very similar, at least in concept, to how LEDs are used in edge-lit backlighting for liquid crystal displays (LCDs) for televisions, computer monitors, and phones/tablets. Variations on this theme can enable luminaires with the look and feel of fluorescent tube lighting. Indeed, the design flexibility associated with edge-lit waveguides can, through complex nonlinear shapes and blends of direct and indirect illumination, enable luminaires that go far beyond the look and feel of fluorescent tube lighting.

1.1.3.2  Distributed-Source Lamps  In a distributed-source lamp, the white light originates from a distributed area, and hence, cannot be precisely imaged or directed with downstream optics. One example of such a distributed-source lamp is an array of small point-source lamps distributed over a large area and covered with a diffuser. Another increasingly common example of such a distributed-source lamp is one in which phosphors are “remotely” placed away from the blue LED. In Edison-socket-replacement lamps, the phosphors can coat the surface of the bulb and can be excited by light from one or more blue LEDs. The blue light is scattered as well as phosphor converted and reemitted as green, yellow, and/or red light over the distributed surface of the bulb.

Distributed-source lamps are easier to achieve than point-source lamps when “useful” amounts of light for general illumination are desired. In the remote-phosphor example, the blue light can come from multiple LEDs driven at lower input power densities with decreased heat management challenges. The phosphors are not exposed
to high blue-light fluxes, and can themselves be cooled by conduction over a larger surface area.

However, distributed-source lamps do have significant disadvantages. In the remote-phosphor example, the lamp requires large quantities of phosphor, and typically exhibits a less desirable (for some applications) nonwhite off-state appearance (typically yellow or orange). Perhaps, most importantly, they are not compatible with non-diffuse lighting applications that require focused or directed beams. Hence, as discussed above, point-source lamps are generally more desirable: they have the flexibility to serve, using downstream optics, both non-diffuse lighting applications requiring focused or directed beams and, using waveguides and light pipes, diffuse lighting applications.

1.1.4 SSL Applications

Beginning with the humble, small-signal indicator and the display applications of early hundredth-lumen-per-lamp red LEDs, applications for the current generation of hundred-lumens-per-lamp white LEDs have grown enormously. Here, we mention two of the most important: mature applications associated with displays and a just emerging first wave of rapidly growing applications targeted at retrofitting general illumination lamps (both dumb and "rudimentarily smart").

1.1.4.1 Displays and Display Backlighting

Displays are by far the largest present-day use for LEDs: either white or red–green–blue (RGB) LEDs for backlighting of LCDs or RGB LEDs for ultralarge video displays.

The first of these uses, backlighting, was driven initially by mobile LCDs for which small form factor was important, but now even larger LCDs for computer displays and televisions have shifted to LED backlighting. Convolved with the shift from vacuum-tube displays to LCDs, backlighting of LCDs has become the single largest application for LEDs. For most of this backlighting, color quality needs are high but not ultrahigh, so white point-source LEDs are used. But for some backlighting, color quality needs (such as more-saturated colors and a larger color gamut) are ultrahigh, and RGB point-source LEDs are used.

In the long run, however, the future of LED backlighting of LCDs is not clear, because the future of LCDs is not clear. Organic LED (OLED) displays have made tremendous progress in recent years, and they promise many performance advantages (higher efficiency, larger field of view, higher switching speed, compatibility with nonplanar form factors) over LCDs. For small mobile displays, for which cost and reliability are less important, OLEDs are already displacing LCDs; for larger displays they may also, provided their costs continue to decrease.

The second of these uses, ultralarge displays (e.g., LED video billboards), has grown less spectacularly than backlighting of LCDs, but nonetheless steadily. The reasons are twofold. First, for ultralarge displays every light-emitting technology is too expensive per unit area to use directly, but must be restricted to small areas with larger pixel-sized tiles that are end-stacked into an ultralarge-scale geometric arrangement. Second, because LEDs have such high efficiencies and high power
densities, they have lower cost per lumen than any other light-emitting technology, and hence, are the most cost-effective choice for such light-emitting tiles. In other words, “LEDs have the lowest cost for the empty space between the pixels” (R. Haitz, personal communication).

In the long run, because of the above economics, the future of large LED video displays, unlike that for LED backlighting of LCDs, is virtually assured. Moreover, these applications are likely to continue to grow steadily. Vastly more large outdoor displays (along streets and on building exteriors) and large indoor displays (inside large spaces in buildings) may be needed as humanity continues to urbanize and advance its standard of living.3

1.1.4.2 Retrofit “First-Wave” Lighting: Dumb and Rudimentarily Smart The most rapidly growing use for LEDs is retrofit lighting for general illumination. Although still in its infancy, past and projected future progress is such that it is now taken for granted that SSL will ultimately replace virtually all conventional (including incandescent and fluorescent) lighting technologies. Indeed, a first wave of retrofit lighting is already in motion.

Initially, this first wave will be “dumb” retrofit SSL lamps which fit into existing Edison sockets (for incandescent bulbs) or troffers (for fluorescent lamps), and which offer simple but important performance improvements in efficiency, color rendering quality, lifetime, absence of environmental contaminants (e.g., mercury), and overall life ownership cost. Because of the easy tailoring of these various performance attributes, SSL will eventually serve virtually any current general illumination market better than traditional technologies.

The transition, though, may take longer than many current market analysts predict, due to a required coevolution of technical and cost innovation (particularly in lamp packaging, requiring power converters, drivers, secondary optics, sockets, and heat sinks); markets and business models for lighting companies; and consumer acceptance of lighting designs that are slightly dissimilar from traditional designs. Indeed, we note that the transition has already been delayed somewhat due to the parallel transition from extremely inefficient incandescent bulbs to compact fluorescent lamps (CFLs), which until recently have beaten SSL in efficiency and are still ahead in price/lm. CFLs have overcome their initial shortcomings (too bluish and too expensive) in the 1990s and now compete well with incandescent bulbs. By 2020, however, LED consumer prices will likely be around $2–3/klm and LED efficiencies will likely be decisively higher than those of CFL lamps. CFL lamps will then suffer the same extinction as the Edison lamp, marking the beginning of the end for traditional lamps in all applications.

The second stage of this first wave will be to add rudimentary “smarts” to retrofit SSL lamps. Mainly, these capabilities will center around occupancy and daylight sensing, networked intelligence, and on/off/dimming control. These concepts in lighting are, of course, not new, but their implementation will be more pervasive than in the past. First, SSL is based on semiconductor components, and hence, unlike

3Within limits, of course: too much visual information might distract and even impair cognitive function.
high-intensity discharge (HID) or fluorescent lamps, is much more compatible with electronic switching circuitry. Second, the separate advance of wirelessly networked sensors, intelligence, and mobile devices has in parallel created the necessary control infrastructure. Indeed, there is a tremendous amount of activity in the hardware and software infrastructure for these kinds of control: drivers based on embedded microprocessors and pulse-width modulation (PWM), wireless protocols (Zigbee integration), and distributed sensor networks. These sensors, wireless controls, and protocols can easily be integrated into the LED driver electronics to enable full on/off/dimming control that responds to occupancy, daylight levels, and perhaps even user preferences.

1.2 BEYOND THE STATE-OF-THE-ART: SMART AND ULTRAEFFICIENT SSL

In Section 1.1, we gave a brief history of SSL, up to the current state-of-the-art device and lamp architectures, and of the system applications these device and lamp architectures have enabled. If the evolution of SSL were to end at only incremental advances beyond this state-of-the-art, and at the “first” wave of dumb and rudimentarily smart retrofit lighting, then a huge revolution in lighting would have already been accomplished.

In Section 1.2, we discuss the possibility that the evolution of SSL does not end with just incremental advances, but progresses well beyond—into a performance domain that might be called both smart and ultraefficient (>70%). We first discuss the general characteristics of smart, ultraefficient SSL; second, we discuss the potential systems applications of such lighting; and third, we discuss the macroeconomic and human productivity benefits of such lighting.

1.2.1 Characteristics: Multicolor Electroluminescence, Narrowband Spectra, High Modulation Speed

We first discuss some of the likely characteristics of smart, ultraefficient SSL. We believe there are two and that they are mutually compatible and complementary.

1.2.1.1 Multicolor Electroluminescence One likely characteristic of smart, ultraefficient SSL is that, unlike in the current dominant paradigm, it does not make use of phosphor-based wavelength downconversion. This is so for two reasons. First, because about 80% of white light power is green or red, and because the Stokes deficit on converting from blue to green and red is about 25%, SSL in which wavelength downconversion is used to produce green and red is automatically at most $0.2 + 0.8 \times 0.75 = 80\%$ efficient,\(^4\) and likely even less due to other loss

\(^4\)The factor of 0.2 is the fraction of white light that is blue, with the blue assumed to be produced with 100% efficiency; the factor of $0.8 \times 0.75$ is the fraction of white light that is red or green, with the red and green light produced with 80% efficiency due to the Stokes deficit. See, for example, Reference 16.
factors. So the first likely characteristic of ultraefficient SSL is that it makes use of efficient electroluminescence, rather than wavelength downconversion, across the visible spectrum. Of course, as illustrated in Figure 1.3, this will be challenging due to the well-known green–yellow gap in the electroluminescence efficiency of compound semiconductors [17]. However, it will be necessary to achieve ultraefficient SSL.

Second, wavelength downconversion does not lend itself easily to simultaneous attainment of two desirable attributes of smart lighting: real-time tuning of spectra to enable tailoring of white (and perhaps nonwhite) light chromaticity, and real-time tuning of beam directionality and placement. In a point-source architecture, downstream optics can be used for beam directionality and placement, but the green-to-blue and red-to-blue power ratios, and hence, chromaticities in the architecture are set at the factory rather than tailorable in the field (although there is the possibility of circumventing this limitation using quantum dots as wavelength downconverters) [18]. In a distributed-source architecture, multiple laterally placed and independently electrically driven monochromatic (for example, red, green, yellow, and blue) light sources can be used to tailor chromaticity but, as discussed in Section 1.4.1, they would not be readily compatible with downstream optics for beam directionality and placement.

1.2.1.2 Narrowband Spectra Another likely characteristic of smart, ultraefficient SSL is that, also unlike the current dominant paradigm in SSL technology, its white light spectrum would not be broadband and continuous, but rather narrowband.

First, narrowband spectra maximize luminous efficacy of radiation (LER) for any desired color rendering quality [19]. For a lamp with a color rendering index (CRI) of 90, LER is maximized with four narrowband spikes of light, while for a lamp with CRI of 85, LER is maximized with three narrowband spikes of light. In both cases, so long as the narrowband spikes are optimally spaced to fill the visible spectrum, the resulting white light renders well the colors of objects typical in the environment around us (see Fig. 1.5) [20]. If a different spectral quality metric is to be maximized (e.g., color quality scale (CQS) [21] or gamut area index (GAI) [22] or some combination of indexes) [23], then additional narrowband spikes may of course also be added [24].

Second, narrowband spectra are compatible with chromaticity tuning. For example, by tuning the red-to-blue, green-to-blue, and yellow-to-blue power ratios, any chromaticity point within the gamut defined by the spectral spikes of the monochromatic LEDs can be created, and any chromaticity along the blackbody Planckian can of course also be created.

1.2.1.3 High Modulation Speed A final likely characteristic of smart, ultraefficient SSL is modulation speed. Many aspects of smart lighting will require only relatively slow (seconds to minutes) timescales. Indeed, for on/off/dimming triggered by the transit of occupants through the area, fast on/off/dimming can be disconcerting and undesirable. However, some aspects of smart lighting may require relatively faster (millisecond) timescale on/off/dimming—for example, when used as cues for human response in rapidly changing and dangerous vehicular-traffic environments.
And some aspects of smart lighting may require even faster (nanosecond) timescale modulation—for example, when communications and/or light-field-mapping functionality (discussed in Section 1.2.2) is desired.

All of these modulation speeds are compatible with the characteristics (multicolor electroluminescence and narrowband spectra) just discussed. Electroluminescent semiconductor devices (LEDs and especially lasers) have higher modulation speeds than most wavelength downconversion materials. And the use of multicolor electroluminescence can support even higher effective bandwidths using wavelength
division multiplexing techniques similar to those widely used in optical communication systems [25].

A key challenge, however, may be to maintain high efficiency while increasing modulation speed: these two characteristics are not always mutually compatible. A common way to increase modulation speed is to increase the nonradiative rate at which electrons and holes recombine; however, doing so decreases simultaneously the radiative efficiency. Instead, one must find ways to increase the radiative rate, through, for example, enhanced light-matter interactions or stimulated emission (as with lasers). In addition, as always with high-speed devices, careful attention must be paid to reducing capacitances and their associated resistance-times-capacitance (RC) time lags.

1.2.2 Potential Future System Applications

In Section 1.2.1, we discussed some of the likely characteristics of smart, ultraefficient SSL. If these characteristics can be achieved, unprecedented control of light properties would be enabled, and potential new system applications and markets would be enabled or expanded.

In Section 1.2.2, as illustrated in Figure 1.6 we speculate on some of these potential system applications: a “second wave” of lighting that is smart [26] and feature rich; integrated illumination and displays; human health and well being; agriculture; communication; and light-field mapping. These potential system applications will coevolve with other global and societal technology changes, like the increasing demand for video information and bandwidth, the critical need for energy conservation and the deployment of sustainable technologies, and the growth of highly interconnected and diversified sources of alternate energy. They will also involve a wide range of supply-chain technology components, as well as new industries previously foreign to the lighting or LED marketplaces.

1.2.2.1 “Second Wave” Lighting: Smart and Feature Rich A first system application is illumination itself. As discussed in Section 1.1.4, the first wave of dumb and rudimentarily smart SSL is already beginning to penetrate illumination applications. Though important, this first wave will likely ultimately be succeeded by a second wave of SSL that makes use of features that are unique to SSL and that are not possible with traditional incandescent, HID, or fluorescent lighting.

A first aspect of such smart lighting will be its networkability. With the separate advance of mobile wireless devices that sense ambient light levels and space occupancy, SSL lighting systems will enter an era in which lighting systems have the information necessary to customize light to user preferences.

A second aspect will be the unprecedented device-level control of the luminance and spectral content of light in space and time. At a simple level, it will be possible to reproduce the spectral changes associated with dimming of incandescent sources (brightness-dependent correlated color temperature (CCT)). At a more complex level, it will also be possible to customize spectra to improve (as discussed in more detail below) the health, well-being, and productivity of individuals.
A third aspect will be the real-time tailoring of spectra to favorably impact energy efficiency. For example, in situations (e.g., parking lots viewed from a distance) for which color rendering quality is less important, energy efficiency could be improved through use of spectra that better match the human photopic (or scotopic, depending on the situation) eye response, even if they render colors somewhat less well. Or, in situations (e.g., parking lots viewed up close) for which color rendering quality is more important, spectra that better fill the human photopic eye response could be used, even if energy efficiency is compromised somewhat.

A fourth aspect could be the subtle tailoring of absolute luminance levels to compensate for utility-scale fluctuations in electricity availability and consumption. Though electricity generation at the utility is difficult to change instantly to adjust to overall electricity demand by consumers, some forms of electricity demand might be tradeable for other forms, nearly instantly. In particular, because illumination is such a major percentage (∼20%) of the world’s electricity budget, small (visually unnoticeable) changes in illumination levels could in principle be used to make such adjustments [27]. Fast timescale networked micro-pricing on a smart grid could even be incorporated to enable “illumination arbitrage.”

1.2.2.2 Integrated Illumination and Displays A second system application, displays, is more than just a potential application; it has been a key driver in the past
for the development of LEDs. The ubiquity of LCD displays and their need for compact, long-lived, efficient backlights has driven tremendous progress in LEDs and phosphor-converted white LEDs. Very soon, virtually every LCD display, from the smallest mobile displays to the largest television displays, is likely to be backlit by LEDs.

In the future, as displays become larger and produce more total light, their functionality might become “fused” with illumination functionality. In fact, the integration of illumination and displays has been under development for some time, and includes the use of LCD display technology for virtual windows and skylights [28], and the use of color-tunable LED lighting panel technology to simulate illumination from an “open sky” source [29]. Significant technical development of both display and LED technologies will be needed to fully develop this fusion, but it is likely that future lighting systems will more closely approximate natural lighting (and the scenes that accompany it). This trend will be analogous to trends observed in telephony, where what was once known as “plain old telephone service” (or POTS) has evolved to become smart mobile communications systems with a fusion of communications, computation, and display technologies.

Note that OLED technology may also be important in this vision of display and illumination functionality fusion. As mentioned in Section 1.1.4, OLED displays are already displacing LCDs in small mobile displays; for larger displays they may eventually also, provided their costs can continue to decrease.

1.2.2.3 Human Health, Well-Being, and Productivity A third system application is human health and well-being. It has been known for some time that there is a strong link between the spectral content of the light used for illumination and human health, well-being, and productivity.

For example, in the late 1990s, the discovery of nonvisual light receptors in the human retina [30] and the role of these receptors in setting and altering human circadian rhythm [31] led to research suggesting that future lighting systems could play an important role in human sleep management. Indeed, it is well known that lighting can mitgate some of the impact of seasonal affective disorder (SAD)—a well-studied condition linking depression with limited exposure to daylight [32]. Since the spectral content of conventional incandescent and fluorescent lighting systems is fixed, however, detailed studies of the impact of lighting spectral content on human health have been somewhat limited. Smart SSL has the potential to enable much richer experimentation, ultimately leading to empirically sound strategies for improving human health and well-being.

Or, for example, recent studies suggest new approaches for control of light spectral content, not just for human health but also for enhancing human performance. Recent studies on subtracting a narrow band of blue wavelengths from conventional lighting systems show that subtractive spectral management may have a positive impact on maintaining the circadian period and on the alertness of shift workers [33]. Other studies show that the spectral qualities of light can impact cognition [34], educational

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5Such panels are now commercially available, see http://www.neonny.com/news/html/?464.html
performance [35], and the treatment of elderly patients suffering from Alzheimer’s disease [36].

Finally, we note that human health and well-being are especially important in healthcare environments. Exposure to sunlight has a large impact on hospitalized patient health and well-being [37]; and exposure to color-temperature-tailored solid-state illumination may also [38]. The impact may be both intangible (patient mood and psychological state of mind) as well as tangible (patient recovery times) [39].

1.2.2.4 Agriculture A fourth system application is agriculture. With the increased urbanization and localization of the world’s population, there is a need for food sources to be local to urban centers (bypassing transportation costs and enabling tailoring to local preferences) and to be maximally productive all year round (extending the growing season).

Simple LED lighting is already being investigated actively for agriculture [40], and more continues to be learned about the specific effects of wavelength on plant growth. The presence or absence of certain wavelengths can impact different phases of the plant’s growth cycle, as well as the nutritional value of the produce from the plants. Production yield under optimized illumination can be higher than under natural growth conditions, though the impact of spectral distribution can be complex and can depend on plant type [41]. Moreover, the intensity and price point of LED systems are reaching a level at which they can be considered for large-scale horticultural applications.

A related emerging use of LED lighting is to grow genetically engineered plants for production of pharmaceutical products (sometimes referred to as Pharming) [42]. Such transgenic plants could be engineered to require particular illumination wavelengths at particular phases of their life cycle. Those illumination wavelengths could then be preferentially supplied by tailored LED illuminants, thereby optimizing pharmacological yield. At the same time, the relative absence of those illumination wavelengths in sunlight would help ensure the lack of viability of such transgenic plants in natural environments.

1.2.2.5 Communication A fifth system application is communication. Communicating with light is of course already commonplace in the infrared, both in free space (low-bandwidth remote control of televisions) and in fibers (high-bandwidth fiber optic communications). But with the advent of LEDs that can be modulated at high speed even while providing illumination functionality, a new area called visible light communication (VLC) is emerging. Multicolor electroluminescent devices would be ideal for such dual illumination + communication functionality, since LEDs can be modulated at relatively high speed (faster than the human eye can resolve) and VLC applications might be partitionable by color. But even the current phosphor-converted white LED systems can be used: the blue LED can be modulated at high speed even

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6TheVisibleLightCommunicationsConsortiumwasestablishedinJapanin2003.Seewww.vlcc.net/modules/xpage3/.