Transcending the replacement paradigm of solid-state lighting

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Abstract: The field of photonics starts with the efficient generation of light. The generation of efficient yet highly controllable light can indeed be accomplished with light-emitting diodes (LEDs), which are, in principle, capable of generating white light with a 20 times greater efficiency than conventional light bulbs. Deployed on a global scale to replace conventional sources, such solid-state light sources will result in enormous benefits that, over a period of 10 years, include (1) gigantic energy savings of 1.9×10^{20} joule, (2) a very substantial reduction in global-warming CO_2 emissions, (3) a strong reduction in the emission of pollutants such as acid-rain-causing SO_2, mercury (Hg), and uranium (U), and (4) financial savings exceeding a trillion (10^{12}) US$. These benefits can be accomplished by the "replacement paradigm" in which conventional light sources are replaced by more energy efficient, more durable, and non-toxic light sources. However, it will be shown that solid-state light sources can go beyond the replacement paradigm, by providing new capabilities including the control of spectrum, color temperature, polarization, temporal modulation, and spatial emission pattern. We will show that such future, "smart" light sources, can harness the huge potential of LEDs by offering multi-dimensional controllability that will enhance the functionality and performance of light sources in a wide range of applications. These applications include optical microscopy, imaging, display technologies, communications, networking, and transportation systems.

OCIS codes: (230.3670) Light-Emitting Diodes; (350.0250) Optoelectronics.

References and links

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1. Introduction

The highly efficient conversion of electricity to light and the converse, namely the conversion of sunlight to useful electricity are subjects of intense global research, and, at the same time,

#100003 - $15.00 USD Received 11 Aug 2008; revised 15 Sep 2008; accepted 16 Sep 2008; published 17 Dec 2008

of great interest to humanity, particularly since it is becoming increasingly apparent that fossil energy sources are strongly limited. As new global powerhouses such as China and India demand their fair share of the global “energy pie”, as the price of oil increases in a galloping manner, countries whose energy usage is high, will strongly feel the limited supply of fossil energy sources. New drilling for mineral oil in new regions, such as the oceans and the Polar Regions has a limited benefit since the global availability of oil will, within a matter of years, decrease.

Yet there is a tremendous hope: Photonics, that is, the confluence of semiconductor technology and optics, is a tremendous resource for the generation of electrical power and the conservation of this valuable resource. In contrast to our fossil resources, solar energy will be available indefinitely: As long as humanity exists, solar energy will be free and available to all.

What the transistor meant to the development of electronics, the light-emitting diode (LED) means to the field of photonics. This core device has the potential to revolutionize how we use light. These uses include illumination, communication, sensing, and imaging. Deployed on a large scale, LEDs have the potential to tremendously reduce pollution, save energy, save financial resources, and add new and unprecedented functionalities to photonic devices.

These factors make photonics what could be termed a *benevolent tsunami*, an irresistible wave, a solution to many global challenges currently faced by humanity and will be facing even more in the years to come.

2. Driving forces for solid-state lighting

The efficacy of the conversion of electrical power to luminous flux of white light is measured in terms of lumens (lm) per watt (W), where the “lumen” is the unit of luminous flux (optical power as perceived by a human). The theoretical limit of the conversion for white light generated by three LEDs has been shown to be 320 lm/W [1]. The light generated by LEDs can be very high quality, that is, with a color rendering index of > 80, and with a color temperature that is equal to that of natural daylight (“true white”, 4000 – 6500 K). In practice, it is unlikely that this theoretical limit can be reached due to practical limitations and cost-benefit considerations. However, it is reasonable to presume that 1/2 to 2/3 of the theoretical limit could indeed be attained in large-scale manufacturing of LEDs. This would mean that in the long term, a luminous efficacy of 160 – 213 lm/W should be attainable. Light being available at a high quality and luminous flux is useful for illumination applications. Generally, high-quality light is characterized by a color-rendering index exceeding 80, and by a natural color temperature, e.g. 4000 – 6500 K (daylight or true white).

Given these precursory conditions, we compare the potential performance of future LED technology with mature, state-of-the-art conventional lighting technologies, particularly incandescent and fluorescent sources. Figure 1 displays the luminous source efficacy of common light sources, used in home and office lighting, along with the efficacy of solid-state lighting technology implemented through semiconductor LEDs.

In order to reach highest efficacies for LEDs, very significant progress is yet to be made. At the present time, a multitude of exciting technical trends allows one to conclude that there are good reasons for optimism: Vertical-structure LEDs allow for better management of the injection-current distribution; Thin-film LEDs, pursued by major industrial players, allow for the light-extraction limitations imposed by substrates to be eliminated; Larger epitaxial growth reactors allow for lower costs in the manufacturing of LEDs; The thermal management of LEDs and the associated deleterious junction heating is continuously improving through both, increasing device efficiency as well as power packages that provide an engineered thermal path with low thermal resistance.

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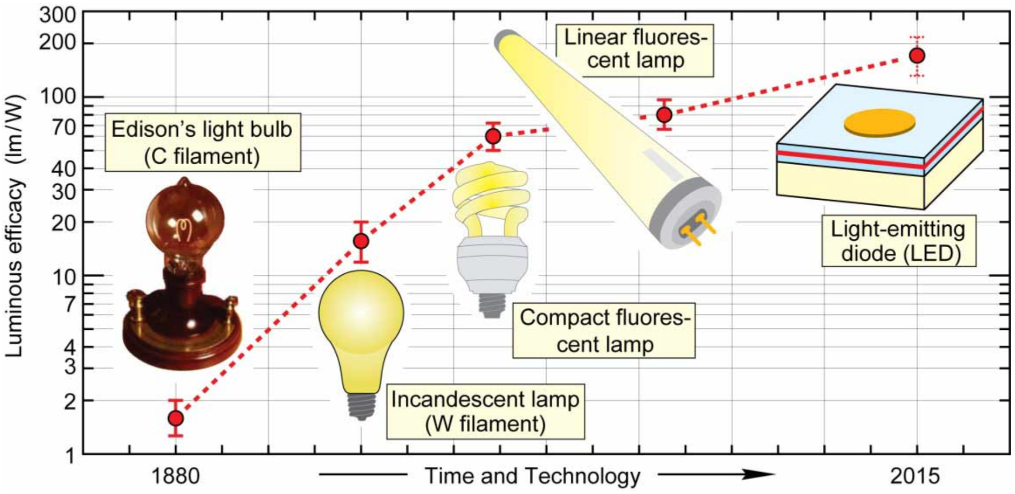


Fig. 1. Comparison of the luminous efficacy (source efficacy) of conventional lighting technologies with the potential of light-emitting diode technology.

3. Anticipated source efficiency gains

There are several ways to generate white light with LEDs: (i) the all-semiconductor approach in which the white light is generated by multiple LED chips; (ii) the LED-phosphor approach in which the white light is generated by a short-wavelength-emitting LED chip and a long-wavelength-emitting wavelength-converter material such as a phosphor; and (iii) a combination of these two approaches (e.g. a blue LED, a green phosphor excited by the blue LED, and a red LED).

In order to identify the technical areas of potential efficiency improvement, we analyze the efficiency of a white LED consisting of a blue semiconductor chip and a yellow phosphor. The flow of power and light of the device is schematically illustrated in Fig. 2. The overall efficiency of the white light emitter, measured in percent, with 100% indicating perfect conversion of electricity to light without heat losses, can be written as:

$$\eta = \eta_{\mathrm{EPS}} \times \left[(\eta_{\mathrm{Vf}}\, \eta_{\mathrm{internal}} \eta_{\mathrm{extraction}})\, T + (\eta_{\mathrm{Vf}}\, \eta_{\mathrm{internal}} \eta_{\mathrm{extraction}})\, (1 - T)\, \eta_{\mathrm{phosphor}} \eta_{\lambda} \right] \times \eta_{\mathrm{luminaire}}$$

Where we define the symbols as follows:

η	is the overall efficiency of white LED
η_{EPS}	is the efficiency of the electrical power supply which can be as high as 100%. In AC-driven scenarios, η_{EPS} = 100%. In DC scenarios, η_{EPS} can be greater than 90%.
η_{Vf}	is the electrical forward-voltage efficiency of the LED chip. It is $\eta_{\mathrm{Vf}} = h\, \nu_{\mathrm{blue}} / (e\, V_{\mathrm{f}})$. Ideally, the forward energy ($e\, V_{\mathrm{f}}$) would be equal to the photon energy, so that $\eta_{\mathrm{Vf}} = 100\%$. However, for many current LED structures, V_{f} exceed this target value, particularly at high currents, where the series resistance loss, IR^2, is large. Thus, there is room for significant improvement of η_{Vf}.
η_{internal}	is the internal quantum efficiency of the LED chip. For most LED chips, there is room for significant improvement of η_{internal}.
$\eta_{\mathrm{extraction}}$	is the quantum efficiency for light to be extracted out of the LED chip and housing. For most LED chips, there is room for significant improvement of $\eta_{\mathrm{extraction}}$.

T	is the fraction of light transmitted through the yellow phosphor.
η_{phosphor}	is the quantum efficiency of the phosphor material, i.e. the ratio of photons emitted by the phosphor divided by photons absorbed by the phosphor. For optimized structures, η_{phosphor} can be high, greater than 90%. However, for non-optimized structures, such as structures having non-uniform phosphors distribution, η_{phosphor} can less than 50%.
η_λ	is the wavelength conversion efficiency, limited by the energy loss when converting one blue photon into one yellow photon ("quantum deficit"). It is $\eta_\lambda = h\nu_{\text{yellow}} / h\nu_{\text{blue}} = \lambda_{\text{blue}} / \lambda_{\text{yellow}}$. This loss is unavoidable in LEDs employing a phosphor and is particularly high when UV excitation is used. Note that the quantum deficit is particularly high for conventional fluorescent sources that are based on Hg discharge lamps which emit in the deep UV at about 250 nm.
$\eta_{\text{luminaire}}$	is the efficiency of the luminaire housing surrounding the LED. Depending on the application, not every application requires a luminaire housing. Therefore, the luminaire efficiency can be as high as 100%.

The above discussion shows that the core areas of improvement, which promise the greatest gain in efficiency, are the LED chip and phosphor. For the LED chip, the internal quantum efficiency provides potential for improvement, particularly in the green spectral range where the LED efficiency has been lower than for other colors. Yet even in the blue color range, there is potential for significant improvement, particularly at high injection currents, for example through a migration from conventional GaInN / GaN, i.e. ternary / binary active regions to ternary / ternary and ternary / quaternary active regions. These advanced active regions hold great promise due to their polarization-matching characteristics [2, 3]. Furthermore one can anticipate that structures enabling complete light-extraction will be demonstrated through the pervasive control of the refractive index and its spatial distribution. For wavelength converters used in white LEDs, the trend towards remote phosphor structures [4] and specularly transparent phosphors (i.e. non-scattering phosphors) will further enhance efficiency.

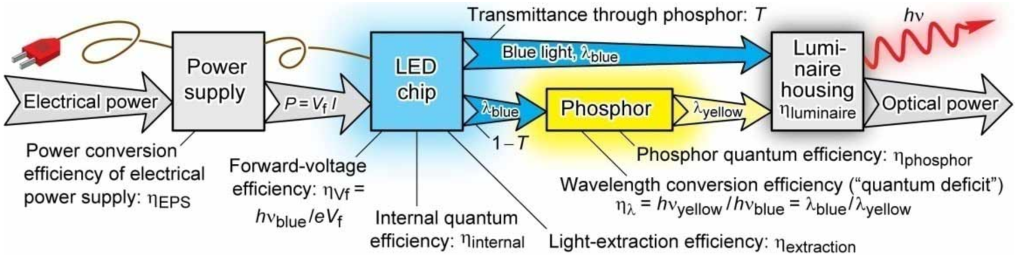


Fig. 2. Schematic flow of power and light of a white LED consisting of a blue-emitting semiconductor chip and a yellow phosphor.

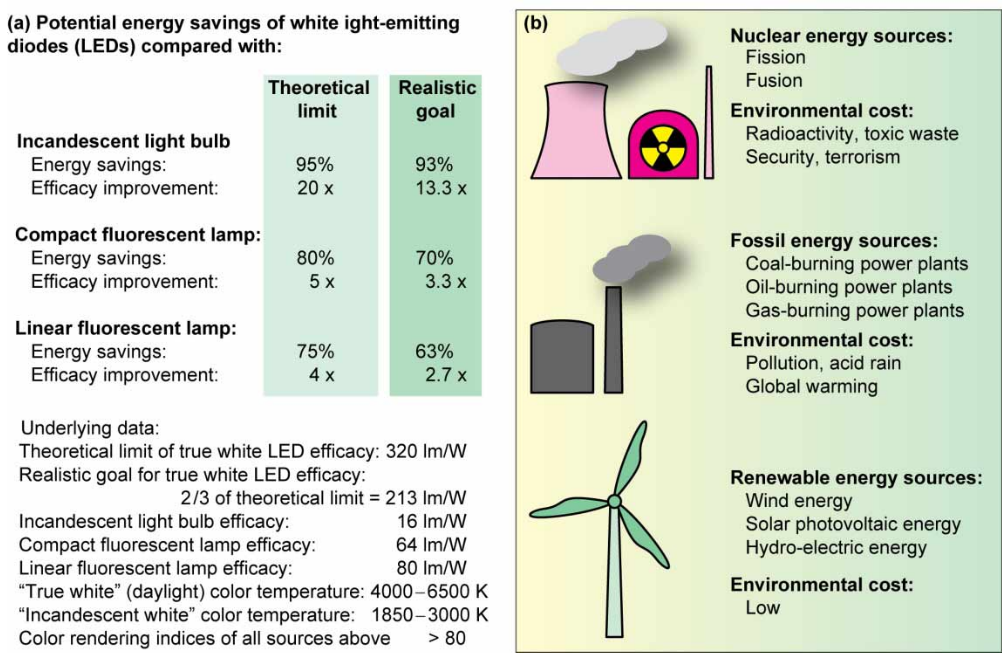
4. Quantification of benefits enabled by the "replacement paradigm"

Under the "replacement paradigm", power-hungry conventional light sources, such as incandescent and fluorescent lamps, are replaced by highly efficient solid-state sources that have the same overall quality as the conventional sources they are replacing. There are potentially huge benefits of solid-state lighting technology under the replacement paradigm, when these sources are deployed on a large, global scale. These benefits can be categorized into (i) reduced energy consumption, (ii) reduced pollution, and (iii) financial savings. The latter depends on the cost of energy which currently increases at a rapid rate.

#100003 - $15.00 USD Received 11 Aug 2008; revised 15 Sep 2008; accepted 16 Sep 2008; published 17 Dec 2008

Realistic gains in efficiency and reduced power savings of solid-state lighting technology over conventional lighting technology are shown in Fig. 3(a) including the underlying assumptions used to estimate the efficiency gains.

Reduced energy consumption also results in gigantic environmental benefits, since electrical energy is generated from a mix of technologies that are schematically illustrated in Fig. 3(b). Reduced radioactive exposure, emission of acid-rain-producing SO_2, likely global warming-causing CO_2, emissions of mercury, and a number of other pollutants are the direct result of these power-generating technologies, and many of these pollutants could be reduced with the broad deployment of solid-state lighting technology.



(a) Potential energy savings of white ight-emitting diodes (LEDs) compared with:

	Theoretical limit	Realistic goal
Incandescent light bulb		
Energy savings:	95%	93%
Efficacy improvement:	20 x	13.3 x
Compact fluorescent lamp:		
Energy savings:	80%	70%
Efficacy improvement:	5 x	3.3 x
Linear fluorescent lamp:		
Energy savings:	75%	63%
Efficacy improvement:	4 x	2.7 x

Underlying data:

Theoretical limit of true white LED efficacy:	320 lm/W
Realistic goal for true white LED efficacy: 2/3 of theoretical limit =	213 lm/W
Incandescent light bulb efficacy:	16 lm/W
Compact fluorescent lamp efficacy:	64 lm/W
Linear fluorescent lamp efficacy:	80 lm/W
"True white" (daylight) color temperature:	4000 – 6500 K
"Incandescent white" color temperature:	1850 – 3000 K
Color rendering indices of all sources above	> 80

Fig. 3. (a) Potential efficiency increases of solid-state light sources. (b) Major sources of electrical power.

Over a 10-year period, the global benefits of solid-state lighting technology have been determined to include [5]:

Table 1. Global benefits enabled by solid-state lighting technology over period of 10 years.

	Estimated Savings
Reduction in total energy consumption	1.892×10^{20} J
Reduction in electrical energy consumption	18,310 TWh
Financial savings	1.831×10^{12} \$
Reduction in CO_2 emission	10.68 Gt
Reduction of crude-oil consumption	962.4×10^{6} barrels
Number of power plants not needed	280

5. Beyond the "replacement paradigm"

It should be noted that LEDs have capabilities that make them extremely useful when going beyond the replacement paradigm. In contrast to conventional light sources, LEDs can be controlled to a great extent. Figure 4 illustrates the new dimensions that are opened by the unique controllability of LEDs. The specific controls include the emission spectrum, color temperature, polarization, temporal modulation, and spatial emission pattern. These controllable LED sources, called *smart* lighting sources [6], will result in tremendous benefits to society and humankind, including:

- **Biology and imaging**: Leapfrog advances in quantitative biology, particularly the rapid identification and counting of biological cells through adaptive and fully tunable reflectance and fluorescence imaging.
- **Display systems**: Liquid-crystal-displays and projectors with unprecedented efficiency and brilliancy (huge color gamut) through polarization-controlled lighting sources.
- **Transportation**: Enhanced visibility (less glare) and safety through polarization-controlled headlights, temporal-controlled communicating headlights/brake lights/traffic lights, and interactive roadways.
- **Communications**: Fundamentally new modes of broadcasting, communications, and sensing through temporal control of solid-state-light sources.
- **Human factors**: Reduced dependency on sleep-inducing pharmaceuticals, higher productivity, prevention of certain cancers, and higher quality of life.
- **Agriculture**: Efficient plant growth in non-native regions (including space) and non-native seasons.

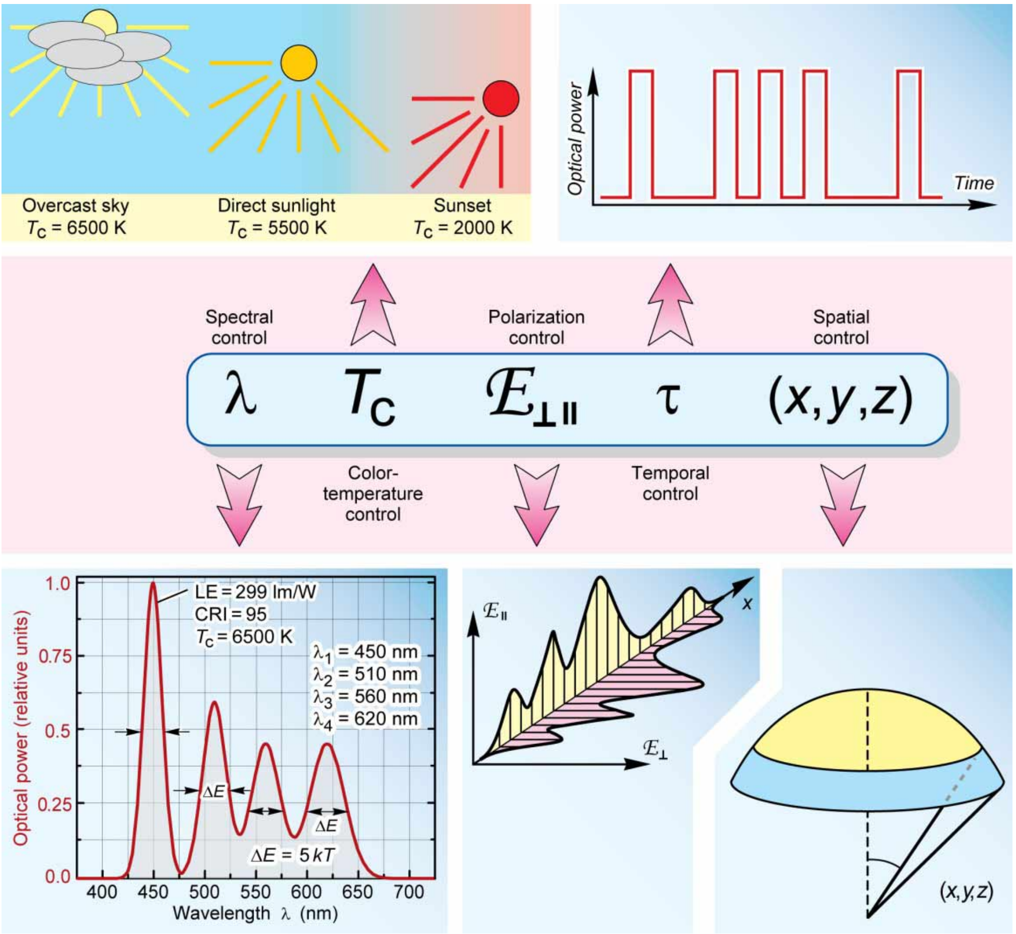


Fig. 4. Illustration of the multi-dimensioanl controllability of smart solid-state light sources.

We wish to compare the development of the role of LED technology in photonics with the development of the role of the transistor in electronics. The transistor was originally intended to replace the vacuum diode. However its use ultimately far exceeded the “replacement paradigm” as exemplified by the development of the integrated circuit. Similarly, it is advisable not to limit the technical endeavor of solid-state lighting to its replacement function, i.e. to the benefits to be reaped by replacing conventional light sources. Transcending the replacement paradigm will open up a new chapter in photonics: Smart lighting sources that are controllable, tunable, intelligent, and communicative.

6. Conclusions

The field of photonics starts with the efficient generation of light that can be controlled in terms of its optical properties. The generation of efficient yet highly controllable light can indeed be accomplished with LEDs, which are devices capable of generating white light with a 20 times greater efficiency than conventional light bulbs. Deployed on a global scale to replace conventional sources, such solid-state light sources will result in enormous benefits that, over a period of 10 years, include (1) gigantic energy savings of 1.9×10^{20} joule, (2) a very substantial reduction in global-warming CO_2 emissions, (3) a strong reduction in the emission of pollutants such as acid-rain-causing SO_2, mercury (Hg), and uranium (U), and (4) financial savings exceeding a trillion (10^{12}) US$. These benefits can be accomplished by the “replacement paradigm” in which conventional light sources are replaced by more energy efficient, more durable, and non-toxic light sources. However, solid-state light sources can go beyond the replacement paradigm, by providing new capabilities including the control of spectrum, color temperature, polarization, temporal modulation, and spatial emission pattern. Future, “smart” light sources fulfill the true promise of solid-state lighting by harnessing the huge potential of LEDs by using multi-dimensional controllability in a wide range of applications that include optical microscopy, imaging, display technologies, communications, networking, and transportation systems.

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