Hybrid Inorganic/Organic Devices for Solid State White Lighting Applications

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Abstract

Solid state hybrid inorganic/organic (Hybrid I/O™) lamp prototypes based on the light wave coupling [1] have been fabricated. A violet LED source is combined with organic dye wavelength conversion to achieve the desired color. Current performance is 7 lm/W with a correlated color temperature (CCT) of 7500 K. Improvements in LED pump efficiency and lamp optical design are expected to lead to an order of magnitude increase in efficiency.

Introduction

Advances continue in improving efficiency and power of InGaN based LEDs for solid state lighting applications. The Optoelectronics Industry Development Association (OIDA) has produced a roadmap to reaching 200 lm/W efficiencies from solid state lighting by the year 2020 [2]. Efficiencies of 75 lm/W and 150 lm/W are expected by 2007 and 2012, respectively. In principle, maximum luminous efficiency could be obtained by mixing output from red, green, and blue LEDs of properly chosen wavelengths. However, the absence of efficient LEDs in the green and yellow regions limits this color mixing approach. Alternatively, a single UV or violet LED could be wavelength converted to white by a suitable phosphor. Current production white LEDs utilize a blue InGaN chip coated with an *inorganic* phosphor mixture for partial wavelength conversion to white. We propose using hybrid *inorganic/organic* light emitting devices [3], which take advantage of the high external quantum efficiency of violet (400 nm) InGaN LEDs, and high photoluminescent wavelength conversion efficiencies of organic dyes. Hybrid I/O™ lamps using the Light Wave Coupling (LWC) approach were fabricated. Application of the LWC approach to display technology is treated in a companion paper [4]. The LWC concept involves three components seen in Figure 1: (i) an edge-mounted violet pump LED; (ii) a waveguide to transmit and store pump light; (iii) an organic thick film color conversion material (CCM). This paper focuses on the fabrication and characterization of Hybrid I/O™ lamp.

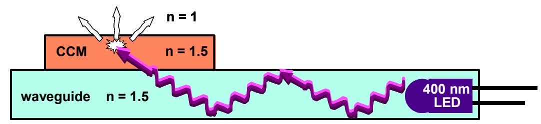

Figure 1. Light wave coupling concept. Pump light is distributed through a transparent waveguide to an index-matched CCM which converts wavelength to desired color.

Figure 2. Photograph of violet (no CCM), blue,green, red, and white hybrid I/O lamps.

Technology	η_L (lm/W)	CCT (K)	Lifetime (kHr)
Incandescent	16	2850	1
Fluorescent	85	4000	10
Luxeon™ LED	15	5500	>50
Hybrid I/O™ (current)	7	7500	2*
Hybrid I/O™ (projected)	76	5500	>50*

Table 1. Comparison of luminous efficiency, correlated color temperature (CCT), and lifetime of current lighting technologies with the hybrid I/O lamp. *Limited by LED pump lifetime.

Experimental

Commercially available 400 nm LEDs in a 5 mm package were mounted into holes drilled into the end a ½” diameter acrylic rod and secured with transparent CCM host polymer. The rods were dip coated into the polymer/dye CCM solutions. The CCM consists of a thick film host polymer matrix doped with an organic dye. Fabrication of CCMs requires three basic steps: (i) dissolving the host polymer and dye in a solvent; (ii) applying this solution to the substrate; (iii) a baking step to drive off solvent and cure the polymer.

Solutions used to produce CCMs were prepared by dissolving the desired weight of polymer host and dye in a suitable solvent. The material used for the acrylic waveguide (a PMMA/polystyrene mixture) is also a suitable CCM host material. Many organic dyes are soluble to >1% concentrations and the waveguide and CCM are index-matched for efficient coupling of pump light. For simplicity the white CCM used here included only two organic dyes: blue and orange. The deposited films were cured in an oven at 150° C for 30 minutes.

Total output power for the violet LEDs were determined using a 6” integrating sphere and Si photodiode detector. Total output power of the lamps were determined by averaging several power per unit area measurements along the length and ends of the rod, and summing all contributions.

Emission spectra were collected with a fiber optic CCD spectrometer.

Results and Discussion

Cylindrical red, green, blue, and white lamps were fabricated. These have the form factor of fluorescent tubes, so they can take advantage of existing fixtures. The 5 mm violet LEDs used in the lamps were characterized in the integrating sphere have only 18.1% wall-plug power efficiency and 20.4% external quantum efficiency at 34mW. Table 2 lists the photon conversion efficiencies of the colored CCMs, which range from 49% for blue to 62% for green, along with the efficiency of the pump LED mounted in the lamp. The white CCMs had color temperatures ranging from ~4000-10,000 K as seen in Fig. 3. The white lamp had CIE coordinates (0.30, 0.29), CCT of ~7500 K, and had a luminous efficiency of 7.0 lm/W.

Significant efficiency improvements are expected in several areas: (a) increased power efficiency of the violet LED chip; (b) improved coupling between LED and waveguide; (c) increased Stokes conversion efficiency; (d) reducing the color temperature from 7500 K; and (e) extraction efficiency.

Color	Optical Output Power (mW)	Wall-Plug Power Eff. % (W/W)	Relative Photon Conversion Efficiency
Violet*	2.35	6.86%	100%
Blue	1.02	2.98%	49%
Green	1.14	3.31%	66%
Red	0.82	2.38%	55%
White	1.06	3.09%	62%

Table 2. Optical output power, wall-plug power efficiency, and photon conversion efficiencies of the lamps pictured in Fig. 2. *Pump LED only, no CCM coating.

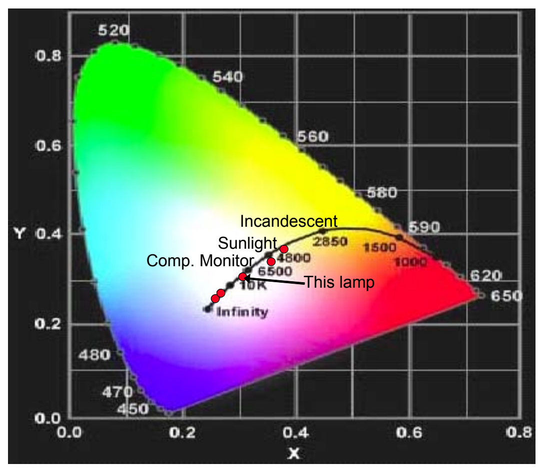

Figure 3. Red dots indicate CIE coordinates of 5 white CCMs of different compositions. Typical values for incandescent bulbs, sunlight, and a computer monitor are provided for comparison. Modified from [2].

Interestingly, Kudo et al. have reported [5] a 110 mW, 405 nm LED with an external quantum efficiency of 43%. The use of this pump would more than double our lamp efficiency. In these early prototypes, a significant portion of the violet LED output escaped out the sides or ends of the lamp without wavelength conversion. Improving the geometry of the lamp or optimizing the CCM layer thickness will prevent any violet photons from escaping the waveguide. Using a longer wavelength LED (switching from 400 to 450 nm) and adjusting the dye content to better cover the spectrum will increase the Stokes conversion efficiency. Lowering the relatively hot color temperature of the lamp by adjusting dye content to include more green and yellow and less violet would increase the luminance of the lamp, but would also increase the complexity of the CCM composition. Finally, the cylindrical shape of the lamp acts as a good waveguide, resulting in long photon path lengths and low outcoupling efficiency (~25%) of dye-converted light. Incorporating a diffuser in the CCM or changing the lamp geometry could reduce this effect by a factor of 3 or more.

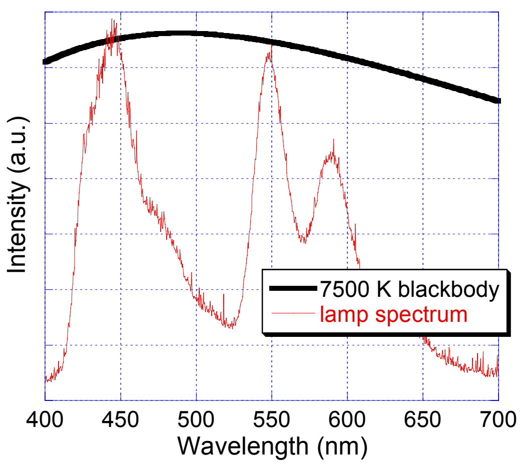

Figure 4. Emission spectrum of the white cylindrical lamp pictured in Fig. 2 along with a 7500 K blackbody for comparison.

What kind of efficiencies could a properly optimized Hybrid I/O™ lamp achieve? The OIDA roadmap has a table of maximum luminous efficiencies for color mixing given three LEDs with a 20 nm bandwidth. Assuming a CCT of 5500 K and a CRI of 80, the maximum luminous efficiency is 368 lm/W. This efficiency actually be considered a lower bound in our approach because mixtures of organic dyes could easily include more than three colors for better spectral coverage. Using a state of the art LED, a ~35% external power conversion efficiency can be achieved. Surrounding the LED with a sufficiently thick CCM will result in 100% absorption of the pump light by the CCM. Organic dyes with photoluminescent efficiencies of 90% or greater can cover the entire visible spectrum. Assuming a 400 nm pump and three dye colors (470, 550, and 610 nm), the approximate Stokes conversion efficiency given by $3\lambda^{in}/(\lambda^{out}_1 + \lambda^{out}_2 + \lambda^{out}_3)$ is 73%. Changing the lamp geometry from a rod to a more spherical shape and the addition of a diffuser would reduce internal reflection and increase outcoupling efficiency to 90% or more. The external luminous efficiency of this lamp is calculated to be 76 lm/W. As violet LED technology matures this number will increase. Even with the LED used here, with an optimal design an efficiency of 39 lm/W is possible.

Conclusions

A white solid state Hybrid I/O™ lamp with a luminous efficiency of 7 lm/W has been demonstrated. Further optical design optimization and use of a state-of-the-art pump LED will result in a luminous efficiency of 76 lm/W. This is 5X that of current commercially available white LEDs and is approaching the efficiency of fluorescent lamps. We believe that the Hybrid I/O™ concept is the optimal approach for meeting the OIDA roadmap recommendation for year 2007.

References

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