ELiXIR—Solid-State Luminaire With Enhanced Light Extraction by Internal Reflection

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***Abstract*—A phosphor-converted light-emitting diode (*pc*LED) luminaire featuring enhanced light extraction by internal reflection (ELiXIR) with efficacy of 60 lm/W producing 18 lumens of yellowish green light at 100 mA is presented. The luminaire consists of a commercial blue high power LED, a polymer hemispherical shell lens with interior phosphor coating, and planar aluminized reflector. High extraction efficiency of the phosphor-converted light is achieved by separating the phosphor from the LED and using internal reflection to steer the light away from lossy reflectors and the LED package and out of the device. At 10 and 500 mA, the luminaire produces 2.1 and 66 lumens with efficacies of 80 and 37 lm/W, respectively. Technological improvements over existing commercial LEDs, such as more efficient *pc*LED packages or, alternatively, higher efficiency green or yellow for color mixing, will be essential to achieving 150–200 lm/W solid-state lighting. Advances in both areas are demonstrated.**

***Index Terms*—Efficiency, green light-emitting diode (LED), package efficiency, phosphor-converted LED (*pc*LED), solid-state lighting (SSL).**

I. INTRODUCTION

THE primary advantage of solid-state lighting (SSL) over conventional lighting technologies is the potential energy savings as a result of higher luminous efficiencies. The Department of Energy (DOE) has set a goal of 50% electrical to optical system efficiency with a spectrum accurately reproducing the solar spectrum [1]. The Optoelectronic Industry Development Association (OIDA) aims for 200-lm/W luminous efficiency with a color rendering index greater than 80 [2].

Generation of high efficiency white light with *inorganic* LEDs requires one of the following options: 1) color mixing: multiple LEDs across the visible spectrum (e.g., blue + green + red LEDs); 2) wavelength conversion: a single efficient short wavelength LED at least partially converted to longer wavelengths by phosphor(s) (e.g., *pc*LED consisting of a B LED + YAG:Ce phosphor); 3) combination of 1) and 2) (e.g., B + *pc*G + R LEDs). Option (1) is hindered by the absence of an efficient LED material system in the 500–570-nm region, while option (2) suffers from poor package efficacy demonstrated by conventional *pc*LEDs. One or both of these problems must likely be solved to reach the efficiency goals set by DOE and OIDA. While not the focus of this work, efficiencies of *organic* LEDs are limited by low external efficiency and high driving voltage.

II. PHOSPHOR-CONVERTED LED EFFICIENCY

The efficiency of a fully wavelength converted *pc*LED lamp can be expressed [3]

$$\eta_{\mathrm{pcL}} = \eta_{\mathrm{LED}}\eta_S\eta_Q\eta_P \tag{1}$$

where η_{pcL} is the *pc*LED wall-plug efficiency, η_{LED} is the pump LED wall-plug efficiency, η_S the Stokes conversion efficiency, η_Q the phosphor quantum efficiency, and η_P the package efficiency. The Stokes efficiency (or quantum deficit) is given by the quantum ratio of the average emission wavelengths of the LED and the phosphor. We have defined the package efficiency as the product of two components: the coupling efficiency of pump light from the LED to the phosphor and extraction of phosphor-converted light from the device. Loss of blue LED light before reaching the phosphor and absorption of phosphor-converted light by the LED chip, reflectors, and encapsulation reduces η_P.

The conventional *pc*LED approach to solid-state lighting utilizes a blue LED chip coated with a phosphor layer, as shown in Fig. 1(a). The prototypical example of this is the InGaN blue/YAG:Ce white LEDs available commercially. YAG:Ce is a broadband yellow emitting phosphor which when combined with the partially transmitted blue LED light yields an acceptable white spectrum. Advantages of this configuration include compact device size, minimal phosphor mass, and consistent color vs. angle. The primary drawback of this configuration is poor package efficiency. Conventional *pc*LED losses are dominated by reflection of pump light back into the LED chip and the large fraction of phosphor emission directed into the LED chip. Secondary losses are encountered at imperfect mirrors used to reflect light out of the device. Because of these limitations, conventional *pc*LEDs may never be capable of the high efficiencies demanded by DOE and OIDA. For the case of InGaN/YAG:Ce white, $\sim 40\%$ of the blue LED flux is transmitted into the phosphor, while the remaining $\sim 60\%$ is directed back into the chip [4], [5]. In addition, by simple geometric reasoning, half of the phosphor-converted light is emitted directly back into the chip, resulting in further loss. The OIDA roadmap [2] indicates that currently the range for η_P is 40%–60%. In the case of *pc*LEDs with 100% phosphor conversion, as in this work, lower η_P values are normally expected because of increased losses from the reabsorption of additional converted light. The approach addressed in this paper aims to obtain enhanced light extraction by internal reflection (ELiXIR). The ELiXIR device, shown schematically in Fig. 1(b), seeks to maximize η_P by: 1) separating the chip and phosphor to nearly eliminate phosphor emission and LED

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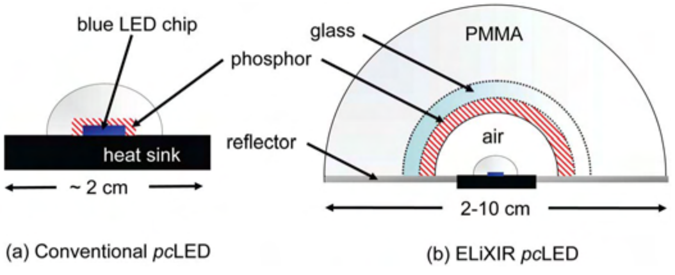

(a) (b)

Fig. 1. (a) Conventional pcLED and (b) ELiXIR *pc*LED.

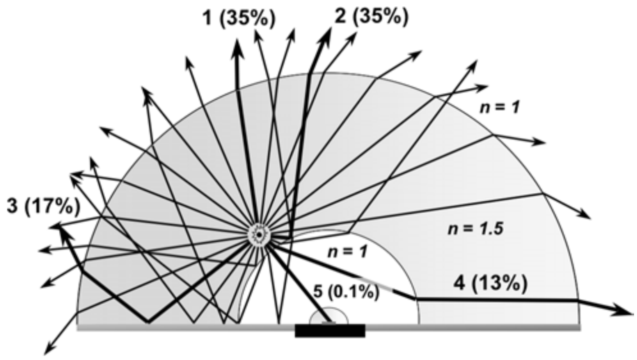

Fig. 2. Ray trace diagram of phosphor emission in the ELiXIR luminaire.

reflection back into the LED chip and 2) the use of internal reflection to reduce the number of mirror reflections.

Separation of the chip and phosphor has been shown to produce higher efficiencies. Scattered photon extraction (SPE) [4], for example, was used to demonstrate a 61% increase in both light output and luminous efficiency compared to conventional white InGaN/YAG:Ce *pc*LEDs. If the efficiency can be raised 61% over conventional *pc*LEDs, an upper bound of conventional *pc*LED package efficiency is set at 1/1.61 or 0.62 assuming 100% package efficiency for the SPE *pc*LED. This value is consistent with the upper end of the $\eta_{\rm p}$ range in the OIDA estimate above. The package efficiency, as defined in (1) here, is not determinable.

Currently, no material system provides high efficiency LEDs in the green-yellow regions of the spectrum. The InGaN material system performs best in the short wavelength regions: $\sim$ 60% internal quantum efficiency at 460 nm, with efficiency dropping at longer wavelengths to $\sim$ 10% at 550 nm. The AlGaInP system performs best in the red ($\sim$ 85% IQE at $\sim$ 650 nm), with efficiency dropping at shorter wavelengths ($\sim$ 20% IQE at 590 nm) [6].

A green *pc*LED using a blue InGaN pump LED coated with a $SrGa_2S_4$:Eu phosphor has been demonstrated [7]. The *pc*LED achieved a flux of 50 lumens and efficiency of 35 lm/W at 400 mA. After accounting for η_S and η_P, blue to green conversion efficiency ($\eta_{\rm pcL}/\eta_{\rm LED}$ in this work) was given as $\sim$ 50%. The results were still favorable compared to InGaN green LEDs. Flux and efficiency can be potentially increased $\sim$ 61% by improving the package efficiency.

The concept of combining blue or violet LEDs with organic dyes in a polymer matrix, such as luminescence conversion LEDs (LUCOLEDs) [8], [9] or hybrid organic-inorganic LEDs [10]–[13] have been previously reported. Efficiencies of such devices have been less than optimal, however, due to locating the dye in close proximity to the LED chip as in *pc*LEDs [8]–[11] and limited extraction or package efficiency due to the planar [10], cylindrical [12], or external coating [13] organic converter geometry.

The ray tracing diagram of Fig. 2 is used to illustrate the various paths phosphor-emitted photons take in the ELiXIR structure. Ray 1 exits the device without encountering any reflections and comprises $\sim$ 35% of the phosphor emission. Ray 2 (representing $\sim$ 35% of the phosphor emission) demonstrates the advantage of the ELiXIR concept. The ray is headed toward the planar reflector, where significant loss normally occurs, but is instead internally reflected at the phosphor–air interface. The ray can now exit the device and may avoid the reflector entirely. Since internal reflection is a lossless process, it is the most efficient way to steer light out of the device. Ray 3, comprising $\sim$ 17% of phosphor emission, heads directly to the reflector before exiting the device and never encounters the phosphor–air interface. Ray 4 is transmitted across the phosphor–air interface but avoids the LED chip and recrosses the air/phosphor interface before exiting the device ($\sim$ 13%). Finally, ray 5 is transmitted across the phosphor–air interface and enters the LED packaging or chip where the highest losses are incurred. In the ELiXIR structures fabricated with a separation between chip and phosphor of 1.9 cm, ray 5 comprises less than 0.1% of the total phosphor-converted light.

Note the absence of internal reflection at the PMMA/air interface, which had limited external efficiency in previous similar designs [10], [12], [13]. In the ELiXIR device presented here, the ratio of the phosphor layer radius to that of the outer lens ($r_{\rm phosphor}/r_{\rm lens}$) is 0.5. A calculation shows that for a hemispherical shell lens with an index of refraction of 1.5 and an index-matched interior phosphor, internal reflection can be avoided by keeping $r_{\rm phosphor}/r_{\rm lens}$ under $\sim$ 0.67.

Although the ELiXIR implementation discussed in this paper utilizes a dye-doped polymer phosphor with uniform refractive index, use of internal reflection to steer phosphor emission is also possible with conventional inorganic powder phosphors or quantum dots in a polymer matrix.

III. ELiXIR LUMINAIRE FABRICATION

Luminaire fabrication required casting and finishing of a hemispherical shell lens, application of the phosphor, and attaching the planar reflector to the lens base. The lens consisted of a thin glass inner shell surrounded by a thick polymethyl methacrylate (PMMA) outer shell, and was fabricated by polymerization of methyl methacrylate monomer around a 25-mL round bottom flask with an outside diameter of 3.8 cm. The outer surface of the lens was shaped by a 7.6-cm diameter spherical aluminum mold, while the inner surface was defined by the flask.

Preparation of the methyl methacrylate monomer involved washing the monomer with a solution of sodium hydroxide to remove the hydroquinone inhibitor, rinsing with deionized water, drying with anhydrous magnesium sulfate, and filtering. The polymerization was initiated by the addition of 0.1%

benzoyl peroxide and heating to 90 °C in a water bath until a viscous syrup was obtained. The flask was positioned in the mold and the cooled syrup was poured into the mold. The entire assembly was placed in an oven at 35 °C for one week for complete curing. After curing, the lens was separated from the mold after being placed in a freezer for one hour.

The phosphor consisted of Johnson Polymer Joncryl 587 modified styrene acrylic with 0.2% BASF Lumogen F Yellow 083 fluorescent dye [14], [15] and was applied to the inner surface of the lens from a solution in acetone. Phosphor layer thickness was on the order of 100 μm. The reflector consisted of aluminized Mylar attached to an acrylic sheet. Reflectance of the aluminized Mylar reflector with adhesive layer was greater than 70% across the visible spectrum. The commercial blue power LED had a peak wavelength of 455-nm and 1000-mA d.c. drive capability. The complete structure of the luminaire is shown in Fig. 1.

It should be noted that the ELiXIR luminaire design is well suited to low cost mass production, so the luminaire cost would be dominated by the pump LED. The lens could be produced with high quality at low cost by injection molding of the PMMA rather than polymerization of the monomer. Aluminized Mylar and acrylic sheet are very low cost materials. In addition, though the luminaire here is large (7.6-cm diameter lens) by LED standards, the design can be easily scaled to a size approaching that of conventional LEDs. The high package efficiency is maintained as long as the proportions of the luminaire, namely the $r_{\text{phosphor}}/r_{\text{lens}}$ ratio, are preserved. The package size is ultimately limited by the chip size. The phosphor distance from the chip must be sufficiently long so that only a small fraction of converted light re-enters the chip, where high losses occur. For example, a typical power LED chip has an area of $\sim 1\ \text{mm}^2$. If we specify that less than 1% of phosphor light emitted from any point on the phosphor may reenter the chip, a minimum chip-phosphor separation of approximately $\sqrt{1\ \text{mm}^2/(4\pi(0.01))}$, or ~ 2.8 mm, is obtained. The minimum lamp diameter would be four times this value, ~ 1.1 cm, which is approaching the size of the transparent lens encapsulation and smaller than the heatsink diameter on a typical power LED.

IV. ELiXIR LUMINAIRE CHARACTERISTICS

The ELiXIR luminaire and the blue LED were characterized for color and total power output. The total power output was measured by placing the device on a rotation stage and simultaneously measuring the power and spectrum as a function of angle from a distance of 38 cm. Care was taken to minimize reflections and subtract contributions not coming directly from the lamp. The output power was measured with a calibrated silicon photodiode. The angular dependence of the optical power of the blue LED and the ELiXIR luminaire are shown in Fig. 3. The LED power has a bi-wing angular dependence, while the ELiXIR luminaire has more uniform distribution in the forward direction with values of $\sim 90\%$ of the maximum emission over a $\sim 100^\circ$ range. Output spectra were collected with a CCD spectrometer with fiber optic cable input, which had been calibrated by a photodiode and variable monochromatic source over the visible region. The spectra seen in Fig. 4 are the weighted averages over all angles. The blue pump LED was confirmed to have peak power emission at 455 nm. The phosphor absorption spectrum is also shown in Fig. 4. The luminaire emission spectrum peaks at 526 nm and nearly completely absorbs the pump emission. The spectrum has a dominant wavelength of 557 nm and CIE color coordinates of (0.34, 0.62), placing it in the yellowish green region of the color gamut. The Stokes conversion efficiency (η_S) from LED to luminaire spectra was 0.83. The luminaire emission spectrum by itself has a luminous efficiency of 509 lm/W.

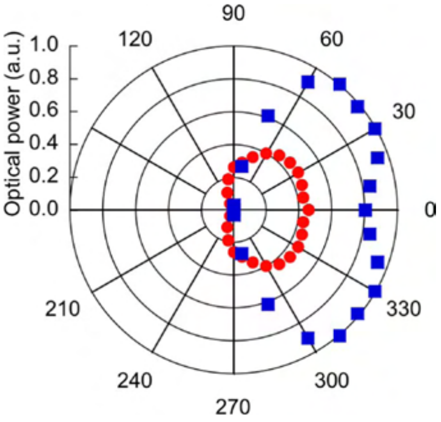

Fig. 3. Blue LED (squares) and ELiXIR luminaire (circles) normalized flux versus angle.

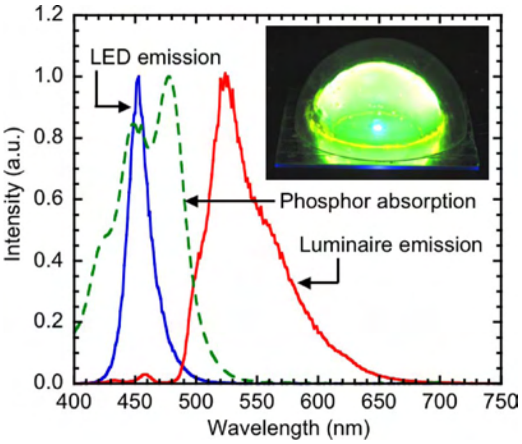

Fig. 4. Blue LED emission, phosphor absorption, and ELiXIR luminaire emission spectra. Photograph of the luminaire in operation (inset).

LED efficiency (η_{LED}) was determined to be 0.19 under drive conditions of 3.0 V and 100 mA. Under identical conditions, the luminaire wall-plug efficiency (η_{pcL}) is 0.12, yielding an optical power conversion efficiency of 0.63 and resulting in a luminous flux of 18 lumens at 60 lm/W. Efficacy and flux range from 80 lm/W and 2.1 lm at 10 mA LED current, to 37 lm/W and 66 lumens at 500 mA. All measurements were under d.c. conditions after allowing the LED to reach steady state. Luminous efficacy and flux results are shown in Fig. 5 as a function of LED drive current. The efficiency roll-off at higher currents is due to the increasing junction temperature in the blue LED and is independent of the phosphor. This was expected since pump intensities at the phosphor are only of the order of mW/cm^2 when the drive currents are hundreds of milliamps in this device.

TABLE I
VARIOUS EFFICIENCY AND FLUX ESTIMATES FOR PHOSPHOR-CONVERTED LEDs AT 400-mA DRIVE CURRENT.

*pc*LED	η_{pcL}	η_{LED}	η_S	η_Q	η_P	η_{lum} (lm/W)	flux (lm)
ELiXIR green (this work)	0.08	0.13	0.83	0.97	0.78	40	56
$SrGa_2S_4$:Eu green [7]	*	*	~ 0.9	~ 0.9	~ 0.6	37	50
commercial white [4]	-	-	-	-	0.4 - 0.62	~ 30	~ 43
SPE white [4]	-	-	-	-	> 0.64	~ 47	~ 63

* η_{pcL} / η_{LED} *was given as ~ 0.5; dashed values were not given or calculable*

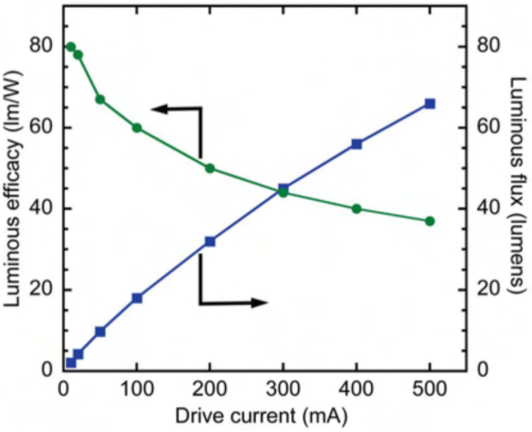

Fig. 5. Luminous efficacy (circles) and luminous flux (squares) versus LED drive current.

An independent experiment using a planar phosphor thick film determined the phosphor quantum efficiency (η_Q) to be $\sim$ 0.97. All quantities from (1) with the exception of the package efficiency (η_P) were experimentally determined. Using values obtained at 100 mA and using the value of η_Q, one calculates that the package efficiency is 0.78. Considering that white YAG:Ce *pc*LEDs have η_P ranging from $\sim$ 0.4 to 0.62, implementation of our ELiXIR approach would immediately increase efficiency and flux by $\sim 95\%$ to $\sim 26\%$, respectively.

The ELiXIR *pc*LED outperforms the reported green *pc*LED [7] in efficacy and flux by $\sim$ 10%. At 400 mA, this ELiXIR luminaire achieves 56 lm at 40 lm/W, compared with 50 lm at 37 lm/W for the conventional *pc*LED. Approximate efficiencies of $\eta_{\rm pcL}/\eta_{\rm LED}(\sim 0.5)$, $\eta_S(\sim 0.9)$, $\eta_Q(\sim 0.9)$, are given for this literature *pc*LED. Insertion of these values into (1) gives an estimate for η_P of 0.6. Based on package efficiencies alone, the ELiXIR luminaire should outperform the literature *pc*LED by $\sim 26\%$. Given the high η_Q of the phosphor, likely higher lumen conversion for the spectrum, and similar η_S values for the ELiXIR *pc*LED, we conclude the relatively high performance of the literature *pc*LED is due to a superior pump LED, the efficiency of which was not given. A summary of all efficiency values discussed here along with literature values is presented in Table I.

Further improvement of package efficiency above the current 0.78 can be expected for this luminaire design. The dominant package loss mechanism is absorption by the reflector. A significant fraction of the phosphor-converted light still encounters the reflector before exiting the device, and at least 30% of that fraction is absorbed. Total loss at the reflector is estimated to be $\sim 10\%$. Coupling of the LED into the lamp base was found to be imperfect, as blue emission can clearly be seen from the edge of the acrylic sheet in the Fig. 3 photograph. A measurement of the LED power output with and without the acrylic sheet and reflector revealed a coupling loss of 5%. With further optimization of device geometry, improved reflector reflectivity and LED to phosphor coupling, this package is likely capable of achieving the year 2020 target of 0.95 efficiency for *pc*LEDs specified by OIDA [2].

V. SUMMARY AND CONCLUSION

In summary, ELiXIR, a new *pc*LED architecture has been demonstrated. Much of the phosphor-converted light that would otherwise encounter the lossy LED chip or mirrors is internally reflected and efficiently extracted from the device. The ELiXIR *pc*LED had a dominant wavelength of 557 nm and exceeded the performance of commercial and laboratory LEDs of similar color. With the implementation of the luminaire package presented here, conventional InGaN/YAG:Ce *pc*LED flux and efficiency could be increased immediately by a minimum of 26%.

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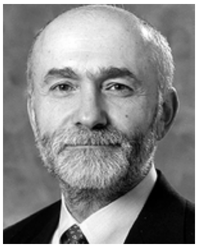

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