WHITE LED WITH HIGH PACKAGE EXTRACTION EFFICIENCY

Final Report

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DISCLAIMER

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PROJECT OBJECTIVE

The goal of this project is to develop a high efficiency phosphor converting (white) Light Emitting Diode (pcLED) 1-Watt package through an increase in package extraction efficiency. A transparent/translucent monolithic phosphor is proposed to replace the powdered phosphor to reduce the scattering caused by phosphor particles. Additionally, a multi-layer thin film selectively reflecting filter is proposed between blue LED die and phosphor layer to recover inward yellow emission. At the end of the project we expect to recycle approximately 50% of the unrecovered backward light in current package construction, and develop a pcLED device with 80 lm/W_e using our technology improvements and commercially available chip/package source. The success of the project will benefit luminous efficacy of white LEDs by increasing package extraction efficiency.

TECHNICAL APPROACH

In most phosphor-converting white LEDs, the white color is obtained by combining a blue LED die (or chip) with a powdered phosphor layer. The phosphor partially absorbs the blue light from the LED die and converts it into a broad green-yellow emission. The mixture of the transmitted blue light and green-yellow light emerging gives white light. There are two major drawbacks for current pcLEDs in terms of package extraction efficiency. The first is light scattering caused by phosphor particles. When the blue photons from the chip strike the phosphor particles, some blue light will be scattered by phosphor particles. Converted yellow emission photons are also scattered. A portion of scattered light is in the backward direction toward the die. The amount of this backward light varies and depends in part on the particle size of phosphors. The other drawback is that yellow emission from phosphor powders is isotropic. Although some backward light can be recovered by the reflector in current LED packages, there is still a portion of backward light that will be absorbed inside the package and further converted to heat. Heat generated in the package may cause a deterioration of encapsulant materials, affecting the performance of both the LED die and phosphor, leading to a decrease in the luminous efficacy over lifetime. Recent studies from research groups at Rensselaer Polytechnic Institute found that, under the condition to obtain a white light, about 40% of the light is transmitted outward of the phosphor layer and 60% of the light is reflected inward.[1,2] It is claimed that using scattered photon extraction (SPE) technique, luminous efficacy is increased by 60%.

In this project, a transparent/translucent monolithic phosphor was used to replace the powdered phosphor layer. In the normal pcLED package, the powdered phosphor is mixed with silicone either to be deposited on the top of LED die forming a chip level conversion (CLC) white LED or to be casted in the package forming a volume conversion white LED. In the monolithic phosphors there are no phosphor powder/silicone interfaces so it can reduce the light scattering caused by phosphor particles. Additionally, a multi-layer thin film selectively reflecting filter is inserted in the white LED package between the blue LED die and phosphor layer. It will selectively transmit the blue light from the LED die and reflect the phosphor's yellow inward emission outward. The two technologies try to recover backward light to the outward direction in the pcLED package thereby improving the package extraction efficiency.

Package Extraction Efficiency

It is necessary to analyze the package extraction efficiency of current pcLEDs as a baseline. The package efficiency, η_{pkg}, sometimes also referred to as scattering efficiency, is the ratio of the number of photons emitted from the LED package to the number of photons emitted from the semiconductor chip within the package.[3]

The number of photons per second F from a radiation source, S, is

$$F = \int \frac{\mathrm{S}(\lambda)}{E(\lambda)} d\lambda = \int \frac{\mathrm{S}(\lambda)}{h\nu(\lambda)} d\lambda = \int \frac{\lambda \mathrm{S}(\lambda)}{hc} d\lambda = \frac{\lambda_c \int S(\lambda) d\lambda}{hc} = \frac{\lambda_c W_o}{hc}$$

where $S(\lambda)$ is the radiation source power spectral distribution, $E(\lambda)$ is the energy of a photon at wavelength λ. λ_c is the centroid wavelength and W_o is the optical power of the radiation. λ_c is the wavelength that divides the integral of a spectrum into two equal parts according to

$$\lambda_c = \frac{\int \lambda S(\lambda) d\lambda}{\int S(\lambda) d\lambda}.$$

F_1 for a LED package is easy to obtain from the optical power measurement in an integrating sphere. If F_0 from the same LED die used in the packaged LED is known, the ratio of F_1 to F_0 gives the package efficiency η_{pkg}. But it is difficult to measure F_0 of the LED die directly, because photons extracted from the die is determined by many factors, such as encapsulation medium (air or silicone, etc.), medium optical geometry, quality of the blue LED die itself (wavelength, surface roughness, etc.). So the die extraction efficiency η_{ext} is intertwined with the package efficiency η_{pkg}. In the ideal case, the photons from the die would be measured when the die is sited in the center of a transparent sphere with high refractive index matching the die materials. In practice, the optical power of the die in the air without encapsulation is measured as a baseline reference; photons$_{_B}$ is obtained from this measurement. The package efficiency η_{pkg} is then calculated by photons/photons$_{_B}$. Quite often the lumens are normalized to the optical power measured by the blue die in the air, lm/W$_o$, to eliminate the variation of the performance of blue dies. It is used to evaluate the lumens performance of the phosphor. But one should be cautious when using the optical power of blue LED die measured in the air as a baseline, because when the blue die is encapsulated, the extraction efficiency is quite different for different bins of blue dies.

For comparison, two different bins of blue LED dies were chosen. The first group has lower light output than the second group. The LED dies were die bonded into OSRAM Golden Dragon packages first, Fig.1(a), and then casted with silicone forming a planar surface, Fig.1(b), and last a silicone lens was dispensed on top Fig.1(c). In each step of the package, the light output was characterized by a LED measurement system consisting of an integrating sphere and a spectrometer.

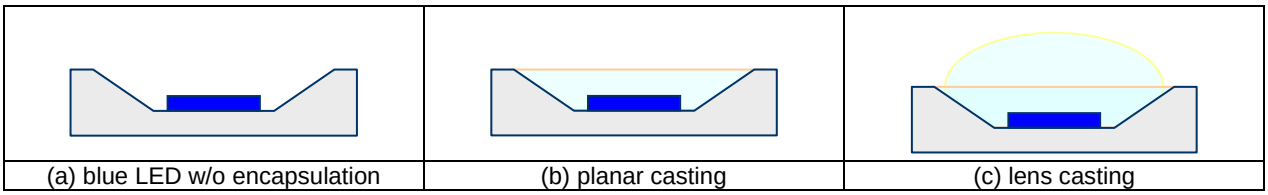


Fig.1 Schematic of a blue LED package design

The measurement results in different LED package stages are shown in the Table 1. The average optical power for the lower bin blue LED group 1 is 0.301 W. It is 0.382 W for the higher bin of blue LED group 2. After planar casting, both groups see the reduction in optical power, caused by the total internal reflection at the planar interface between the silicone and air. As for lens package, blue LED group 1 shows a 22% increase in the optical power output compared to the package without encapsulation. Blue LED group 2 only shows a 12% increase.

Table 1. Blue LED package configuration measurement results

	Fig.1(a)	**Fig.1(b)**	**Fig.1(c)**	**Fig.1(c) / Fig.1(a)**	
	W_O avg (W)	W_O avg (W)	W_O avg (W)	W/W	Photons/Photons
Blue LED Group 1	0.301	0.291	0.368	1.22	1.22
Blue LED Group 2	0.382	0.358	0.428	1.12	1.12

It is interesting to see that different bins of blue LED dies assembled in the same package have different extraction efficiency. It is evident this is caused by the difference in the LED dies. InGaN materials have much higher refractive index than air. The light generated in the active layer has tendency to be trapped inside the die by total internal reflection if it does not fall into the extraction escape cone. One purpose of the encapsulation materials is to enlarge the escape cone. The LED die surface texture (roughening) is also applied to extract more light by mitigating the total internal reflection. Blue LED group 1 has lower optical power than group 2 in the package without encapsulation. It is possibly due to the weaker surface texture in group 1, so it has less die extraction efficiency. It has more photons available to be extracted when encapsulated with high refractive index materials, such as silicone. The result indicates that performance of lens packaged blue LEDs will not be in proportional to the performance of blue LED dies. The same conclusion applies to phosphor converting white LEDs using blue LED dies. The result also has implication in color steering of pcLEDs using blue LED dies. The color coordinate C_x of pcLEDs using lower-bin blue LED dies will decrease more (shifting more to blue) in the final lens package than the pcLEDs using higher-bin blue LED dies, because more blue light will be extracted out. It also implies that when comparing the phosphor performance in an encapsulated package, it is better to use the same bin of blue LED dies, not simply the same bin of white pcLED product, for study.

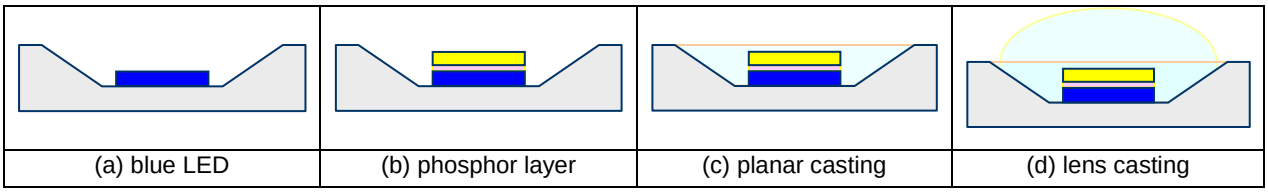


Fig.2 pcLEDs package steps

For pcLED package, a blue LED die was die bonded and wire bonded into a Golden Dragon package without any encapsulation, Fig.2(a). A phosphor layer was glued right on the blue die with a thin silicone layer, Fig.2(b). The silicone was then dispensed in the reflector cup to form a planar casting Fig.2(c). This is standard Golden Dragon package. In more advanced packages, a silicone lens was added on the planar casting to form a Golden Dragon Plus (GD+) package, Fig.2(d). The performance of the phosphor layer is evaluated by its lumens output, color coordinates and CCT, etc. The vision efficacy lm/W_{o_B} and package extraction efficiency (photon extraction efficiency) $photons/photons_{\_B}$ are normally two parameters for evaluation. But since the different bins of blue LED dies have different photon extraction efficiency, this simple normalization may give misleading results.

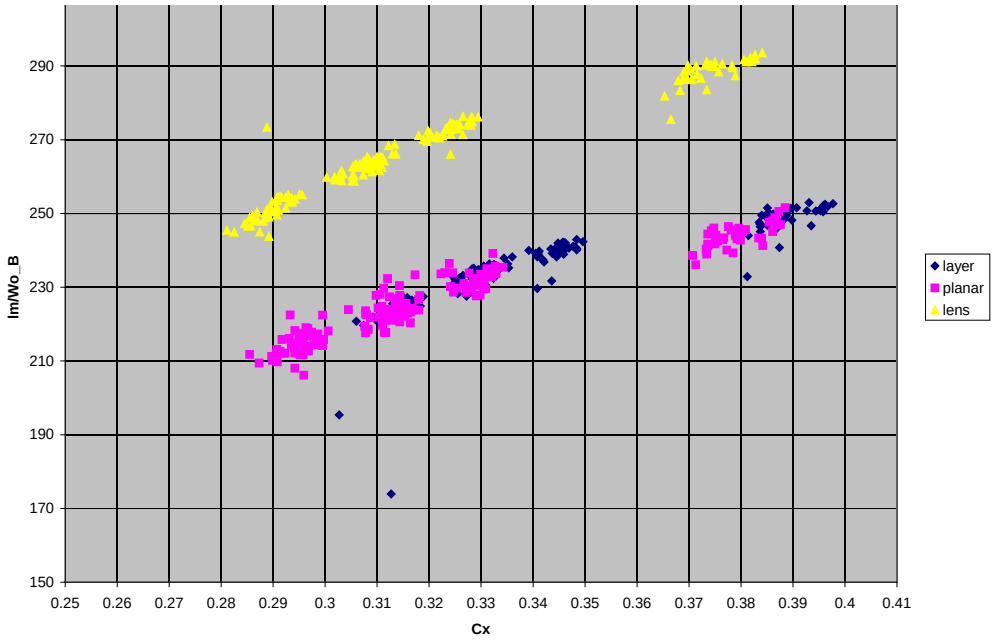


Fig.3 $lm/Wo_{\_B}$ of lower bin of blue LED dies in the different steps of Golden Dragon Plus package

Various concentration of premium YAG phosphor powders were mixed with silicone. Chip size phosphor-silicone layers were deposited on the top of blue LED dies in the Golden Dragon Plus package. The same bin of blue LED dies (group 1) in Table 1 was used. The lm/W_{o_B} and $photons/photons_{\_B}$ are plotted against C_x. in Figs. 3 and 4, respectively. The color of packages shifts to blue when changing from without encapsulation, Fig.2(b), to silicone planar casting, Fig.2(c), and it shifts a little further to blue for lens packages, Fig.2(d). The color blue shifting means the portion of blue light increases after silicone encapsulation. It seems that the blue light

benefits more than the yellow light from the encapsulation. The possible reason is that Ce:YAG is highly absorptive in blue and transparent in yellow. The blue photons not extracted at the interface of phosphor layer-air at the first opportunity will likely be absorbed during reflection and scattering in the phosphor layers, while the yellow photons can be scattered a few times and still be extracted out by silicone encapsulation because of low absorption in yellow. Fig.5. shows the average color shifting from the layer package to lens package. The color shifts more towards blue at lower $C_{x,}$ where phosphor concentration is lower and the blue light is dominant. At higher C_x, the color shifts less towards blue, because the yellow light is dominant.

As shown in Fig.3, the lm/W_{o_B} increases as C_x increases because the portion of yellow light increases as phosphor concentration increases, but the rate of increase decreases at higher C_x ($C_x \geq 0.37$). The photons/photons$_{_B}$ always decreases as C_x increases. There are a few reasons for the photon extraction efficiency decrease as phosphor concentration increases. First, higher C_x is obtained by adding more phosphors in the phosphor-silicone mixture. More phosphor means more photon loss due to phosphor quantum efficiency less than 100%. Secondly, as phosphor concentration increases, scattering due to the phosphor particles increases.

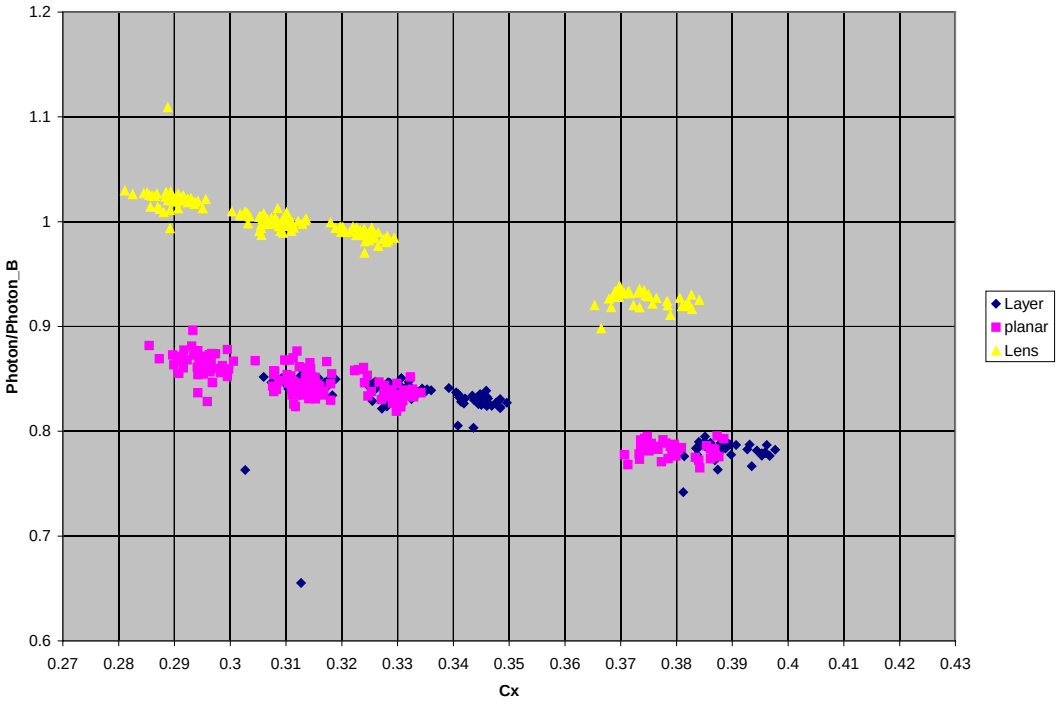


Fig.4 Photons/Photons$_{_B}$ of lower bin of blue LED dies in the different steps of GD+ package

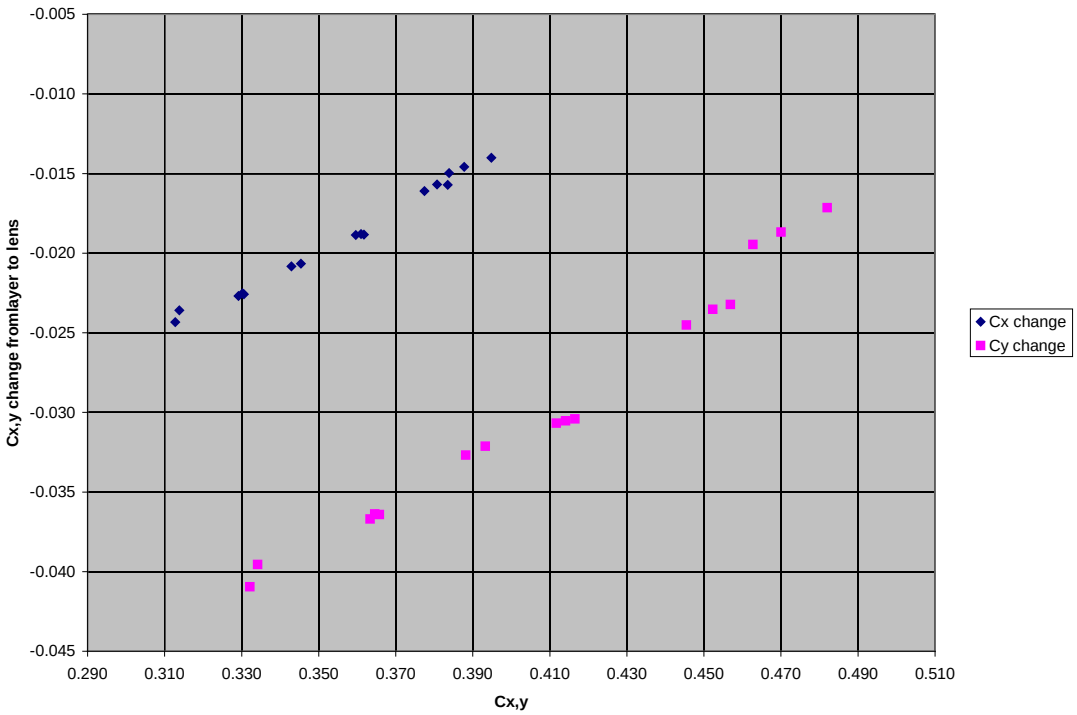


Fig.5 Average $C_{x,y}$ change of green YAG premium phosphor in GD+ package from layer to lens package

The blue LED group 2 (higher bins) in the Table 1 was used in similar experiments, including pushing the color to higher C_x by increasing the phosphor loading in silicones to see the effect of increased scattering.

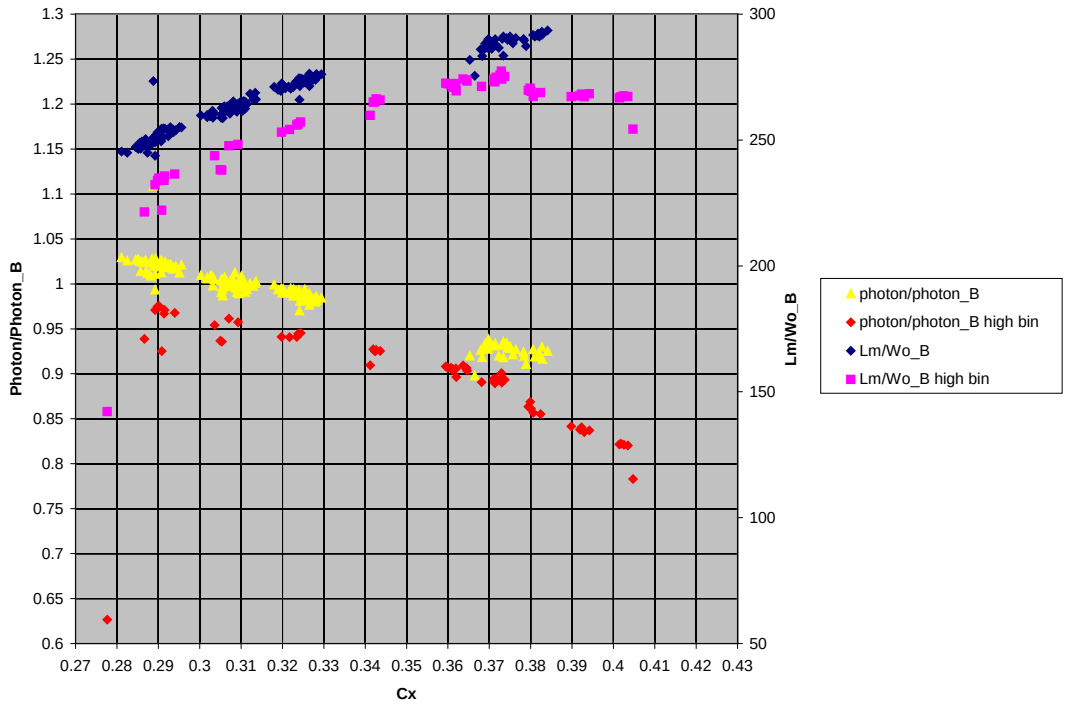


Fig.6 lm/Wo$_{_B}$ and photons/Photons$_{_B}$ of blue LED dies in the Golden Dragon Plus lens package

The performance results of lens package pcLEDs using the higher bin of blue LED dies are shown in Fig.6. The lm/W_{o_B} increases as C_x increases until it is about 0.37, then it starts to decreases. The lumens gain from converting blue to yellow light which has higher luminous efficacy of radiation is offset by scattering at higher C_x. The photons/photons$_{_B}$ always decreases as C_x increases, but the rate of decrease appears to accelerate as C_x reaches 0.37. This is due to stronger scattering at higher C_x where the phosphor concentration is much higher.

The lm/W_{o_B} and photons/photons$_{_B}$ of lens package LEDs using lower bins are also plotted for comparison in Fig.6. It shows that both lm/W_{o_B} and photons/photons$_{_B}$ of lens pcLED packages using the lower bin of blue LED dies are higher. They should be roughly the same because both use the same phosphor loading and package design. The difference again is due to the blue LED dies. As shown in Table 1, the lower bin of blue LEDs have more blue light extracted than the higher bin of blue LEDs. This clearly demonstrates that it is necessary to use the same bin of blue LED dies when the phosphor and package performance are evaluated. The obviousness of this statement underscores its importance in studying pcLED improvement efficiency. The same bins of blue LED dies were used for the following studies.

If the different extraction efficiency of different binned blue LED dies, from without encapsulation to lens package, is normalized (or in other words, the optical power from the blue LED lens package is used as a baseline), the lm/W_{o_B} and photons/photons$_{_B}$ of lens package LEDs from the lower and higher bins are about the same, Fig.7. So the package extraction efficiency η_{pkg} of pcLED with phosphor powder in silicon conversion is estimated to be 0.75-0.87. It is dependent on color coordinate C_x. The "package loss" includes not only the real package loss but also quantum efficiency and phosphor scattering loss, which are not directly related to the package.

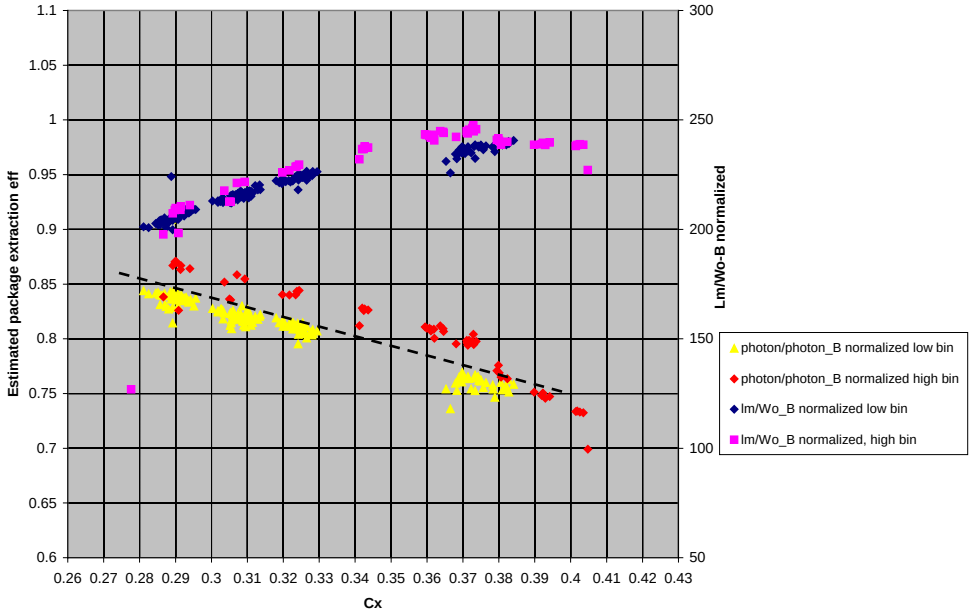


Fig.7 Normalized lm/Wo$_{_B}$ and photons/Photons$_{_B}$ of blue LED dies in the Golden Dragon Plus lens package

The phosphor scattering becomes more severe at high C_x > 0.37 where phosphor loading is high. Scattering loss is estimated to be 5-10%. The quantum efficiency loss is about 5% for Ce:YAG phosphor. So the real package loss is estimated to be 10-15%.

Design and Deposition of Multi-layer Thin Film Coatings

The purpose of this task is to improve package extraction efficiency by applying a selectively reflecting filter between the blue LED die and phosphor layer. The filter has such optical properties that the transmission in the blue region is high and reflectance in the yellow region is high to reflect the backward yellow phosphor emission in the forward direction.

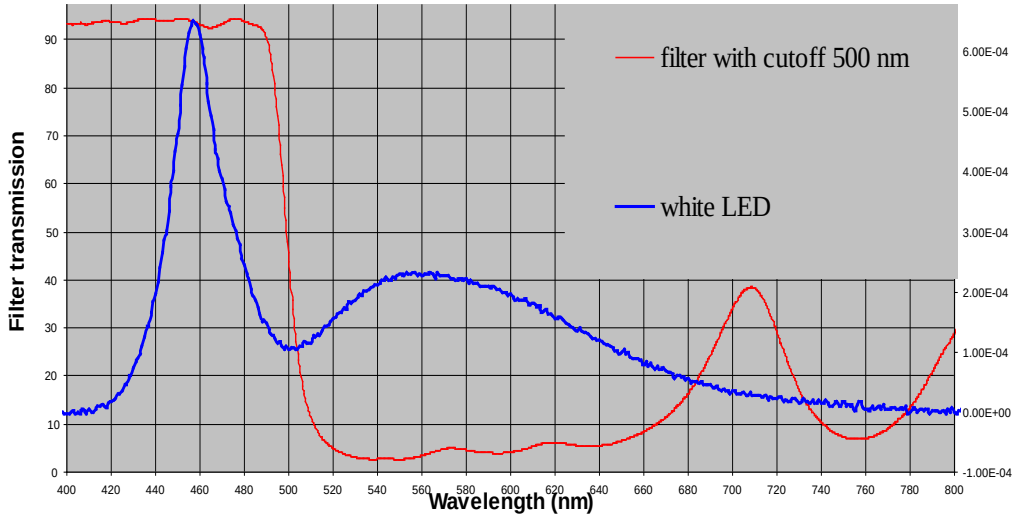


Fig.8 A typical white LED spectrum and transmission curve of a filter.

The white LED spectrum has a combination of blue LED die emission and broad yellow emission from Ce:YAG phosphor, Fig.8. It would be natural to choose the cutoff wavelength of the filter to correspond the valley between the blue emission peak and yellow phosphor emission peak. So the cutoff wavelength of the first filter was designed at 500 nm. But since blue light from the LED die is not collimated and the filter works best only at 0 degree of incident angle, the blue light loss becomes severe at large degree of incident angle. As shown in the simulation for a blue pass filter with a cutoff wavelength 500 nm, Fig.9, the transmission at 460 nm is only 50% at 45 degrees of incident angle. Since the blue light is the pumping source for pcLEDs, it is critical to keep the blue transmission through the filter high for better efficiency. Another blue filter was designed with the cutoff wavelength at 520 nm. For this design, the blue transmission is over 90% at 460 nm at 45 degrees of incident angle.

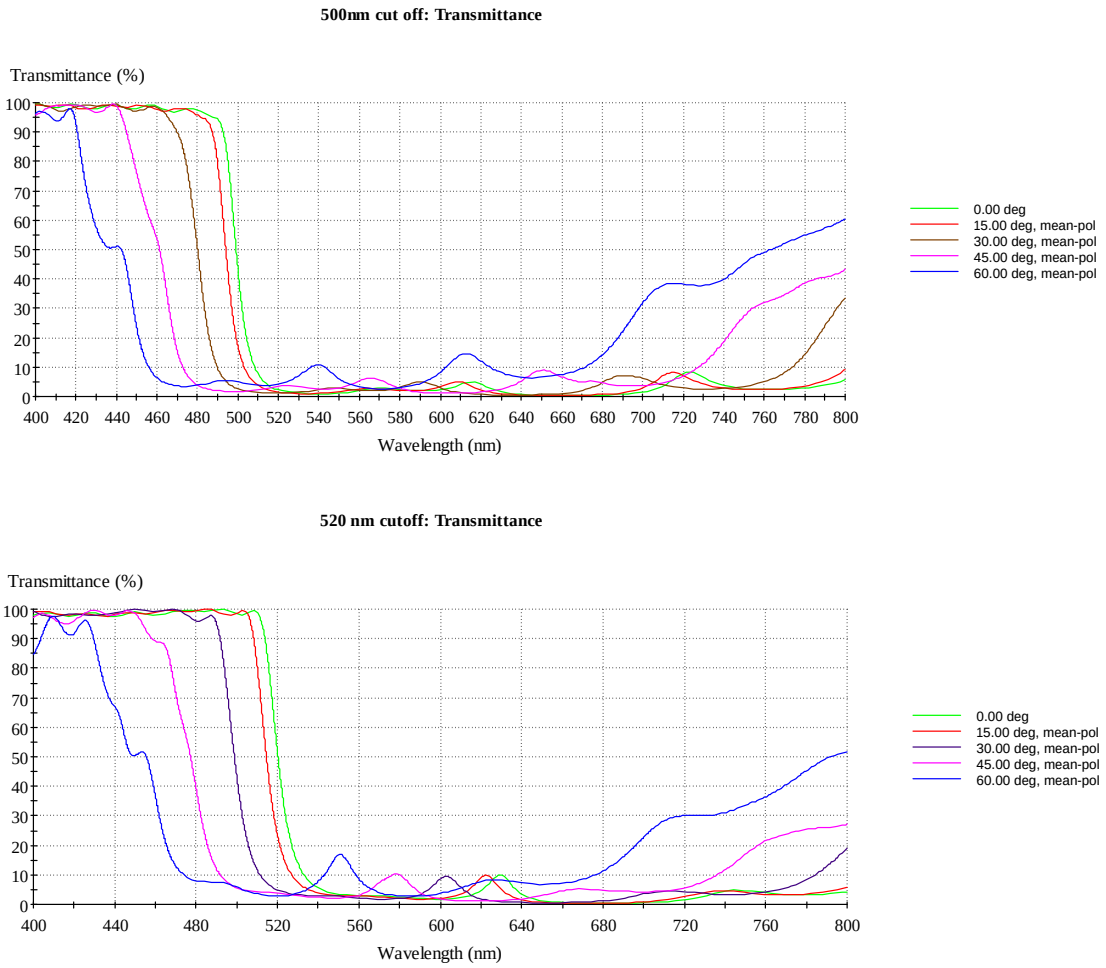


Fig.9 Simulated transmittance data for the filters with various incident angles

The coating design was fabricated in a physical vapor deposition chamber. It is a batch-type reactive sputtering technology employing a drum geometry substrate carrier, surrounded by sputter cathodes mounted in close proximity to microwave oxygen-argon plasma sources. The microwave sources both promote the oxidation of the deposited material and improve stability of the sputtering cathode operation.

The coating was made first on a flat glass substrate. The coating was also deposited on curved substrates, such as a half ball glass lens, Fig.10(a). The purpose of coating on curved substrates is to mitigate the angle dependence problem of the filter. The LED die is positioned ideally at the center of the hemisphere so that most of the light will strike the filter coated on hemisphere surface, at near zero degrees incidence.

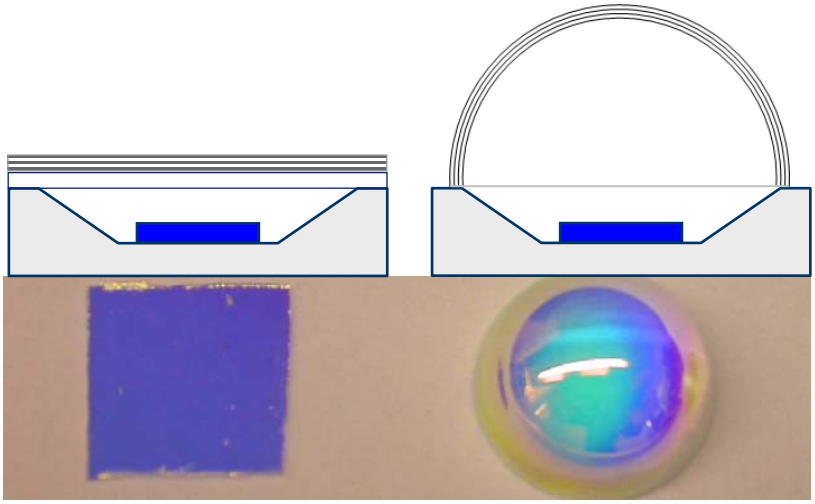


Fig.10(a) Coating on flat glass (left) and half ball glass lens (right) substrates.

The radiant power from a blue LED die in the package without encapsulation and from a filter on the top of the same blue LED package was measured. The ratio gives the blue total transmission of the filter. The measured total transmission for the filter made on flat glass substrate is 90.6% and for the filter made on half ball glass lens is 91.5%, demonstrating achievement of 90% total transmission of the blue light through the filter design.

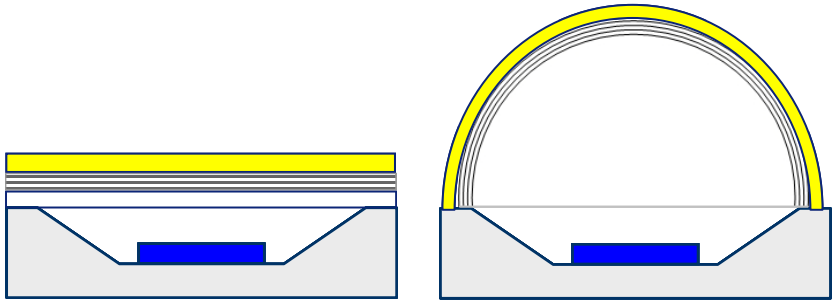


Fig.10(b) Phosphor layer on the flat glass filter (left) and half ball glass lens filter (right).

A phosphor layer was deposited on the top of the filters, Fig.10(b). The lumens were compared without and with the filter. Although the total transmission of the filters is high, the gain from the filter was not realized. The lumens actually decrease 7% and 2% for the filter on flat glass substrate and half ball glass lens, respectively, and demonstrating that additional losses in the system outweigh achievement of 90% blue transmission as the pumping source.

From the analysis in the previous section on the package extraction efficiency, the real package loss is about 10-15%. When the filter is applied in the pcLED, the blue loss due to the filter alone is already about 10%. It is very difficult to gain efficiency improvement from the filter proposed and tested in this project. Therefore, we concluded that improving the 0 to 45 degrees angle of incidence integrated transmission to greater than 95% would be technically interesting, even admirable if achieved, but outside the scope of possible development in the timeframe of this project.

Glass Ceramic Monolithic Phosphor Development

Cerium doped YAG transparent ceramic has high transparency and high quantum efficiency. It is a very good candidate as monolithic phosphor for white LEDs. It is normally sintered in vacuum or hydrogen atmosphere at high temperature. Some times further hot isostatic pressing is needed to improve transparency. The cost is relatively high due to the processing. As a cost effective alternative, glass ceramic monolithic phosphors have been developed. Rare earth, normally Ce, doped glass is melted by conventional glass melting methods. The melted glass is heat treated to convert some glass into crystalline YAG phase(s) with some degree of Ce partition inside. This method is low cost and has potential for the mass production. The glass ceramic monolithic phosphor development was subcontracted to Alfred University.

The starting glasses are based on the yttria, alumina and silica system doped with ceria. Raw materials were batched as oxides or nitrides and mixed in a mortar and pestle. The glasses were melted at ~ 1600°C with some compositions melted as high as 1630°C. Glasses were quenched onto a steel cooling plate. The glass samples were then heat treated at certain temperature to partially crystallize and form glass ceramics. The vast majority of glasses were crystallized isothermally. Some were crystallized by microwave heating. During the heat treatment, small pieces were put on chunks of alumina. The glasses were kept from sticking to the alumina by using zirconia powder, since at the crystallization temperature there is some viscous flow of the glass.

The glass ceramic samples were analyzed by X-ray diffraction to determine the crystalline phases in the sample. The photoluminescence properties are evaluated in a SPEX fluorimeter. Samples were crushed to small particles and measured in the reflectance direction. Several measurements were taken, but normally the emissions were taken under an excitation wavelength of 462 nm to imitate the emission from blue LEDs. A blue LED was modified by removal of the lens and the sample was placed where the lens was. The emission was measured with an Ocean Optics 2000 spectrophotometer, attached to an integrating sphere. The apparatus was used for comparison of samples. The microstructure of the sample was characterized by Scanning Electron Microscopy (SEM). Micrograph images were taken by backscattered electron mode, and the amount of YAG (crystalline phase) in volume percent was measured. An attempt was made to estimate the mole fraction of YAG and glass. The density of several samples was measured in a gas pycnometer. The literature value of the density of YAG was used for the density of the YAG and the density of the residual glass was estimated. These numbers were then used to estimate the weight fraction of glass and YAG and the final composition in mole fraction of the glass.

YAG proved to be relatively easy to crystallize in some compositions. Typically crystallization temperatures above 1400°C produced YAG glass ceramics, and by 1450°C the only phase precipitated was usually YAG. At lower temperature, a second phase, yttrium disilicate ($Y_2Si_2O_7$) was formed, Fig. 11.

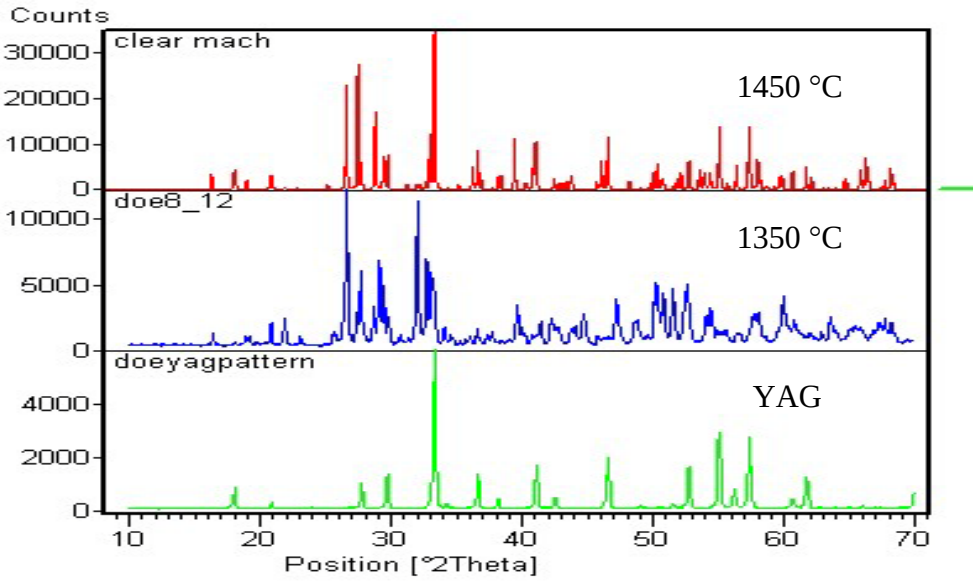


Fig.11 The effect of crystallization temperature on the glass ceramic composition.

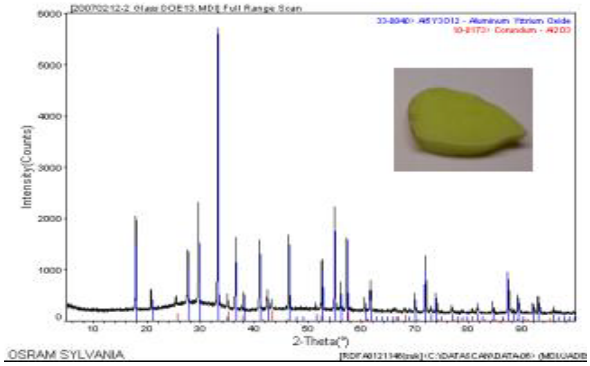


Fig.12 Glass (DOE 13) heat treated for 8 hrs at 1450 °C shows YAG phase.

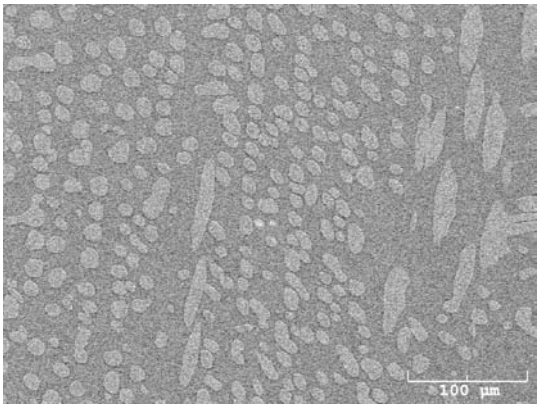


Fig.13 SEM micrograph of glass (DOE 13) heat treated for 8 hrs at 1450 °C.

Another composition (DOE 13) shows the main crystalline phase is YAG phase after heat treatment at 1450 °C for 8 hours, Fig. 12. Fig. 13 shows the microstructure of this sample. It is YAG phase dispersed in the glassy phase.

The glass ceramic samples emit a broad emission with the peak wavelength at 532 nm. It implies that Ce:YAG crystals existed in the glass ceramics. The quantum efficiency (QE) for glass ceramic is lower than commercial Ce:YAG phosphor. The wavelength dispersive spectroscopy (WDS) reveals information about where the activator ions sit inside the glass ceramic. Fig. 14 shows WDS mapping for Si and Ce. In the left image, the dark blue phases are YAG; the long yellow shape phases are $Y_2Si_2O_7$; the green phases are glass.

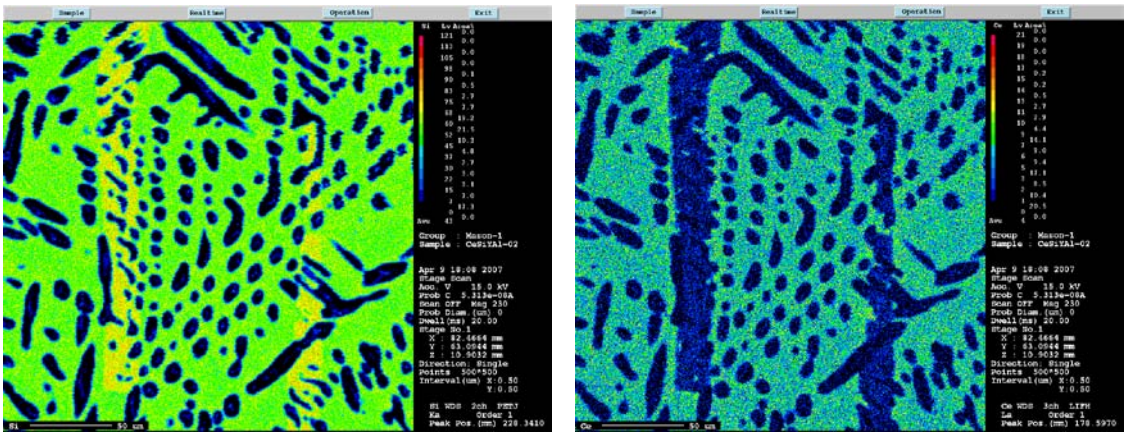


Fig.14 Element mapping (DOE15) for Si content (left) and for Ce Content (right)

From the Ce mapping micrograph, it can be seen that most of the cerium remains in the glassy phase. That may be the reason for lower QE, since the Ce in YAG phase is more efficient. Another possible reason for low QE is related to the oxidation state of Ce ions, whether it is Ce^{4+} or Ce^{3+}. The Ce ions only emit at trivalent state. The general trends for Ce ions in silicate and borate glasses is that Ce ions increase in $[Ce^{4+}]^*$ with increasing basicity of the glass, increase in $[Ce^{4+}]$ with a decrease in temperature, and increase in $[Ce^{4+}]$ with total concentration of the Ce ions.[4]

Substitution of nitride for alumina produced potentially a very high efficiency material as measured in terms of the overall counts from the fluorimeter. The possible reason is that nitride keeps more cerium in the Ce^{3+} state as $6Ce^{4+} + 2N^{3-} \rightarrow 6Ce^{3+} + N_2$.

But excess nitride may have an opposite effect. It is possible that nitride may enter the YAG structure and reduce its quantum efficiency. Fig. 15 shows element mapping for Al and N in glass DOE25. It contains 5% mole percent nitride. Although the nitrogen content in YAG is less than in the glass, it is clear that N existed in the YAG phase.

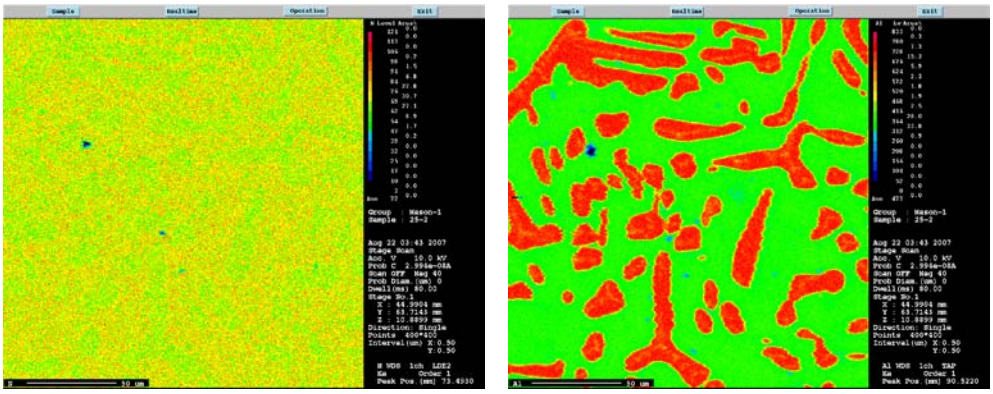


Fig.15 Element mapping (DOE25) for Al content (left) and for N Content (right)

* [Ce] = "concentration of" Ce

Another possible approach to make good emitting glass ceramics would be to make a better microstructure. The idea is to add the alkali earth in the Y_2O_3-Al_2O_3-SiO_2 glass to form a solid solution of cerium doped yttrium aluminum garnet and alkali earth aluminum silicon garnet. It would have good transmission because it would contain only a single phase, thereby reducing the scattering. If an alkaline earth enters the YAG structure, silicon may also have to enter the structure in the tetrahedral position to maintain electrical neutrality. Some glass ceramic compositions were more successful at producing large volumes of crystalline phase. Fig. 16 shows the highest fraction of garnet recorded in this investigation, which was in DOE glass 40. Unfortunately the emission of many of these glass ceramics was not particularly high. The best samples made used strontia (SrO) as a modifying ion in the glass. This is the alkaline earth that enters the YAG the least, and also keeps the silicon out of the structure, suggesting that putting alkaline earth ions into the YAG structure reduces the quantum efficiency of the crystals.

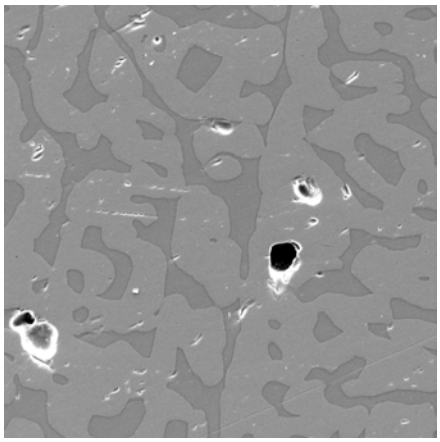
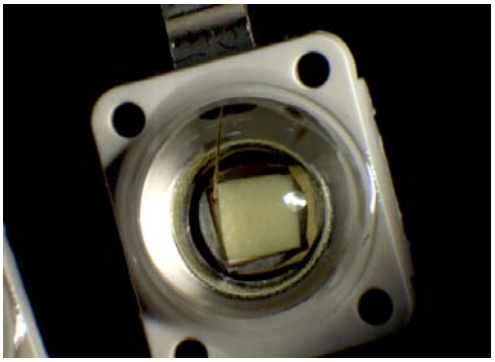
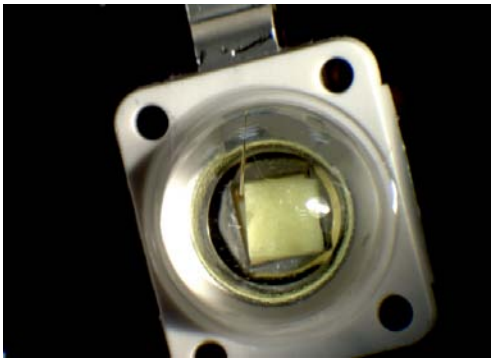


Fig.16 SEM micrograph of DOE glass 40 shows very high YAG content.

Fig. 17 shows the pictures of pcLEDs using glass ceramic phosphors. Fig.18 compares the lm/W_{o_B} of pcLEDs using glass ceramic phosphors with pcLEDs using CLC Ce:YAG phosphor-silicone layers. The best glass ceramic sample DOE 49 is about 82% as efficient as of CLC Ce:YAG phosphor which has QE 97%, thereby meeting our goal of glass ceramic composition with ≥ 60% QE.



DOE glass 46: Average performance is 56.9 lm/W, $C_{x,y}$ (0.3209, 0.3541), 6058 K, CRI 65, at 350 mA



DOE glass 49: Average performance is 73.5 lm/W, $C_{x,y}$ (0.3543, 0.4055), 5001 K, CRI 62, at 350 mA

Fig.17 pcLEDs using glass ceramic phosphors

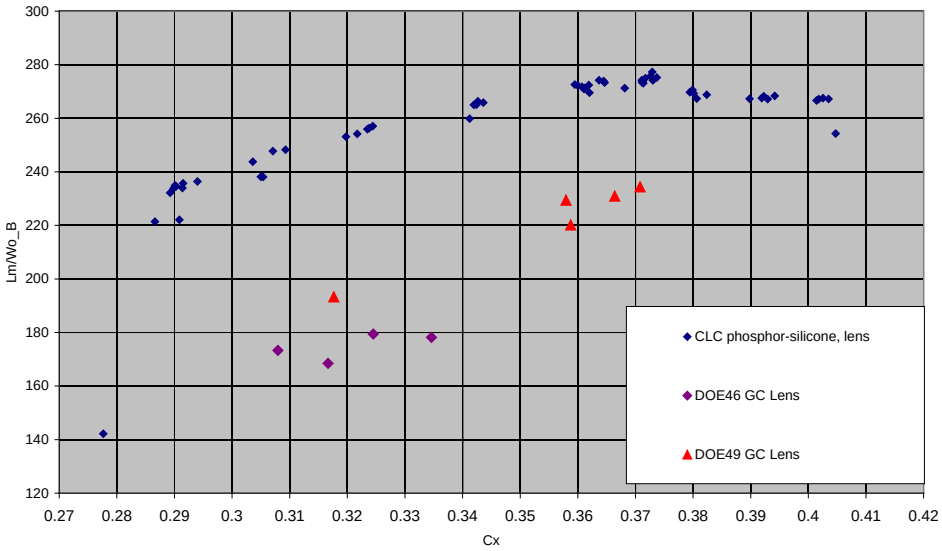


Fig.18 Efficacy comparison of glass ceramic phosphor and CLC Ce:YAG phosphor.

Ce:YAG Ceramic Phosphor

Since current chip level conversion (CLC) white pcLEDs use phosphor-silicone mixtures deposited on the top of blue dies, the scattering caused by refractive index difference between the phosphor and silicone reduces the extraction efficiency in the pcLED package. This was shown in Fig.6 where the lm/W_{o_B} has a maximum and photon extraction efficiency decreases more abruptly at higher C_x. Similar behavior has been observed in phosphor volume conversion package, too.

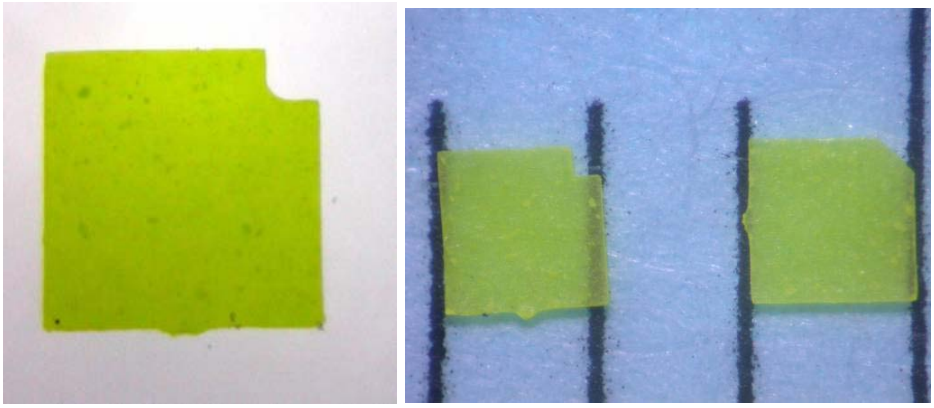


Fig. 19. Ce:YAG ceramic phosphor samples

Monolithic Ce:YAG ceramic phosphors, Fig.19, are fabricated by ceramic forming, pre-firing and sintering. In monolithic Ce:YAG ceramic phosphors, the Ce ions are distributed in the polycrystalline YAG matrix. They emit similar to Ce ions in YAG phosphor powders. There is no YAG-silicone interfaces compared to the normal powdered phosphor-silicone layer save for the glue interface between LED die and monolithic ceramic, so it can reduce the scattering from the conversion layer. Fig.20 compares vision efficacy lm/W_{o_B} of CLC phosphor-silicone

layers and ceramic phosphor plates in the Golden Dragon Plus package with lens. The lm/W_{o_B} of CLC phosphor-silicone layer increase as Cx increases and shows a roll over at $C_x > 0.37$. The decrease in higher C_x is clearly due to the phosphor particle scattering. In the contrast, lm/W_{o_B} of Ce:YAG ceramic phosphors keeps increasing as the C_x increases. At the same C_x, their lm/W_{o_B} is higher than that of CLC phosphor-silicone layer. Konoshima ceramics are highly transparent Ce:YAG ceramic. #1145 is OSRAM SYLVANIA sintered near transparent Ce:YAG ceramics. This is mainly due to the transparency of ceramic samples with much less scattering. The benefit from the transparent ceramic is more prominent at higher C_x, which is a result of controlling the ceramic microstructure features.

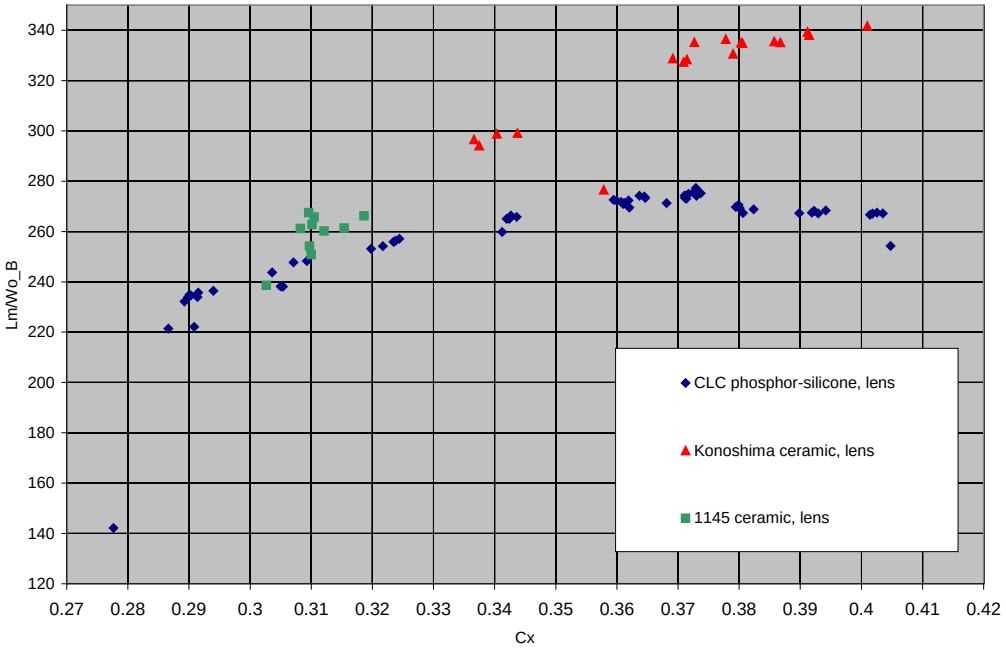
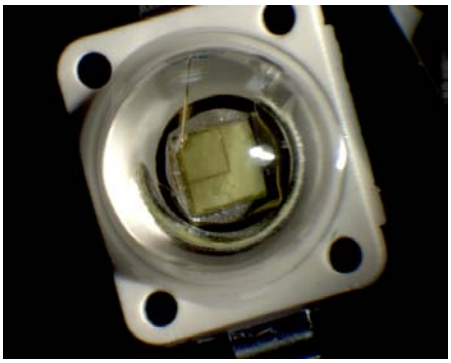


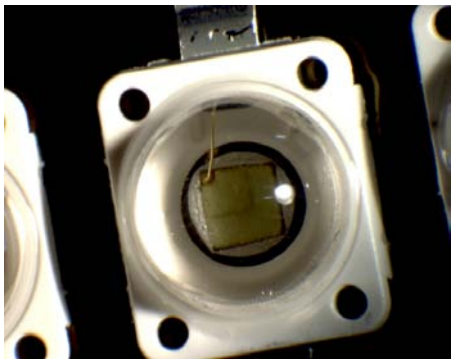
Fig.20 Comparison of lm/W_{o_B} of CLC gYAG premium and ceramic phosphors in lens GD+ package

Fig.21 shows the Ce:YAG ceramic plate and CLC phosphor-silicone layer assembled in OSRAM Golden Dragon Plus package. The average efficacy of the ceramic plate package is 85 lm/W_e, demonstrating our target efficiency of $\geq$ 80 lm/W_e. At similar C_x, the CLC phosphor-silicone package has an average efficacy of 80 lm/W_e.

Currently yellow phosphor used in CLC pcLEDs has a high Ce concentration. The phosphor-silicone layer is about 20 microns in thickness. Because the thickness is so thin, a small variation in layer thickness plus inhomogeneous phosphor distribution in the silicone can change the color of pcLEDs noticeably. The color spreading can be as large as 0.045 in C_x, or $\Delta C_x = 0.045$. The large color spreading is not desired, because the packages with the color outside of the target bins will be rejected. It is costly because of the waste of expensive dies.



Ce:YAG Ceramic 1145: 84.8 lm/W_e; x,y (0.3107, 0.3396); 6542 K; CRI 65 at 350 mA



CLC Phosphor-silicone: 80.0 lm/W; x,y (0.3088, 0.3261), 6744 K; CRI 72.6 at 350 mA

Fig.21 pcLEDs using Ce:YAG ceramic phosphor (left) and CLC phosphor-silicone layer (right)

The normal composition of ceramic phosphor has much less Ce concentration. The composition is chosen so that a ceramic phosphor plate with larger thickness can give white color under blue LED illumination. It is relatively easy for ceramic forming processes to make such thicker ceramic plate. If the thickness is too small, the process becomes more challenging and ceramic mechanical strength is not strong enough for handling. Larger thickness also makes Ce:YAG ceramic phosphors more tolerant to the thickness variation-induced color shifting. Conversely, if the microstructure and Ce distribution are well controlled, the target color bins can be obtained by controlling ceramic phosphor plate thickness.

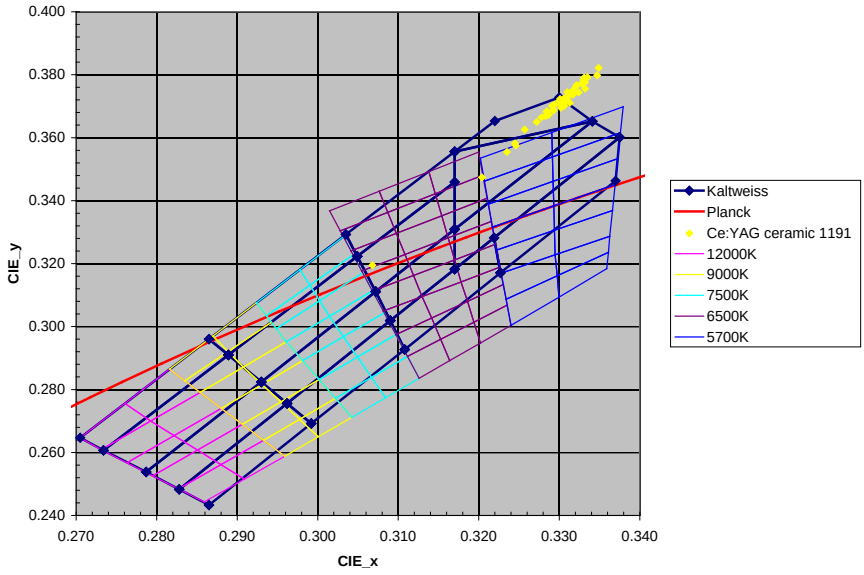


Fig.22 Color spreading of ceramic phosphor 1191

Fig. 22 shows the color distribution of Ce:YAG ceramic phosphor plates combined with the blue LED dies in Golden Dragon Plus package without encapsulation. The color will shift to blue after encapsulation and lens placement in a package. Most of them will fall in the bins of 6500°K Among a total of 48 samples, the color spreading ΔC_x of 47 samples is less than 0.015.

Color angular shifting is the color change when the LED emission is viewed at different angles. The color angular shifting should be minimized so the human eyes can't sense the color inhomogeneity at different angles. The color angular shifting is caused by waveguide effect and mean free path of blue and yellow photons in the phosphor converter layer. Blue photons travel much less distance in the perpendicular direction than in the horizontal direction to the phosphor layer surface. The C_x is lower in the small view angles, because there is more portion of the light in blue. For large viewing angles (of incidence), blue photons travels longer, more blue is absorbed, and more yellow light emits, resulting in higher C_x. If color angular shifting is large enough, a yellow ring or edge can be seen when the LED shines on a white surface. An appropriate amount of scattering in the phosphor would reduce the waveguide effect, resulting a less color angular shifting. There is a tradeoff between the scattering and efficiency. The scattering is necessary to reduce color angular shifting, but too much scattering can reduce the efficiency. Simulation of pore size and concentration effect in the ceramic on efficacy and color angular shifting was performed. The result in Fig.23 suggests it is possible to achieve high efficiency while keeping the color angular shifting low, but finding then holding fixed the requisite process conditions for 0.5% pores around 100 nm in size is challenging.

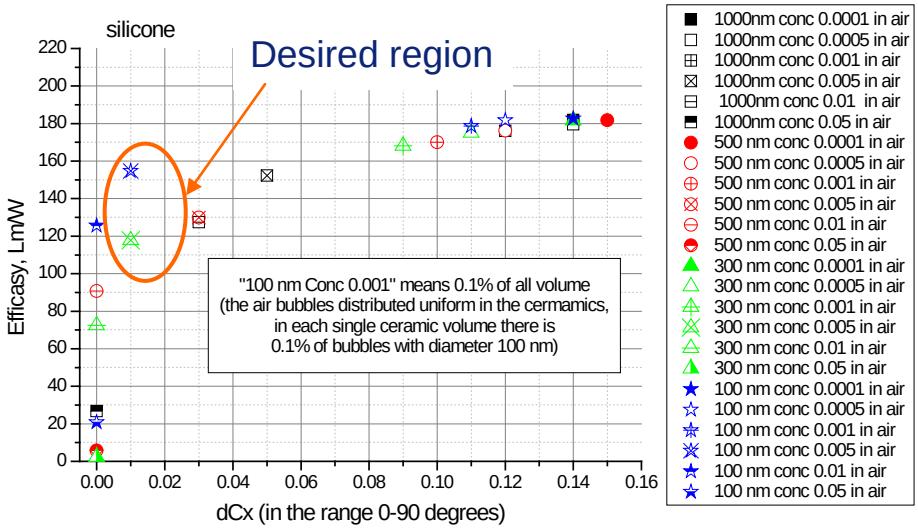


Fig.23 Efficacy lm/Wo v.s. ΔC_x of ceramic phosphors with different pore size and concentration

Fig.24 shows angular color of some LED packages using different phosphors. From 0 to ±70° viewing angle, the color shifting, ΔC_x, for Lumiramic[†] in Golden Dragon Plus package is 0.02. For CLC phosphor-silicone layer, in the same package, it is 0.045. The angular shifting of a near transparent Ce:YAG ceramic plates #1145 in Ceramos package is 0.05. For a less transparent Ce:YAG ceramic sample #1138 with more controlled pores, the angular color shifting ΔC_x is less than 0.02 in Ceramos package. The efficiency measurement shows that #1138 is as efficient as #1140 and #1145. So it is possible to introduce the appropriate amount of pores in the ceramic to reduce the color angular shifting while maintaining the efficiency.

[†] Lumiramic is a trade name for a product provided by Philips Lighting / Philips Solid State Lighting.

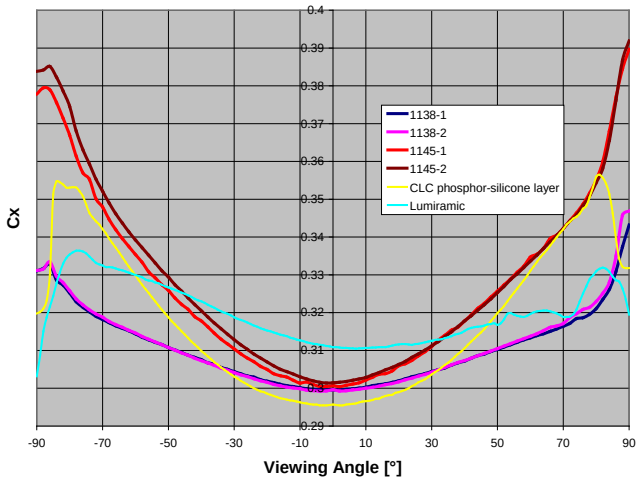


Fig.24 Color angular shifting of ceramic phosphors

Fig.25 shows color shifting of different phosphor converter layers in the temperature range from -40°C to 120°C. The color all shifts to blue as the temperature rises. It implies that blue emission from the LED die and phosphor yellow emission respond at different rates against temperature change. Yellow emission decreases at a higher rate than the blue emission (shifting is greater along the C_x axis than along the C_y axis). For CLC phosphor-silicone layer which has higher concentration of Ce, the C_x decreases about 0.03. For ceramic phosphors which have much less Ce, the C_x only decreases less than 0.015. The low Ce concentration doped YAG has better thermal stability. This might be due to less cross relaxation of capable yellow emission transition energy levels at higher temperature because of lower Ce ion density in the ceramic phosphor. The lower thermal stability for higher Ce doped YAG can be explained by thermally activated concentration quenching where less blue accepting and yellow emissive transition energy levels exist. High thermal stability is an attractive property for certain applications, such as automotive LED lamps.

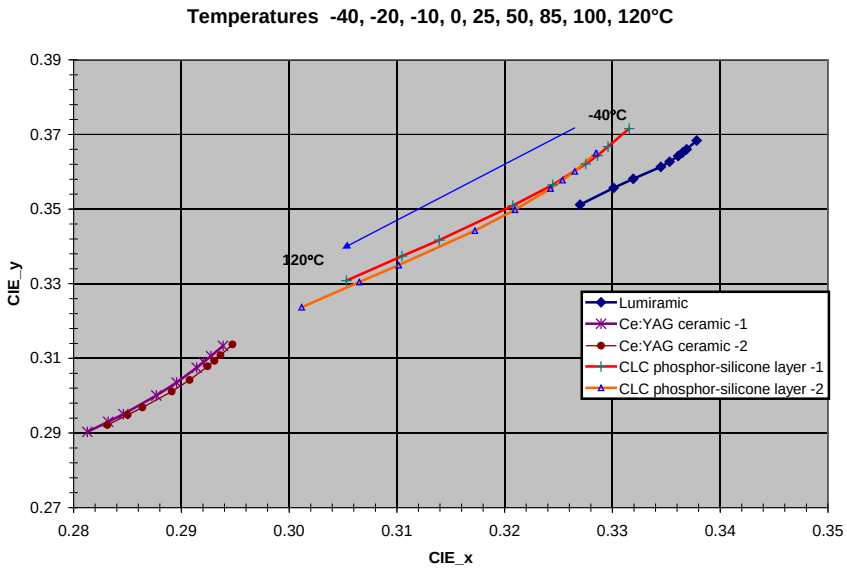


Fig. 25. phosphor color shifting with the temperature

A manufacturing test was conducted to study the handleability of ceramic monolithic phosphors at the point of substitution for today's traditional phosphor/silicone converter layer application. Automatic pick-and-place was tested, Fig.26. The ceramic phosphor plates were positioned on different foils in a 5 x 10 array with 1.5 mm pitch. A thermal release foil, UV foil and lower sticking power foil were tested. The low sticking power foil worked the best. In the pick-and-place test, the chips were raised by ejector needle from bottom, picked by a vacuum tweezer, and placed in Ceramos packages. 92% of ceramic phosphor plates were successfully transferred to Ceramos packages with little deviation from standard pick-and-place settings. There was a concern that rigid ceramic plates might be too close to the bonding wires, causing damage; however, no evidence of scrapping or marking the wire was found. By accurate pattern recognizing, incorporation of monolithic phosphor into the volume production lines is feasible.

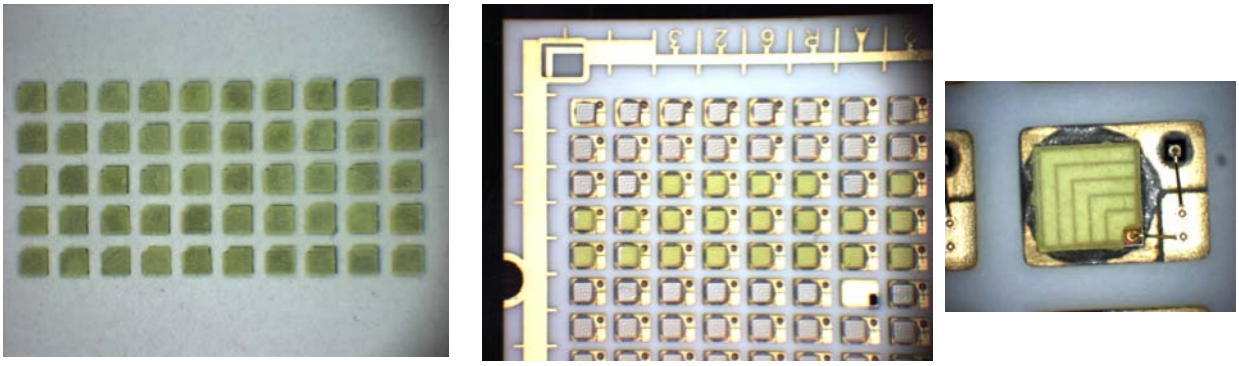


Fig.26. pick and place trial for ceramic phosphor

CONCLUSION

Compared to the CLC phosphor-silicone layers, the Ce:YAG ceramic phosphors demonstrates some advantages. It shows very high efficiency, comparable to the most efficient YAG premium phosphor. Its efficiency is even higher than YAG premium phosphor at higher Cx, i.e. Cx>0.34. It has better thermal stability than CLC phosphor-silicone converter system due to its lower Ce concentration. It is possible that the color shifting of white LEDs using ceramic phosphors can be narrowed compared to using CLC phosphors, and that the color angular shifting of white LEDs using ceramic phosphors can be less than the CLC phosphor-silicone layer. The ceramic phosphor also has better thermal conductivity.

One possible application is automotive head lamps. Fig.27 shows preliminary results to compare the ceramic phosphor plates and phosphor-silicone layers in a 3-chip OSTAR package. The test monolithic ceramic phosphors show better luminance homogeneity.

Another possible application for ceramic phosphor would be in the area that can take advantage of its higher efficiency at higher C_x. In this case, the efficiency is the most important and angular color shifting can be ignored or is not an issue. One example is Ce:YAG dome for remote conversion. The color angular shifting is not as severe as in CLC because of the hemisphere geometry of converter. In this case, transparent Ce:YAG ceramic would be a perfect solution. Transparent thick Ce:YAG ceramic for full conversion could be another

application, where a thick green monolithic ceramic phosphor paired with blue LED can provide full color conversion to efficient green light.

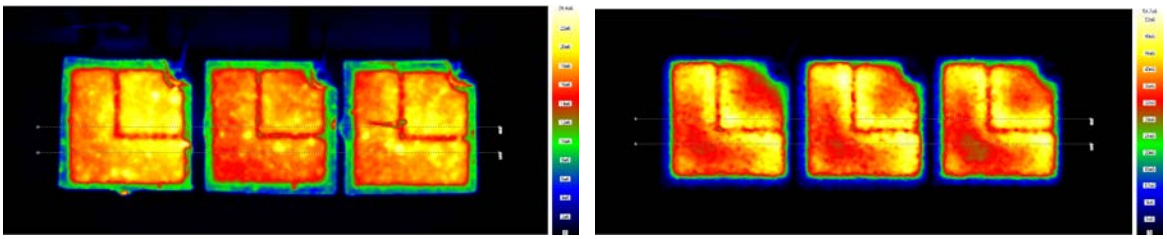


Fig.27 Luminance comparison of ceramic phosphor plate(left) and CLC phosphor-silicone layer(right)

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