APPLICATION NOTE

Mixing Chamber Design Considerations for
ChromaLit™ Remote Phosphor Light Sources

Introduction: This document contains technical information for mixing chamber materials and designs. The mixing chamber is a critical component along with the high output blue LED excitation source and high conversion efficiency ChromaLit remote phosphor. With a properly designed mixing chamber, light sources with extremely high luminous efficacy, low glare, and uniform light output are possible. With a properly designed mixing chamber and high wall plug efficiency (WPE) LED, efficacy improvements of up to 30% over white LED systems can be achieved.

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INTEMATIX

Specular and Diffuse Reflectance

Specular and diffuse reflections are shown in Figure 1. The mirror-like reflection of the specular ray (blue) has the same incident and reflected angles. The diffuse rays are spread over a wide angle; if Lambertian, then the observed brightness is independent of viewing angle. Reflection from an irregular surface will provide a diffuse reflectance that can be designed to be nearly perfectly Lambertian. Most surfaces used for mixing chambers can be either diffuse or specular in nature.

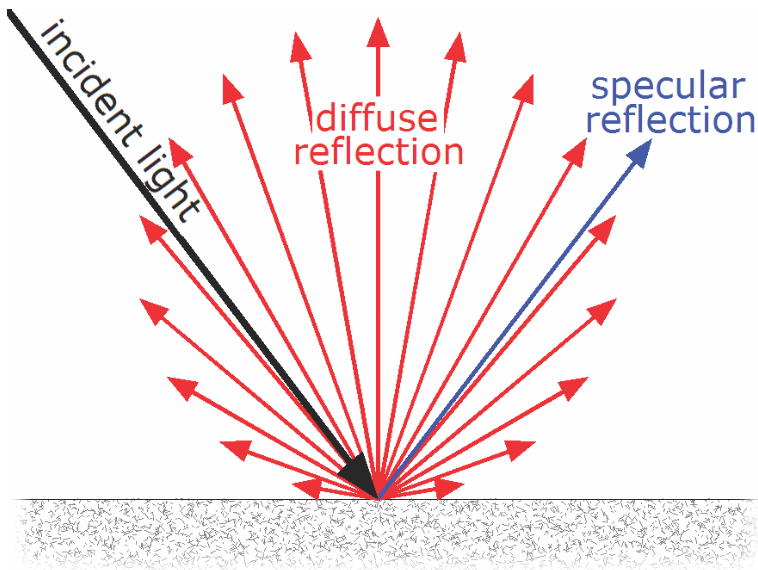


Figure 1 Diffuse and specular reflection

Basic Theory of Mixing Chamber Operation

Standard white LED light source systems require diffuse optics to properly distribute the light from the individual LEDs. Typical losses due to the diffuse optics are 8-10% or higher depending on the uniformity requirement. The alternative system approach as shown in Figure 2 is a blue LED pump which illuminates a phosphor source (ChromaLit) that is remote from the LED die. The blue LED and remote phosphor approach provides a low glare system capable of up to 30% higher luminous efficacy.

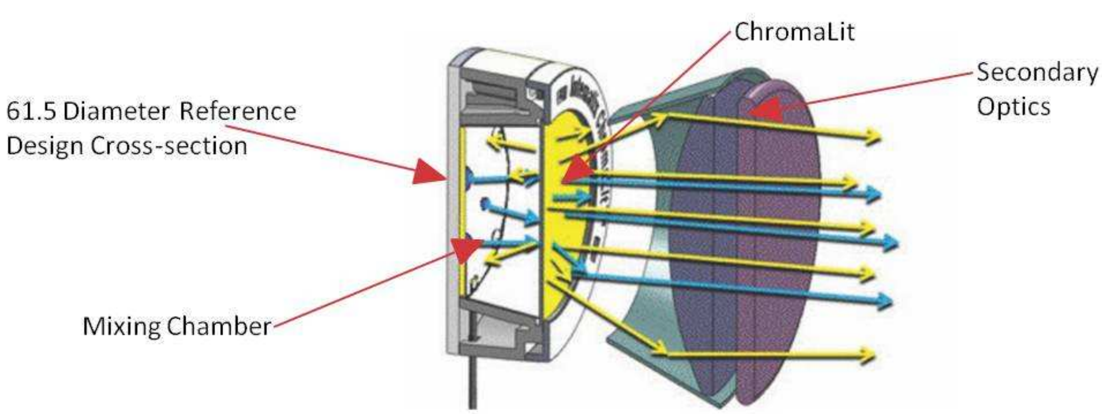


Figure 2 LED rays are shown in blue; down converted rays are shown in yellow

Reflectivity of mixing chamber	Remote phosphor system improvement
99%	30%
98%	22%
97%	19%
96%	15%
95%	11%

Figure 3 Performance improvement as a function of mixing chamber reflectivity

The mixing chamber in a blue LED system with remote phosphor requires a broad spectrum, highly reflective material between the blue LED(s) and the remote phosphor source. With this configuration, the color and spatial mixing of the light is optimized. The output beam is then exceptionally uniform with regard to color and brightness across the exit aperture of the remote phosphor.

The output efficiency of the ChromaLit LED lighting system is impacted by the reflectance of the mixing chamber material.

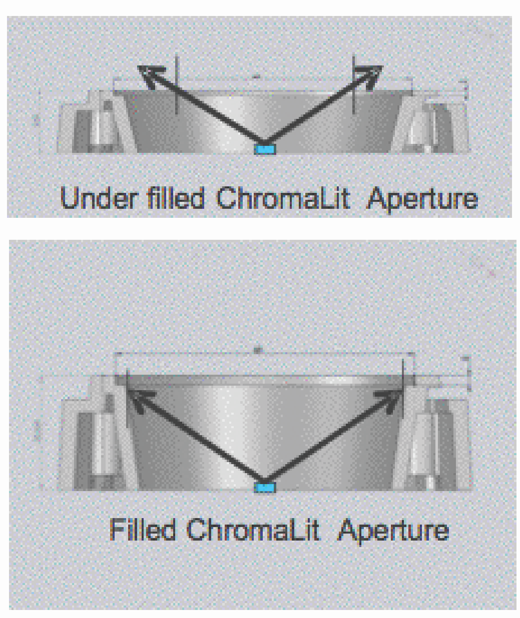
Figure 3 above shows the approximate improvement in system efficacy for the remote phosphor system compared to an equivalent white LED system as a function of mixing chamber reflectance. With 99% reflective mixing chamber material a 30% gain in efficacy compared to a white LED system is achievable.

Mixing Chamber Configurations

A diffuse or specular surface provides good performance with the Intematix remote phosphor as long as the reflectance (either total or diffuse) is very high. Typically materials will provide greater than 97% reflectance. Since the down converted light from the remote phosphor is also Lambertian, a specular material with very high reflection can be considered as part or all of the mixing chamber. The distance between the LED and remote phosphor may be less sensitive when using a diffuse material that creates additional ray bounces before exiting the remote phosphor, so it is recommended to test and prove appropriate for the application any specular material design.

The mixing chamber is best designed so that its aperture size and shape matches the remote phosphor size and shape. Maximizing the mixing chamber reflective surface area surrounding the LEDs and keeping LED surface area low ensures a higher efficiency mixing chamber. For large LED arrays, some chamber efficiency is sacrificed due to this lower reflective surface area around the LED. It is good practice to cover any non-radiating portions of the LED device and light source housing with reflective material that would otherwise absorb light, and minimize any ray trapping around the LED by using thin material and chamfers on the leading edge near the LED.

Figure 4 shows cross sections of mixing chambers with a single LED. The mixing chamber at the bottom ensures that the LED viewing angle fills the ChromaLit aperture. The mixing chamber at the top does not provide sufficient distance and the remote phosphor is under filled. A good starting point for height to width ratio is 1:3. Output will drop for deeper mixing chambers due to more ray bounces along the walls of the chamber prior to impinging the remote phosphor. The Intematix 61.5mm reference design has about 3.5% more light output with 10mm wall height versus 20mm.



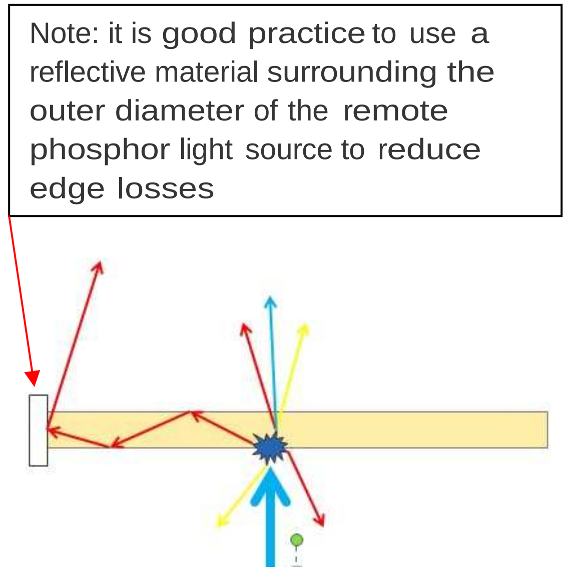


Figure 4 Mixing chamber cross-section

Figure 5 and Figure 6 below show the differences in terms of total luminous flux and CCT for the standard height (20mm), half height (10mm), and quarter height (5mm) mixing chamber reference designs. Total luminous flux is up about 3.5% from 20mm height to 10mm height with little additional increase under 10mm height. The CCT is nearly identical for all.

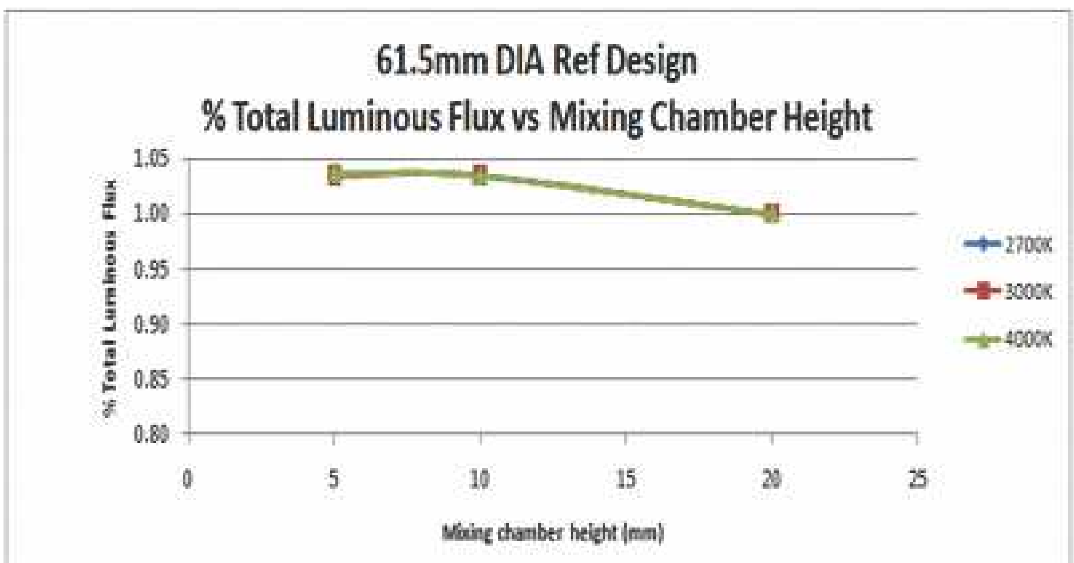


Figure 5 Luminous flux versus mixing chamber height

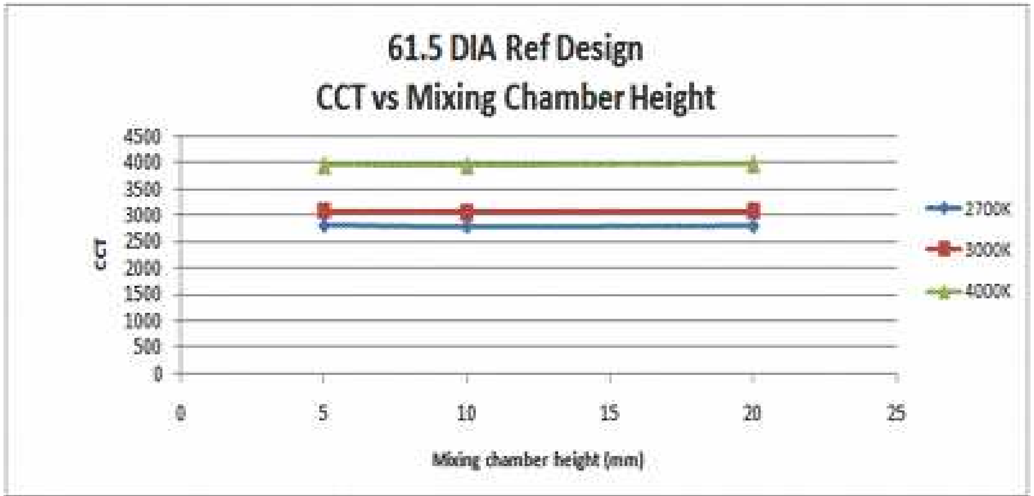


Figure 6 The CCT is invariant with mixing chamber height

To further explore the benefits of a low profile mixing chamber, Intematix development team designed a low profile 20,000 lumen high bay unit. A significant reduction in LED quantity could be used and still produce the required lumens going to the low profile mixing chamber design

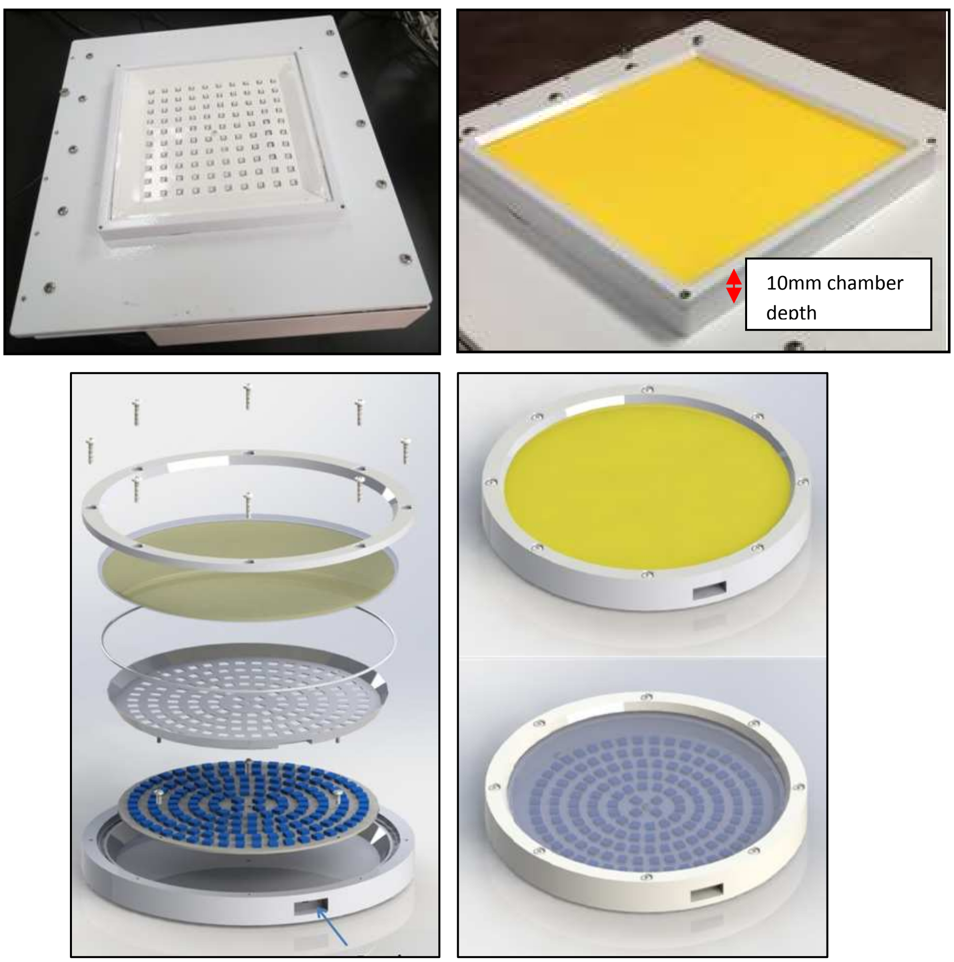


Figure 7 Low profile mixing chamber design concepts

Figure 8 below shows a six LED round Intematix reference design. The mixing chamber consists of a bottom reflective material MC-PET by Furukawa die punched or laser cut and a side reflector band. A chamfer around the LED opening is recommended to minimize light loss at high angles from the LED.

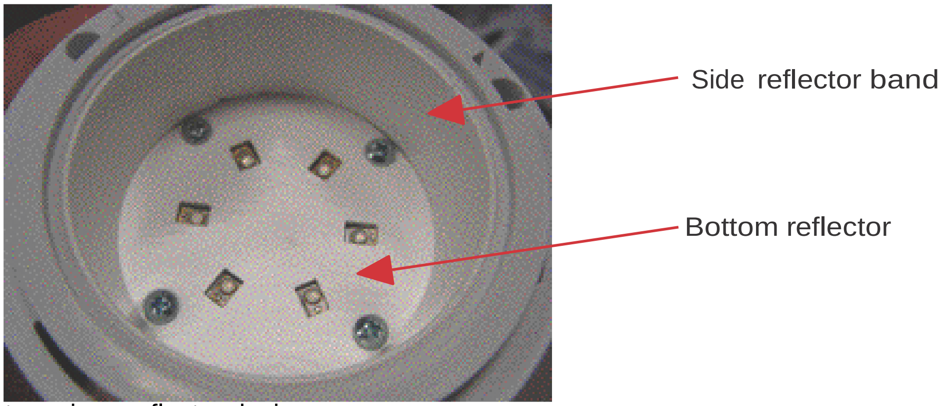


Figure 8 Mixing chamber with two-piece reflector design

With reference to Figure 8, elimination of mounting screws can be accomplished through use of adhesive or mechanical sandwiching of components. Additional improvements in blue LED output can be achieved by creating small circular aperture around the LED dome as long as the edges are outside of the LED illumination range.

The data below demonstrates the impact of removing the bottom reflector in the assembly in Figure 7. With the diffuse reflector in place the lumens are 240 and without the reflector it drops to 209.9 lumens.

Test Configuration

Number	I(A)	U(V)	P(W)	Lumens	x	y	Tc(K)	Ra	Eff.(lm/W)
Standard reflector	0.1601	16.69	2.673	240.0	0.433	0.400	3032	79.5	89.81
PC board only	0.1601	16.7	2.673	209.9	0.422	0.394	3192	80.4	78.54

Data measured at battery current equivalent

Figure 9 Typical mixing chamber data with and without reflector materials

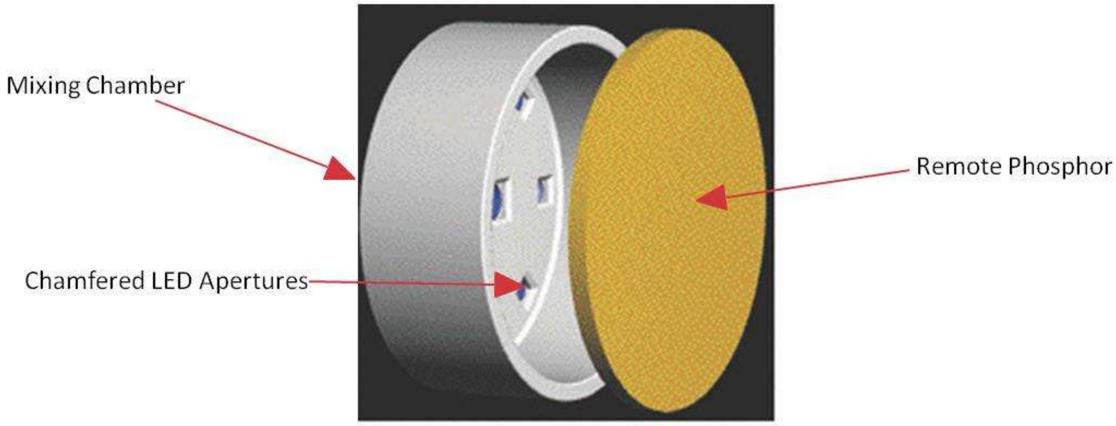


Figure 10 Single piece reflector mixing chamber design

A one-piece mixing chamber as shown in Figure 10, whether made by thermoforming diffuse reflector material, painting a preformed metal or plastic base part, or made from pressed or machined alternative raw material, combines the bottom and side reflector into one piece. The bottom of the one-piece mixing chamber must be designed in such a way that it has precise LED aperture locations and aperture size and shape suitable for maximizing the blue flux throughput. The edges of the LED apertures, whether circular or rectangular, must have a chamfer for thicker materials to prevent any of the wide angle blue flux from being lost.

Note: current data on laminated and thermoformed material indicates lower temperature resistance and lower reflectance for similar material not thermoformed and is therefore not currently recommended for systems requiring highest output performance.

2D Linear Mixing Chamber Designs

For 2D linear remote phosphor light source designs such as that shown in Figure 11, a mixing chamber will have a bottom reflector strip covering the LEDs as well as side reflectors. The design could also be a one piece design with formed LED apertures. As with the round remote phosphor, a pressed one piece U-shape trough design could be utilized but might have to consist of multiple sections depending on the overall length. In many cases a die cut and folded thermo plastic may be the lower cost alternative.

Figure 11 Linear mixing chamber design

The surface luminance uniformity of light for the linear case is a bit more sensitive to LED separation and mixing chamber height; however, the far field beam pattern can still be quite uniform. Some indirect applications may in fact not be sensitive to surface luminance. In general, the remote phosphor design approach lends itself to linear lighting with reduced multiple shadowing even when some surface luminance variation is observed.

A good starting point for the linear array is to design the mixing chamber height and LED separation as to overlap the full width half maximum (FWHM) of one LED over the peak of the subsequent LED as shown in Figure 12 below. Using this method, for a chosen mixing chamber height of 12mm and with an LED with FWHM = 120 degrees, the recommended LED separation is 21mm. Without advanced optical modeling, experimental verification of uniformity is recommended for the specific lighting requirements.

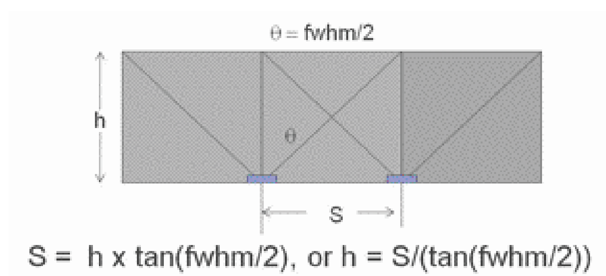


Figure 12 Side view of linear mixing chamber design

The diagram below shows a linear string of LEDs and the associated intensity patterns. As noted previously, the separation recommended places the 50% point of one LED at the same location as the peak of the neighboring LED. The equation in Figure 12 can be used to either set a lower limit on the height of the mixing chamber or if the height is already established, to set the maximum LED separation.

It is also important to position the outer most LEDs close enough to the mixing chamber end walls to maintain sufficient brightness and prevent a dark end appearance.

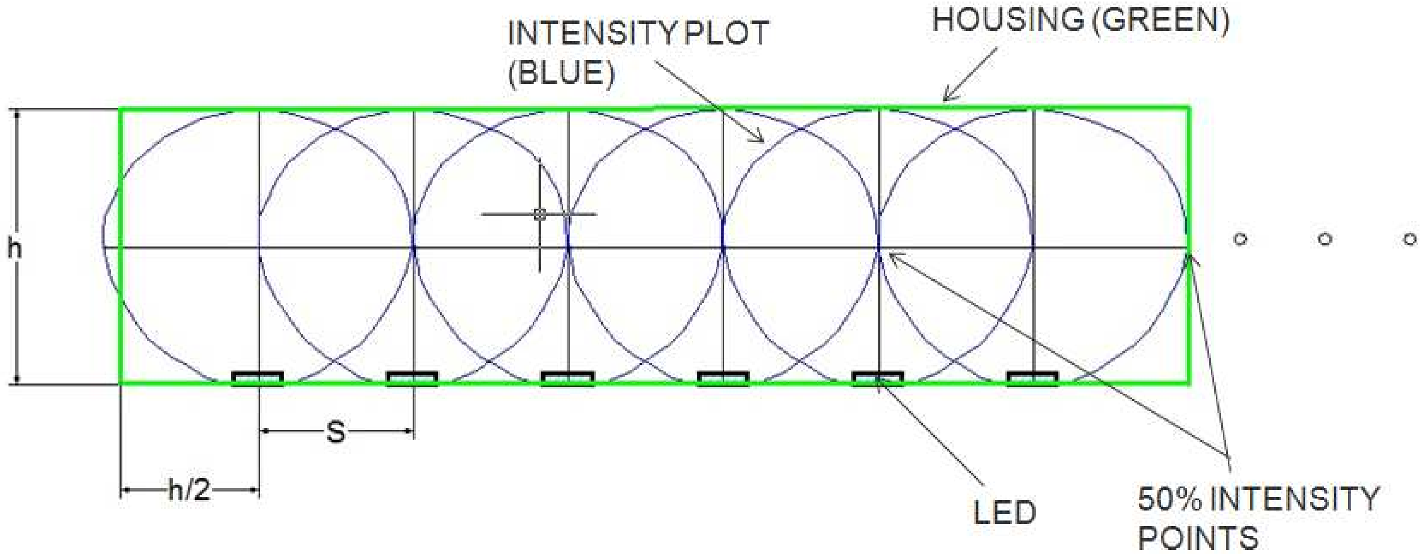


Figure 13 Position LED at ends approximately equal to half the mixing chamber height

3D Extruded Linear Mixing Chamber Designs

For the linear extrusion products such as the assembly shown below, the minimum LED spacing has been experimentally shown to be about 12mm for good uniformity even at low dim settings when using an asymmetrically distributed source such as the Lumenmax 5630 Robin LED. For smaller devices with rotationally symmetrical beam shape, such as Seoul Semi 2525 the maximum spacing is about 8mm.

Figure 14. Linear remote phosphor extrusion based design

For the extruded linear remote phosphor, the PCB should have a very reflective solder mask or a thin reflective material placed onto the surface (such as Furukawa S4 material). See ChromaLit Linear Application Note for further details.

Mixing Chamber Materials

Thermal management of the mixing chamber material along with the ChromaLit remote phosphor should be considered early in the design phase. Thermoforming may not be a suitable alternative for higher power density systems and higher mixing chamber temperatures. Although Teflon based materials may be very well suited for high performance systems, the price structure may not be acceptable for practical designs. Thermoplastics are also becoming available. Finally, high performance metal reflectors are available from Alanod and Almeco.

Furukawa produces a micro cell - polyethylene terephthalate (MC-PET), which is a microfoamed material with typically less than 10 micron feature size. After processing, it provides a flat reflectance curve verses wavelength. PET refers to the base material of polyethylene terephthalate in which the microbubbles are formed with the use of clean carbonic acid. Performance is rated at 99% total reflection with 96% of that being diffuse reflectance for RB grade and 97.3% diffuse for E3. These materials have a maximum temperature (deformation) of 177℃. Typical operating temperatu res for the MC-PET materials are <100℃. The RB gra de material has UV stabilization integral to the product and is 0.94mm +/- 0.08mm thick and their E3 grade with external UV stabilization is 0.88+/- 0.08mm thick. Contact Furukawa if considering thermoformed or metal backed materials. S4 grade Furukawa material has thickness of 0.55mm and is well suited for extruded linear remote phosphor light source designs. Furukawa also produces a 1.0mm thick thermoformable reflective polycarbonate MCPOLYCA material rated to 120℃.

WhiteOptics White97 film is a high density polyethylene material with a UL Relative Thermal Index of 100℃/110℃ and a deformation temperature of 124℃. The material can be provided in rolls, die cut and thermoformed shapes with and without adhesive backing and has a reflectivity of 97.4% at 550nm. Its reflectance is fully diffuse which can be used for efficient cavity mixing while diffusing individual lamp image. WhiteOptics has a higher temperature substrate material designated F16 (F16A with adhesive, M16 bonded with metal backing). The material has an upper limit of 180^{o}C and is a good high temperature alternative to their standard F23. Materials are less than 0.5mm thick (without metal backing) and can be die cut or thermoformed to shape. WhiteOptics also produces diffuse white material laminated on to a metal backing.

Almeco has a line of Vega98 reflective materials for lighting. Their V98100-WF has been tested in the Intematix reference design with good luminous flux results. Their material uses a protected PVD silver over anodized aluminum. Loss of reflectance occurs rapidly above 160^{o}C, but has quite stable reflectance stability to 100^{o}C. The V98100-WF is a specular material.

Alanod produces Miro-Silver super reflective oxide-layer on Alanod base material Their MIRO20 AG Scattergloss was tested in the Intematix 61.5mm reference design with good performance results. Alanod does not recommend exceeding 160^{o}C in HID luminaires. One can surmise that100^{o}C is a good temperature for long term stability, but this should be proven out in the final application. Alanod MIRO20 has good diffuse reflectance properties (97% diffuse and total).

> Note: Electrical isolation between the LED and the metal reflector must be achieved. This can be accomplished through a ground plane stand off on the PCB (grounded solder tabs or posts) or through use of a

dielectric barrier layer. It is also recommended to contact the silver coated metal suppliers to discuss other potential electrical isolation methods. When using an adhesive on the back of the metal reflector, sufficient voltage stand-off may be provided, however, this will depend on the material type and thickness and should be investigated.

Raw Materials Supplier

Bayer has polycarbonate material suitable for injection molding, which is formulated for high reflectance in a molded part. It is designated as Macrolon 6265X color 010226. This material achieves about 96% reflectivity. RTP for this material is 125^{o}C. Higher temperature Apec material is also available, but Bayer should be contacted for color mix details to achieve high reflectivity for these materials.

Idemitsu Kosan Co., Ltd produces reflective polycarbonate materials for molding.

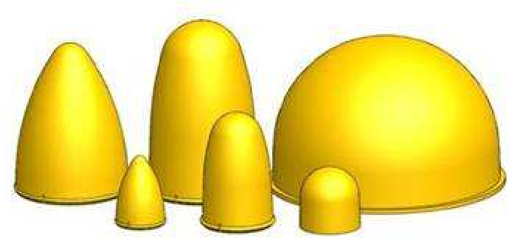
Taiyo Ink Mfg. Co.,LTD manufactures reflective solder mask materials which have high reflectance and high resistance to UV light and heat.

Dow Corning offers MS-2002, which is a moldable white reflective silicone with very high operating temperature capability. The resulting parts have very high reflectivity and can be combined with their clear moldable materials for special beam controlled designs.

Reliability

The material used in the mixing chamber must be stable under long term operation; free from yellowing or corrosion. Maximum operating temperature for the material must be selected based on the expected operating temperatures in the application, which is determined by the size and power density of the light source. It is recommended that the material of choice be life tested at maximum operating temperatures to ensure degradation free performance. The metal based reflectors will have reflectivity degradation at temperatures above about 120^{o}C. Therefore, even for these materials, conductive cooling to the LED housing may be required. Although the silver coated metals are designed with protective coatings, a sealed LED assembly may be required for harsher environments such as salt fog and high atmospheric sulphur content.

Figure 16 3D polycarbonate remote phosphor shapes produced by Intematix



ChromaLit 360 Shapes

Intematix also manufactures and sells the ChromaLit 360 line of products, which are illustrated in Figure 16. For 3D remote phosphor designs, the mixing chamber is simply a two dimensional highly reflective material surrounding the LEDs. The same materials can be used for this reflective surface or a highly reflective PCB solder mask material could be implemented but it must be of high total reflectance. Since a typical CAN40 reflector increases output about 4-6%, a reflective solder mask might be the simplest approach. Standard solder mask materials are known to change color over time so use of a stable alternative is recommended.

Material Properties Summary

Mfg/Grade	Material Type	Recommended Maximum Temperature	Thickness(mm)	Reflectivity (total/diffuse)
Furukawa/RB	MC-PET	~100ºC	0.94	96% / 96%
Furukawa/E3	MC-PET	~100ºC	0.88	97% / 97%
White Optics /F16A	PET	~150ºC	0.31	97% / 97%
Furukawa S4`	MCPET	~100ºC	0.55	97% / 97%
Furukawa MCPOLCA	PC	~120ºC	1.00	99% / 99%
White Optics /F23A	PET	~150ºC	0.62	97% / 97%
Almeco/vega 98110	Protected PVD silver on anodized aluminum	~150ºC	0.35	>=98% / <7%
Almeco/vega 98100-WF	Protected PVD silver on anodized aluminum	~150ºC	0.35	>=98% / <7%
Alanod/Miro 20 AG Scattergloss	Super reflective oxide-layer system on Alanod base	~150ºC	0.35	97% / 97%
Raw Materials				
Bayer/Makrolon 6265X color 010226	Injection moldable polycarbonate starting materials	~120ºC	Shape dependant	~96% depends on surface condition
Idemitsu URC2501	Injection moldable polycarbonate starting materials	~120ºC	Shape dependant	~96% depends on surface condition
Dow Corning	MS-2002 injection moldable reflective white silicone	~150ºC	Shape dependant	~98% / 98% depending on molded surface texture
Panasonic	Full Bright PP injection and transfer molding plastic	~120ºC	Shape dependant	>=95% / 95% depending on molded surface texture

Figure 17 Mixing chamber materials

3M Adhesive Transfer Tape with adhesive 200 is recommended for bonding the metal reflectors.Type 467 has been used and is 0.06mm thick. Thicker 3M VHB, which is an acrylic foam tape, can also be used. 3M recommends type 300 and 350 for low energy plastics. It is recommended to verify that the adhesive is suitable at the operating temperatures of the mixing chamber. 3M type 200 tape is rated to 121°C for long term operation.

(1) Although some thermoplastics have maximum operating temperatures similar to the metals, the metal mixing chamber operating temperature can be greatly reduced through direct conduction cooling through the LED housing and attached heat sink. For corrosive environments, the maximum temperature of the metals is reduced and sealing of the mixing chamber is recommended.

Trouble Shooting Notes

If the color temperature measured is significantly higher than that specified for the remote phosphor, it is likely that the mixing chamber reflectivity is low or spectral reflectance is not uniform. With low reflectance, the mixing chamber will not efficiently recycle the returning down converted light. The spectral output will then have more blue spectral energy than normal, and a higher measured color temperature results. Color temperatures for low reflectivity mixing chamber systems can easily be 800K higher than expected.

For more information on ChromaLit solutions please visit our website **www.intematix.com/chromalit**