APPLICATION NOTE

Designing With Intematix ChromaLit Linear Remote Phosphor for High Efficacy Lighting

This document provides design guidance to enable efficient luminaire designs using Intematix ChromaLit Linear remote phosphor products. Combining the benefits of remote phosphor with a unique delivery system, ChromaLit Linear delivers the uniform, glare free, color consistent lighting associated with remote phosphor systems with the additional benefit of a clean and familiar off state white appearance for a wide variety of lighting applications including troffers, mid and high bay fixtures, cove lights, architectural lights, and task and under cabinet light fixtures.

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INTEMATIX

Introduction to Remote Phosphor

What Does Remote Phosphor Do?

Phosphor materials transmit and down converts blue LED output power into alternative wavelengths which are combined to create a white light spectrum. The phosphor materials and concentrations used determine the properties of the spectrum such as the correlated color temperature (CCT), color rendering index (CRI), and chromaticity coordinates. Phosphor materials are used in most LEDs used for general lighting.

In a remote phosphor system the phosphor is applied as a separate 2D or 3D component energized by a blue LED source rather than being included as a part of the packaged LED. Remote phosphor systems can deliver several advantages to a lamp or luminaire manufacturer including increased system efficacy, reduced system costs, increased quality of light, improved reliability and color maintenance and a simplified supply chain with reduced inventory costs.

Intematix has extensive expertise in phosphor materials and remote phosphor system architectures that enables precise recipe formulations to achieve the desired spectral output for all of its remote phosphor product lines. This application note focuses on ChromaLit Linear remote phosphor sources which are produced by method of extrusion, but many of the light source design considerations included in this application note apply to other product architectures as well.

While the phosphor recipe determines the color point, spectrum and CRI, the shape of the part determines the spatial distribution of the light output. The ChromaLit Linear products discussed here produce a uniform linear distribution of light similar to that of a T5 linear fluorescent lamp but with a forward emission (about 170 degrees full width half maximum, FWHM) rather than 360 degree radiation. The remote phosphor light source also provides a high quality pixilation-free uniform source that is difficult to achieve with low and mid-power white LED solutions. Additional benefits compared to fluorescent lamps include instant light output at full intensity, increased robustness and ruggedness, no mercury or disposal issues, increased efficacy and a useful service life of over 50,000 hours.

How Remote Phosphor Works

When a blue photon generated by the LED pump source impinges on the remote phosphor component the photon can either be scattered and transmitted without conversion or can interact with the phosphor material to raise its energy state. After the excited energy level decays to a lower energy state, this process results in a photon emission at a longer wavelength (lower energy) and increased lattice vibrations (heating). The wavelength difference between the blue photon and the down converted photon is called the Stokes shift and the difference in energy, which generates heat, is referred to as the Stokes loss. The emitted photon can re-excite other phosphor material types or can be transmitted without further interactions. The lower energy (longer wavelength) light is referred to as “down converted” since the energy of the derived photon is lower than the original blue excitation photon.

The remote phosphor component fully defines the light emission source with the blue LED simply providing a photon engine. As is mentioned above, some of the spectral output is composed of blue photons that escape without going through a down conversion process. This blue light is mixed with the down converted light to deliver the required spectrum and is also scattered by passing through the remote phosphor layer to create a uniform and diffuse lambertian emission pattern. Due to this effect, remote phosphor provides an extremely uniform source of low glare light without pixilation. This ensures a pleasant and homogeneous source of light distribution, avoiding common challenges such as the multi-shadow effect caused by pixilated white LED sources which can be particularly challenging in task lighting applications.

Important Characteristics of Remote Phosphor

Reflectivity of the mixing chamber, or area surrounding the blue LEDs in the lighting system, is critical to ensure a high efficiency product using remote phosphor. On average 50% of the photons that impinge upon a remote phosphor component will bounce back on the first pass in an omni-directional emission pattern. In order to increase the chance of recycling and exit of these photons the blue LEDs must be surrounded by highly reflective material. Most remote phosphor systems involve several internal light bounces internally prior to exiting the mixing chamber. A good rule of thumb is to assume three internal bounces prior to exit.

As these photons bounce the light is also mixed. Due to this effect the chamber surrounding the LEDs is referred to as the mixing chamber and the reflective material is often referred to as mixing chamber material. Different remote phosphor systems require different geometries for their respective mixing chambers. For the ChromaLit Linear sources discussed here, the mixing chamber is comprised of the white reflective feet of the ChromaLit Linear product, the reflective material mounted on top of the printed circuit board, and the end caps. The table below provides an approximation of the percentage of light loss as a function of different values of reflectivity of the mixing chamber material assuming three ray bounces in the mixing chamber.

Percent Reflectance	Loss Assuming Three Ray Bounces
97%	8.7%
95%	14.3%
90%	27.1%
80%	48.8%

Table 1: Reflection losses for three ray bounces

It is important to note that the difference between a 90% and a 97% reflective material is not 7% but instead nearly 20% as it is the difference raised to the power of three as three ray bounces are assumed. Small differences in reflectivity of the mixing chamber can have a significant impact on the efficiency of the system design and must be carefully considered when designing with remote phosphor.

Important Note: Small changes in the reflective properties of materials used in the mixing chamber can have a significant impact on system performance.

If the reflective material surrounding the LEDs is of poor reflective quality the amount of recycled light is reduced while the amount of blue light transmitted on first pass is unchanged. This will cause the spectral output to shift to a higher CCT (also known as a blue shift). Conversely, if the reflective material is especially high performing and recycled light losses are minimized, the CCT will be warmer and should measure close to the nominal CCT of the part.

In addition to the importance of highly reflective material to ensure proper white point, the LEDs themselves must operate with dominant wavelengths in the range of 450nm to 460nm. All of the remote phosphor products from Intematix are engineered to deliver optimum performance with a 455nm dominant wavelength blue LED pump source. It is possible to use a much broader distribution of blue LEDs as long as the average distribution is maintained to this center point. Using an average dominant wavelength of 455nm will ensure the proper white point is obtained.

Important Note: Proper dominant wavelength and efficient mixing chambers ensure optimized performance and a proper white point.

Along with the importance of dominant wavelength, the blue LED selected will also have an inherent efficiency of producing blue radiated power. The efficiency of blue LEDs is measured in WPE or wall plug efficiency rather than lumens per watt. The WPE is defined as the ratio of total blue light power emitted divided by the electrical input power to the LED.

The efficacy of a remote phosphor system is a function of the WPE of the blue pump, the conversion efficiency of the remote phosphor component, the temperature of the system and the quality of the mixing chamber. If a poor performing blue pump is used it will be difficult to achieve acceptable system efficacy values. There is an ever expanding portfolio of blue pump LEDs available from a growing number of global LED manufacturers – please consult your Intematix sales representative for the latest list of available blue pump solutions. In general a WPE of greater than 50% (0.50) should be achievable and there are several suppliers offering products with WPEs approaching 60% (0.60).

As with white LEDs, the efficiency of the blue (WPE) is dependent on the current density. When blue pumps are operated at lower drive currents the WPE is typically higher than when the same product is operated at higher drive currents. Using this information can allow you to optimize your system design to meet light output and performance requirements.

Blue pump LEDs must contain a light extraction feature to ensure a high WPE. Simply removing the phosphor from a white LED package may not result in a high efficiency blue pump package as the phosphor adds a scattering element (as described above) that aids in light extraction. If the phosphor is simply removed from a white LED and a flat encapsulation surface is left, the blue light can bounce inside the package rather than exit resulting in a low WPE. This can be easily solved by adding an extraction surface to the LED package (see Figure 1). This extraction feature does not need to be a hemispherical dome but just a curved non-flat surface to aid in light extraction. This can be added to the package by a simple dispensing step aided by surface tension to improve the light extraction.

Figure 1: Examples of LEDs with (left) and without (right) extraction surfaces

Important Note: Blue LED WPE directly impacts system efficiency using remote phosphor; a WPE of 50% or higher at rated current and operating temperature is recommended.

The final important characteristic for remote phosphor is the operating temperature. As noted previously, there are energy loss mechanisms in the process of blue conversion that generate heat in the remote phosphor component. The blue LED spectral power density incident on the remote phosphor will determine, to a great extent, the operating temperature. In general the surface first exposed to blue excitation power and closest to the LED will be the hottest region of the remote phosphor component.

Remote phosphor is mainly cooled by radiation and convection. Since the thermal conductivity is relatively low for the material used for remote phosphor components, heat transfer by conduction is not a significant source of cooling. As with white LEDs, high operating temperatures reduce the conversion efficacy (CE) of the remote phosphor and reduce the efficiency of the lamp or luminaire. Additionally it is important to ensure that the system design maintains the remote phosphor component at operating temperatures below the recommended maximum operating temperature in the product data sheet. Remote phosphor enables highly reliable lighting systems with extremely tight color consistency over time and minimal lumen loss. Exceeding the maximum use conditions, however, can result in degradation mechanisms in the carrier materials that can reduce the lifetime expectations for the lighting system.

In the case of ChromaLit Linear the maximum operating temperature is 90º C. Due to Stoke's heating, the inside surface closest to the blue pump source will generally be the hottest and should be verified less than 90º C in the final application. Temperature verification testing must include all potential heat sources such as the electronic driver, applicable mounting and expected airflow conditions (mounting conditions and luminaire enclosure components may impact the natural air circulation and the associated convective cooling) and be conducted at the maximum expected ambient environment to ensure that the temperature of the remote phosphor component is maintained below the maximum operating temperature under all expected use conditions.

> ***Important Note: Verify that the operating temperature of the remote phosphor component in the light source design at maximum ambient temperature is below the recommended maximum limit listed in the product data sheet.***

Introduction to ChromaLit Linear

ChromaLit Linear is the fifth remote phosphor product line developed by Intematix, complimenting previously released 2D and 3D (2-dimensional and 3-dimensional) remote phosphor products. This extruded linear source delivers high efficiency uniform white light when energized with efficient mid or high power blue pump LEDs with dominant wavelengths ranging from 450nm to 460nm.

The LIN01 profile, shown in Figure 2, is the first profile of ChromaLit Linear commercially launched. Many additional profiles are under development to help enable new and innovative lighting solutions. Although most of the material contained in this application note will be applicable to all profiles of the ChromaLit Linear product line, this note will focus on design guidelines specific to the LIN01 profile. This note will be updated with additional information as new profiles are brought to market.

In order to simplify the design of the mixing chamber and increase the probability of successful lighting system design, the LIN01 profile includes a white reflective material for the construction of the mating flanges (Figure 2). Using a reflective material for the mounting flange helps to direct the light in the useful direction and avoids trapping light in the mounting feet. This enables simplified mixing chamber designs and minimizes light losses in the luminaire.

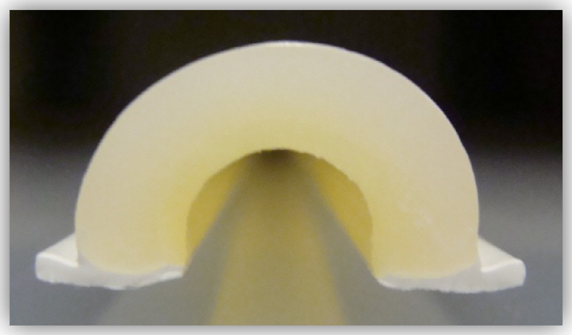


Figure 2: ChromaLit Linear LIN01 profile with reflective mounting features

In a typical light source construction, the bottom of the remote phosphor component is mounted flush against the top of the reflective material which is typically adhesively bonded to the top of the LED PCB as shown in Figure 3. The width of the PCB typically ranges from 10mm to 18mm. The reflective layer over the PCB can be reduced to 10mm to help reduce system costs. While it is critical that the reflector be at least as wide as the opening in the remote phosphor, it serves little purpose under the reflective feet of the remote phosphor and is not required to be present in this location.

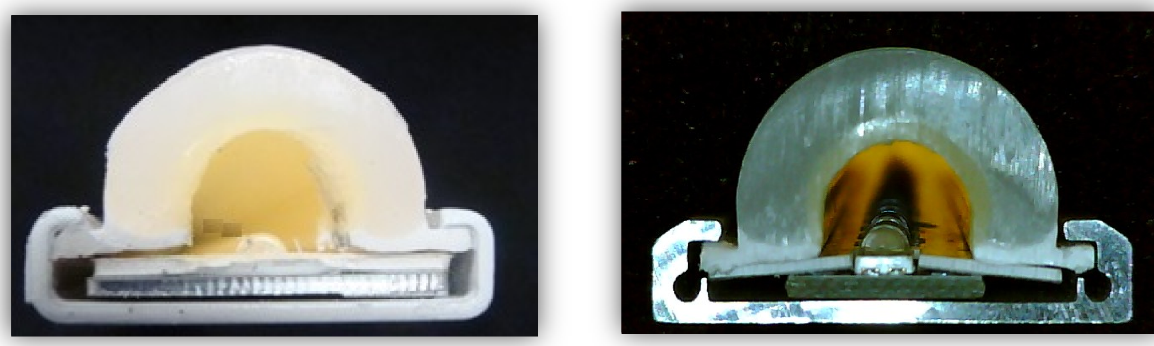


Figure 3: Remote phosphor extrusion in bent aluminum slider assembly (left) and extruded aluminum slider assembly (right); note PCB width is 18mm in left assembly and 10mm wide in right assembly

The LED emission surface insertion depth into the cavity of the ChromaLit Linear remote phosphor should be between 0.5mm and 2.0mm. This will ensure that a significant portion of the high angle rays from the LED will impinge upon the remote phosphor near the bottom of the cavity (Figure 4). If the LED is inserted too deeply in the remote phosphor cavity it is possible that the profile will not be excited near the bottom, resulting in a non-uniform lit appearance and a darker area along the flange.

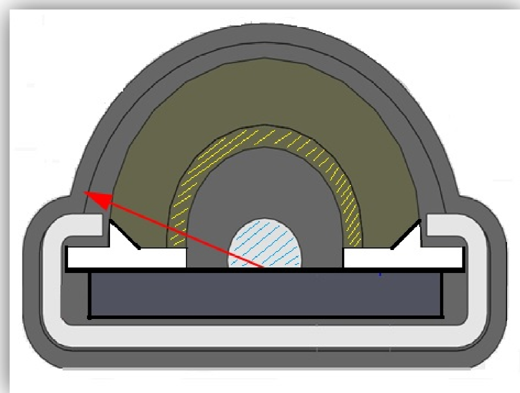


Figure 4: Insertion depth of LEDs

Although most luminaire designs using ChromaLit Linear leverage mid and low power LEDs where less heat is generated, effective thermal management remains important as with any solid state lighting system. It is recommended to use a thermal interface material between the LED PCB and the luminaire housing. Double stick, thermally conductive transfer tape is a good option to use for this purpose. The thermally conductive material can be easily cut with an X-Acto knife or can be purchased pre-cut to match the PCB size. Thermally conductive pastes are also available and should be applied according to the manufacturer's recommendation (generally very thin only to fill air voids between metals).

Figure 5: Thermal interface material used under LED PCB

Important Note: Ensure there is good thermal contact between the LED PCB and the luminaire housing by using a thermal interface material in the assembly.

To ensure that the ChromaLit Linear remote phosphor component is held properly into its housing and that no blue light leakage occurs, it is important that the flange of the remote phosphor is captured by features of the housing with the smallest practical gaps while taking into account the consideration that the plastic remote phosphor component will expand and contract over temperature. Please refer to the housing design consideration section later in this document for additional design recommendations.

Effective Mixing Chamber Design

Importance of Reflectivity

As stated previously, the reflective material on the PCB surrounding the blue LEDs is critical for recycling light inside the mixing chamber and creating a high efficacy light source. The reflective material should be operated at temperatures within the manufacturer's specification to prevent any adverse spectral reflectance variation over time. Failure to use a highly reflective material on top of the LED PCB can result in a reduced system efficacy on the order of 15-20%.

Important Note: Use a reflector with very high reflectivity (97% or greater is recommended) to prevent light losses.

PCB Reflector Materials and Die Cutting Examples

Recommendations for reflective materials proven to work well with ChromaLit Linear and the processes for fabricating these materials for assembly is discussed in this section.

An attractive option from an assembly perspective is to use a highly reflective solder mask, eliminating the need for a separate reflective material on the LED PCB. Berquist produces Stabilux coated PCBs which can be used for this purpose; however the reflectivity of this material is typically on the order of 95% compared to the 97-98% reflectivity achievable with specialized materials. As discussed previously, this 2-3% reduction in reflectivity can have an impact of 6-9% in the system due to the three bounce average assumed for remote phosphor systems. However, for some applications, the reduced bill of material costs and simplified assembly process may warrant the use of such materials. Intematix typically recommends the use of a separate reflective material to maximize product performance.

In addition to the reflective properties it is also important to consider the thickness of the reflective material. LED packages vary in geometry and it is important to ensure that the height of the reflective material is not greater than that of the LED package to ensure that it does not block light and reduce the efficiency of the lighting system.

Furukawa MCPET materials (grade E3 and S4) have proven to provide highly reflective and reliable layers for high efficiency mixing chamber designs. Grade E3 is 0.88mm thick and Grade S4 is 0.51mm thick. If the LEDs selected for use have a very low height, S4 material is preferred and is also the lower cost option of these two materials.

White Optics offers a White 98 model F16A reflective material that is very thin (0.17mm thick) and is provided with an adhesive backing to simplify the assembly process. This material has also been found by Intematix to be an excellent choice for high efficiency mixing chamber designs.

These materials can be purchased in sheet form and then die stamped or laser cut into the appropriate shapes for direct attachment to the top surface of the LED PCB. Laser cut material should be mask protected to reduce vapor deposits during laser processing and ensure reflectivity is not adversely affected. A simple masking tape (free of contaminant residue) may be used for this purpose. For die stamping masking of the reflective surface is not required. Appropriate care should be used to keep the material free of contaminants and surface damage during the die stamping process.

Mueller Die Cutting in Charlotte North Carolina can provide a low VOC adhesive backed die cut Furukawa or White Optics reflectors as shown in Figure 6. The adhesive holds the reflector in place reliably to streamline the assembly process.

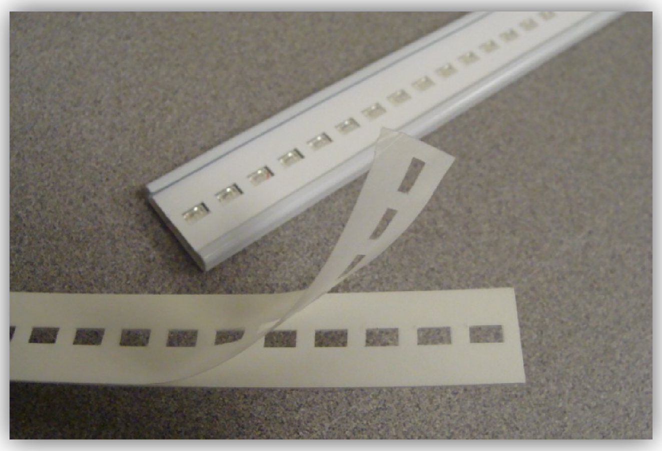


Figure 6: Adhesive backed reflective material

Fits and Gaps

It is important to maintain tight tolerances in the design of the mixing chamber. Excessively large gaps can cause light loss and / or blue leakage depending on where they exist in the lighting system.

One area of importance is the tolerance of the clearance between the edge of the LED package and aperture cut in the reflective material. The reflector must have precisely located and sized apertures so that no blue light is lost at the reflector opening. See Figure 7 for an example of typical apertures used with mid power LEDs. In general it is easier and more efficient to use a reflector aperture that fits surrounding the LED case dimensions rather than the LED dome dimensions, allowing the reflector to sit flat against the LED PCB while also ensuring no blue light leakage occurs underneath the reflector.

Figure 7: Reflector LED apertures

The reflector material dimensions can be minimized to reduce system costs. It is necessary for the reflector to completely cover the area of the mixing chamber inside the remote phosphor component. The reflector should extend slightly beyond the 8mm internal radius of the LIN01 ChromaLit Linear remote phosphor profile but it is not required to extend all the way to the edges of the profile or beyond. For the LIN01 profile a good width for the reflective material is 10mm. A 10mm wide strip will adequately cover the area of the PCB exposed inside of the mixing chamber with some room to spare without a significant excess of material outside of the critical area.

> ***Important Note: Ensure that the LED reflector covers as much of the PCB as possible within the mixing chamber and maintains a tight gap surrounding the LED packages to maximize system efficiency. If a highly reflective PCB solder mask is used instead of reflective material remember that any black markings on the PCB are a source of light loss and should be placed at the edges of board that will be located under the reflective remote phosphor mounting features and not inside the mixing chamber.***

Dark Surfaces

It is critical to avoid having any light absorbing (dark) surfaces inside the mixing chamber. Any surfaces on the LED PCB that are light absorbing such as wires, connectors, labels or additional components can impact the efficacy of the lighting system. Connectors or additional components (if used) should be as small as possible and covered by the reflective material. Labels or printed markings should either be under the reflective material, under the reflective feet of the ChromaLit Linear product or located outside of the mixing chamber. Wires should route underneath the reflector if possible. After the linear light source is fully assembled it is good practice to clean all reflective surfaces, LED domes, and the inside surface of the remote phosphor component with lint free tissue dampened with clean isopropyl alcohol and then blow dry with clean filtered compressed air prior to final assembly.

> ***Important Note: Avoid introducing any non-reflective components into the mixing chamber. If additional dark components must be used ensure that they are covered by reflective material. Avoid routing any dark absorptive materials (such as wires) over the reflective material.***

To further understand the impact of a simple white solder mask compared to a highly reflective film, Intematix tested two different LED configurations in a ChromaLit Linear assembly with and without additional reflective material. The two configurations tested were a 36-up 1-foot (305mm) linear assembly and a 40-up 1-foot (305mm) linear assembly. The units tested with a highly reflective material increased in light output and efficacy by 13.3% and 15.2% respectively over a simple assembly with a standard white FR4 PCB.

Important Note: Using a standard white solder mask FR4 board instead of a highly reflective material can reduce both light output and efficiency by 15% or more depending on the quality of the solder mask.

Impact of LED Package Size on Performance

Another design parameter that can affect the performance of the remote phosphor system is the size of the LED components used. As low and mid power LEDs continue to expand their product offerings for use in lighting applications, the trend continues toward smaller LED packages. For example options exist today including 5630, 3535, 3030, and 2525 packages.

If the same number of a smaller LED package is used for a given application this will result in a smaller exposed LED area, enabling a higher percentage of reflective material in the mixing chamber. This increase in the percentage of reflective area in the mixing chamber will improve the efficiency of the mixing chamber and generate more light if the blue watts are held constant.

Below we consider the case of a 298mm long PCB and a reflector of 10mm width. Although the reflector is 10mm wide only 8mm of it is exposed for the LIN01 profile as this is the width of the inner diameter of the remote phosphor component. The tables below compare the reflective surface as a percentage of the overall area in the mixing chamber for four different LED count configurations of two different LED package types of different sizes.

Table 2A: 5630 LED Packages (apertures 3.15mm x 5.35mm = 16.85 mm^2)

Number of LEDs	Aperture Area for LEDs (mm^2)	Aperture Area (%)	Reflective Area (mm^2)	Reflective Area (%)
24	404	17%	1980	83%
36	607	25%	1777	75%
40	674	28%	1710	72%
80	1348	57%	1036	43%

Table 2B: 3030 LED Packages (apertures 3.15mm x 3.15mm = 9.92 mm^2)

Number of LEDs	Aperture Area for LEDs (mm^2)	Aperture Area (%)	Reflective Area (mm^2)	Reflective Area (%)
24	238	10%	2146	90%
36	357	15%	2027	85%
40	397	17%	1978	83%
80	794	33%	1590	67%

Tables 2A and 2B: Relative surface area comparison LED size and quantity

From the table above one can observe that a significant increase in reflective area can be achieved through using a smaller LED package. For example if 36 LEDs per foot (305mm) are used, moving from a 5630 package to a 3030 package can increase the percentage of reflective area in the mixing chamber by 10%. Another way to consider this data is that through selecting a 3030 LED package compared to a 5630 LED package the percentage of reflective area can be maintained at 83% but the LED count can increase from 24 5630 packages to 40 3030 packages.

> ***Important Note: Smaller LED packages can result in a higher percentage of reflective area in the mixing chamber, increasing the performance of the remote phosphor system.***

Housing Design Considerations

The ChromaLit Linear product has been designed with mounting feet to offer flexibility in the design of the housing system. A common construction technique used by Intematix is the use of an extrusion profile into which the assembly is housed. The assembly process involves first mounting the LED PCB to the base of the housing with a thermal interface material, applying the reflective layer, and then sliding the ChromaLit Linear product into the profile. The product is then covered with end caps to complete the assembly.

A sliding frame assembly is shown in Figure 8. The end caps can be pressed on, screw mounted to metal frame or aluminum extrusion, or pressed and bonded with a suitable adhesive. End caps are typically designed to provide a small amount of overlap at the ends of the profile to prevent blue light leakage. Further details regarding important design parameters for such a housing assembly are included in the sections that follow.

Figure 8: Slider assembly architecture

This type of sliding rail construction can also accommodate linear expansion of the polycarbonate remote phosphor material due to thermal expansion. Through designing the lighting system to include sufficient room inside the end caps, the material expansion due to the coefficient of thermal expansion can be managed in the lighting system. Vertical design tolerances can be engineered such that the remote phosphor always applies a compressive force against the reflector, PCB, and housing so that screw mounting of the PCB to the aluminum housing can be avoided. For high performance systems, such as more than 2000 lumens per foot (305mm), screw mounting of the PCB to the housing may be required to improve the thermal contact.

Other assembly options exist including snapping down the ChromaLit Linear using mating click features that grasp the feet of the remote phosphor product or taping or gluing to secure the ChromaLit Linear profile. In some cases an adhesive bonding method may be preferred as it can also act as a moisture seal for IP66 or IP67 enclosures for use in wet locations, but typically a mechanical mounting feature is preferred to a streamline the assembly process.

Avoiding Light Blocking

When designing a housing for use with ChromaLit Linear it is important to avoid blocking the external emitting surface. The ChromaLit Linear product has been designed with white feet to channel the light in a useful direction and avoid light traveling into the mounting feet. This white reflective material extends 1.25mm up the side of the round profile as is shown in the product data sheet. Mounting features in the housing such as rails or clips to secure the remote phosphor component should be kept to a minimal height to fit below the top of the white extension up the side wall of the remote phosphor profile.

Figure 9 demonstrates the importance of avoiding blocking any of the light exiting the remote phosphor profile. A light loss of 8% can be observed if a height of 1mm of the light emitting area is blocked on both sides of the profile. This can result in a significantly lower lumen output and system efficacy and must be avoided.

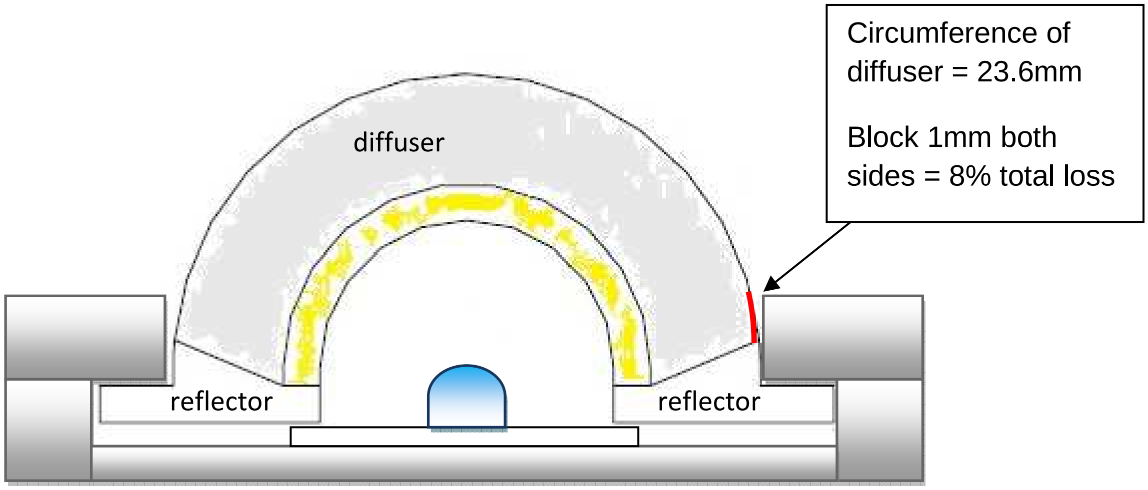


Figure 9: Housing light loss example

While it is not critical to use highly reflective materials for the housing, it is recommended to use non-absorbing materials. A common method is to use a white painted or powder coated material which will reflect rather than absorb light impinging on its surface. Conversely using a black anodized profile would result in additional system losses as light that is incident on the housing will be absorbed. A common misconception is that simply using aluminum material for the housing will act as a reflective surface to avoid light loss. The reflectivity of bare aluminum can be as low as 50%, however, which can significantly impact performance and should be avoided.

Important Note: Ensure that the housing design does not cover any of the light emitting area of the remote phosphor component and is not constructed from highly absorbing materials such as black anodized aluminum.

End Cap Design

The design of the end caps in a ChromaLit Linear remote phosphor product is critical to ensure a lack of blue light leakage, minimize coverage to improve system efficiency and enable a solution that can accommodate the thermal expansion of the remote phosphor component.

Intematix has found that end caps that are designed to overlap the ChromaLit Linear remote phosphor component by 3mm will ensure there is no gap between the end of the remote phosphor and the end cap that would leak blue light (see Figure 10). The inside surface of the end cap should be reflective to maximize the system efficiency. This can be accomplished by covering the inside of the end cap with highly reflective material or by using a white powder coated end cap so that light that hits the inside surface of the end cap will be reflected and not absorbed.

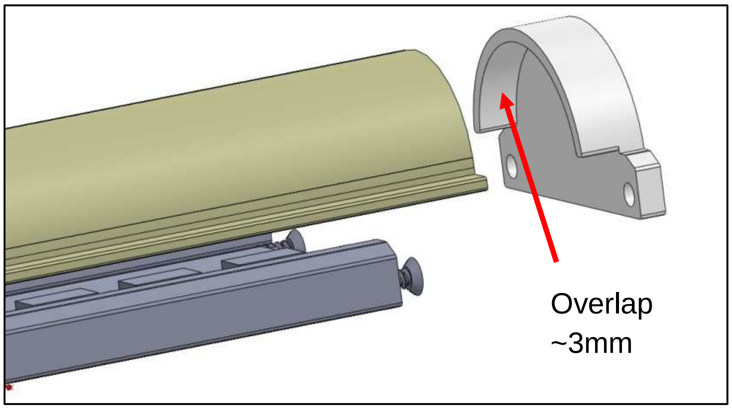


Figure 10: Example of screw on end cap with overlap

As mentioned previously, the end cap can be mounted using several methods. The overlap of the end cap can help to eliminate the chance of blue leakage, but should also be minimized to avoid blocking light and reducing the efficiency of the remote phosphor system. If connectors are to be used to connect to the LED PCB it may also be desired to place these at the end of the PCB and conceal them inside the end cap. This will avoid causing potential dark spots inside the ChromaLit Linear due to optical shadowing of such large components and position the connectors in such a way that they are easily accessible through the end cap for power connection. The end cap design should also consider the effects of thermal expansion of the material as it can help to ensure that there is no blue light leakage over the entire temperature operating range of the product.

> ***Important Note: Engineer end caps to ensure there is no blue leakage and to accommodate thermal expansion of the ChromaLit Linear product but maintain as minimal an overlap as possible to minimize light loss in the system.***

Thermal Expansion Design Considerations

The polycarbonate material used for ChromaLit Linear expands at approximately three times the rate of aluminum. Therefore housing and system designs must allow for this differential expansion, especially for applications with broad operating temperature ranges.

For example, in the case of a four foot (1220mm) product that is expected to see a change in temperature of 40ºC from off state to its maximum use condition, the ChromaLit Linear product will expand approximately 3.4mm while an aluminum housing will expand approximately 1.2mm. This differential in thermal expansion must be considered in designing a luminaire incorporating ChromaLit Linear to ensure there are no challenges associated with bending or bowing over the expected operating temperature range of the finished product.

The thermal expansion of ChromaLit Linear, Aluminum, and FR4 are shown below for comparison purposes based on a change in temperature of 50ºC and for both 1-foot (305mm) and 4-foot (1220mm) lengths.

Material	**12 inches**		**48 inches**	
	ΔL inches	**ΔL mm**	**ΔL inches**	**ΔL mm**
ChromaLit Linear	0.042	1.06	0.168	4.27
Aluminum	0.014	0.36	0.056	1.43
FR4	0.009	0.23	0.036	0.91

Table 3: Linear thermal expansion comparison (assuming $\Delta T=50^{o}C$)

These differences in CTE (coefficients of thermal expansion) can be managed with proper system design but it is important to consider the use conditions of the lighting product to ensure that adequate tolerances are used to accommodate expansion differences.

> ***Important Note: Design with an understanding of variations in thermal expansion coefficients to ensure sufficient assembly gaps to allow for linear thermal expansion and to prevent bowing over the expected operating range.***

Designing Housings to Minimize Light Blocking

As mentioned previously, it is important to avoid designing housings for ChromaLit Linear that block the emitted light. The LIN01 profile of ChromaLit Linear produces a broad lambertian light output as is described in the product data sheets and is shown in Figure 11. It is possible to change the direction of the light emitted from the profile with the use of secondary optics to create differentiated beam patterns. When designing optical systems for ChromaLit Linear it is necessary to take into account all guidance referenced earlier regarding the avoidance of light blocking and ensuring that surfaces within the optical path are reflective and not absorbing.

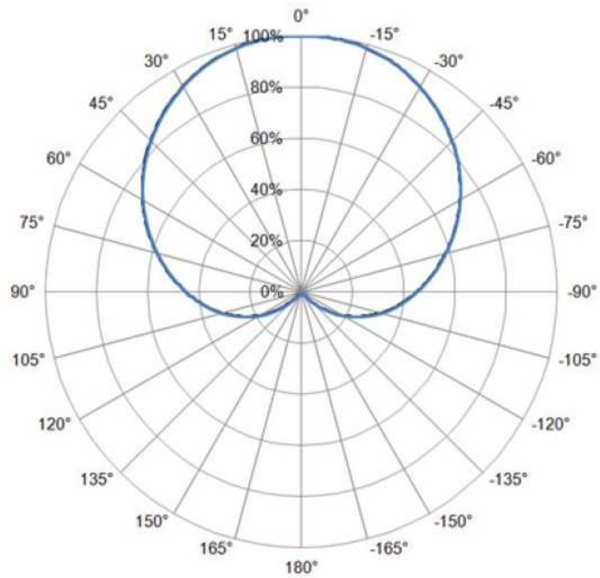


Figure 11: Typical beam angle for standard LIN01 extrusion

Additionally it is prudent to avoid mounting the ChromaLit Linear product deeply recessed in the luminaire housing. The deeper the light source is mounted within the luminaire housing, the higher the probability of reduced light output and efficacy due to system losses. A common mistake is to mount the ChromaLit Linear product in a deep recess in a luminaire, similar to what may be used with white LEDs to remove pixelation and aid in color mixing (problems solved with ChromaLit Linear). Simply burying the ChromaLit product deep inside the fixture housing can result in optical losses of over 20%, resulting in a poor system efficacy.

Another common mistake is to assume that using bare aluminum will enable an effective reflective surface to avoid light loss. The reflectivity of bare aluminum, as mentioned previously, can be as low as 50% if not provided with a highly reflective coating which will result in a significant amount of light loss in the system.

Reference Designs for Housings

Intematix has developed a few different reference designs for housings that work well with ChromaLit Linear products. Housing designs with the profiles shown in Figures 12 and 13 allow the ChromaLit Linear remote phosphor product to be slide mounted within the vertical walls of the design. The vertical walls also prevent blue light from leaking out of the lighting system.

Housing designs without side features to lock down the ChromaLit Linear product are not recommended. The lack of such features can result in blue light leakage. If a system of this architecture is used this blue light leakage can be reduced or eliminated by using tape or glue to secure the edges of the remote phosphor component. 3M VHB doubles sided adhesive can be used for this purpose. Another benefit of such a slide mounting system is that it can be designed to allow for thermal expansion and avoid bowing of the finished product. Rigidly mounting the ChromaLit Linear product can cause design challenges over the operating temperature range of the luminaire.

Figure 12 shows a bent sheet metal design for use with ChromaLit Linear. This is an economical design for short length fixtures but can be challenging to manufacture with adequate tolerances for lengths greater than 2-feet (610mm). Note that the lip that wraps around the feet of the ChromaLit Linear component is held to a height of 1mm which will fit beneath the height of the white reflector that extends up the side wall of the product to a height of 1.25mm to avoid blocking light as is described previously.

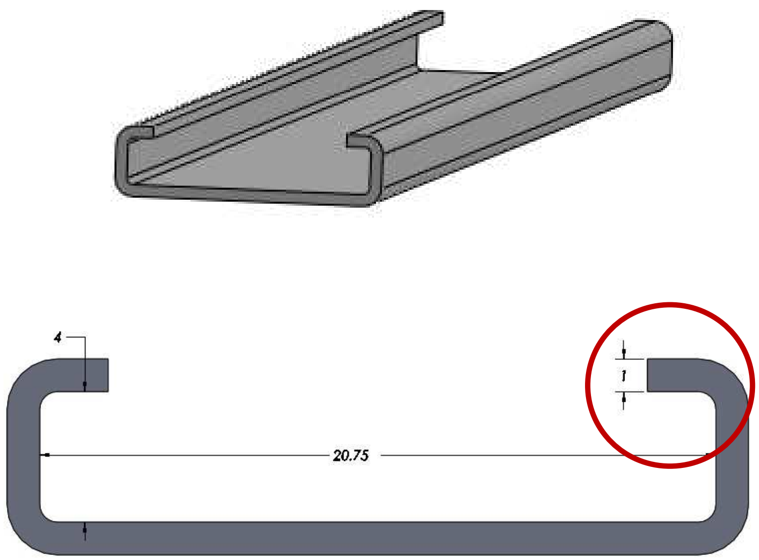


Figure 12: Bent metal slider architecture

Figure 13 shows an extruded design for use with the ChromaLit Linear profile. Extrusions can accommodate extended lengths of ChromaLit Linear with adequate tolerances to ensure an easy slide in assembly. While initial tooling charges may be higher in developing an extrusion housing the end result is a very flexible component that can be easily cut to various lengths and enable a robust fixture design. The design below assumes a 1mm thick LED PCB and a 0.51mm thick reflector. Greater PCB and / or reflector thicknesses will not fit properly and would require a modified design. It is important to consider these parameters when designing such an extrusion profile.

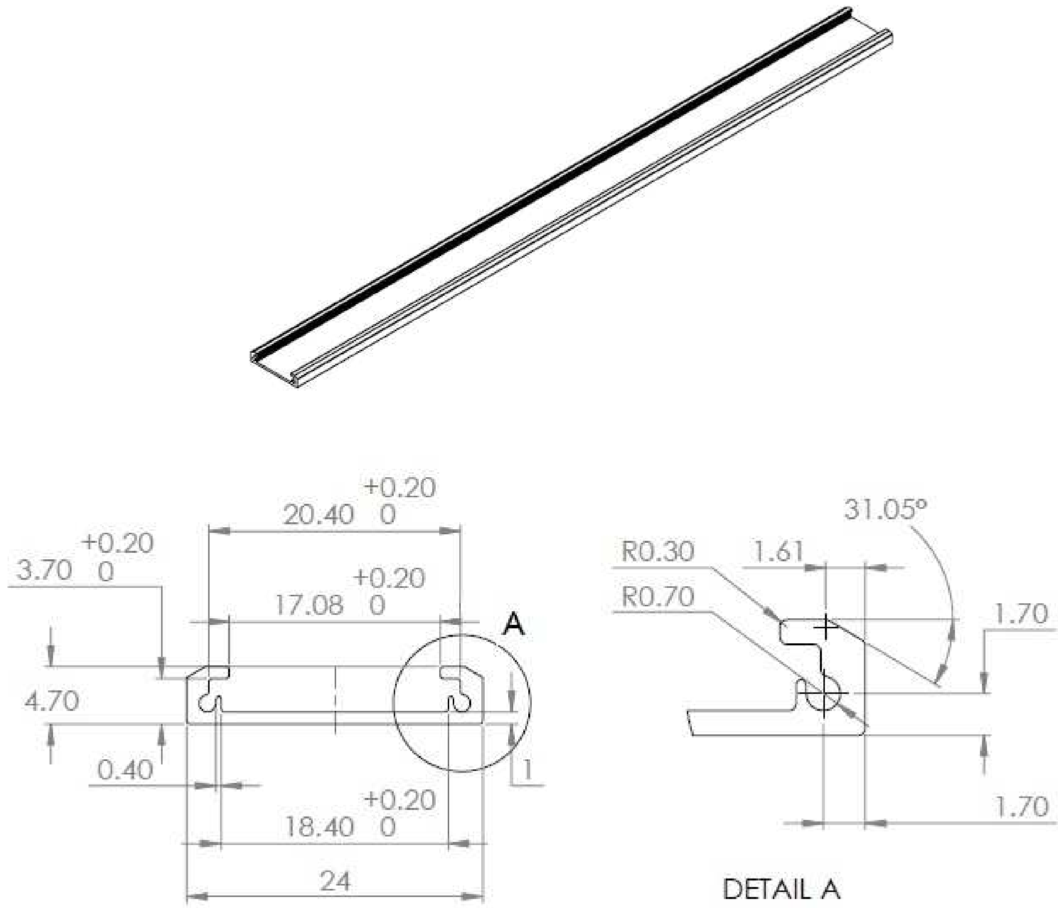


Figure 13: Aluminum extrusion slider architecture

Design Considerations for Multiple Sources

For some luminaire designs it may be desired to use multiple sections of ChromaLit Linear mounted parallel to each other as shown in Figure 14. This can enable a modular product design capable of different light levels depending on lighting system requirements. When designing such a system it is important to understand the function of spacing between the ChromaLit Linear components versus potential light loss due to absorption of the neighboring components.

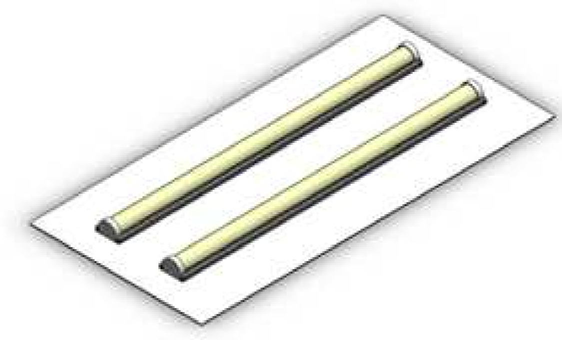


Figure 14: Luminaire design with multiple linear segments

When multiple linear sources are used and mounted adjacent to one another on a flat reflective surface, the source separation can have an impact on total luminous flux. Figure 15 shows the function of total light output for two roughly 1000 lm sources versus the spacing between the two sources. The following light losses can be observed:

- A 4% light loss is observed when two ChromaLit Linear products are mounted right next to each other with no space between the products
- A 2% light loss is observed when two ChromaLit Linear products are mounted in parallel with a 2.5 inch (6.35cm) space between the products
- No light loss is observed when two ChromaLit Linear products are mounted in parallel with a 10 inch (25.4 cm) space between the products

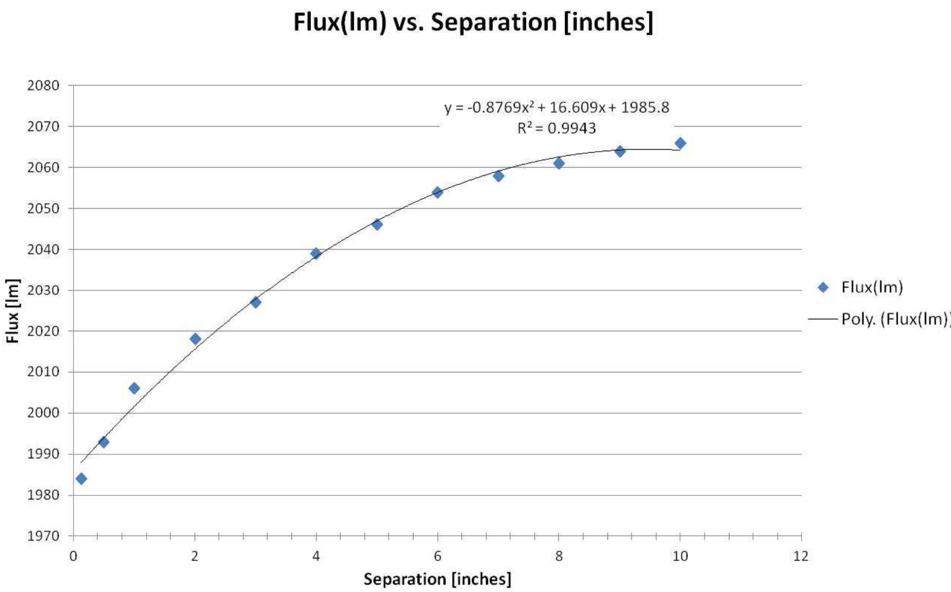


Figure 15: Light loss as a function of center to center spacing of multiple ChromaLit Linear light sources

INTEMATIX

Flammability Ratings

The material currently used for the construction of ChromaLit Linear is HB rated for flammability. The flammability rating of the complete product and luminaire is a function of the material rating and the geometry of the product. Light engine assemblies using ChromaLit Linear have been found to pass not only V0 ratings but also more stringent 5VA flame test ratings due to the wall thicknesses and geometry of the product. Intematix is constantly reviewing material options and can provide ChromaLit Linear products using V0 rated material or higher based on customer specific requirements.

The V0 and 5VA flammability capabilities of the ChromaLit Linear product can enable the use of non-isolated Class 1 high voltage electronic drivers. Typically such drivers are higher efficiency than their Class 2 counterparts and also lower in cost. When considering a luminaire design architecture this can offer significant system level design benefits in terms of efficiency and cost. Please consult your local Intematix sales representative for further information and to discuss how ChromaLit Linear can be optimized to meet your system design requirements.

LED Board Layout Options

Introduction

ChromaLit Linear can be used for a wide variety of lighting applications ranging from a few hundred lumens per foot (305mm) to up to 2500 lumens per foot. The lumen output of ChromaLit Linear is dependent on the number of LEDs used, the type of LEDs used, and the drive current. Intematix is constantly evaluating new LED products from a wide variety of LED manufacturers; please contact your local Intematix sales representative for the latest listing of commercially available blue pump sources. Intematix can also offer application design support and guidance as to potential LED sources and layout configurations to meet customer specific application requirements.

Most of the demonstration units provided by Intematix deliver approximately 1000 to 1200 lumens per foot (305mm) in the range of 120-130 lm/W hot and stable DC and uniform without pixelation. This performance can vary based on the LEDs used, LED count, and the color temperature and CRI that impact the conversion efficiency of the remote phosphor. Similarly to white phosphor converted LEDs, warmer color temperatures and higher CRI values will have lower efficiencies due to increased Stokes losses as is described earlier in this application note. If you have received a demonstration unit from Intematix it likely uses either a LumenMax Robin XTR-5630CDBC-EN 5630 LED or a Seoul Semiconductor STB0FS12A 2525 LED; both of which have been found to provide a great price/performance ratio with high WPE.

Uniformity

The uniformity of the light output from ChromaLit Linear is dependent on the separation of the LEDs (center to center) and the distance from the LED emission surface to the top inside surface of ChromaLit Linear. For excellent uniformity even under extremely deep dimming conditions (<5%) Intematix recommends a maximum LED pitch spacing of 12.4mm. Depending on the LEDs selected and the application requirements, larger or smaller pitch may be required and can be evaluated in the product design phase. Using larger pitch spacing with fewer LED components can result in a lower system cost if the uniformity is found to be acceptable. In cases where deep dimming is not required this may be an option. Insertion depth of the LEDs into the remote phosphor has been covered in previous sections of this application note. Smaller blue LED device surface area and symmetric spatial light distribution will demand smaller pitches for low dimming uniform luminance requirements.

> ***Important Note: For applications where uniformity is critical under deep dimming, Intematix recommends a maximum center to center LED pitch spacing of 12.4mm. It is recommended to prototype the LED layout to ensure the system uniformity meets application requirements prior to finalizing the PCB design.***

Electrical Configuration Options

Intematix has prototyped several different LED PCB layouts including 24, 36, and 40 LED per linear foot (305mm) options. As with any LED layout, different series / parallel arrangements can be selected to achieve the desired total operating current at the necessary device current to generate sufficient blue power to meet system level lumen specifications. Adjusting the series / parallel connections of the individual LEDs can also enable compatibility with a variety of commercially available constant current LED drivers. Typically it is desired to avoid excessively high voltage strings (all LEDs in series) and also high current loads (all LEDs in parallel) to enable the largest selection of LED drivers. In considering the LED PCB layout it is important to ensure that the LEDs operate below their maximum rated current levels and also that they do not exceeded maximum case temperature or junction temperature ratings.

> ***Important Note: When designing the LED layout consider options in series and parallel configurations that offer a good mix of current and voltage that is compatible with commercially available LED drivers.***

As with all multi-LED circuit designs it is important to consider the potential effects of current hogging. When designing LED circuits with series / parallel configurations it is important that voltage of the parallel strings is as equivalent as possible. If one of the parallel strings is lower in voltage that the other strings, the current will selectively flow through the strings with a lower forward voltage resulting in an effect typically referred to as current hogging. This can result in a higher light output from the lower voltage strings than the higher voltage strings which can result in undesirable effects in the lighting application, such as non-uniformity. This effect comes from the fact that the lower forward voltage strings are driven at a higher drive current than the higher voltage strings and can result in overstressing the LEDs in the lower voltage string.

Current hogging can be avoided by voltage matching the parallel LED strings. Longer parallel strings have the benefit of an increased averaging effect. It is not critical to specify that all LEDs used are of a very tight voltage specification if the LEDs are binned by the manufacturer for forward voltage and this is taken into consideration in the population of the LED PCB. It is possible to make use of a wide range of forward voltage bins as long as the LED PCB is smartly populated with this information in mind such that the V_f of the parallel strings is maintained to be consistent. This can also be achieved by using in line resistors within the series strings to ensure a consistent forward voltage of each series string of LEDs connected in a parallel configuration.

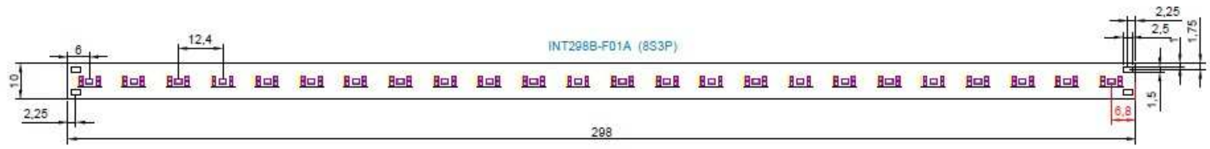
> ***Important Note: When designing series / parallel LED configurations it is important to maintain similar voltages of the parallel LED strings to avoid current hogging.***

For the 24, 36 and 40-up LED PCBs that Intematix has prototyped the LEDs are typically connected in the following configurations:

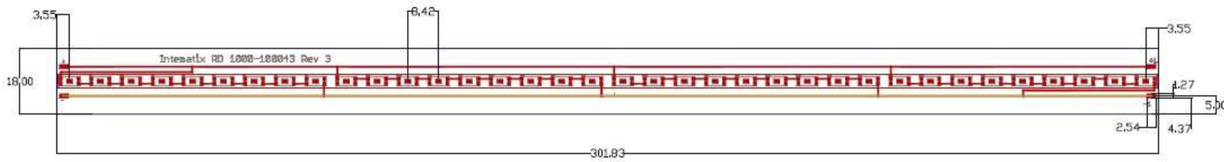
- 24-up: 3 strings of 8 LEDs in series, all 3 strings then connected in parallel
- 36-up: 4 strings of 9 LEDs in series, all 4 strings then connected in parallel
- 40-up: 4 strings of 10 LEDs in series, all 4 strings then connected in parallel

Figure 16 shows a few examples of LED board layouts. For a luminaire design that requires a 4-foot (1220mm) total length, the four individual LED boards are connected in parallel, providing 12 or 16 parallel current paths of 8, 9 or 10 LEDs in series.

24-up Concept Design PCB



36-up Concept Design PCB



40-up Concept Design PCB

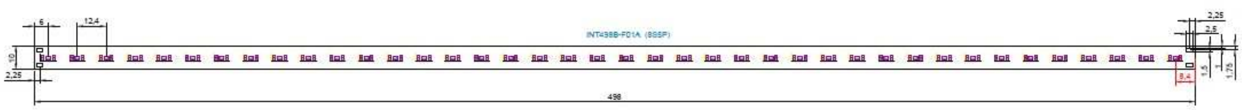


Figure 16: PCB Concept design layouts

When using LEDs with a nominal LED forward voltage of 3V per LED the 24-up, 36-up, and 40-up LED board layouts relate to approximately 24VDC, 27VDC, and 30VDC. As with all LEDs, it is important to use a constant current LED driver rather than a constant voltage LED driver unless the system is designed with additional current limiting components to operate with a constant input voltage rather than constant current. For LEDs with a higher forward voltage, such as 3.2V, total forward voltage requirements are approximately 25.6VDC, 28.8VDC, or 32VDC respectively for the three layout options described above.

Connecting multiple boards in parallel does not alter the input voltage requirement but will increase the input current required. For example, for a case where the 24-up LED PCB layout described above requires a nominal current per LED of 120mA, the constant current required for the single board would be 360mA as there are 3 parallel strings of 8 LEDs in series (3 X 120mA = 360mA). If in the system design 4 of these boards will be connected in series the total LED current would be 1440mA (4 X 360mA = 1440mA).

Depending on the system design it is also possible to connect the power to both ends of the string of linear PCBs, such that each circuit would consist of 2 24-up boards in series. In this case the current required would be 720mA (2 X 360mA = 720mA). Different system designs and driver architectures can be considered by altering both the series and parallel connections within the individual LED PCBs as well as how multiple LED PCBs are connected in the luminaire to enable flexibility in LED driver selection.

> ***Important Note: It is important to not only consider the series / parallel configuration of individual LED PCBs but also whether multiple LED PCBs will be required for the luminaire in order to optimize the overall electrical design, ensure driver compatibility and eliminate current hogging in the lighting system.***

Multi-Board System Considerations

For lighting system designs where more than one LED PCB will be used, considerations should be made for electrical connections between the boards. Most LED pick and place assembly equipment is limited to a board length of 2-feet (610mm) which drives most designs to consider this as a maximum board length. There are suppliers that can deliver narrow PCB boards with lengths of up to 4-feet (1220mm). DK Thermal provides both metal clad and FR4 equivalent PCBs capable of lengths of up to 4-feet which can be an attractive option for simplifying the overall system design. If a 4-foot board is used but LED assembly equipment is limited to a maximum length of 2-feet, it is possible to use a two step LED assembly process where LEDs are mounted to half of the board and then the board is rotated 180º for a secondary LED mounting process for the other end of the board.

Intematix typically uses small wire solder jumpers to connect 1-foot (305mm) boards together for demonstration purposes. If this is used in a lighting system design, Intematix recommends the use of a small gauge (such as 28 AWG) wire with sufficient length to prevent tearing of the solder tabs under bending or shearing moments and to allow for some flexibility in the assembly (see Figure 17). As stated previously, best practices are to cover the exposed wires with reflective material to avoid sources of absorption and light loss inside the mixing chamber.

Figure 17: PCB Wiring connection of multiple boards

If wiring between boards is not an acceptable option, a few alternatives for board to board interconnection exist. One option is to use top side connectors to connect boards together and for power feed at the end of the boards. When using a top side connector it is important to avoid interference with the ChromaLit Linear remote phosphor. As the inner diameter of the phosphor component is quite small it is critical to select miniature connectors for this purpose. Bender+Wirth supplies a miniature board to board jumper connector. The Molex Pico EZmate connector is also very small and may work for some applications. TE Connectivity also has a range of very small board to board connectors designed for solid state lighting that may work in the application.

Another alternative is to use through holes or a double sided PCB to mount connectors to the back side of the LED PCB facing in the opposite direction of the ChromaLit Linear component. Using such an interconnect method requires clearance underneath the LED PCB. If such an option is used, it is important to ensure good thermal contact with the bulk of the LED PCB to the housing and minimize the dimensions of the cutouts to avoid a significant reduction in the thermal contact area form the LED PCB to the housing.

> ***Important Note: When selecting board to board connectors it is important to select miniature components that will fit underneath the ChromaLit Linear component without interference.***

When designing lighting systems that will use more than one LED PCB, it is important to consider the LED pitch and spacing from the end LEDs to the end of the LED PCB. The distance from the end LED to the end of the board must be less than or equal to half of the desired LED pitch spacing to maintain the pitch spacing across multiple LED boards. For example, if an LED pitch spacing of 12mm is to be maintained, the length from the end LED to the end of the LED PCB must be less than 6mm such that when two LED PCBs are aligned end to end the pitch spacing is maintained.

Important Note: For lighting systems that will use multiple LED PCBs, care must be taken to ensure consistent LED pitch spacing not only on the individual LED PCBs but also when two LED PCBs are mounted in line to ensure spacing is maintained along the length of the blue pump engine.

There also exist multiple options for power feeds to a multi LED PCB engine. In all scenarios current limiting circuitry should be considered especially if a wide voltage range is used to ensure that the LED power for parallel strings of series / parallel LED PCBs is constant across the combined blue light engine. Typical electrical connection options are:

- Feed power from one end and interconnect the boards in a series, parallel or series / parallel configuration depending on the board layout design
- Feed power from both ends with an isolation spot in the center of the lighting system
- Feed power from the center of the system

For many of the 4-foot (1220mm) demonstration units produced by Intematix, power entry is made at the middle of the string. This prevents excessive current hogging for non-regulated PCBs and may be a desired option to reduce PCB costs. No matter what architecture is selected, it is critical to ensure that the maximum rated current applied to the blue LEDs does not exceeded the specified maximum as provided by the LED manufacturer.

Important Note: Ensure the total drive current in a series parallel string of single or multiple PCBs operates all LEDs below the manufacturer's maximum specified limits.

Calculating White Lumen Performance

Introduction

When designing a lighting system using remote phosphor it is important to understand the language. As has been described in this application note, different terminology is used when describing remote phosphor systems compared to white LED systems. This can create confusion if the proper equations are not understood.

Typically the values of concern at the luminaire level are the light output (measured in lumens), the power consumed (measured in electrical watts), the efficiency (measured in lumens per watt), and the color point and CRI. As with all white LED based lighting systems, the application values of these parameters can be influenced by system losses due to optical losses, thermal losses, and driver efficiencies.

For white LEDs the language is fairly straight forward as LEDs are typically specified by CCT or x,y color coordinates, CRI, white lumens, electrical power, and/or lumens per watt. These values can directly translate to system luminaire values based on the system architecture and system losses. However, when designing with remote phosphor, different variables are used to describe both the blue pump LED and the remote phosphor light source. Critical parameters for the blue LED and remote phosphor component are defined below.

Blue Pump LED

- Optical watts (W_{RAD}): The optical power output of the blue LED in mW or W. Blue pump LED output is not measured in lumens but in blue optical watts.
- Electrical watts (W): The electrical power needed to drive the LED. This is the same term used with white LEDs and is a function of the voltage and current used to energize the light source.
- Wall plug efficiency (WPE): This is the efficiency of the blue LED measured in optical watts per electrical watts (W_{RAD} / W) and indicates the percentage of electrical power converted to blue light. The LED manufacturer may not publish this value in product documentation but may instead bin products by their optical watt performance and forward voltage. If this is the case the WPE can be calculated by dividing the optical watt output by the input power ($W_{RAD} / (I_f \times V_f)$).
- Dominant wavelength: This is the critical color point parameter for blue LEDs, measured in nm. ChromaLit remote phosphor products are engineered to deliver optimum performance with a 455nm dominant wavelength blue LED.

Remote Phosphor

- Conversion efficiency (CE): The white lumen output in a given spectrum per optical watt defined in the units of lm/W_{RAD}. The CE of remote phosphor will vary depending on the characteristics of the emission spectrum. Warmer color temperatures and higher CRIs will have a lower CE, just as white LEDs have a lower efficacy under these conditions, due to increased Stokes losses. It is important to note that the CE is defined in lumens per optical blue watt and not lumens per electrical watt. Confusing these terms can result in unrealistically high performance expectations. Typical CE value range from 180 to 230. Note that the CE and color point will depend on the mixing chamber. Intematix uses specific reference designs for CE measurements.
- Color temperature and CRI (CCT and CRI): These values describe the spectral output from the remote phosphor component when energized with a blue pump source and are the same variables used when designing with white LEDs. The spectrum of the remote phosphor system is dependent on the remote phosphor component just as the spectrum of a white LED is dependent on the phosphors used in the LED package.

Once these variables are understood it is simple to calculate expected system performance values using the following equations. Lumens can be calculated using either of the following two equations:

Lumens = (WPE) * (CE) * (Electrical watts)

Lumens = (Optical watts) * (CE)

In effect in the first equation the white lumen per watt efficacy is first calculated and then multiplied by the power. As such the following two equations can be used to calculate the DC (not including driver losses) efficacy of the lighting system:

Lumens / Watt = (WPE) * (CE)

Lumens / Watt = ((Optical watts) * (CE)) / (Electrical watts)

A few system level examples are discussed in the section that follows. For additional questions regarding how to calculate the performance of lighting systems using remote phosphor please consult your local Intematix sales representative for assistance.

Performance Options

White lumen output is dependent on the CE of the remote phosphor and the blue radiant power of the LEDs used. To achieve 1000 lumens per foot (305mm) using remote phosphor material with a CE of 220 lumens/W_{RAD}, 4.54 blue watts per foot are required (1000 lm / 220 lm/W_{RAD} = 4.54 W_{RAD}). For a 0.30 watt LED with 55% WPE this would imply about 0.165 blue watts per LED (0.30 $W_{electrical}$ X 55 W_{RAD} / $W_{electrical}$ = 0.165 W_{RAD}). For a 36-up 1-foot (305mm) board a total of 5.94 Watts of blue would be produced (36 X 0.165) which would produce 1307 white lumens (5.94 W_{RAD} X 220 lm/W_{RAD} = 1307 white lumens). Typical performance achieved under this use condition for a 4-foot (1220mm) linear source is about 5200 lumens at 120 lumens per watt DC in 4000K 80 CRI when using a 0.55 WPE blue LED.

It is possible through altering the drive current to either produce fewer lumens at a higher efficacy (under driving the LEDs) or to produce more lumens at a lower efficacy (often referred to as over driving the LEDs). It should be noted that as long as the LEDs are being operated at drive currents below their maximum rated values the LEDs are not in effect being over driven, just operated at a current above their nominal test current. Different LEDs have different rated test currents and maximum use conditions and the designer should keep these limits in mind when designing the blue pump engine for use with the ChromaLit Linear.

Intematix has demonstrated significantly higher efficacies by using higher LED counts and under driving the LEDs to increase the WPE of the devices. When LEDs are under driven, the WPE will increase but the total number of blue watts will reduce, meaning that fewer white lumens are produced but at a higher efficacy. Figure 18 shows the relationship of white lm/W versus WPE based on the typical CE value of 220 for a 4000K 80 CRI ChromaLit Linear product. Please contact your local Intematix sales representative for design assistance in obtaining the lumen and efficacy levels needed for your application. Intematix can also recommend blue pump sources that can help you to achieve your design objectives.

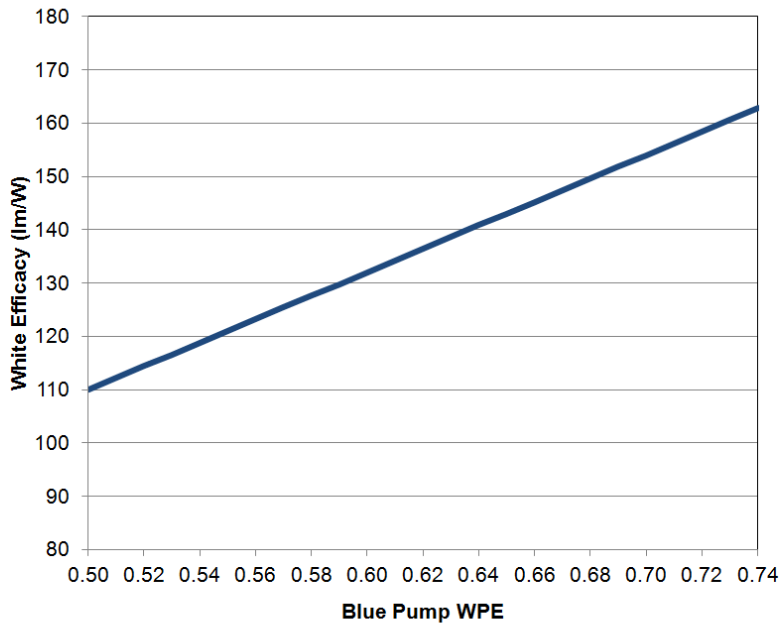


Figure 18: Relationship between white lm/W and WPE for a 220 CE component

To deliver higher lumens per foot (305mm), a higher amount of blue power is required. The LIN01 ChromaLit Linear profile has been designed to enable performance of up to 2500 white lumens per foot (305mm). This limitation is based on the geometry of the inner phosphor layer. As the remote phosphor component is not 100% efficient, heat is generated in the conversion process as is described earlier in this application note. The LIN01 profile has been sized to enable up to 2500 lumens per foot (305mm) while maintaining the remote phosphor component below its maximum use condition of 90ºC. It may be possible to achieve higher lumen per foot (305mm) levels depending on the luminaire system design and the heat transfer conditions surrounding the ChromaLit Linear product. For significantly higher lumen per foot (305mm) requirements a larger profile would be required to avoid excessive heating at the phosphor layer.

In a case where 2500 white lumens per foot (305mm) is required and a 4000K 80 CRI ChromaLit Linear with a CE of 220 is used, 11.36 watts of blue are required. 40 pieces of 0.5W LED at 55% WPE would produce 11 watts of blue, slightly short of the blue power required. Such a blue light engine would produce 2420 white lumens. If either higher performance or higher efficacy is required it may be necessary to consider higher power LEDs such as 0.6W to 1W LEDs under driven to deliver the necessary power and desired efficacy.

LED Driver Recommendations

As with all LED systems, constant current as opposed to constant voltage drivers are preferred. LEDs operate best under constant current operation. Variations in system architecture design may enable the use of a constant voltage driver but typically this involves a system design where additional components are required to ensure constant current to the LEDs through the use of current limiting resisters or other electronic components within the system design. Intematix recommends the use of constant current drivers for lighting system designs.

There is a broad selection of commercially available LED drivers with a wide variety of input voltages, constant current and maximum DC output voltages. As discussed previously, the blue LEDs selected and the design of the series and parallel interconnection both on the individual LED PCBs and of the overall light engine design can enable the ability to optimize the DC current and voltage requirements of the lighting system to be tailored to work with a wide variety of LED drivers. As ChromaLit Linear is suitable for use with low, mid, and high power LEDs, a high degree of flexibility exists in how the system is engineered to align with multiple LED driver options. A few examples of which Intematix has experience are included in the section that follows but a wide range of options exist to the luminaire manufacturer.

Meanwell provides high efficiency, current adjustable drivers such as the PLN-100-36 with a 36 volt maximum output and an adjustable constant current range from 2000 to 2650mA. The Meanwell HLG-120H-36 is also current adjustable with a constant current output range from 1700 to 3400mA.

TCI produces a wide range of constant current drivers suitable for use with LED PCB designs that work well with ChromaLit Linear. One option is the Maxi Jolly Dali, a compact lower power driver with dip switch settable current settings of 350mA, 500mA, 700mA, 900mA, and 1050mA. The maximum power and forward voltage of this driver is dependent on the current setting selected.

A wide variety of other LED drivers with similar characteristics are commercially available to suit application needs for efficiency, dimming (Dali / 0-10 / TRIAC) and AC input range. Some driver manufacturers such as TCI use pulse width modulation when dimming using an added 100k Ohm potentiometer. For applications that require fully stabile non-modulated output this may not be acceptable. Many constant current drivers dim smoothly with constant DC output. The full dimming range should be evaluated to ensure that it meets the requirements of the application. In some cases, such as many of the Meanwell drivers, the output current may not be adjustable to a deep enough dimming level from the maximum drive current. If deep dimming to less than 5% of maximum output is required, verification of the dimming capability of the LED driver can require careful evaluation.

Important Note: When selecting an LED driver for use with ChromaLit Linear, ensure that it provides a constant current output to the LEDs, has adequate voltage output for the design, and is compatible with the dimming topology required for the application.

Thermal Management Recommendations

Design Considerations

Thermal management, as with all solid state lighting systems, is important to ensure both product performance and long term reliability. In most application uses for ChromaLit Linear, low to mid power LEDs are used which enable design flexibility and a highly uniform light output. The distributed nature of these sources can also simplify the thermal management of the LED system compared to a point source solution where a product such as a COB (chip on board) high power density source may be considered. Distributing these low to mid power sources along the length of the linear array can ease the challenges of thermal management as, by nature of the design, a reasonable amount of thermal area is already present per watt of input power.

The efficiency of the LED source used in the ChromaLit Linear light source will partly determine the conducted power that will be required to be managed in the luminaire design. As the efficiency of LEDs has increased over the past several years, a non-trivial portion of the electrical power is dissipated as light rather than as heat, therefore reducing thermal management requirements. For example, if the LED selected has a WPE (blue power out / DC input power) of 55%, less than half (45%) of the total input power to the LEDs will need to be conducted away from the LEDs and then transferred via convection and radiation to air. Although the remote phosphor layer generates heat due to the fact that it is not 100% efficient, this heat load is not included in this estimation as this heat is dissipated by convection and radiation.

For example, the 36-up LED PCB described in previous sections of this application note which can deliver up to 1250 lumens per foot (305mm), can be operated continuously with only the slider housing design shown in Figure 13 if this housing is exposed to convection in an open air environment with an ambient temperature of 25ºC. Under such use conditions, the maximum temperature of the slide housing / heat sink will be on the order of 40ºC. If four of these 36-up LED PCDs are used with a simple 1/8 inch (3.2mm) extrusion rail as a heat sink, this system can deliver approximately 5000 white lumens. For higher power systems, or for systems which will experience elevated ambient temperatures, additional heat sinking may be required.

When designing, prototyping, and testing the thermal management of a lighting system it is important to consider all sources of heat and to carefully consider the entire range of application conditions. The system must be tested as a complete unit including all elements of the housing which may impact heat transfer mechanisms and with all heat generating components including the driver and any control circuitry to be imbedded in the lighting system. If a partially assembled system is tested the results may not be indicative of the actual system performance.

The area of heat sink material exposed to the environment for convective cooling is important. For example, if the system is to be mounted to a non-conductive surface, such as to wood in an under cabinet application, additional heat sink area may be required to ensure adequate convective heat transfer.

> ***Important Note: When considering the thermal management requirements of the lighting system, take in to account all heat sources (including the driver), the expected mounting conditions, and the maximum allowable ambient conditions of the lighting installation.***

As mentioned previously, effective thermal transfer from the LED PCB to the housing is required to ensure optimal system performance. Intematix recommends the use of a thermal interface material between the LED PCB and the housing to improve the system thermal performance. Options include mounting the LED PCB to the aluminum housing with a thermally conductive paste or heat transfer tape or pad. A double stick adhesive table with very high thermal conductivity has been used successfully on 1-foot (305mm) and 4-foot (1220mm) linear concepts developed by Intematix. 3M VHB adhesive can also be used for adhering the LED PCB to an aluminum housing, but due to its low level of thermal conductivity it should only be considered for low power modules.

> ***Important Note: Ensure that the LED PCB is in good thermal contact with the fixture housing by using an effective thermal interface material at the interface to ensure good contact without voids in the thermal path.***

To ensure reliable long term operating of the lighting system, there are several critical temperature locations to be considered in the design process. The first of these is the LED operating temperature which is a factor of the power applied to the LED, the thermal resistance of the LED, and the thermal management of the lighting system. LEDs are typically specified with a maximum case temperature, junction temperature, or in some cases both. For low to mid power LEDs, typically a maximum case temperature is specified which is an easier parameter to measure than the junction temperature which must be calculated as it cannot be easily measured.

The LED case temperature should be measured during the prototype phase of the development effort and be verified to operate under the manufacturer's maximum case temperature for all specified input power levels and the complete range of expected ambient operating conditions. It is also important to understand if the lumen maintenance is a function of the LED case temperature as this may impact the long term reliability of the lighting system. It is best to consult with your LED manufacturer to determine if reliability is a function of case temperature, and if so under which case temperature the system must be maintained to ensure adequate system reliability. This value will vary for different LED package types and for different LED manufacturers.

> ***Important Note: Ensure that the LED case temperature is below the manufacturers maximum recommended limits over the entire expected operating range of the lighting system and ensure that the maximum temperature limit ensures adequate reliability of the LED component.***

Other important temperatures to consider are the housing temperature and the LED driver Tc point temperature. In some cases it may be important to maintain a housing touch temperature below a specified value to ensure that there is no risk of burn to an end user. LED drivers are typically specified with a maximum Tc point temperature which must be met to ensure long term reliability. As with the LED case temperature, the entire lighting system with all heat generating elements, must be considered as a complete assembly over the entire operating range to ensure that these values are below acceptable maximum limits.

Measuring the Remote Phosphor Temperature

It is important to ensure that the maximum operating temperature of the ChromaLit Linear component is kept below its limit. The maximum operating temperature listed on the product data sheet is the temperature of the internal surface of the phosphor layer. Although this value is challenging to measure once the system is assembled, it is possible to measure this value in the prototype and development phase of the lighting system to ensure compliance with maximum limits.

The first step is to locate external hot spot temperatures on the ChromaLit Linear component. As with comments made previously for other critical temperature points, it is important to test the product as a completed assembly with all sources of heat and to validate that the temperature is maintained below the maximum value over the entire expected operating range of the product. External hot spots can be located and measured using a thermal imaging camera such as a FLIR A300/A310 or equivalent. The IR camera can be used to locate hot spots on the outside surface of the remote phosphor as well as for outside housing surfaces. The surface emissivity should be set to 0.95 for measurements of the remote phosphor. For measuring the temperature of other housing materials, an appropriate surface emissivity value must be selected dependant on the material used for the housing component.

After establishing external hot spot locations, a thermocouple can be mounted to record and data log absolute temperatures over time or over the expected operating range by loading the lighting system into an environmental chamber to replicate expected use conditions. Intematix recommends the use of 36 gage K-type thermocouples and Arctic

Silver Alumina™ thermal adhesive. Thermal measurements in the light path of the remote phosphor system can be challenging and can easily result in false high readings. The blue flux emitted from the blue light engine or transmitted through the ChromaLit Linear component can cause thermocouples to generate false high readings. These readings can be on the order of 10-15ºC higher than the actual temperature reading. Simply mounting a thermocouple on the interior surface of the ChromaLit Linear component with Kapton tape will result in a false high reading which may raise system design concerns.

For measuring inside surface temperatures of ChromaLit Linear, it is recommended to drill a hole in the material at the location of the external hot spot identified using the IR imaging of the assembly. This hole can be drilled with a small drill bit or small Dremel engraver tool. This should be a blind hole and not a through hole that ends just prior to punching through the internal wall of the remote phosphor layer in the ChromaLit Linear component as is shown in Figure 19. The thermocouple should then be bonded into place using Arctic Silver 2-part Alumina adhesive or equivalent. The adhesive used should have both a high thermal conductivity and be highly reflective to ensure accurate thermal measurements without causing high readings due to the blue light effect. Typically a small amount of the adhesive is dispensed on the tip of the thermocouple and then the thermocouple is inserted into the hole and cured.

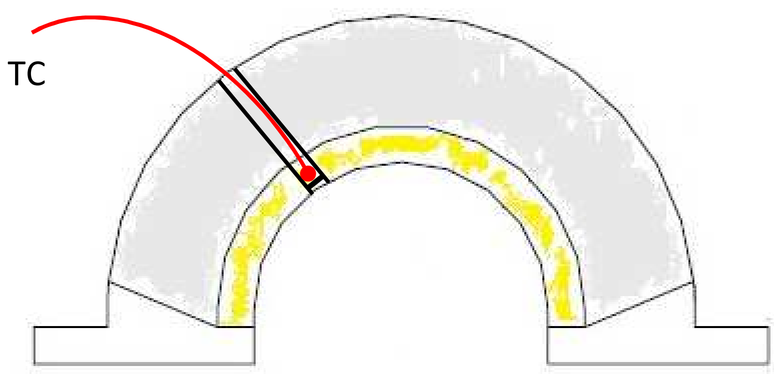


Figure 19: ChromaLit Linear thermocouple insertion

> ***Important Note: Blue light can cause false high temperature readings; care must be taken to avoid these effects and to record accurate readings.***

For measuring housing temperatures the thermocouple can be either taped, glued or held mechanically (e.g. sandwiched under a screw) into place depending on whether or not it is in the light path of the lighting system. If the measurement point will be in the light path it is recommended to glue the thermocouple in place using a highly conductive and highly reflective adhesive. The thermocouple can first be taped down into position using Kapton tape and then the two part thermal adhesive can be applied to hold the thermocouple weld bead in place, after which point the tape can be removed.

Cutting and Handling of ChromaLit Linear

ChromaLit Linear is provided in 4-foot (1220 mm) rough cut lengths as is specified in the product data sheet. Intematix can supply ChromaLit Linear in other lengths and with different cut tolerances, please consult your Intematix sales representative for more information. If cutting or trimming of the ChromaLit Linear product is required, Intematix recommends the use of a high speed band saw. After the cut is made, residual material on the edges should be removed either by hand or with a fine grit sand paper.

ChromaLit Linear is not designed to be bent or heat formed into other shapes. Bending is not recommended and will cause a negative impact on color point consistency. The product has not been tested to understand whether long term exposure to bending stress may also cause cracking of the product which could result in mechanical failure or leakage of blue light in the light beam.

For cleaning of the ChromaLit Linear product use electronic grade isopropyl alcohol and a lint free cloth. Intematix recommends cleaning both the inside and outside surface prior to final assembly to ensure that any debris or dust is removed from the lighting system to ensure maximum performance. After cleaning it is good practice to use clean filtered compressed air to blow away any residual contaminants. This same cleaning technique can be used for the LED PCBs and reflector material.

ChromaLit Linear should be stored in environments below 60ºC and 90% relative humidity (non-condensing). Typically material is stored on horizontal racks. The product can be stored in the cardboard shipping boxes with a maximum of six boxes high to avoid crushing of the product. If a large inventory of ChromaLit Linear is to be stored multiple shelves should be use to avoid excessively tall stacks of the material.

System Design Inputs

The purpose of this application note is to provide general guidance and advice for successful design integration of ChromaLit Linear products. Intematix is also capable of providing additional design guidance and assistance. When working with a customer on a specific design challenge, it is useful for Intematix to understand the light source system characteristics and performance targets. The items listed below can help Intematix understand the expected light source performance and how remote phosphor might best be implemented to achieve the design goals of the product.

1. Target system performance
   a. Lumen output, color temperature and CRI
2. Length and quantity of light sources per luminaire
   a. Is a single 4-foot length desired, 2x2-foot lengths in a side by side architecture, other schematic
3. Light pattern required
   a. Lambertian, wide angle, asymmetric or other
4. System efficiency targets lumens per watt (DC or AC)
5. Expected driver efficacy
6. Dimming requirements
   a. If required, which scheme will be used (0-10, TRIAC, DALI)
7. Environment concerns
   a. Moisture, spray, dust
   b. Minimum and maximum operating temperature range
   c. Indoor or outdoor location
   d. IP ratings (IP66 or IP67) if required
8. Application and fixture type
9. Off state and design appearance
   a. Examples of competitive designs or design concepts
   b. Is off state white required or is a more yellow off state acceptable
10. Glare requirements
    a. How bright can the light density at the source be in direct view
11. Cost considerations and targets for ChromaLit, blue LEDs and entire fixture
12. Open to consideration of a non Class 2 power supply
13. Blue pump source selected or preferred LED partner (if any)

Common Design Challenges and How to Avoid Them

Design Challenge	Issue	Solution
Blue light leakage	Blue light is visible outside of assembly	Use a slider type housing that wraps over the reflective edges of the remote phosphor. Use end caps that extend partially over the surface of the remote phosphor. Eliminate gaps between the LED PCB, reflector and reflective feet of remote phosphor that may result in blue light leakage.
System level efficiency	Lumens per watt is lower than expected	Verify that the LED used for the blue light engine has high wall plug efficiency (WPE). WPE should be greater than 50% at nominal operating current and at application case temperature. Verify that a highly reflective material is used to cover the LED PCB. Simply using a white solder mask can result in a loss of light output of 10-15%. Also ensure that the reflective material covers any dark surfaces or components included in the light engine. Do not use a secondary diffuser in the lighting system above the ChromaLit Linear component. The remote phosphor output is extremely diffuse and secondary diffusion may not be necessary. Ensure that the surface area of ChromaLit Linear is not blocked by tall mounting features or buried deeply in a reflector cavity which can cause system level losses. Verify that the LED driver used is a high efficiency driver that does not contribute to a low system level efficiency.
Chromaticity	CCT is low	Low reflectivity in the mixing chamber (the reflective material on top of the LED PCB) can cause a blue shift in the spectral power distribution. Verify that the reflectivity of the material used in the mixing chamber is >95% and has flat spectral reflectance characteristics.

Design Challenge	Issue	Solution
Chromaticity	White point is outside of the anticipated 3-step MacAdam Ellipse	Verify that the dominant wavelength of the blue LED used is in the range of 450-460nm at fully stabilized operating temperatures. ChromaLit Linear is optimized to work with a 455nm dominant wavelength. If other wavelength sources are used the chromaticity point will shift (consult the product data sheet for more details). Verify that the reflectivity of the material used in the mixing chamber is >95% and has flat spectral reflectance characteristics. Absorption of white light will blue shift spectrum.
Chromaticity	CRI is low	Verify that the dominant wavelength of the blue LED used is in the range of 450-460nm at fully stabilized operating temperatures. ChromaLit Linear is optimized to work with a 455nm dominant wavelength. If other wavelength sources are used the CRI will shift (consult the product data sheet for more details). Higher CRI can be obtained with longer dominant wavelengths. However using pump wavelengths beyond 460nm will cause the color point to move outside of a 3-step MacAdam ellipse distance from the nominal white point.
Thermal management of remote phosphor	Temperature of remote phosphor inside surface is greater than 90ºC	The ChromaLit Linear LIN01 profile has been engineered to support a maximum lumen output of 2500 lumens per foot (305mm). When energized with excessive blue power density the temperature of the remote phosphor component can increase above acceptable limits due to Stokes losses in the phosphor conversion process. Temperature can be reduced by ensuring that the surface of the remote phosphor is exposed to free air convection. Maximum allowable use conditions should also be considered to ensure that in the maximum use condition adequate thermal management is required to prevent excessive heating. Increasing the remote phosphor surface area (through using a longer length) for the same blue input / white output will also reduce the temperature of the remote phosphor. Ensure that the blue LEDs are centered inside the remote phosphor and reduce the LED protrusion depth to further reduce the phosphor temperature.

Design Challenge	Issue	Solution
LED case temperatures are beyond manufacturer's recommended ranges	Heat sink has insufficient surface area for convective cooling	Insure that the LED PCBs are compressed against the housing and a thermally conductive interface material is used between the LED PCB and housing. A 0.25-inch (6.4mm) thick 1-inch (25.4mm) wide aluminum bar is typically sufficient surface area to maintain a 2000 lumen per foot (305mm) light bar at acceptable temperatures in a 25ºC ambient environment. However the mounting and orientation of the bar can have an impact on the thermal management depending on the thermal conductivity of the mounting surface and the available airflow. For a proper thermal management design it is necessary to calculate the conducted heat requirements and design adequate heat sinking. A good rule of thumb is that 50% of the DC input power will be dissipated as heat (assuming a WPE of 50%). Once this value is calculated it can be assumed that approximately 6-10 square inches (39-65 square cm) of heat sink is needed per conducted watt. Note that this is an area requirement, not a volumetric requirement. Surfaces that are not exposed to free convection will be less effective in thermal management.
Driver selection	Difficult to find a driver compatible with the LED light source	The LEDs in the linear PCB can be arranged in different series and parallel arrangements offering a wide variety of different input voltage and current requirements. For example if 36 LEDs per foot (305mm) are to be used this could be arranged in the following serial/parallel arrangements which would all have different current and voltage requirements: 18S X 2P, 12S X 3P, 9S X 4P, 6S X 6P, or the inverse of any of these series / parallel relationships.

Critical Design Parameter Checklist

The following checklist is provided to assist in diagnosing design challenges that may exist when designing a luminaire based on ChromaLit Linear. If in reviewing your system design you check “no” for any of these questions there is a reasonable probability that your product has not been optimized for performance. Please review the application note for further detail or contact your local Intematix sales representative for further assistance.

Critical Design Parameters	YES	NO
Is the dominant wavelength of the blue LEDs used between 450 and 460nm?		
Is the WPE of the blue LEDs used greater than 50% at the operating power and temperature of the product?		
Is the operating current of the blue LED below the maximum specification on the manufacturer’s data sheet?		
Does the operating current selected support the lifetime / lumen maintenance requirements of the application based on the LED manufacturer’s recommendations?		
Is the LED PCB covered with a highly reflective material with a reflectivity of 97% or higher?		
Has the internal assembly of the mixing chamber been checked to ensure that no gaps or voids exist that could result in blue or white light loss?		
Have all dark components inside the mixing chamber (such labels, wires, other components or connectors) been covered with highly reflective material?		
Has the reflective material covering the PCB been precision cut to allow for tight tolerances around the LED packages without blocking any blue light?		
Is the end cap either constructed from a reflective material or coated/painted on the inside to ensure high reflectivity inside the mixing chamber?		
Is the LED center to center pitch spacing less than or equal to 12.4mm? If not, is the uniformity acceptable even at full dimming (if applicable)?		
If more than one LED PCB is used in the application has the pitch spacing between LEDs at the ends of neighboring boards been maintained consistent with the pitch spacing within the LED PCBs?		
Has the LED PCB (or PCBs if multiple boards are used in the lighting system) been designed and populated to avoid current hogging?		

Critical Design Parameters	YES	NO
Does the housing allow for sufficient linear expansion of the remote phosphor over the full range of operating temperatures expected?		
Does the housing incorporate a slider design that wraps over the edge of the reflective white feet to prevent blue light leakage?		
If the luminaire has been designed for suspended applications has the housing been engineered to deliver sufficient rigidity to prevent bowing?		
Have the mounting features for the ChromaLit Linear been kept below the height of the white reflective material (less than 1.25mm tall) to avoid light blocking?		
Has the end cap been designed to cover the end of the remote phosphor component without introducing excessive light blocking?		
Is the ChromaLit Linear product exposed (not covered with a diffuse or clear cover) in the luminaire design?		
Is the ChromaLit Linear at the top surface of the luminaire design (i.e. not buried in a deep reflector cavity)?		
Is the LED driver selected a constant current driver with sufficient voltage output to fully drive the LED PCBs?		
Is the product dimmable and if so, is the driver selected compatible with the desired dimming protocol?		
Is the driver efficiency >90% for non-dimming applications or >85% for dimming applications?		
Is the operating temperature of the remote phosphor maintained below its maximum use condition under the entire operating range of the product?		
Is the case and / or junction temperature of the blue LED maintained below its maximum use condition under the entire operating range of the product?		
For the maximum use conditions above have all heat sources been considered, mounting conditions of the final product and the allowable ambient temperature range to ensure maximum use conditions are respected over the entire operating range of the completed product?		
Has a thermal interface material been used between the LED PCB and the luminaire housing for effective thermal transfer?		