

## **LIGHT REDISTRIBUTION PRISM ASSEMBLY**

### **Background of the Invention**

Many lighting fixtures designed over the last several decades have been designed for fluorescent tubes. These tubes are gas filled, vary in length from approximately 12 to 96 inches, and are usually from 1 inch to 1 1/2 inch in diameter. A fluorescent material coated on the inside of the glass tube is excited by the discharge within the tube. As a result of this excitation, light emission along the length of the tube is quite uniform. As a result of this uniformity, architectural illumination panels can be designed that are pleasing to the eye, devoid of any significant spatial variation along the length of the emitting tube.

More recently LEDs have been introduced into architectural lighting fixtures as drop-in replacements to fluorescent tubes. The LEDs are characteristically arrayed along the length of the tube structure. Unlike fluorescent tubes, the individual LED emission is highly localized. This results in a spotty light distribution within the fixture, and this characteristic increases as the power levels of the LEDs increase, and the devices are spaced farther and farther apart. As a result, not only are the tubes less pleasing visually, but they often interact with the fixtures in which they are placed in a way that negatively impacts the distribution of emitted light.

Due to the initial higher cost per watt of the LED, as well as the higher assembly cost, an inexpensive means of redistributing the emitted light along the length of the tube is highly desirable.

Lightpipes have been employed extensively in illumination systems. They make use of both refraction of light and total internal reflection (TIR). In order for the TIR to succeed, the high refractive index material (plastic) must be surrounded by a comparatively low index material, generally air.

A prismatic lightpipe offers multiple TIR and refraction opportunities to distribute the light in an efficient manner away from the source.

### **Summary of the Invention**

The present invention provides several embodiments of a linear LED light redistribution system.

### Brief Description of Figures

Figure 1 depicts the appearance of a section of fluorescent lamp measuring 1 inch in diameter of approximately 1 foot in length as seen by a viewer positioned approximately 3 feet distant from the lamp. The plot is a 2 dimensional grid of 50 x 350 cells. The incident irradiance level is indicated by the shade of gray: black being the lowest and white being the highest level of irradiance.

Figure 2 depicts the appearance of a section of an LED equipped fluorescent lamp replacement of the same dimensions as Figure 1. The LEDs have a cylindrical plastic cover of 1" diameter that scatters transmitted light in a manner similar to actual LED tubes. The plot has the same dimensions and depicts the irradiance level the same as Figure 1. The LEDs are spaced 70mm apart, such that a 48 inch tube will require 17 LEDs.

Figure 3 depicts the same section of LED equipped fluorescent lamp replacement as in Figure 2, but with an optimized prismatic lightpipe interposed between the LEDs and the cylindrical cover.

Figure 4 shows the profile of the Prismatic Lightpipe. The LED is positioned under the center gap.

Figure 5 shows the important components of the invention viewing the invention along the long axis of the lamp.

Figure 6 shows the important components of the invention viewing the invention across the long axis of the lamp.

Figure 7 is a drawing of the prismatic lightpipe identifying critical features/surfaces of the device.

Figure 8 is a simplified drawing of the prismatic lightpipe showing a variety of ray paths through the device.

Figure 9 depicts the radiance of the simulated lamp as a function of angle in a plane perpendicular to the long axis of the lamp.

Figure 10 depicts the radiance of the simulated lamp as a function of angle in a plane along the long axis of the lamp.

Figure 11 shows that the prismatic lightpipe of Figure 6 and Figure 8 may be readily modified to accommodate concentrated light emitters spaced at other intervals.

Figure 12 depicts the same arrangement as that of Figure 3, but with the shorter prismatic lightpipes and smaller emitter intervals shown in Figure 11.

Figure 13 shows a simplified prismatic lightpipe having only 6 primary surfaces.

Figure 14 shows the irradiance of the simulated fluorescent tube equipped with the prismatic lightpipes of Figure 13.

#### Description of Invention

Various embodiments of the present invention provide a viable means to redistribute the light from a sparse linear array of LEDs to a relatively uniform linear emission area when used in conjunction with the closely spaced tubular diffuser. As depicted in figures 5 and six, the primary components of this system are LEDs mounted on a PCB with large spaces between them, a reflective covering for the PCB, or alternatively coated on its surface, a prismatic light pipe array, and a diffusive cylinder that serves to enclose and protect the LEDs.

The LEDs addressed in this disclosure are relatively inexpensive LEDs consuming approximately 1 W of electrical power. It should be obvious to one skilled in the art that the specific power simply alters the spacing of the LEDs while the nature of the present invention remains intact, simply requiring change of key parameters. The present design and analysis suggested that approximately 17 LEDs would be required along the length of a 48 inch tube in order to output irradiance level comparable to a typical fluorescent lamp. Increasing or decreasing the number of LEDs within this tube length can be readily accomplished through a modification of the key elements of the prismatic light pipe array. The LEDs of the present invention have been assumed to be surface mount technology (SMT) devices, and that these LEDs incorporate a solder pad half to dissipate thermal energy to a heat sink that is an integral part of the tube structure. The heatsink structure of LED tubes is well known and is not addressed here. The PCB to which the LEDs are mounted has been defined in the present invention to have a vacuum metallized

upper surface. Alternatively, a thin plastic sheet can be assembled on top of the printed circuit board with the metallization layer on the thin sheet.

The prismatic array serves to capture the bulk of the light emitted from the LED over which it is positioned, and has been designed to redistribute that light over a larger area along the length of the lamp. However a small gap between elements of the prismatic array is critical in order to allow some of the light to be emitted straight to the diffuser from the LED without impinging on the prismatic light pipe. Key features of the prismatic light pipe will be addressed below.

The diffusive cylinder serves multiple functions. This component is present on most LED lamps that are substituted for fluorescent lamps. When the LEDs are closely spaced this diffusive cylinder is often adequate to the task of scattering the light from the individual LEDs along the length of the tube so that the spotty nature of the individual LEDs is less objectionable. The second function this diffusive cylinder serves is to provide protection for the PCB and LEDs while simultaneously preventing unwanted contact with electrical connections on the PCB. Characteristically the spacing between the diffusive cylinder and the LEDs is measured in a small number of millimeters. As long as the spacing between the LEDs is small, this proximity of the diffusive cylinder to the LEDs in combination with the modest spacing of LEDs is sufficient to create the impression of uniformity of light along the length of the tube. However as the spacing of the LEDs increases it is necessary to increase the spacing between the LEDs and the diffusive cylinder in order to preserve relatively good radiant uniformity along the length of the lamp. The spacing between the LEDs and a diffusive cylinder becomes untenable as the spacing between LEDs exceeds 10 to 15 mm.

Figure 1 is a simulation of a common fluorescent lamp in which a cylindrical glass tube radiates in a Lambertian fashion, thereby generating a comparatively uniform distribution of radiance along its length. Figure 2 is a simulation of a sparsely arrayed set of LEDs under a diffusive cylinder. These LEDs have been spaced with a 70 mm separation.

In the preferred embodiment shown in figure 5 and figure 6, a prismatic light pipe has been positioned between the LEDs and the diffusive cylinder. The diffusive cylinder has a 25.4 mm diameter. The LEDs used in the simulation were modeled on the basis of the 3535 type LED, although a variety of LEDs can be readily adapted without invalidating the design concept. The reflective PCB surface was placed at the approximate plane of the LEDs solder pads. While the surface of the PCB can be successfully be treated with a white Lambertian scattering surface, the resulting uniformity of the lamp remains largely unaffected, but simulations indicate a loss of light.

In the preferred embodiment, a diffusive cylinder with diffusion properties common to LED fluorescent lamp replacement tubes has been used. The scattering characteristics of this diffusive cylinder were measured in the laboratory and implemented in the simulations.

In the preferred embodiment the prismatic light pipe has a profile illustrated in figure 4. It is readily evident to the left and the right half of this prismatic light pipe are exact replicas simply rotated through  $180^\circ$ . The prismatic light pipe has, at present, at least eight key parameters. The first of these is the index of refraction of the polymer from which the prismatic light pipe is molded. A variety of transparent polymers can be successfully utilized. However, since the TIR condition is determined by the index break between the index of the polymer and the surrounding air, the larger the index break, the more aggressively we can define critical angles within the geometry of the light pipe. For this reason the preferred embodiment uses a polycarbonate material, simply because polycarbonate represents a reasonable compromise between cost and higher index of refraction. Polymers of other indices of refraction can be utilized provided that geometry is altered appropriately.

Figure 7 depicts the critical surface geometry features that must be modified in order to achieve uniformity along the length of the lamp. Feature 701 of figure 7 is an aspheric/acylindrical surface. This surface tends toward an off axis parabolic segment, but in the preferred embodiment it has been adjusted slightly away from this shape in order to achieve the performance attained. The primary function of surface 701 is to reflect light down the length of the prismatic light pipe. In the process of achieving this function it tends to generate a dark spot nearly directly over the LED placement. To remedy this problem, each pair of prismatic light pipes has been spaced apart from one another directly over the LED such that light emitted from the LED and hitting the diffusive cylinder directly fills in this dark spot. Surface 702 has a dual purpose. It provides TIR reflection for those rays that must be piped away from the LED position. However it also refracts light to the diffusive cylinder once rays have reflected from some of the other surfaces of the prismatic light pipe. Surface 703 likewise reflects some of the rays using TIR, but the bulk of the rays striking the surface are simply refracted out of the end of the prismatic light pipe. These rays are not lost, but contribute in a different fashion to the uniformity of the pattern as will be addressed below. Surface 703 in the present embodiment is at  $90^\circ$  to surface 702, however this is not a necessary condition. Surface 704 biases the distribution of rays refracted by surface 703 toward the diffusive cylinder, and the angle the surface 704 makes with surface 703 must be adjusted carefully. Surface 705 is one of the most critical surfaces of the prismatic light pipe, consisting of serrated

surfaces whose function it is to scatter light through TIR reflections to surfaces 702, 703, and 704 such that the refraction of these rays sends them at multiple angles and multiple positions along its length to the diffusive cylinder. Surface 706 is principally a refractive surface used to couple the light from the LED into the prismatic light pipe such that the majority of rays are contained within the light pipe to be operated on by the other surfaces. The two side surfaces 707 are likewise used to contain the light through TIR reflections. In the present embodiment the two side surfaces 707 are parallel and at right angles to both surface 702 and surface 703. However this is not a necessary condition, and modest angles between the 2 707 surfaces may be employed to alter the distribution of light radiated about the long axis of the lamp.

In another embodiment of the prismatic array surface 702 may be serrated in a fashion similar to surface 705. However the angles of this serrated surface must be carefully controlled and relatively modest.

Figure 8 depicts a fan of rays emitted from the LED into only one of the prismatic arrayed components, and for the sake of clarity, all lie within a single plane that avoids reflection from the two side surfaces, surfaces 707. The function of the various surfaces addressed above can be more readily seen in this diagram. It is clear that some of the rays escape the prismatic light pipe and strike the reflective surface of the PCB. These rays are not lost, but rather reenter the prismatic array or are reflected towards the diffusive cylinder. A relatively wide range of angles and positions of the escaping rays is depicted. This wide range of both angle and position contribute to the uniformity of lamp emission. It is also apparent from figure 8 that some rays escape from surface 703, and that many of these enter surface 703 of the adjacent prismatic light pipe and are likewise reflected and refracted by that component. This behavior contributes still more to the uniformity of lamp emission.

In another embodiment of the prismatic array, surfaces 703 and 704 may be combined in a single surface at a different tilt angle relative to surface 702 and/or with a curvature rather than a planar surface.

In another embodiment of the prismatic array, either surface 702 or 705 are tilted to create a tapered prismatic light pipe. Serrated facet angles are adjusted to accommodate for the taper.

In yet another embodiment of the prismatic array both surface 702 and 705 are tilted to create a tapered prismatic light pipe. Serrated facet angles are adjusted to accommodate for the taper.

Spatial frequency of the serrated facets on the surfaces must be sufficiently high so that the evidence of single facet reflections do not appear at the diffusive cylinder.

As the spacing between LEDs is altered, the angles and shapes of these key surfaces, as well as the separation between surface 702 and 705 and between surfaces 707 must be modified. The interaction between these surfaces is extremely complex, and not reducible to closed form equations. Nonsequential ray tracing simulations utilizing well-crafted merit functions combined with experience is the best way to achieve uniformity along the length of the lamp.

Figure 9 depicts the angular radiation pattern of the lamp. The plane of this pattern is perpendicular to the long axis of the lamp. The plot represents a nearly Lambertian radiation pattern, however this can be modified to some degree by the angle established between surfaces 707.

Figure 10 depicts the angular radiation pattern of the lamp in a plane along the axis of the lamp. The two lobes that occurred just above the horizon are a result of the light emitted through surface 703. Their relatively large in this particular case because the plots only evaluate the output of three LED systems. As the number of LEDs in the arrayed increases the relative magnitude of these lobes will decrease.

Figures 11 and 12 depict the effect of shorter intervals between both the concentrated emitting sources, and prismatic light pipe pairs. Modification of the prismatic lightpipes involved little more than shortening the component parts. The flexibility of this design approach is quite evident from a comparison of figures 3 and 12.

Figures 13 and 14 depict a different prismatic lightpipe configuration that can be useful for close interval arrays. The difficulty of this approach is that as the intervals increase in dimension, the prisms expand in both length and height, rapidly outgrowing the confines of the tube. This can be countered, to some degree, by adding angled serrations to the bottom angled surface in a fashion similar to Figure 4. Adding curvature to the upper angled surface also tends to enhance the flexibility of the lightpipe in handling larger intervals. So it is evident that there is a transition phase possible from close intervals using the geometry of Figure 13, and a larger intervals using geometries more like Figures 11 and 6.

The present invention together with the various embodiments provide a great deal of flexibility in achieving radiation patterns and uniformity along the length of the lamp.

However, it should be obvious to one who is skilled in the art that other specific goals of nonuniformity of radiant output may also be pursued using the same geometries with other parameter ratios.

Claim:

1. A single prismatic light pipe for use with a concentrated light source comprising; an optical component constructed of material of index refraction higher than that of the surrounding material, said prismatic light pipe possessing a refractive input surface, a curved TIR (reflective) surface, and at least five other surfaces, all said surfaces performing both refractive and TIR reflective functions such that the light emission area is spread beyond the extent of the concentrated light source.
2. The prismatic lightpipe of claim 1 mounted above a reflective surface which lies in the approximate plane of the concentrated emitter.
3. The prismatic light pipe of claim 1 with a second duplicate prismatic light pipe of claim 1, both disposed symmetrically about the concentrated light source.
4. The prismatic lightpipe pair of claim 2 mounted above a reflective surface which lies in the approximate plane of the concentrated emitter.
5. The prismatic lightpipe of claim 1 in which the curved surface is replaced by a series of flat surfaces that form an approximation of the curved surface in a piece-wise continuous fashion.
6. The prismatic lightpipe of claim 5 mounted above a reflective surface which lies in the approximate plane of the concentrated emitter.
7. The prismatic light pipe of claim 5 with a second duplicate prismatic light pipe of claim 5, both disposed symmetrically about the concentrated light source.
8. The prismatic lightpipe pair of claim 7 mounted above a reflective surface which lies in the approximate plane of the concentrated emitter.
9. The prismatic lightpipe of Claim 1 in which the curved surface is coated with a reflective coating, and serves only as a reflective surface.
10. The prismatic lightpipe of claim 9 mounted above a reflective surface which lies in the approximate plane of the concentrated emitter.
11. The prismatic light pipe of claim 9 with a second duplicate prismatic light pipe of claim 1, both disposed symmetrically about the concentrated light source.

12. The prismatic lightpipe pair of claim 10 mounted above a reflective surface which lies in the approximate plane of the concentrated emitter.
13. The prismatic lightpipe of claim 9 in which the curved surface is replaced by a series of flat surfaces that form an approximation of the curved surface in a piece-wise continuous fashion.
14. The prismatic lightpipe of claim 13 mounted above a reflective surface which lies in the approximate plane of the concentrated emitter.
15. The prismatic light pipe of claim 13 with a second duplicate prismatic light pipe of claim 13, both disposed symmetrically about the concentrated light source.
16. The prismatic lightpipe pair of claim 15 mounted above a reflective surface which lies in the approximate plane of the concentrated emitter.