I. INTRODUCTION

Solid state light emitters, Light Emitting Diodes, LEDs have been widely used in signal lights, automobile lights, large screen display, decorative lights and general illumination. Recent technology advancement has triggered consideration of LED as an alternative light source for the traditional xenon flash tubes in fire alarm notification strobes. The consideration is driven by four key factors, lower power consumption, reduced costs, potential reliability enhancement and increased design flexibility.

The proposed xenon tube alternative has triggered considerable controversy and in turn has resulted in the publication of a number of research papers examining the performance of LED light sources as effective replacements for the traditional xenon flash tube. Savage [1] reported LEDs have a very different light output profile than a xenon tube. Since the power capability of high brightness LEDs is limited relative to that of the xenon tube, LEDs can only achieve candela ratings in the range required in mainstream fire notification applications by lengthening the light output pulse width. Savage found that light sources with longer durations tended to have lower detectability and in some cases [2], 100 ms pulse was essentially invisible.

Bullough et al [3] proposed that the absolute or instantaneous intensity from a light source when viewed indirectly should be used to measure the source’s performance. Bullough et al [4] further proposed to use Indirect Effectiveness Quantity (IEQ) to measure the performance of a light source and establish a baseline for an indirect detection rate of 90% with IEQ value of more than 750 cd under a room illuminance of 500 lux for light sources at a distance of 20 feet.

In this paper, we discuss how this baseline luminous intensity requirement can be achieved using an LED light source while maintaining a short pulse length. Based on the equation of IEQ [4], we will derive a formula for the luminous flux requirement of LED. Since strobe light is a very unique LED application, special design considerations and optimizations are needed for the selection of LED, over driving LED with pulse
current, thermal design and optical design parameters. We will present a list of design considerations for LED strobe light. We will also examine the performance of a LED prototype by presenting analytical as well as experimental results.

II. IEQ and LED FLUX

Bullough et al [4], based on the definition of effective intensity, developed IEQ to measure the performance of a light source:

\[
IEQ = \int_{t_1}^{t_2} I(t) \, dt \quad \text{as} \quad a = 0.01 \text{s.}
\]

where \( t_1 \) and \( t_2 \) are the start and end times (in seconds) of the flash of light respectively; \( I(t) \) is the instantaneous luminous intensity (in candela) of the flash at time \( t \); and \( a \) is a constant equals to 0.01s.

A LED can attain its full brightness in very short time (in orders of ns). The luminous intensity pattern of a LED driven by a flat pulse current is very effective as it is rectangular with flat peak, which is shown in Fig. 1.

![Fig. 1. Luminous intensity of a LED driven by a flat pulse current.](image-url)
For the LED luminous intensity pattern shown in Fig. 1, the IEQ as given by (1) becomes

$$I_{EQ} = \frac{I_p t_p}{a + t_p}$$  \hspace{1cm} (2)

where $t_p$ is the pulse duration (in seconds); $I_p$ is the peak luminous intensity (in candela).

Rearranging, we get

$$I_p = \frac{I_{EQ}(a + t_p)}{t_p}$$  \hspace{1cm} (3)

A complete LED lighting solution always includes an optical component such as a lens or reflector to achieve of the required optical performance of the product. One important parameter of the optical component is the on-axis intensity, which is in terms of candela per lumen (cd/lm), as it specifies the height of the light distribution curve in absolute scale.

High power LEDs are usually specified in terms of lumen for the luminous flux output. To get the flux requirement $\Phi_v$ for a specific IEQ value, it is assumed that the on-axis intensity of the optical system is $K_i$.

$$\Phi_v = \frac{I_p}{K_i} = \frac{I_{EQ}(a + t_p)}{K_i t_p}$$  \hspace{1cm} (4)

Putting practical values of $t_p = 0.01s$ and $K_i = 0.25$ cd/lm into (4), the baseline IEQ value of 750 cd can be achieved with $\Phi_v$ of 6000 lm.

**III. LED SELECTION**

With the establishment of (4), the LED can be selected according to the luminous flux requirement for a specific design. To achieve certain flux requirement, one can use multiple LEDs or a single package LED. It is preferred to use single package LED in strobe light applications as a lens is required for a desired light distribution. The LED should be selected with high rated pulse current to deliver high output lumen while the LED package should remain small for easy accommodation in the optical lens.
Some LEDs can be over driven to 300% of its maximum rated continuous current without any reliability issue on the condition that the pulse duty cycle is less than 10% [5]. A lower power LED can be selected to achieve same pulse intensity if its overdrive performance is also taken into account. It should be noted that the relationship between light output and forward current is non-linear. Doubling the current will not double the output. Fig. 2 shows the plot of a certain LED’s luminous efficacy when it is driven by a 10% current pulse with different magnitude. It can be seen that the LED efficacy degrades with increasing current. In fact, relative to the point of maximum rated continuous current, it takes three times rated LED power to double the luminous flux output.

![Fig. 2 LED luminous efficacy vs. input current (maximum rated continuous current is 3000 mA).](image)

**III. THERMAL MANAGEMENT**

LED light output tends to degrade with increased temperature. When the LED is turned on by the pulse current, heat is being generated and the junction temperature of the LED is increased. Once the LED is off, the junction temperature begins to drop as heat is dissipating through the thermal system. The semiconductor technology determines the maximum permitted junction temperature. Fig. 3 shows the change of junction temperature when a pulse current is applied to a LED. Unlike in DC operation, the usual description of the thermal performance of a LED system, the thermal resistance $R_{thJA}$ (junction to ambient), is not useful in pulse mode operation as the pulse width is often limited to milliseconds [6].
Fig. 3 LED junction temperature change with a pulse current.

In DC operation, the LED junction temperature $T_j$ can be found by:

$$T_j = T_A + P_D R_{th,JA} = T_A + P_D (R_{th,JS} + R_{th,SA})$$

(5)

where $T_A$ is the ambient temperature; $P_D$ is the LED power; $R_{th,JS}$ is the LED package thermal resistance (junction to solder point) which is usually specified in the LED datasheet; $R_{th,SA}$ is the application-specific thermal resistance (solder point to ambient) which depends on the system’s thermal characteristic. Rearranging (5),

$$R_{th,SA} = \frac{T_j - T_A - P_D}{R_{th,JS}}$$

(6)

Eq. (6) shows the minimum thermal resistance value that the system must achieve in order to provide an adequate thermal management.

While the thermal characteristics for DC operation can be described by the thermal resistance $R_{th,JA}$, pulse operation requires to consider the dynamic thermal impedance $Z_{th}$ of the system. Refer to Fig. 3, for a single pulse of length $t_p$, a transient thermal resistance $Z_{th}(t_p)$ is defined as the ratio between the rise of temperature at the end of the pulse and the dissipated power.

$$Z_{th}(t_p) = \frac{T_{max}(t_p) - T_{min}(t_p)}{P_D(t_p)}$$

(7)

For a train of continuing pulses, which is a mixture of pulsed and continuous operation, the resultant transient thermal resistance $Z_{th,R}(t_p,D)$ depends on the repetition rate and the duty cycle of the pulses.
\[
Z_{th,R}(t_p,D) = (1 - D) Z_{th}(t_p) + D R_{th,JA}
\]

where \( D = \frac{t_p}{T} \);

It should be noted that when \( t_p \to \infty \), \( Z_{th}(t_p) \to R_{th,JA} \).

Fig. 4 shows a set of resultant transient thermal resistance versus pulse length curves for a particular LED with thermal systems constructed with different types of PCBs and heat transfer materials. It can be seen that the transient thermal resistance increases with increasing pulse length until it reaches the \( R_{th,JA} \) value. It is worth knowing that for pulse length below 20ms, the thermal system characteristic does not have much effect on the transient thermal resistance.

To calculate the LED junction temperature in the system:

\[
T_j = T_A + P_D Z_{th,R}(t_p,D)
\]

Based on (9), the maximum LED junction temperature can be found for a particular system. If this temperature is higher than the desired value, the thermal management system needs to be improved. On the other hand if this temperature is lower than the
desired value, there is room for operating the system at a higher current or ambient temperature.

IV. OPTICAL LENS

The light pattern of a LED can be modified with the addition of an optical lens. Unlike reflector designs, almost all the light generated by an LED can be directed to the lens for distribution. Spilled light can be recovered by the use of a lens with efficiency over 90%. Adequate coverage of light pattern requirement can save energy. Fig. 5 shows the photo of light pattern and luminous intensity diagram of a cross pattern LED lens.

**Fig. 5 Light pattern and luminous intensity diagram of a cross pattern LED lens.**
The on-axis intensity of the cross pattern lens is about 0.5 cd/Im. The blue dashed lines indicate the ideal UL1971 [7] distribution pattern. The lens cannot fulfill the ideal pattern at varies angles which can be visualized as dark zones in the photo.

Fig. 6 shows another lens that is designed to match the UL1971 requirement. The lens produce a near square pattern with on-axis intensity 0.2763 cd/Im. Comparing the on-axis intensity of the two lenses, it can be found that the cross light pattern lens uses about half amount of light energy of the square pattern lens to achieve same intensity. In the design of lens, it is important to produce a light pattern that is just good enough for coverage in order to minimize wasted light energy.

Fig. 6 Light pattern and luminous intensity diagram of a square pattern LED lens.
V. EXPERIMENTAL PROTOTYPE

To verify the design equations and compare the performance of LED with xenon, a LED prototype strobe light was built. The LED is a 12V device with maximum rated continuous current of 2400mA which produces 3250lm at junction temperature of 85°C. It was driven by current pulses of 7700mA (peak flux: 7000lm) with 10ms width at a rate of one pulse per second. A 40° lens with on-axis intensity of 3.1 cd/ lm is used for light collimation which should produce 20150 peak cd. From (1), the IEQ value should be 10075cd. Fig. 7 shows the measured waveforms of LED current and forward voltage. The average power consumed by the LED is about 1.5W.

![Fig. 7 Measured waveforms of LED current (red trace) and forward voltage (purple trace).](image)

The LED strobe light is setup at a distance of 20 feet from a wall of a dark room. A camera is placed next to the LED strobe light to capture the light pattern on the wall. Fig. 8 shows the setup of the experiment. The camera was set with shutter speed 1s, aperture F/8 and ISO 200. Fig. 9 shows the light pattern captured by the camera. It can be seen that the light pattern is quite evenly spread over the wall surface.
Fig. 8 Setup of the experiment

Fig. 9 Light pattern of LED strobe light.
For comparison purposes, the light pattern of a xenon strobe light with effective candela setting at 185 cd is also captured as shown in Fig. 10. The light pattern is a cross shape. The pattern was captured with same camera setting as the LED pattern. Although the very center intensity of xenon seems to be higher than the LED, the intensity at other areas especially the corners are lower than the LED. Fig. 11 shows the image histograms of the light pattern photos which indicates the photo of LED light pattern is brighter than the photo of xenon light pattern. The effective intensity of the xenon is 185 cd which is equivalent to an IEQ value of 3380 cd (assuming pulse width of xenon is 1ms). The higher IEQ value of LED (10075 cd) implies a brighter photo.

Fig. 12 shows the voltage waveform across the xenon tube (185 cd) which is parallel connected with an 80uF capacitor rated at 330v. From the energy discharged from the capacitor, the average power consumed by the xenon tube can be found as 2.5W which is higher than the power consumption of LED in the prototype.
Fig. 11 Histograms of light pattern photos.

Fig. 12 Measured voltage waveform of xenon tube.
VI. INDIRECT VIEWING EXPERIMENT

To further verify the actual indirect detection rate, experiments of indirect viewing were performed. Fig. 13 shows the floor plan of the room for the experiment. A strobe lamp was placed at 6 feet height and 20 feet away from a wall. Ten persons who were unaware of the purpose of the experiment were sitting at 10 feet away facing the same wall. A five-minute questionnaire was given to each person. The average horizontal illuminance on table tops was 635 lx. While they were answering the questionnaire in the middle of the session, the strobe light flashed for a period of time. At the end of the questionnaire, people were asked whether they noticed the flashing.

Fig. 13 Floor plan of the indirect viewing experiment.

The first experiment used the 7000lm peak flux LED prototype with a uniform square pattern lens of on-axis intensity 0.27 cd/ lm. Calculated IEQ value is 945 cd for 635 lx ambient which is about same proportion with 750 cd for 500 lx ambient. The LED strobe lamp flashed for 10 seconds.
The second experiment used a 135 cd effective intensity xenon strobe lamp. Assuming the xenon pulse width is 1ms, the calculated IEQ value is 2466cd. The xenon strobe lamp flashed for 10 seconds.

Table 1 summarizes the results of LED and xenon experiments. It can be seen that the detection rates for both LED and xenon lamps were very low. We interviewed the participants and found that they were too focused to be aware of the flashing. We then decided to increase the disturbance to the test subjects by lengthening the flashing period.

<table>
<thead>
<tr>
<th>Lamp type</th>
<th>IEQ / cd</th>
<th>Duration / s</th>
<th>#1</th>
<th>#2</th>
<th>#3</th>
<th>#4</th>
<th>#5</th>
<th>#6</th>
<th>#7</th>
<th>#8</th>
<th>#9</th>
<th>#10</th>
<th>Detection rate / %</th>
</tr>
</thead>
<tbody>
<tr>
<td>LED</td>
<td>945</td>
<td>10</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>30</td>
</tr>
<tr>
<td>Xenon</td>
<td>2466</td>
<td>10</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 1 indirect detection of LED and xenon with 10s flashing duration.

To find out the proper period of flashing, we used the 135 cd xenon strobe lamp with a new set of 10 persons. This time the xenon lamp was kept flashing until we noticed all 10 persons were aware of the flashing. It took more than a minute for all the people to realize that there were flashes.

We then repeated the LED and xenon experiments with flashing period increased to 60s. The results are shown in Table 2.

<table>
<thead>
<tr>
<th>Lamp type</th>
<th>IEQ / cd</th>
<th>Duration / s</th>
<th>#1</th>
<th>#2</th>
<th>#3</th>
<th>#4</th>
<th>#5</th>
<th>#6</th>
<th>#7</th>
<th>#8</th>
<th>#9</th>
<th>#10</th>
<th>Detection rate / %</th>
</tr>
</thead>
<tbody>
<tr>
<td>LED</td>
<td>945</td>
<td>60</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>90</td>
</tr>
<tr>
<td>Xenon</td>
<td>2466</td>
<td>60</td>
<td>No</td>
<td>Yes</td>
<td>-</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>89</td>
</tr>
</tbody>
</table>

Table 2 indirect detection of LED and xenon with 60s flashing duration.

The detection rates for both LED and xenon lamps are up to 90%. The LED prototype strobe lamp with uniform light pattern lens shows similar detection performance as a 135 cd xenon strobe lamp. Also, the LED experiment obtained similar result (90% detection rate with 945 cd @ 635 lx) as the baseline luminous intensity requirement of 750cd @ 500lx.
VII. CONCLUSION

LED can provide a reasonably high luminous intensity with short pulse length for strobe light applications. A formula for estimating the lumen requirement of LED for strobe lights is derived. Short LED pulse current can ease the design of thermal system. Light energy could be reduced with lens of shaped light patterns. Experimental verification has shown that the design of LED based visible notification appliances is feasible.
References


