Degradation analysis of secondary lens system and its effect on performance of LED-based luminaire

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1. Introduction

Light-emitting diode (LED)-based luminaires have emerged as new and revolutionary light sources as they surpass conventional light sources in terms of energy conservation, environmental protection, small volume, and new functionalities [1–3].

As a general lighting source, LED-based luminaires are designed to redirect a light output pattern to produce a specific light distribution [4]. Secondary lens systems, also known as secondary optics, are often used to customize the light output pattern of an LED when its light distribution does not satisfy the desired distribution of a luminaire. The most critical drawback of the secondary lens system is reduction in luminous flux. Typical luminous flux reduction through the secondary optics ranges from 10\% to 15\% [5].

The reflective or refractive type systems are employed in the secondary lens system [4–9]. Various glass or plastic materials are used to fabricate the system. Plastic based lens systems are widely accepted for the industry due to its cost advantage over glass based lens system with similar optical properties. Numerous examples in luminaires can be found in the literature [5,9,10].

The lifetime of an LED system is determined in terms of lumen depreciation and chromaticity change over time. For example, the operating time of L70\% or L50\% is widely used to define the lifetime of an LED system, which is the time to 70\% or 50\% of the initial light output [11]. In the case of color maintenance, a change in chromaticity over the lifetime should be within 0.007 on the CIE 1976 (\textit{u},\textit{v}) diagram according to the ANSI ANSLG C78.377-2011 standard of the solid state lighting [12]. These two important criteria are affected not only by the LED component but also by the secondary lens system.

Reliability of LEDs has been investigated extensively by numerous researchers [13–21]. A recent study of LED-based luminaire revealed that the degradation of a light engine that consisted of LEDs and secondary lens systems was the major contributor to the luminaire degradation [21,22]. Yet, the effect of each component was not studied separately. To the best of authors’ knowledge, only limited analysis on degradation of the secondary lens system can be found in the literature. Consequently, the performance of LED-based luminaires cannot be estimated at the design stage even when the LED reliability data is available. This is the motivation of the current study. The objectives of this paper are, thus, (1) to analyze the degradation of a plastic lens system under an actual operating condition, and (2) to investigate the effect of the degradation on the performance of LED-based luminaires.

2. Lens system and aging test configuration

2.1. Description of lens system

A plastic lens system tested in this study is shown in Fig. 1. The system consists of a 25\textdegree\ collimating lens (top) and a holder (middle); the lens and holder assembly is also shown at the bottom. Both lens and holder are made of polycarbonate; a standard white pigment is used to make the holder opaque. A hexagonal format of the lens system is to maximize packing density and assembly flexibility.

2.2. Aging test configuration

A test configuration to investigate the degradation of the plastic lens system is shown in Fig. 2. High power warm white LEDs were used in the test. The LEDs were operated at a forward current of...
500 mA. The heat sink was designed to maintain the junction temperature at 100 °C. The average ambient temperature was 23 °C and the corresponding temperature of the bottom area of the lens system was 90 °C. A total of ten LED/lens systems were tested before and after operation (9500 h).

A numerical analysis was conducted to assess the temperature distribution of the lens system more accurately. A model created by a commercial package (ANSYS Icepack 14.0) is shown in Fig. 3a. In order to use the actual conditions of the aging test in the model, the heat generation power (1.3 W) was determined experimentally [23]; it was determined by subtracting the total radiant flux from the total electric power. The typical conductivity of polycarbonate was used for the lens system. The conductivity of other materials used in the model is summarized in Table 1 [24–27].

A temperature distribution obtained at the steady-state condition is shown in Fig. 3b, where the ambient temperature is 23 °C. The temperature of lens holder varied from 57.3 °C to 87.6 °C.

The maximum temperature (87.6 °C) occurred at the bottom of the lens holder; this was confirmed by the experimental data. The temperature of lens was relatively low compared to that of the lens holder.

3. Measurement setup and initial characterization

A setup to measure SPD at a constant condition is described. The initial performance of the lens system is characterized by the measurement system.

3.1. Measurement setup

SPD measurements before and after degradation should be conducted at the same LED junction temperatures; otherwise, the SPDs would contain the effect of the LED junction temperature, which would make it difficult to quantify the effect of the lens system degradation only.

Fig. 4 shows the schematic illustration of the measurement setup. The junction temperature of LEDs was controlled by a high power thermoelectric cooler (TEC) (LB320: Silicon Thermal). When a desired junction temperature was reached (e.g., $T_j = 100 \degree C$), the SPDs were measured by an integrating sphere equipped with a
spectrometer (SMS-500: SphereOptics). The LEDs were operated by a sourcemeter (2401: Keithley Instruments), which provided the forward current of 500 mA to each LED. A data acquisition (DAQ) module (USB-6212: National Instruments) measured the forward voltage of LEDs. In order to control the TEC, the sourcemeter and the DAQ simultaneously, the control routines were integrated by a LabVIEW program. The light outputs were analyzed by a spectrometer software (SLM-800: SphereOptics).

The desired junction temperature was achieved through an iteration process based on the well-known forward voltage method [28–31]. The calibration curve was first obtained from a fresh LED. A low injection current of 10 mA was applied for 10 ms to minimize the heat generation when the forward voltage was measured. From the linear forward voltage plot shown in Fig. 5, the slope and the y-intercept were determined to be −1550 × 10⁻³ V/K and 2.6704 V, respectively.

In the iteration process, a surface temperature that corresponded to the desired junction temperature was first estimated using the conduction thermal resistance network model [23,32–34], and the TEC was controlled to produce the estimated surface temperature. The surface temperature was adjusted continuously until the measured junction temperature reached the target junction temperature (100 °C) within ±0.5 °C.

3.2. Initial characterization

The initial performance of the lens system was investigated. The SPDs of a warm white LED with/without the lens system measured at the test condition (the forward current of 500 mA and the junction temperature at 100 °C) are shown in Fig. 6a. The reduction of SPD caused by the lens system is evident.

The ratio between the two SPDs, ηF(λ), (i.e., the SPD with the lens system divided by the SPD of the LED only) are shown in Fig. 6b. The division process amplified the measurement random noise of each SPD; the results shown in Fig. 6b were obtained using
the well-known Savitzky–Golay smoothing filter to suppress the noise. Lower ratios in the blue wavelength (400–500 nm) indicate that the lens system absorbs more light in that range.

The initial light characteristics of the warm white LED are summarized in Table 2. The lens system decreased the luminous flux by approximately 10%. With the lens system, the correlated color temperature (CCT) decreased by 30 K but the color rendering index (CRI) increased by 0.3.

4. Aging test results and analysis

The spectral power distributions of the LED/lens assembly obtained before and after 9500 h of continuous operation are presented. The results are analyzed to identify the most critical parameter on the lens system degradation.

4.1. Aging test results

The SPDs after the aging test are compared with the initial SPDs in Fig. 7a, where the SPD after aging was obtained by averaging 10 experimental data (will be shown in Fig. 8a). In order to investigate the effect of the lens and the holder degradations separately, two extra combinations (the aged lens with the fresh holder for the effect of lens only and the fresh lens with the aged holder for the effect of the holder only) were also tested and compared with the initial SPDs; the results are shown in (b) and (c), respectively.

The lens system degradation reduces the radiant flux over the entire visible spectrum although the reduction ratio varies as a function of wavelength (Fig. 7a). It is worth noting that the aged lens increases the radiant flux of the phosphor converted light (Fig. 7b) while the holder degradation shows a large reduction of radiant flux (Fig. 7c). The results clearly indicate that the holder degradation plays a major role in the SPD reduction.

The effect of the lens system degradation can be further analyzed using the SPDs of the aged lens system normalized by the initial SPDs; the results are shown in (b) and (c), respectively, where the thick lines represent the averaged data.

In order to investigate the degradation effect of the lens and the holder separately, the ratios of the lens degradation, \( \eta_L(\lambda) \), and the holder degradation, \( \eta_H(\lambda) \), are also defined; they are expressed as:

\[
\eta_L(\lambda) = \frac{\Phi_{ALS}(\lambda)}{\Phi_{FLS}(\lambda)} \quad \text{and} \quad \eta_H(\lambda) = \frac{\Phi_{ALH}(\lambda)}{\Phi_{FLS}(\lambda)}
\]

where \( \Phi_{ALS}(\lambda) \) is the SPDs obtained from an aged lens with a fresh holder; and \( \Phi_{ALH}(\lambda) \) is the SPDs obtained from a fresh lens with an aged holder. The results are shown in Fig. 8b and c, respectively, where the thick lines represent the averaged data.

![Fig. 7](image-url)

Fig. 7. SPDs after the aging test are compared with the initial SPDs; (a) aged lens system, (b) aged lens only, and (c) aged holder only.
The most surprising result was the effect of the lens degradation; the aged lens actually increased the radiant flux (Fig. 8b). The increase was the largest over the wavelength range of 550–600 nm, which resulted in lens yellowing ("yellowing" will be explained further in Section 4.2). This trend was consistent with all the lenses tested in the experiment (i.e., virtually no variation). As a result, the luminous flux increased by 3% while CCT and CRI decreased by 5 K and 0.5, respectively (see "Aged Lens with Fresh Holder" in Table 3).

The holder degradation shows a trend similar to the lens systems degradation (i.e., a larger reduction over the short wavelength and a large variation). The holder degradation contributes to the luminous flux reduction by 6.3% and the CCT change by 50 K, which is about 80% of the CCT decrease in the lens system (see "Fresh Lens with Aged Holder" in Table 3). The following analysis was conducted to investigate the effect of the holder in greater details.

### 4.2. Effect of lens holder degradation on the lens system performance

The light travel inside the lens system is illustrated in Fig. 9. Some of emitted light from the LED package transmits through the lens, and then reflected diffusively on the surface of the lens holder. As a result, the surface of the lens holder can affect the light output significantly.

A supplementary experiment was conducted to quantify the contribution of the lens holder to the final SPD. The lens holder was first painted with a matte black paint (the painted surface is indicated by a thick line in Fig. 9), and the SPD was measured with Table 3

**Table 3**

<table>
<thead>
<tr>
<th></th>
<th>Radiant flux (mW)</th>
<th>Luminous flux (lm)</th>
<th>CCT (K)</th>
<th>CRI CIE u’</th>
<th>CIE v’</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh lens system</td>
<td>314</td>
<td>89.6</td>
<td>2969</td>
<td>83.5</td>
<td>0.253</td>
</tr>
<tr>
<td>Aged lens system</td>
<td>310</td>
<td>85.9</td>
<td>2909</td>
<td>82.9</td>
<td>0.255</td>
</tr>
<tr>
<td>Aged lens with</td>
<td>318</td>
<td>92.3</td>
<td>2964</td>
<td>83.0</td>
<td>0.253</td>
</tr>
<tr>
<td>fresh holder</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fresh lens with</td>
<td>300</td>
<td>84.0</td>
<td>2919</td>
<td>83.5</td>
<td>0.255</td>
</tr>
<tr>
<td>aged holder</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

Fig. 8. SPDs ratios of (a) lens system degradation, (b) lens degradation, and (c) holder degradation.

Fig. 9. Illustration of light travel inside the lens system.

Fig. 10. Effect of the lens holder surface.
A lens system that consists of the fresh lens and the black painted holder. The test result is shown in Fig. 10 and the corresponding light parameters are summarized in Table 4. In the absence of the lens holder contribution, the radiant flux was reduced over the entire wavelength, which decreased the luminous flux by over 23%.

A visual comparison between the fresh and aged lenses as well as the holders is shown in Fig. 11. The transparent lens was changed to slightly yellowish color, and the color of the holder was changed from white to yellow.

The color of polycarbonate materials can be changed due to ultraviolet radiation and high temperature [35–40]. In the current test, the main reason of discoloration is high temperature. Polycarbonate materials are thermally sensitive due to the limited strength of covalent bonds of polymer structures. The high temperature influences the overcoming bond dissociation energy, leading to the formation of different molecular bonds in the main chains and thus the discoloration [37,38]. Thermo-oxidation due to dehydration reactions by the high temperature can also cause the discoloration of polycarbonate materials [37].

The degree of yellowing in the polycarbonate lens (Fig. 11b) was not significant. It is important to recall that the transparency of the lens increased after aging (Fig. 8b) and the lens yellowing was resulted from the increased yellow transmission.

As can be seen from Fig. 11d, however, the lens holder yellowing was much more significant, especially around the hole to position the LED (the region marked by a dotted cycle) where the temperature was highest. The lens holder is designed to be opaque and diffusive, and thus the holder yellowing is resulted from the fact that the surface absorbs more blue light. It is speculated that the white pigment degraded thermally during the operation together with the polycarbonate matrix.

5. Discussion: Effect of lens system degradation on cool white LED

The lens system degradation showed the wavelength-dependent behavior. Its effect on a cool white LED was also investigated.

![Fig. 11](image1.png)

![Fig. 12](image2.png)

![Table 4](table1.csv)

![Table 5](table2.csv)
The most representative aged lens and holder (i.e., their performance was closest to the average) were selected for the test. The SPDs obtained from a cool white LED with the fresh and aged lens systems are compared in Fig. 12a. The SPD ratios of the lens system degradation, the lens degradation and the holder degradation are shown in Fig. 12b. The results show a trend similar to that of the warm white LED, but the effect on the light characteristics is significantly different. The degradation of the light characteristics is summarized in Table 5.

The aged lens system decreased the luminous flux by 7% and CCT by 180 K, but CRI remained virtually the same. The amount of the luminous flux reduction was nearly twice as high as that of the warm white LED. The CCT decrease is about 50% of the CCT requirement range of the ANSI ANSLG C78.377-2011 standard (CCT change within ±335 K) [12]. In addition, the chromaticity changed about 29% of the CIE 1976 (u’v’) criteria.

As expected, the effect of the lens system degradation on the cool white LED was significantly different simply because the cool white LED has a higher intensity over the blue wavelength region compared to the warm white LED.

6. Conclusion

The degradation of a polycarbonate secondary lens system was investigated. The lens system was operated under an actual user condition using high power white LEDs. The SPDs of the LED/lens assembly obtained before and after 9500 h of operation were analyzed. The most interesting results were that (1) the aged polycarbonate lens actually increased the radiant flux and (2) the lens holder degradation was the major contributor to the changes of the optical parameters.

Although it did not affect luminous flux considerably, the degradation of the lens system led to a significant impact on color maintenance. The chromaticity changed by about 29% of the color maintenance criterion of the warm white as well as the cool white LEDs. The CCT of a warm and a cool white LEDs changed by 60 K and 180 K, respectively, 80% and 70% over which was caused by the holder degradation only. More thermally resistant pigments and polymers should be used to reduce this change.

The chromaticity change caused by the lens system degradation can be worse at the end of the lifetime of LED-based luminaires, which is typically claimed to be longer than 25,000 h. Reliability data of the lens system should be incorporated into the design of LED-based luminaires; otherwise, the luminaires may not satisfy the reliability requirements even when the LEDs can.

References