LED filament standard lamp for total luminous flux with uniform spatial distribution

J Yan, H Liu, W Zhao and Y Su
National Institute of Metrology, No.18, Bei San Huan Dong Lu, Chaoyang District, Beijing, P.R. China
yanjy@nim.ac.cn

Abstract. To measure the total luminous flux emitted by a light source, the standard lamp which provides an absolute value of the total luminous flux is used with a sphere-photometer. Many institutes have developed their standard lamps based on LED. However, it is difficult to acquire uniform light distribution like the traditional incandescent lamps. To solve this problem, a novel LED filament standard lamp for total luminous flux is developed. First, a luminous intensity distribution model of a single LED filament is established. Based on this model, a method to calculate the luminous intensity distribution of multiple LED filaments is derived. To evaluate the uniformity of a light source, a spatial distribution uniformity index is introduced. Second, the spatial distribution uniformity index of the developed standard lamp is calculated by simulation and the optimal design is obtained. Experiment shows that the LED filament standard lamp for total luminous flux with the optimal design obtained uniform luminous intensity distribution in 4π geometry.

1. Introduction
Total luminous flux is an important unit in the field of optical metrology and is one of the six units selected by Consultative Committee for Photometry and Radiometry (CCPR) in International Key Comparison [1]. The unit of total luminous flux is maintained and transmitted by the standard lamp. The current standard lamps are incandescent lamps, but with the phasing out of incandescent lamps worldwide, incandescent standard lamps are becoming more and more difficult to obtain [2]. At the same time, the market share of light-emitting dioxide (LED) in general illumination applications increases rapidly due to its long lifetime and high luminous efficiency. Since the optical characteristics of the LED light source are quite different from that of the incandescent lamp, measuring the LED light sources with incandescent standard lamps introduces a great uncertainty [3]. Therefore, many national measurement institutes have developed LED standard lamps, including PTB [1], NMIJ [4], NIST [5], VTT [6] etc. The LED dies of these standards are mounted in a heat sink of a thermoccontroller and operated at a constant temperature. Due to this structure, these standard lamps emit light in 2π solid angle, and are only compatible with the sphere photometer system in 2π geometry which means that the lamp needs to be mounted at a port of the integrating sphere wall. However, the traditional incandescent lamp emits light in all directions and is typically mounted in the center of the sphere photometer which is 4π geometry. If a lab decides to choose the LED standards instead of incandescent standards, the measurement system also needs to be upgraded which increases the cost and is not convenient to the industry [7].

To solve this problem, National Institute of Metrology, China (NIM) has developed a LED standard lamp for total luminous flux based on the LED filament. Its structure, shape and interface are
completely consistent with incandescent lamps. Thus, it emits light in 4π geometry. The total luminous flux is about 450 lm, the long-term stability is better than 0.3%, the short-term stability is better than 0.1%, and the decline of the total luminous flux is 2.35% after 6045 hours’ aging which is 1/30 of the incandescent standard lamp [8]. However, the spatial uniformity of luminous intensity of this standard lamp needs to be optimized.

Based on the previous research on LED filament standards, this paper focuses on the spatial distribution uniformity of luminous intensity. Firstly, the luminous intensity distribution of a single LED filament is established, the calculation method of the luminous intensity distribution of a whole light source is given, and the evaluation index of the spatial distribution uniformity is introduced. Then a new type of LED filament standard lamp for total luminous flux is designed and its light distribution is simulated and optimized. Finally, according to the optimization results, sample lamps are made and tested.

2. Theory

2.1. Model of a single LED filament

The LED filament is composed of 24~28 LED dies connected in series and fixed on a transparent substrate, and is covered with phosphor, as shown in figure 1.

The LED dies are uniformly bonded to the front side of the substrate. Obviously, the light emitted from the front side is stronger than the backside, and the luminous intensity distribution of the LED filament in its cross-section (horizontal direction) is not uniform, as shown in figure 2 (a).

The luminous intensity in the horizontal direction is difficult to express by an analytic function. However, the luminous intensity \( I_\alpha \) in the direction of \( \alpha \) in the horizontal range can be obtained by interpolating the measured value \( I_\beta \) and \( I_\gamma \) (\( \beta \leq \alpha \leq \gamma \)) in the adjacent direction.

\[
I_\alpha = f_{\text{interp}} (\alpha | \beta, \gamma)
\] (1)
A single LED die can be regarded as a point source and a series of the LED dies which are equally spaced and coated with the phosphor can be regarded as a Lambertian source, as shown in figure 2 (b). Denote $I_o$ as the luminous intensity normal to the LED filament surface in the vertical plane, and $\theta$ as the angle between $I_o$ and $I_\theta$. The luminous intensity $I_\theta$ can be modeled as:

$$I_\theta = I_o \cos \theta$$

(2)

It can be seen from figure 2 (b) that the measured value of the luminous intensity is in good agreement with the theoretical value shown in equation (2).

Taking the geometric center of the LED filament as the origin O, the cross-section as the XOY plane, the axis of the LED filament as the Z-axis, and the coordinate system O-XYZ is established, as shown in figure 3. In this coordinate system, the luminous intensity of a single LED filament in the direction of $(\alpha, \theta)$ is expressed as:

$$I(\alpha, \theta) = f_{\text{interp}}(\alpha | \beta, \gamma)\cos \theta$$

(3)

The luminous intensity distribution of a single LED filament in $4\pi$ geometry is shown in figure 3.

![Figure 3. The luminous intensity distribution of a single LED filament.](image)

2.2. Model of multiple LED filaments

The total luminous flux of a single LED filament is about 100–150 lm. To increase the total luminous flux level, multiple LED filaments are used with a specific spatial arrangement and electric connection, as illustrated in figure 4.

![Figure 4. Illuminance of multiple LED filaments.](image)

According to the illuminance superposition principle, the illuminance contributed by these filaments on the receiving surface of the detector is expressed as:

$$E = \sum_k \frac{I_k(\alpha_k, \theta_k)}{d_k^2} \cos \phi_k$$

(4)

Where $I_k(\alpha_k, \theta_k)$ is the luminous intensity of the $k$-th filament in the direction of $(\alpha_k, \theta_k)$ with respect to its own coordinate system, $\phi_k$ is the angle between $I_k$ and the normal to the surface of the detector, and $d_k$ is the distance between the center of the filament and the center of the detector.

The maximum size of the illuminant composed of the LED filaments is generally less than 50 mm. In practice, the detector is about 1 m away from the illuminant. Therefore, the illuminant can be regarded as a point source. $d_k \approx d$, $\phi_k \approx 0$. Then, equation (4) can be approximated as:

$$E = \frac{1}{d^2} \sum_k I_k(\alpha_k, \theta_k)$$

(5)

According to the relationship between luminous intensity and illuminance, the intensity of the LED filament illuminator in a given direction is:
\[ I = E \cdot d^2 = \sum_{k} I_k (\alpha_k, \theta_k) \] (6)

2.3. Evaluation of the spatial distribution uniformity of the luminous intensity

Ideally, the standard lamp for total luminous flux has the same intensity in all directions, and its spatial distribution of the luminous intensity forms a spherical surface. In fact, due to the blocking of the lamp base, the nonuniform light distribution of the filament itself, etc., the complete uniform spatial distribution is difficult to acquire. To describe the spatial distribution uniformity of the light source, we introduce the sphericity [9] to indicate how similar a luminous intensity distribution of a LED filament standard is to the ideal spherical luminous distribution. Defining the spatial distribution uniformity index as:

\[ p = \frac{A_{\text{ideal}}}{A_{\text{test}}} = \frac{\pi}{6} \left( \frac{V_{\text{test}}}{A_{\text{test}}} \right)^{\frac{2}{3}} \] (7)

Where, \( A_{\text{test}} \) and \( V_{\text{test}} \) are the surface area and volume of the sphere-like sphere enclosed by the luminous intensity distribution of the test source, respectively. \( A_{\text{ideal}} \) is the surface area of an ideal sphere with the same volume as \( V_{\text{test}} \). At the same volume, the surface area of an ideal sphere is the smallest. Therefore, the more uniform the luminous intensity distribution of the test source is, the more similar to an ideal sphere, and the closer \( p \) is to 1.

3. Simulation and optimization

In our early development of the LED filament standard lamps, LED filaments were arranged nearly in parallel, see figure 5. The spatial luminous intensity distribution of the standard lamp is similar to that of a single filament.

![Figure 5. Prototype of the LED filament standard lamp and its luminous intensity distribution.](image)

Since the luminous intensity of a LED filament along its axis is the weakest, and around its cross-section is the strongest. It is considered that inclining the filament to a certain angle to compensate for the lack of luminous intensity in the axial direction of the lamp. To this end, we designed a novel LED filament standard lamp for total luminous flux, the structure of which is shown in figure 6 (a). Six LED filaments are electrically connected in parallel, and the upper and lower rings are both the electrode and the support structure. The diameter of the ring is determined by the size of glass bulb. If the G150 bulb is used, the ring diameter is \( \Phi 44 \) mm. The length of the LED filament is 60 mm. Once the length of the LED filament and the diameter of the ring are determined, the determination of the structure depends only on the inclination of the LED filament. Figure 6 (b) and (c) show the LED filament structure with the ultimate tilt angles of 70° and 0°, respectively, and the optimum tilt angle is between these two angles.
To obtain the best spatial distribution of the luminous intensity, firstly, the spatial luminous intensity distribution of each LED filament under different tilt angles is simulated by Matlab, as shown in figure 7 (a) ~ (f). Then, the luminous intensity distribution of the whole lamp is calculated by the equation (6), as shown in figure 7 (g), and the spatial uniformity index of the luminous intensity distribution is obtained by equation (7). Finally, plot the $p$ values at different tilt angles, as shown in figure 8.
In figure 8, as the inclination angle increases, the $p$ value first increases and then decreases. When the tilt angle reaches 39°, the $p$ value is maximized and the spatial distribution of luminous intensity is the most uniform.

4. Experiment

To verify that the developed standard lamp has the best uniformity of light distribution, we made a standard lamp of #115 without the glass bulb according to the optimization result, its inclination angle is 39°, as shown in figure 9 (a). For comparison, a #114 lamp with a tilt angle of 50° was produced, see figure 9 (b), and a commercial LED filament lamp with a tilt angle of 0° was tested, see figure 9 (c).

![Figure 9. LED filament lamps with different tilt angles.](image)

The spatial distribution of each lamp is measured using a C-γ goniophotometer. Figure 10 (a) and (b) are the luminous intensity distribution of #115, #114, respectively, and figure 10 (c) shows the distribution of a commercial LED filament lamp with 0° tilt angle. During the measurement, the lamp base is mounted upward. When the detector of the goniophotometer is at 0°, that is, when the detector goes above the lamp base, the light is completely blocked by the lamp base, so the luminous intensity approaches zero.

In figure 10 (a), the luminous intensity in the horizontal direction is equal to the luminous intensity in the vertical direction, and the light distribution is relatively uniform. In figure 10 (b), the luminous intensity in the horizontal direction is smaller than the one in the vertical direction, and in figure 10 (c), the luminous intensity in the horizontal direction is stronger than the one in the vertical direction. The results show that the LED filament tilt angle should not be too small or too large and with the optimal tilt angle of 39°, the optimal luminous intensity distribution uniformity is achieved.

![Figure 10. Experiment results of luminous intensity distribution.](image)
5. Conclusion
In this paper, a luminous intensity distribution model of a single LED filament is established. Based on this model, the calculation method of the luminous intensity distribution of multiple LED filaments is derived. To evaluate the uniformity of a light source, a spatial distribution uniformity index is introduced. A novel LED filaments standard lamp for total luminous flux with uniform distribution is designed. In this design, the uniformity of the developed lamp depends on the tilt angle of the LED filaments. The spatial distribution uniformity index of the developed standard lamp at different inclination angles is calculated by simulation, and the optimal tilt angle is obtained. According to the new design and the optimal tilt angle, the LED filament standard lamp for total luminous flux is made. Compared with the LED filament lamp with non-optimal tilt angle, the developed standard lamp obtains satisfactory luminous intensity distribution.

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