

Article

Design of a Secondary Freeform Lens of UV LED Mosquito-Trapping Lamp for Enhancing Trapping Efficiency

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Abstract: In this study, our proposed ultraviolet light-emitting diode (UV LED) mosquito-trapping lamp is designed to control diseases brought by insects such as mosquitoes. In order to enable the device to efficiently catch mosquitoes in a wider area, a secondary freeform lens (SFL) is designed for UV LED. The lens is mounted on a 3 W UV LED light bar as a mosquito-trapping lamp of the new UV LED light bar module to achieve axially symmetric light intensity distribution. The special SFL is used to enhance the trapping capabilities of the mosquito-trapping lamp. The results show that when the secondary freeform surface lens is applied to the experimental outdoor UV LED mosquito-trapping lamp, the trapping range can be expanded to $100\pi\cdot\text{m}^2$ and the captured mosquitoes increased by about 300%.

Keywords: secondary freeform lens; ultraviolet light-emitting diodes (UV LED); mosquito-trapping lamp; trapping range

1. Introduction

In tropical and subtropical regions of the world, local populations are at risk due to rampant mosquito-borne diseases. For instance, filariasis and the West Nile virus are transmitted by *Culex quinquefasciatus* [1], the Japanese encephalitis virus (JEV) is transmitted by *Culex annulus*, and dengue fever and Zika virus [2,3] are transmitted by *Aedes aegypti* and/or *Aedes albopictus*. The Zika virus has become a recent epidemic in Central and South American countries.

Presently, except for JEV, there are no effective vaccines that can prevent these diseases. Epidemic prevention mainly involves the use of chemical agents for mosquito eradication. However, such a method can cause drug resistance in mosquitoes as well as environmental pollution. Browne et al. found that mosquitoes are highly sensitive to illumination intensity, direction, wavelength, color, and contrast ratio [4,5]. Section analysis of the mosquito eye conducted by Kay et al. revealed its sensitivity to ultraviolet (UV) rays [6]. Shimoda et al. used light-emitting diode (LED) light sources with low energy consumption and specific wavelengths for pest control [7]. Field and laboratory investigations

into mosquito response to artificial light have shown that blue and green light are often more attractive than light in the yellow-orange and red regions of the visible spectrum [8]. Thus, the effectiveness of luminous traps for vectoring mosquitoes has been supported by empirical evidence, and such traps are now mass produced and used widely.

Mosquitoes are mainly induced by three factors: sight, smell, and temperature. Mosquito-repellent products mainly use the visual and phototactic senses of mosquitoes to attract them with UV light. However, the effects are uneven. This study aims to develop new mosquito-trapping tools. It is hoped that the proposed secondary freeform lens (SFL) can be used to control UV LED light toward effective techniques to increase mosquito attraction.

2. Principles and Methods

2.1. UV LED Mosquito-Trapping Lamp(UVLMTL) with SFL

In this study, UV LEDs with a viewing angle of 115° are employed as light engines to supply 395 nm ultraviolet light. The design of a freeform secondary lens is always related to the LED light source. The light-emission patterns of most LEDs can be considered to be correlated to the cosine function, so the normalized luminous intensity distribution curve (LIDC) of the light source can be calculated as follows:

$$I_{LED}(\theta) = I_a \cos^x(\theta) \quad (1)$$

where $I_{LED}(\theta)$ is the luminous intensity for each angle θ , I_a is the axial luminous intensity, and the exponential factor is:

$$x = -\ln(2)/\ln(\cos\varnothing_{0.5}) \quad (2)$$

By the law of energy conservation, the mapping relationships between the light-emission angles of the LED and lens on a vertical surface, $I_{LED}(\psi)$ and $I_{LED+Lens}(\psi)$, and between the light-emission angle of the LED and lens on a horizontal plane, $I_{LED}(\theta)$ and $I_{LED+Len}(\theta)$, are determined. The total energy of the LED light passing through the UVLMTL lens is constant.

The outgoing surface of the SFL is responsible for refracting its incident light to achieve the designed targets. The light refracted by the outgoing surface is governed by Snell's law. The vector equation of Snell's law can be written as follows [9]:

$$O \cdot n_0 - I \cdot n_I = [n_0^2 + n_I^2 - 2n_0n_I(O \cdot I)]^{1/2} \cdot N. \quad (3)$$

where O denotes the refraction unit vector; I denotes the incident unit vector; n_I denotes the refractive index of incident within the lens; n_0 denotes the refractive index of reflection within the lens; and N denotes the normal vector corresponding to the incident and refraction vectors.

In order to increase the optical efficiency of the proposed SFL and its related Outdoor UV LED mosquito-trapping lamp, its reflecting surface is designed to totally and internally reflect the LED emitting light to the outgoing surface. To facilitate prototyping and optical testing, the polymethylmethacrylate (PMMA) is used as the material of the SFL prototyping sample in the experiments.

2.2. Design Method

Set the target light pattern, as shown in Figure 1, and use a PMMA with a refractive index of 1.51 ($n_\lambda = 395 \text{ nm}$) and a TIR (total internal reflection) critical angle of 41.47° [10] as the SFL design material.

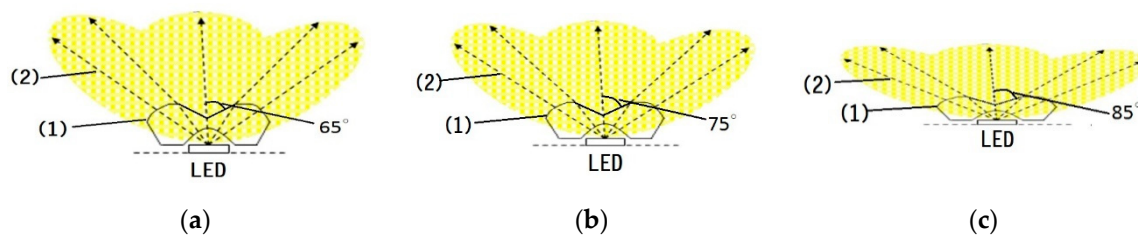


Figure 1. Schematic diagram of the target of secondary freeform lens (SFL) in light-emitting direction with lighting target angles of (a) 130°; (b) 150° and (c) 170°. (1) Refracting surface; (2) projection light passing through the SFL directly.

The intensity distribution and lighting of the outdoor UV LED mosquito-trapping lamp is set as the main target of the SFL design advantage function. In the SFL design process, the total internal reflection surface and output surface can be freely modified, so that the trapping range of the mosquito-trapping lamp can be expanded to increase the attractivity of mosquitoes and better control effects on dengue fever.

The design flow of a secondary free-form surface lens (SFL) is shown in Figure 2.

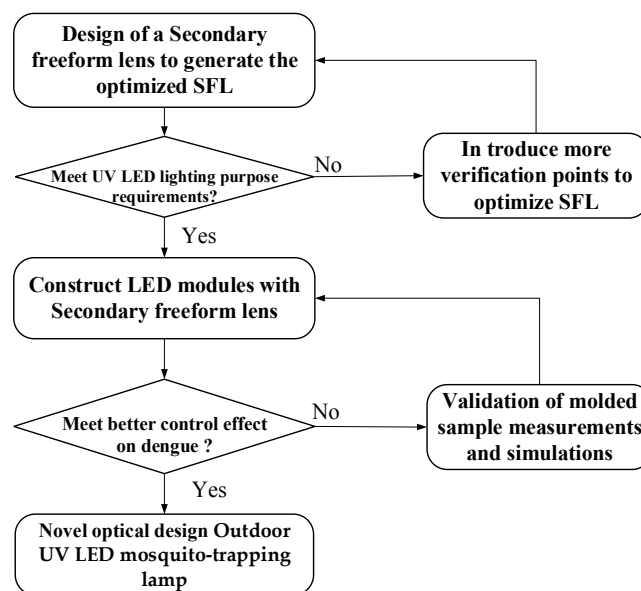


Figure 2. Design process of a secondary freeform lens (SFL).

3. Experiments and Experimental Results

3.1. Design of a Secondary Freeform Lens

3.1.1. Optical Modeling

For finding the best SFL solution, we use OPTISWORKS software to design and optimize the SFL, as shown in Figure 3.

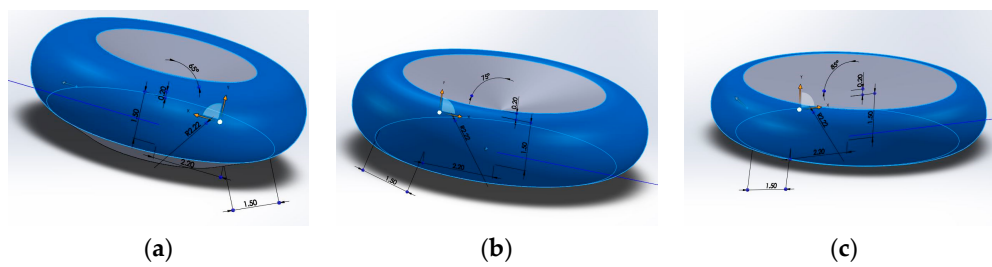


Figure 3. SFL with (a) 130°; (b) 150° and (c) 170° peak intensity angles.

The resulted SFL design file and the 3W UV LED light bar source are composed as the mosquito-trap SFL_UV LED module in TracePro optical software to analyze its light intensity distribution curves (LIDCs) in space, as shown in Figure 4. During the optical simulation, UV LED light bar and mosquito trap UV LED light bar module, each randomly emits one million rays for ray tracing, and the detection region is set at infinity for generating far field LIDCs. The 3W UV LED light bar light source and its intensity distribution is shown in Figure 4a,b, respectively. The simulated illuminance distribution and intensity distributions by SFL_UV LED modules are shown in Figure 4c–h.

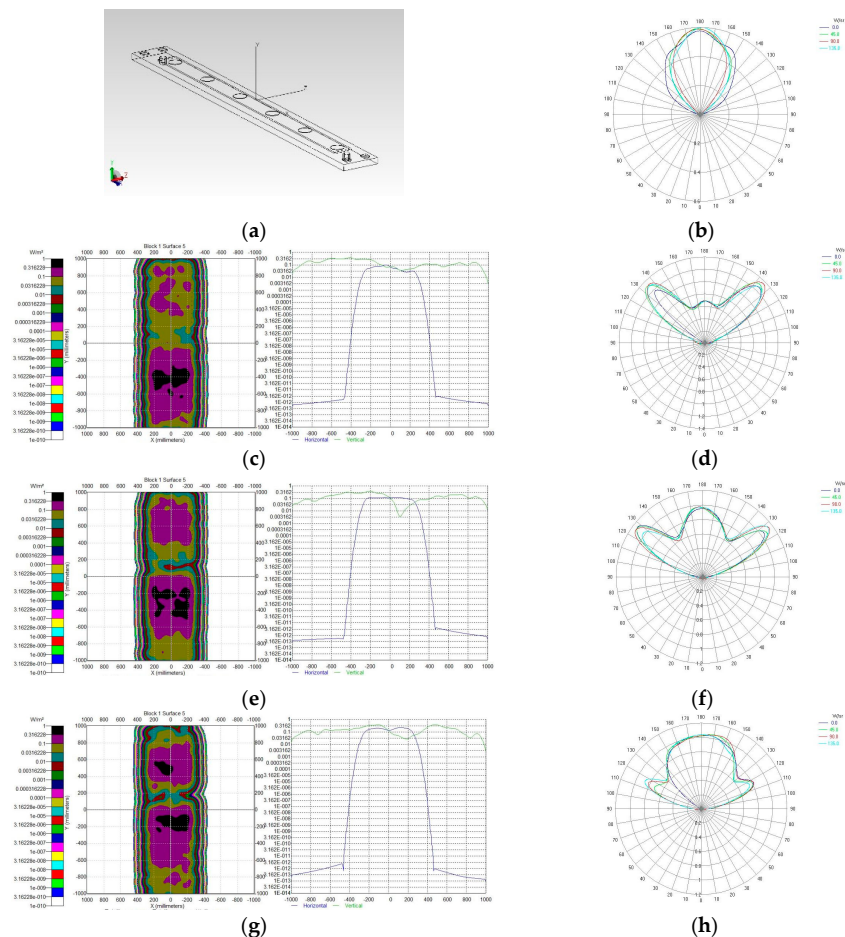


Figure 4. UV LED light bar, and simulated illuminance distribution and intensity distributions of SFL_UV LED modules. (a) UV LED light bar; (b) Simulated LIDC of UV LED light bar; (c) Simulated illumination of 130° SFL_UV LED modules; (d) Simulated LIDC of 130° SFL_UV LED modules; (e) Simulated illumination of 150° SFL_UV LED modules; (f) Simulated LIDC of 150° SFL_UV LED modules; (g) Simulated illumination of 170° SFL_UV LED modules; (h) Simulated LIDC of 170° SFL_UV LED modules.

3.1.2. SFL_PMMA Prototyping

We used OptisWorks software to optimize the SFL and manufacture the SFL_PMMA model using a five-axis CNC milling machine, as shown in Figure 5.

The milling machine uses the workpiece as the XY plane motion and the z-axis as the tool spindle rotation. Milling from the top down, the machine processing can fix the workpiece, and the rotating tool will generally do 3D or 2D workpieces, accurately working the workpiece milling plane, milling surfaces and other different shapes [11].

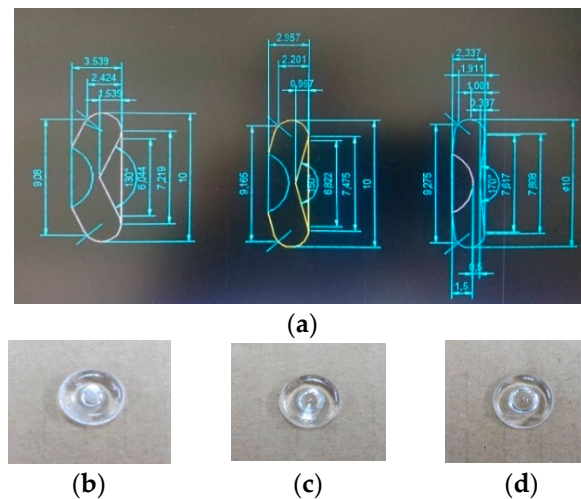


Figure 5. (a) SFL mechanical drawing; (b) 130° SFL prototype; (c) 150° SFL prototype; (d) 170° SFL prototype.

3.2. Luminous Intensity Distribution Measurements

The PMMA model of the SFL and arrayed 3 W UV LED light bar are combined into a new mosquito trap UV_LED light bar module, as shown in Figure 6.

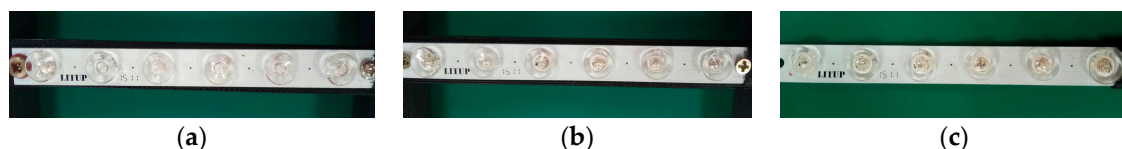


Figure 6. New mosquito trap UV_LED light bar module: (a) lighting of 130° angle, (b) lighting of 150° angle, (c) lighting of 170° angle.

The luminous intensity distribution measurements of the LED light samples were conducted with the ProMetric Near-Field Measurement System (PM-NFMS) gonio-photometer developed by Radiant Vision Systems Co., as shown in Figure 7.

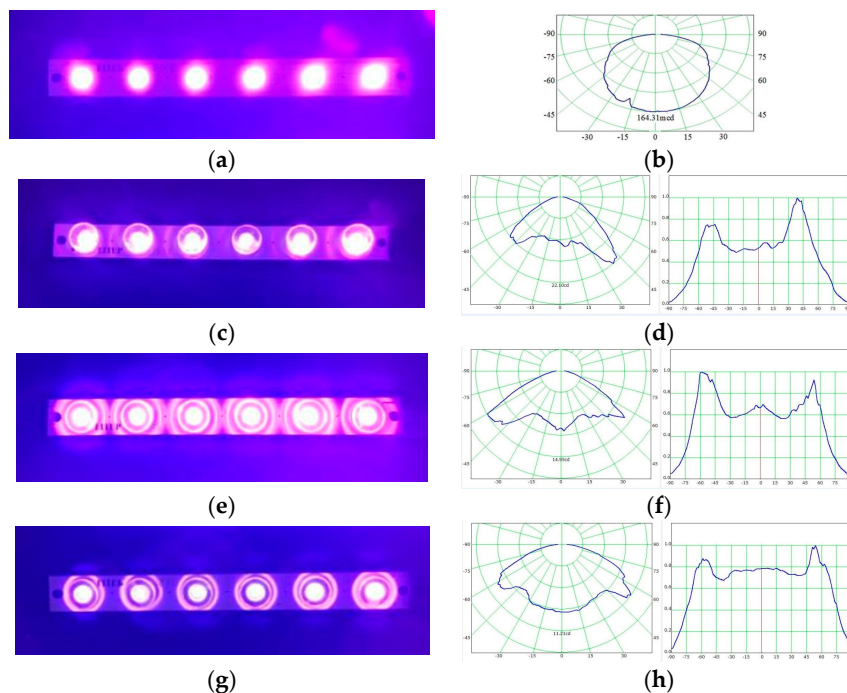


Figure 7. UV LED light bar, SFL_UV LED modules samples and their measured LIDC in space. (a) Turned-on UV LED light bar sample; (b) 2D measured LIDC UV LED light bar sample; (c) Turned-on 130° SFL_UV LED module sample; (d) 2D measured LIDC of 130° SFL_UV LED; (e) Turned-on 150° SFL_UV LED module sample; (f) 2D measured LIDC of 150° SFL_UV LED module sample; (g) Turned-on 170° SFL_UV LED module sample; (h) 2D measured LIDC of 170° SFL_UV LED module sample.

Near-field measurement system (NFMS) was used to measure the luminous intensity distribution of the UV LED light bar and SFL_UV LED light bar. It was found that the luminous intensity distribution of the SFL module with a central angle of 150° was closest to the ideal luminous intensity distribution, as shown in Figure 8.

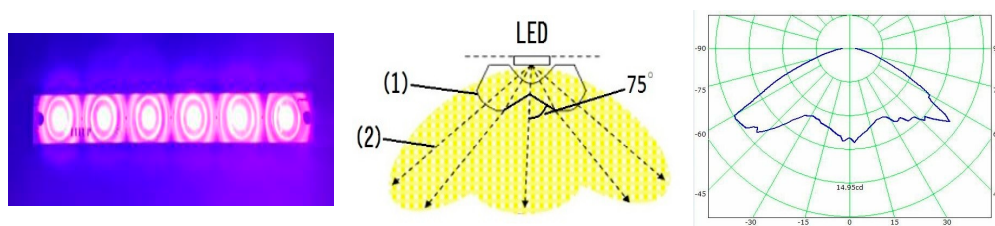


Figure 8. Comparison of luminous intensity distribution and ideal luminous intensity distribution of the SFL module with peak intensity angle 150°. (1) Refracting surface; (2) projection light passing through the SFL directly.

3.3. Real Machine Verification and Data Analysis

Through several experiments, the luminous intensity distribution of the 150° SFL module was demonstrated to have better performance relative to other SFL modules. Therefore, a UV LED mosquito-repellent system using a piece of the 3W 150° SFL 395 nm LED module and a mosquito-catching device with 6 pieces of 400 nm general purple blue 0.5 W LEDs with 15° emitting angle were used for verification in real machines. Test comparisons were conducted on the campus. The measured results are shown in Figure 9, and the data analysis results are shown in Figure 10.

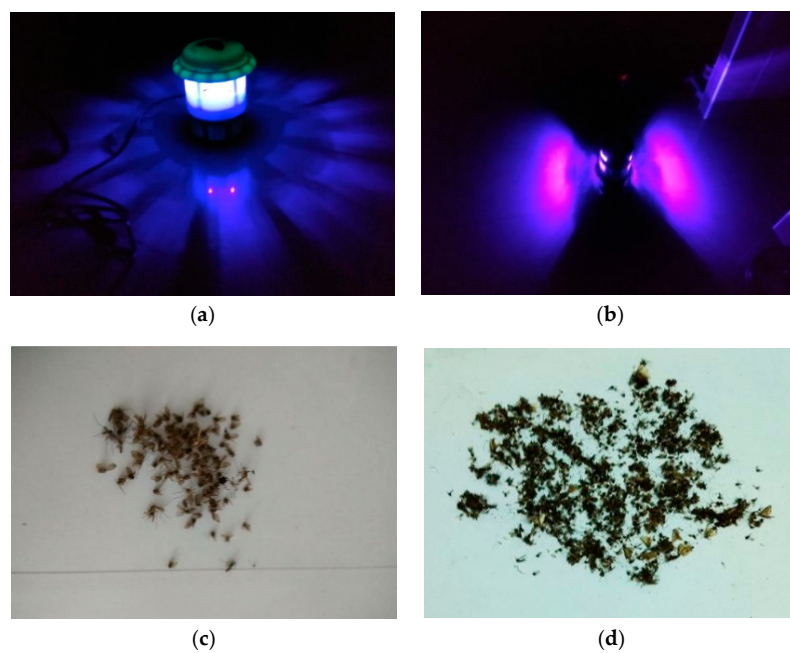


Figure 9. Experimental results of (a) purple blue LED mosquito trapper and (b) UV LED mosquito trapper with 150° SFL module. Total number of trapped mosquitoes (May 20–26, 2018, outdoors); (c) 278 for purple blue LED trapper and (d) 943 for UV LED trapper.



Figure 10. Comparison of (a) indoor and (b) outdoor test results of purple blue LED mosquito trapper and UV LED mosquito trapper with 150° SFL module.

4. Conclusions and Discussion

The experimental results of this study show that the UV LED mosquito-trapping lamp with SFL modules centered at an angle of 150° enhanced the ability to attract mosquitoes. The outdoor trapping range could be extended to $100\pi\text{ m}^2$ and the captured mosquitoes increased by approximately 300% compared to the conventional purple blue LED mosquito trappers. For indoor use, the number of mosquitoes captured can still be better than that with the general purple blue LED mosquito trap, which was increased by about 200%.

In the experiments, a near-field measurement system (PM-NFMS) was used to measure the luminous intensity distribution of the UV LED and SFL_UV LED light bars to compare the influence on trapping efficiency with respect to light intensity distribution. It was found that the luminous intensity distribution of the SFL module with a peak intensity angle of 150° was the closest to the ideal luminous intensity distribution for trapping mosquitos for the experimental samples, and it had the best mosquito repellent effect, as shown in Table 1.

Table 1. Numbers of trapped mosquitos with different kinds of LED modules in the experiments.

General Purple Blue LED	Working Range $100\pi\text{ m}^2$			
	UV LED Light Bar	SFL_UV LED Module (150°)	SFL_UV LED Module (130°)	SFL_UV LED Module (170°)
278	519	943	613	405

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Conflicts of Interest: The authors declare no conflict of interest.

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