

Article

Secondary Freeform Lens Device Design with Stearic Acid for A Low-Glare Mosquito-Trapping System with Ultraviolet Light-Emitting Diodes

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Abstract: Dengue fever is a public health issue of global concern. Taiwan is located in the subtropical region featuring humid and warm weather, which is conducive to the breeding of mosquitoes and flies. Together with global warming and the increasing frequency of international exchanges, in addition to the outbreak of pandemics and dengue fever, the number of people infected has increased rapidly. This study is dedicated to the development of a new mosquito-trapping system. Research has shown that specific wavelengths, colors, and temperatures are highly attractive to both *Aedes aegypti* and *Aedes albopictus*. In this study, we create equipment which effectively improves the trapping capabilities of mosquitoes in a wider field. The design of the special Secondary Freeform Lens Device (SFLD) is used to expand the range for trapping mosquitoes and create illumination uniformity; it also directs light downward for the protection of users' eyes. In addition, we use the correct amount of stearic acid as a mosquito attractant to allow a better control effect against mosquitoes during the day. In summary, when the UV LED mosquito trapping system is combined with a quadratic free-form lens, the experimental results show that the system can extend the capture range to $100 \pi \text{ m}^2$ in which the number of captured mosquitoes is increased by about 350%.

Keywords: mosquitoes; *Aedes aegypti*; *Aedes albopictus*; secondary freeform lens device (SFLD); stearic

1. Introduction

Dengue fever is a public health issue of global concern. Zika virus, dengue fever, [1,2] chikungunya, and yellow fever are all transmitted to humans by the *Aedes aegypti* mosquito. More than half of the world's population live in areas where this mosquito species is present. To date, there are still no dengue vaccines or therapeutic drugs. The worldwide incidence of dengue has risen 30-fold over the past 30 years. Vector-mosquito control is the main prevention and treatment method against this disease.

Taiwan is in the subtropical region and enters the season of facilitated dengue infection every summer, especially in southern Taiwan. According to the statistics of the Disease Control Agency, it enters an epidemic period from July to November every year. Dengue fever is an arthropod-borne virus.

The main vectors are *Aedes aegypti* and *Aedes albopictus*. *Aedes aegypti* are mainly distributed in tropical and subtropical countries south of the Tropic of Cancer, including Southeast Asian countries, parts of the Pacific Ocean, Central and South America, Northern Australia, Africa, and the Eastern Mediterranean, etc. (Guzman et al., 2010; [3] Li et al. 2007 [4]).

There are still no effective vaccines or drugs for treating dengue, but there has been continuous research, development, and improvement. General mosquito repellent products use mosquito vision and phototaxis to attract the insects. Possible physical trapping factors for mosquitoes include light, color, and carbon dioxide concentration (see Brown et al. [5,6]). Mosquitoes have been found to be highly sensitive to wavelength, direction, light intensity, color, and contrast. A cross-sectional analysis of mosquito eyes by Kay [7] et al. revealed their sensitivity to ultraviolet (UV) light. A study by Shimoda et al. [8] explored pest control using low-energy and specific-wavelength light emitting diode (LED) sources.

The effectiveness of the luminescent traps used to guide mosquitoes has been supported by the above studies and experimental evidence. Moreover, such illuminating trap systems for guiding mosquitoes are now mass-produced and widely used. The Secondary Freeform Lens Device can be used to control the angle and range of illumination of UV LED strips to effectively enhance mosquito attraction. For example, to efficiently trap mosquitos, a secondary lens, which relies on total internal reflection (TIR) [9] and the bird-wing asymmetrical reflector [10], was proposed by Tseng et al. to accomplish a UV LED with wide-angled batwing light distribution. In this paper, a system is proposed with a novel TIR lens array with stearic acid can achieve 300% times the effectiveness of commercial products in terms of its mosquito-trapping efficiency.

2. Principles and Methods

2.1. Principles of the UV LED Mosquito-Trapping Device

The outgoing surface of the freeform lens is responsible for refracting its incident light to achieve the design targets. The light refracted by the outgoing surface is governed by Snell's law.

The vector equation of Snell's law is expressed as follows: [11]

$$O \cdot n_0 - I \cdot n_1 = [n_0^2 + n_1^2 - 2n_0n_1(O \cdot I)]^{1/2} \cdot N. \quad (1)$$

where O is the refraction unit vector; n_1 is the refractive index of incidence within the lens; n_0 is the refractive index of reflection within the lens; I denotes the incident unit vector; and N is the normal vector corresponding to the incident and refraction vectors.

To improve the optical efficiency of the mosquito trapping system, the UV LED lamp is combined with a quadratic free-form lens, and its reflecting surface is designed to totally and internally reflect the LED emitting light to the outgoing surface. To facilitate prototyping and optical testing, polymethylmethacrylate (PMMA) is used as the material of the Secondary Freeform Lens Device (SFLD) prototyping sample in the experiments.

2.2. Use of Stearic Acid as a Mosquito Attractant

Previous studies have demonstrated that the attraction of dengue fever mosquitos to humans is increased by the presence of acid. Moreover, humans have uniquely high levels of skin-borne lactic acid when compared with other mammals, which is similar to stearic acid in terms of smell. In previous studies, lactic acid and stearic acid have been shown to be attractants of the yellow fever mosquito *Aedes aegypti* L. (Acree et al. 1968 [12]; Smith et al. 1970 [13]; Eiras and Jepson 1991 [14]; Geier et al.

1996 [15]; Bernier et al. 2002 [16]). Knols et al. (1997) [17] demonstrated that a blend of 12 carboxylic acids affected the behavior of the malaria vector *Anopheles gambiae* Giles sensu stricto.

In summary, lactic acid and stearic acid may play a critical role in the host-seeking behavior of anthropophilic mosquitoes, which seem to have adapted to utilize this human compound (Dekker et al. 2002) [18].

2.3. Design Method

The design flow of the SFLD is shown in Figure 1.

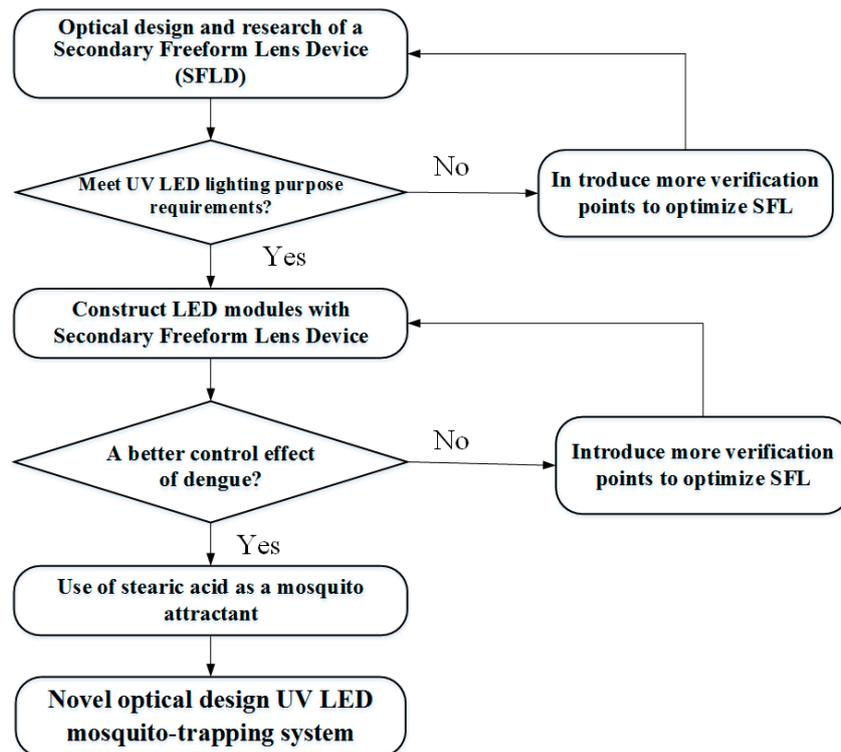


Figure 1. The design process of the Secondary Freeform Lens Device (SFLD).

The luminous intensity distribution curve (LIDC) and uniform illumination of the UV LED mosquito trap system was set as the main target of the SFLD design advantage function. In the SFLD design process, the total internal reflection surface and the output surface can be freely modified; the the trapping range of the UV LED mosquito trapping system can expand the range of trapping mosquitoes and, furthermore, better control the effects of dengue fever.

Additionally, *Aedes aegypti* plays a considerable role in the transmission of dengue fever. The lifespan of *Aedes aegypti* is about 30 days; in contrast, the lifespan of *Aedes albopictus* is about 14 days (Chen, 2006) [19]. After the vector mosquito bites the viremia patient, the virus takes about 10 days to travel from the gastrointestinal tract of the mosquito to the salivary gland. After about 8–12 days, the vector mosquito will have the ability to spread the virus for life. Therefore, the right amount of stearic acid as a mosquito attractant has a better control effect on active mosquitoes during the day (*Aedes aegypti* L.).

Next, we set the target light mode for the secondary freeform lens device (SFLD) and used a PMMA (PolyMethyl MethAcrylate) with a refractive index of 1.49 and a TIR critical angle of 42.15 degrees (10) as the material, as shown in Figure 2.

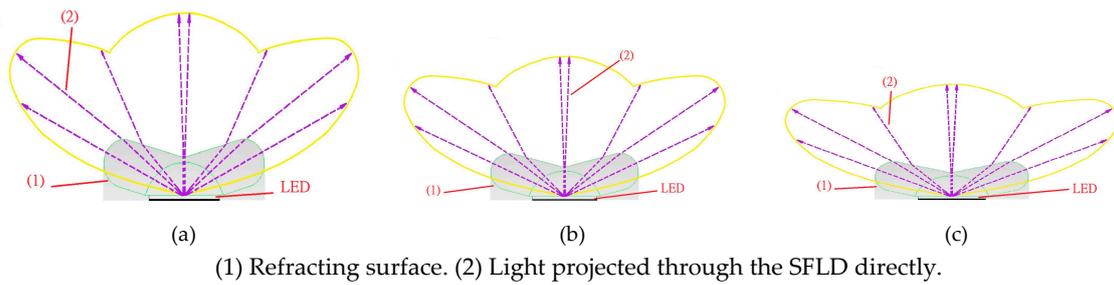


Figure 2. Target light pattern for the SFLD. (a) Lens of angle 130; (b) Lens of angle 150°; (c) Lens of angle 170°.

3. Experiments and Results

3.1. Optical Model of a Secondary Freeform Lens Device

We designed and optimized the SFLD with Solidworks software, as shown in Figure 3.

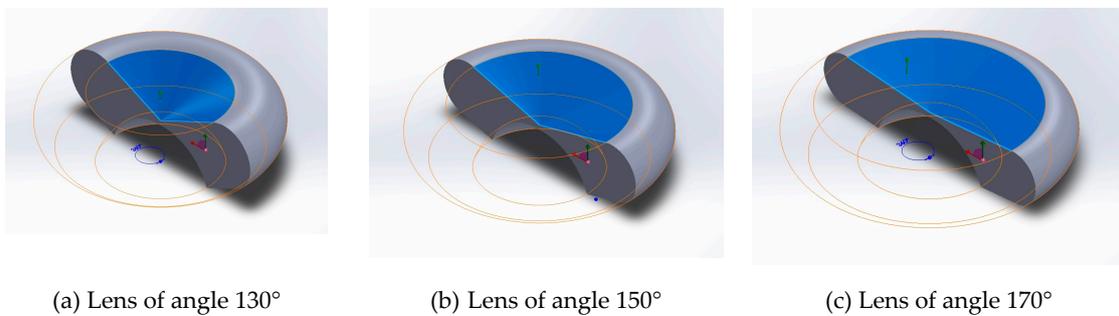


Figure 3. Design and optimization of the SFLD by Solidworks software.

We simulated and analyzed the luminous intensity distribution curve (LIDC) in the space of the traditional LED mosquito lamp and the SFLD’s designed UV LED strip module using the TracePro optical software, as shown in Figure 4.

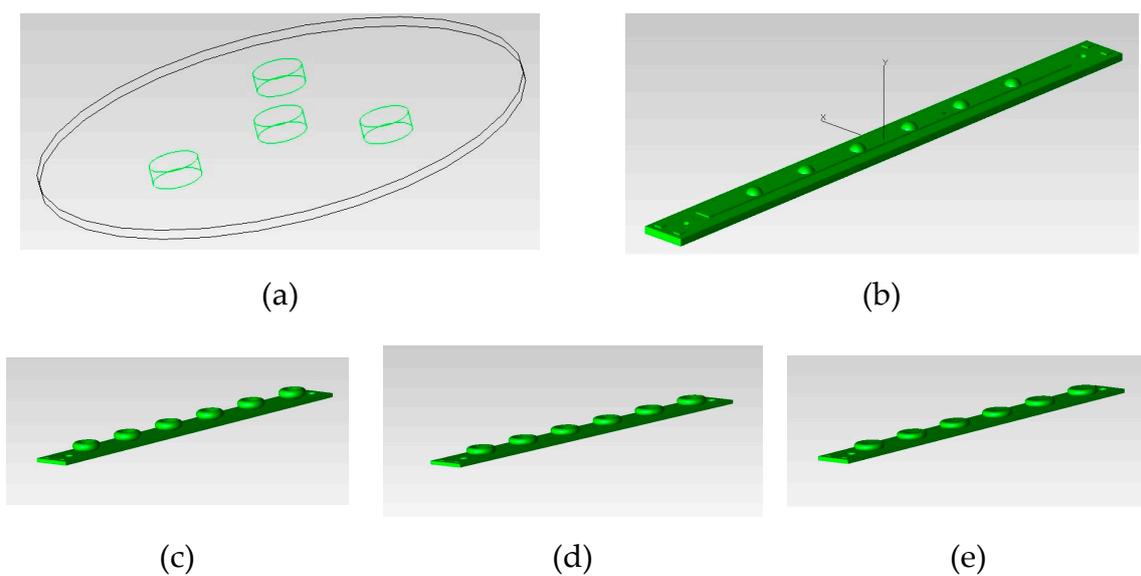


Figure 4. Cont.

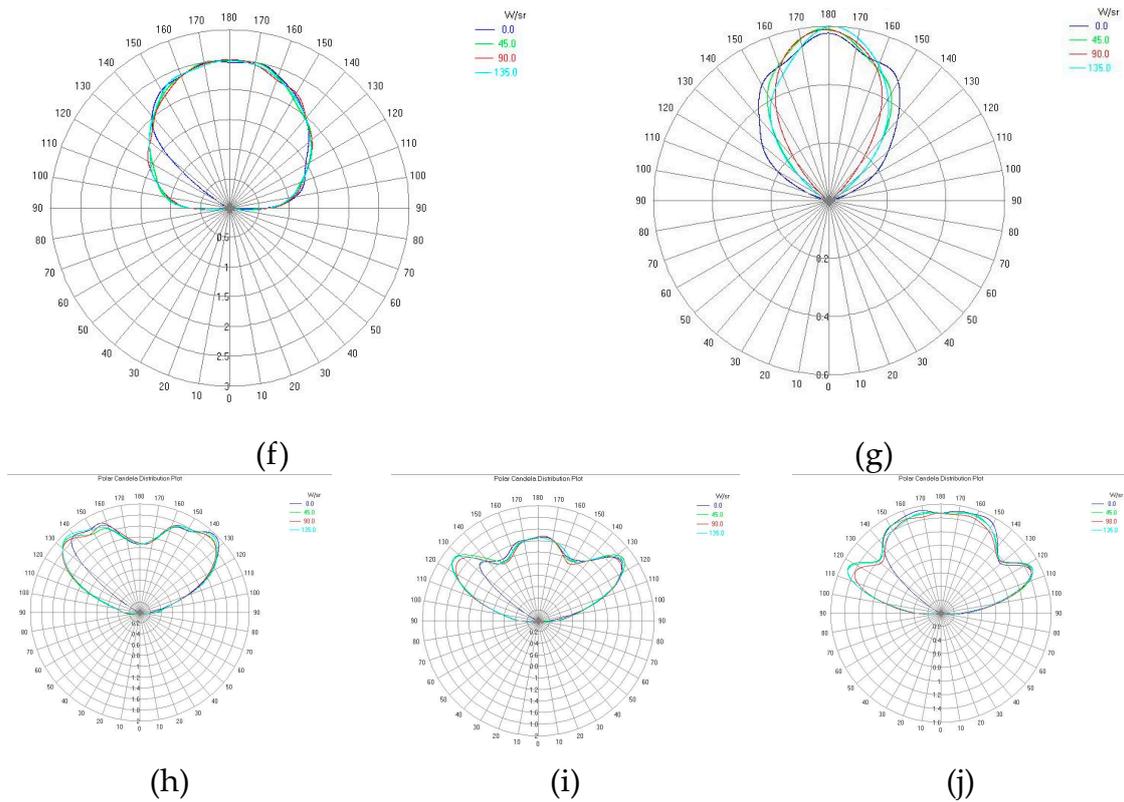


Figure 4. Simulated and analyzed luminous intensity distribution curves (LIDCs) in the space of the traditional LED mosquito lamp and the SFLD’s designed UV LED strip module. (a) The traditional LED mosquito lamp; (b) the traditional designed UV LED strip module of the semicircular lens; (c) the SFLD’s designed UV LED strip module with an angle of 130°; (d) the SFLD’s designed UV LED strip module with an angle of 150°; (e) the SFLD’s designed UV LED strip module with an angle of 170°; (f) the traditional LED mosquito lamp of LIDCs; (g) the UV LED strip designed semicircular lens module of LIDCs; (h) SFLD_UV LED module of LIDCs (130°); (i) SFLD_UV LED module of LIDCs (150°); (j) SFLD_UV LED module of LIDCs (170°).

The light-intensity distribution angle and the divergent angle centering the angle of the new trapper were targeted at 130°, 150°, and 170°, respectively, in the SFLD’s designed UV LED strip module using the TracePro optical software optimization process. We found the SFLD_UV LED module can restrict upward UV ray generation to decrease the glare for the human eye and cover the trapping area as far as possible.

3.2. Process PMMA to Create a SFLD Model

We used a five-axis CNC (Computer Numerical Control) milling machine to process PMMA to create an SFLD model, as shown in Figure 5 [20].

3.3. Luminous Intensity Distribution Measurements

We used the ProMetric near field measurement system (PM-NFMS) developed by Radiant Vision Systems Co, and we measured the LIDC measurements of the LED lights as shown in Figure 6.

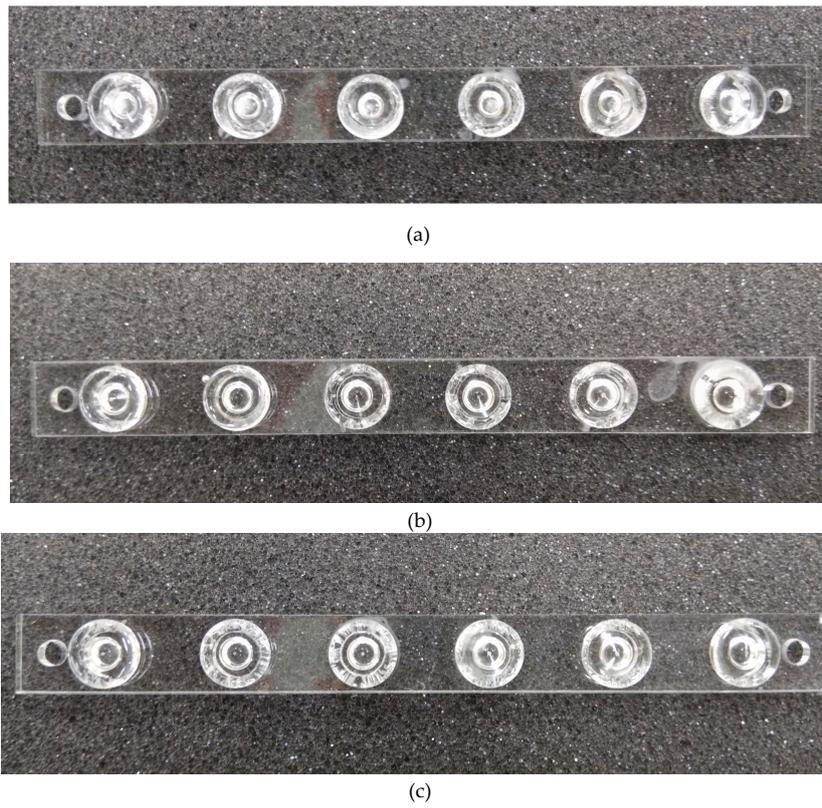


Figure 5. Polymethylmethacrylate (PMMA) model of SFLD. (a) Lens of angle 130° ; (b) Lens of angle 150° ; (c) Lens of angle 170° .

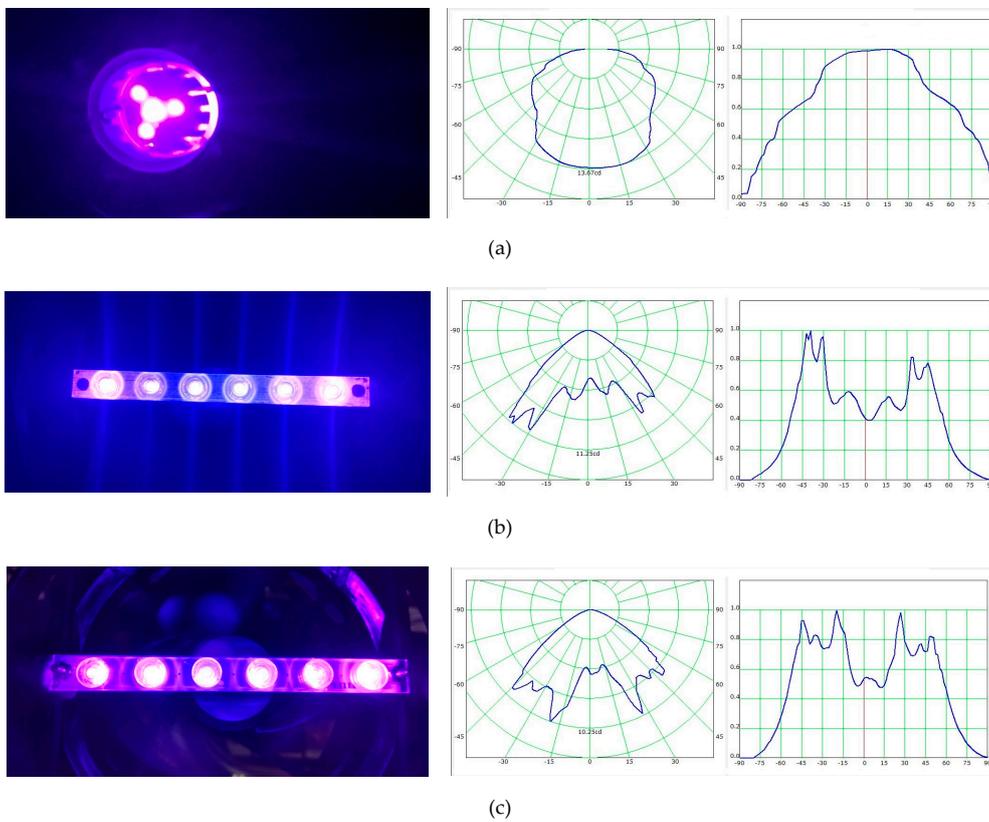


Figure 6. Cont.

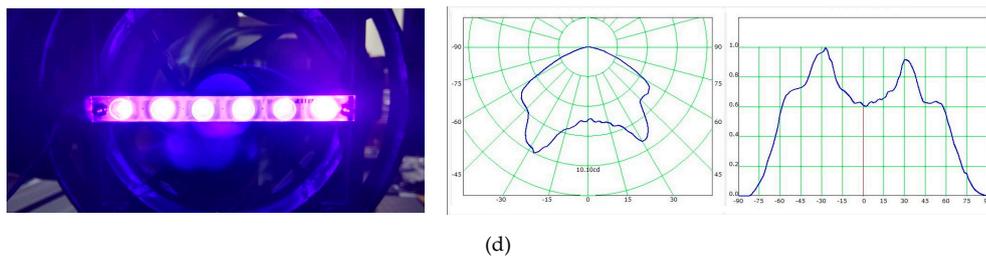


Figure 6. The 2D LIDC of the narrow UV LED strips and novel mosquito coil UV_LED strip modules (unit: mcd/Klm). (a) The 2D LIDC of the module of the traditional LED mosquito lamp; (b) The 2D LIDC of the module of the novel mosquito trap UV_LED light bar module (130°); (c) The 2D LIDC of the module of the novel mosquito trap UV_LED light bar module (150°); (d) The 2D LIDC of the module of the novel mosquito trap UV_LED light bar module (170°).

3.4. Real Machine Verification and Data Analysis

On the basis of the above three different central angles of the SFLD, three sets of the SFLD modules were prototyped and installed with inward air flow for the experiments, as shown in Figure 7. The 3W commercial mosquito trapper was also used in the experiments for comparison, as shown in Figure 8. After the experiments, the amounts of captured mosquitos were compared and are shown in Figure 9. On the basis of the results, it can be calculated that the trapped mosquito numbers are elevated by 350% by the proposed system at most in compared with the conventional method. It was found that the LIDC of the SFLD module with a central angle of 150° had the best result of all experimental systems.



Figure 7. Proposed mosquito trapper with Secondary Freeform Lens Device and its mosquito trapping results.



Figure 8. Traditional mosquito trapper and its mosquito trapping results.

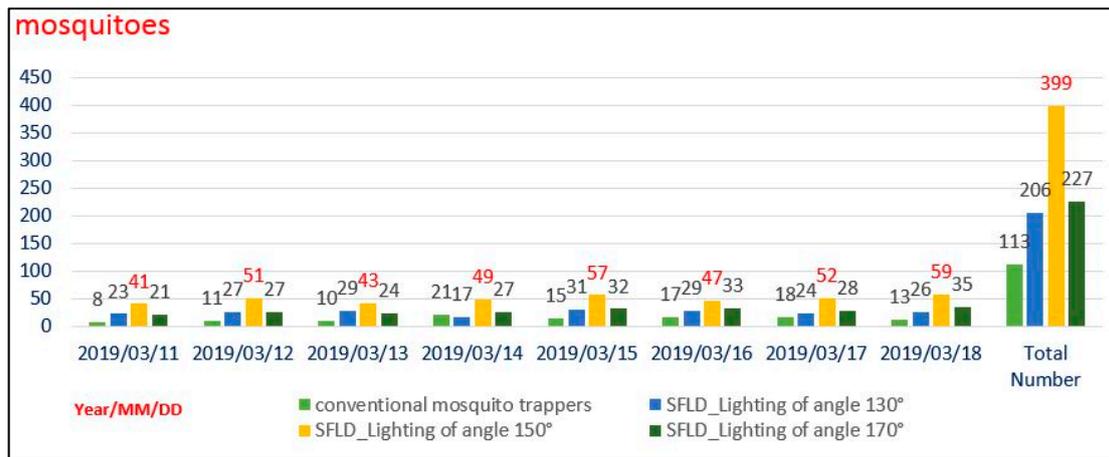


Figure 9. Comparison of the proposed mosquito trapper with Secondary Freeform Lens Device and the traditional one in terms of mosquito trapping number.

To verify the effect of use of stearic acid as a mosquito attractant on the proposed system, stearic acid was smeared on the reflective surface portion of the UV LED mosquito-trapping system, as shown in Figure 10.

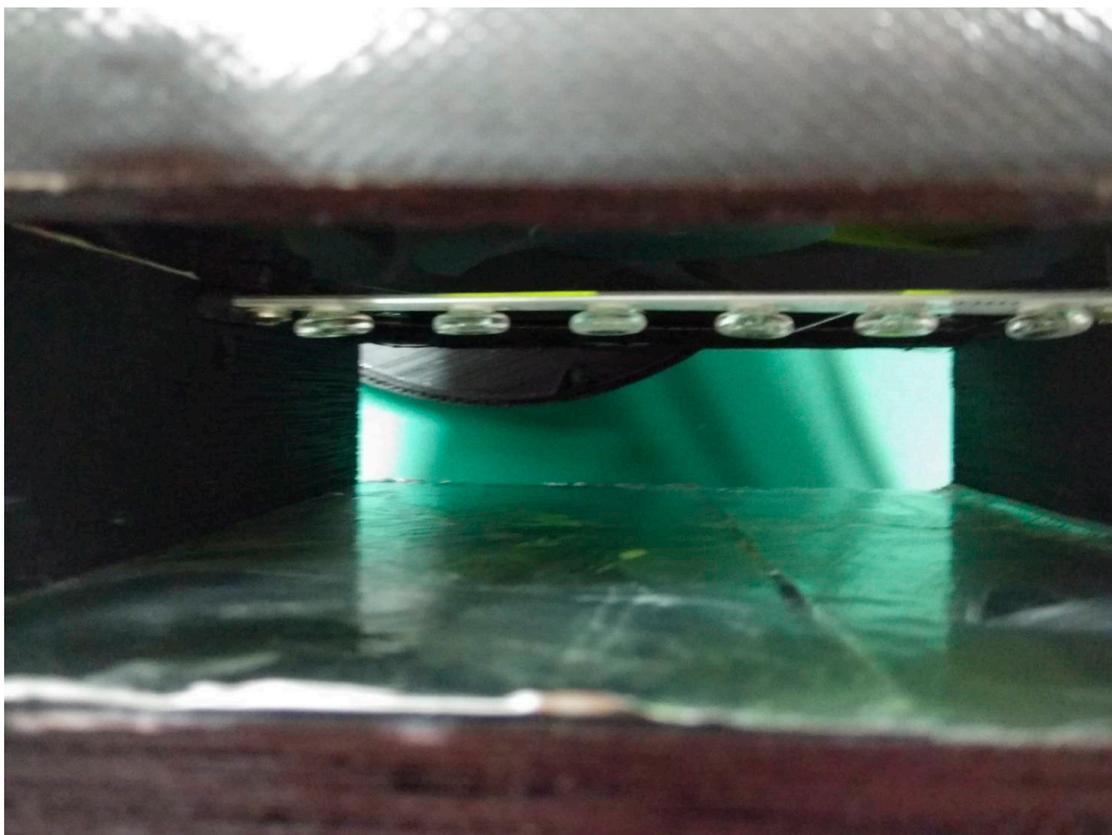


Figure 10. Use of the right amount of stearic acid as a mosquito attractant.

Because stearic acid can have a critical role in the host-seeking behavior of anthropophilic mosquitoes, the SFLD module with a central angle of 150° for a UV LED mosquito-trapper was used as the test sample to evaluate the difference before and after the coating of stearic acid in terms of mosquito trapping efficiency. According to our experiments, it was found that the trapped amount can be even elevated by 50% after applying the coating, as shown in Figure 11.

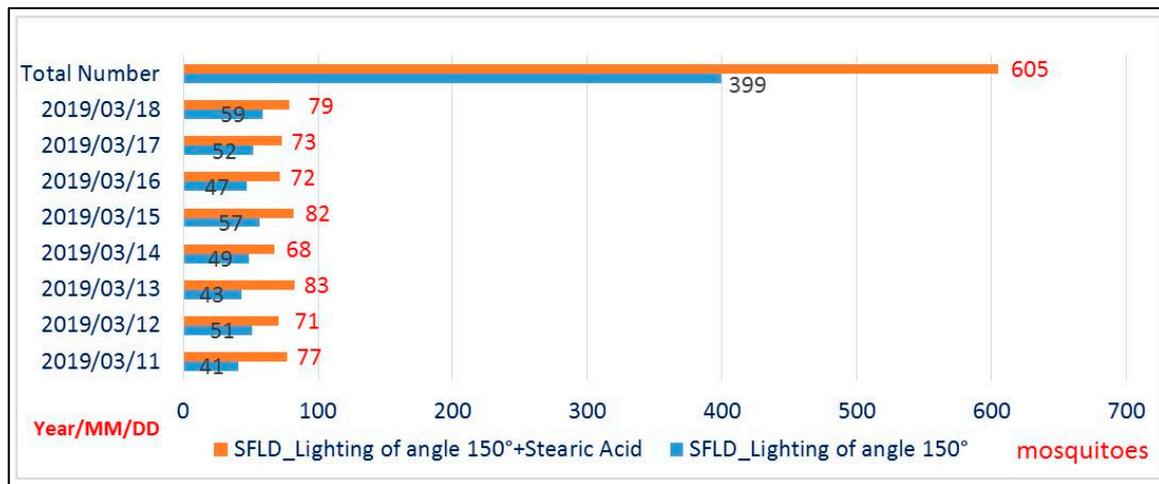


Figure 11. Comparison of the SFLD with a central angle of 150° for the UV LED mosquito-trapping system and that coated with stearic acid.

4. Conclusions

The experimental results showed that the specific secondary free-form lens device (SFLD) can be used to change the trapping range of the UV LED mosquito trapping system. The LIDC of the SFLD module with a central angle of 150° was the best of all experimental systems. Additionally, it can be extended to 100 πm^2 in terms of the outdoor trapping range. The number of mosquitoes captured by the UV LED mosquito trap system increased by about 350% in comparison with the general violet blue LED mosquito trap. In addition, when using the appropriate amount of stearic acid as a mosquito attractant, the UV LED mosquito trapping system of the SFLD module demonstrated a better control effect on mosquitoes during the day. According to our experiments, we found that, after coating, the amount of capture can be increased by 50%.

We can choose not to use chemical methods to fight mosquitoes to avoid harming people and the environment. We designed and optimized a mosquito trap, and, through the actual machine test, the UV LED mosquito trapping system of the SFLD module offers obvious advantages. The effectiveness of mosquito trapping is a disease vector control device that is worth promoting.

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

References

1. Chang, C.; Ortiz, K.; Ansari, A.; Gershwin, M.E. The Zika outbreak of the 21st century. *J. Autoimmun.* **2016**, *68*, 1–13. [[CrossRef](#)] [[PubMed](#)]
2. Chen, H.L.; Tang, R.B. Why Zika virus infection has become a public health concern? *J. Chin. Med. Assoc.* **2016**, *79*, 174–178. [[CrossRef](#)] [[PubMed](#)]

3. Guzman, M.G.; Halstead, S.B.; Artsob, H.; Buchy, P.; Farrar, J.; Gubler, D.J.; Hunsperger, E.; Kroeger, A.; Margolis, H.S.; Martínez, E.; et al. Dengue: A continuing global threat. *Nat. Rev. Microbiol.* **2018**, *8*, S7–S16. [[CrossRef](#)] [[PubMed](#)]
4. Li, Y.C.; Liu, C.W.; Huang, K.P. Dengue Fever and Dengue Hemorrhagic Fever. *Infect. Control J.* **2007**, *17*, 307–315.
5. Bidlingmayer, W.L. How mosquitoes see traps: Role of visual responses. *J. Am. Mosq. Assoc.* **1994**, *10*, 272–279.
6. Browne, S.M.; Bennett, G.F. Response of Mosquitoes (Diptera: Culicidae) to Visual Stimuli. *J. Med. Entomol.* **1981**, *18*, 505–521. [[CrossRef](#)] [[PubMed](#)]
7. Kay, R.E. Fluorescent materials in insect eyes and their possible relationship to ultra-violet sensitivity. *J. Insect Physiol.* **1969**, *15*, 2021–2038. [[CrossRef](#)]
8. Shimoda, M.; Honda, K.-I. Insect reactions to light and its applications to pest management. *Appl. Entomol. Zool.* **2013**, *48*, 413–421. [[CrossRef](#)]
9. Tseng, W.-H.; Juan, D.; Hsiao, W.-C.; Chan, C.-H.; Ma, H.-Y.; Lee, H.-Y. Design of a Secondary Freeform Lens of UV LED Mosquito-Trapping Lamp for Enhancing Trapping Efficiency. *Crystals* **2018**, *8*, 335. [[CrossRef](#)]
10. Tseng, W.-H.; Juan, D.; Hsiao, W.-C.; Chen, Y.C.; Chan, C.-H.; Ma, H.-Y.; Lee, H.-Y. Bird-Wing Optical-Reflector Design with Photocatalyst for Low-Glare Mosquito Trapping System with Light-Emitting Diodes. *Crystals* **2019**, *9*, 139. [[CrossRef](#)]
11. Lai, M.F.; Quoc Anh, N.D.; Gao, J.Z.; Ma, H.Y.; Lee, H.Y. Design of multi-segmented freeform lens for LED fishing/working lamp with high efficiency. *Appl. Opt.* **2015**, *54*, E69–E74. [[CrossRef](#)] [[PubMed](#)]
12. Acree, F.; Turner, R.B.; Gouck, H.K.; Beroza, M.; Smith, N. L-Lactic Acid: A Mosquito Attractant Isolated from Humans. *Science* **1968**, *161*, 1346–1347. [[CrossRef](#)] [[PubMed](#)]
13. Smith, C.N.; Gouck, H.K.; Weidhaas, D.E.; Gilbert, I.H.; Mayer, M.S.; Smittle, B.J.; Hofbauer, A. L-Lactic Acid as a Factor in the Attraction of *Aedes aegypti* (Diptera: Culicidae) to Human Hosts2. *Ann. Entomol. Soc.* **1970**, *63*, 760–770. [[CrossRef](#)] [[PubMed](#)]
14. Eiras, A.E.; Jepson, P.C. Host location by *Aedes aegypti* (Diptera: Culicidae): A wind tunnel study of chemical cues. *Bull. Entomol. Res.* **1991**, *81*, 151–160. [[CrossRef](#)]
15. Geier, M.; Sass, H.; Boeckh, J. A search for components in human body odour that attract females of *Aedes aegypti*. *Ciba Symp.* **1996**, *200*, 132–148.
16. Bernier, U.R.; Kline, D.L.; Schreck, C.E.; Yost, R.A.; Barnard, D.R. Chemical analysis of human skin emanations: comparison of volatiles from humans that differ in attraction of *Aedes aegypti* (Diptera: Culicidae). *J. Am. Mosq. Assoc.* **2002**, *18*, 186–195.
17. Knols, B.G.; Van Loon, J.J.; Cork, A.; Robinson, R.D.; Adam, W.; Meijerink, J.; De Jong, R.; Takken, W. Behavioural and electrophysiological responses of the female malaria mosquito *Anopheles gambiae* (Diptera: Culicidae) to Limburger cheese volatiles. *Bull. Entomol. Res.* **1997**, *87*, 151–159. [[CrossRef](#)]
18. Dekker, T.; Steib, B.; Cardé, R.T.; Geier, M. L-Lactic acid, a human-signifying host cue for the anthropophilic mosquito *Anopheles gambiae* sensu stricto. *Med. Vet. Entomol.* **2002**, *16*, 91–98. [[CrossRef](#)] [[PubMed](#)]
19. Chung, C.L. Talking about dengue prevention and control. *Taiwan Epidemiol. Bull.* **2006**, *22*, 589.
20. Wei, Z.C.; Guo, M.L.; Wang, M.J.; Li, S.Q.; Liu, S.X. Prediction of cutting force in five-axis flat-end milling. *Int. J. Adv. Manuf. Technol.* **2018**, *96*, 137–152. [[CrossRef](#)]

