Implementation and characterisation of a sterilisation module consisting of novel 265 nm UVC LED packages

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ABSTRACT

To efficiently fight against the COVID-19 pandemic, a sterilisation module using 265 nm UVC LED packages was developed. In this paper, the performance of the sterilisation module in terms of irradiance uniformity, junction temperature increase and sterilisation efficiency were characterised. The irradiance uniformity fluctuation across the four corners and the centre point in a 130 mm × 130 mm area was below 10%, exhibiting good uniformity. Uniform irradiance was important to achieve consistent sterilisation, which was the primary difference between the UVC LED package developed and commercial UVC LED packages. Key to achieving uniform irradiance was the structure, consisting of a stacked silicon reflector and a secondary optical lens designed by ray tracing simulation. The junction temperature increase of the 265 nm UVC LED package driving at 200 mA was only 28°C, sufficiently low to exhibit better reliability and performance. A 99.99% sterilisation efficiency on *E. coli* bacteria was achieved within one minute with UV dosage of 2.7 mJ/cm² at 200 mA driving current. From the results, the novel 265 nm UVC LED package was a time-efficient solution for disinfection purposes.

KEYWORDS COVID-19 Pandemic; 265 nm UVC LED package with uniform irradiance; sterilisation module; time-efficient; large object; long distance; stacked silicon reflector; secondary optical lens

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1. Introduction

Anti-epidemic measures have to be taken to overcome the COVID-19 pandemic. UVC (ultraviolet-C) for surface sterilisation has the advantage of being safe, quick and free from secondary contamination, and has now been widely accepted and used to fight against COVID-19. The UVC inactivation mechanism consists of UVC radiation, which kills microbes by damaging their deoxyribonucleic acid (DNA) and ribonucleic acid (RNA) (Reed, 2020). The principal mode of inactivation occurs when the absorption of a photon forms pyrimidine dimers between adjacent thymine bases and renders the microbe incapable of replicating (Reed, 2020). According to this mechanism, germicidal response functions were characterised by the Deutsches Institut für Normung (DIN) and the Illuminating Engineering Society of North America (IESNA), shown in Figure 1 (Reed, 2020). At 265 nm, it offers the germicidal efficiency (Reed, 2020). Recently, Seoul Viosys and SETi reportedly achieved 99.9% inactivation efficiency of the COVID-19 virus in 30 seconds using 265 nm UVC radiation (*Seoul Viosys and SETi's Violeds Technology Proves 99.9% Sterilization of Coronavirus (COVID-19) in 30 Seconds*, 2020).

Figure 1. Germicidal response functions.

Currently, the predominant UVC light source technology is the low-pressure mercury lamp, which can emit 254 nm radiation. Even though 254 nm is within the range of germicidal wavelengths, germicidal efficiency at 254 nm is not the highest. The low-pressure mercury lamp performs well in continuous operation, offering high power at a low cost. However, mercury lamps take time to warm up, requiring more than one minute to sterilise anything (*Mercury Vapor Lamps*, 2001). Because on/off cycling is strenuous, this can drastically reduce the lamp's service life

to no more than a year (*Mercury Vapor Lamps*, 2001). As consumers are now demanding smaller product footprints to accommodate smaller living spaces, existing sterilisation modules that use mercury lamps are being downsized to save space. But even the smallest mercury lamp sterilisation modules are three to four times larger than UVC LED sterilisation modules, due to the size and orientation of the lamp itself (*Lamps Comparison UV LED DROLED vs Traditional UV Mercury*, 2017). In addition, the Minamata Convention on Mercury has imposed a ban on new mercury mines, the phasing-out of existing ones, and the phasing-out and phasing-down of mercury use in a number of products and processes (*Minamata Convention on Mercury*, 2013).

Figure 2. Commercial UVC LED package.

The light-emitting diode (LED) is the next generation of light source. Deep ultraviolet LED (UVC LED) possesses several advantages over mercury lamps, such as being mercury-free, having a small footprint, instant on/off switching, a much longer lifetime, and no warm-up time (Kim and Kang, 2018). Since the highest germicidal efficiency occurs at 265 nm, the UVC LED with a wavelength of 265 nm has a higher germicidal efficiency than the mercury lamp. It has been reported that 265 nm UVC LED sterilisation modules can achieve 99.9% germicidal efficiency within one minute (Minamikawa et al., 2021), while mercury UV lamps cannot achieve the same germicidal efficiency in such a short period. In addition, mercury UV lamps are not suitable for frequent on/off applications due to their limited on/off cycles, while 265 nm UVC LEDs are suited to this purpose.

The current UVC LED package inherits the standard high-power LED packaging approach of adopting a ceramic substrate and a quartz plate (lens). However, this packaging approach is not specifically designed for disinfection purposes. For disinfection, uniform irradiance of an area is key to ensuring consistent disinfection. Due to the

inefficient optical design of the current UVC LED package, the irradiance is not uniform and its irradiance value is low. Due to these packaging limitations, current commercial UVC LED sterilisation products can only sterilise small objects at close range, such as cellphones, glasses, wallets, keys, tablets and baby bottles. Therefore, in order to perform inactivation for a larger area so that large objects could be sterilised at a longer distance in a shorter time, a method to enhance irradiance uniformity and irradiance value had to be developed to overcome the limitations of commercial UVC LEDs.

Reflectors are widely used in UVC LEDs, shown in Figure 2 (*Deep UV LED*, 2016). The coating material is usually gold (Au). However, Au suffers low UVC reflectance, shown in Figure 3 (Osorio et al., 2012). Also, the side wall of the metal reflectors is vertical and the metal reflectors are short, so they cannot converge UV emission. These properties limit the utility of metal reflectors for light-converging applications. Therefore, low-cost, highly-reflective and reliable reflectors with an acceptable height are required.

Figure 3. Reflectance of gold (Au), aluminium (Al) and silver (Ag).

In order to solve the current limitations of reflectors for UVC LEDs, the team developed a stacked silicon reflector structure in 2017 and successfully applied this novel structure in instant UV LED curing applications (Qiu et al., 2017; Qiu et al., 2019; Qiu et al., 2020; Qiu et al., 2021). Silicon is a UV-resistant material due to its stable atomic structure. Also, a side wall with a precise 54.7° inclination can be easily achieved thanks to its atomic plane arrangement. The inclined side wall can be coated with Al material to improve UVC reflectance. The silicon reflectors can be stacked by soldering to increase the height. Last but not least, silicon reflectors are fabricated at the wafer level, making it a low-cost solution.

2. Irradiance characterisation

Based on the Al-coated stacked silicon reflector technology, a novel UVC LED package was developed providing 265 nm peak wavelength for disinfecting large objects at a long distance. A secondary optical lens together with the Al-coated stacked silicon reflector could achieve uniform irradiance. Considering the Lambertian distribution of the rays emitted by a UVC LED chip, this unique structure could diverge the central rays and converge the surrounding rays, such that uniformity distribution of the UVC LED chip could be improved. A Monte Carlo ray tracing approach was adopted to simulate the irradiance distribution of the UVC LED package. According to optical simulation, the irradiance distribution in a 130 mm $\times$ 130 mm area at a distance of 260 mm was uniform, as shown in Figure 4. Compared with commercial UVC LED packages, the novel UVC LED package exhibited higher irradiance with better uniformity due to high UVC reflectance of the Al-coated stacked silicon reflector and the unique packaging structure given in Figure 5. The irradiance uniformity was an important parameter for disinfection because uniform irradiance could ensure a consistent sterilisation effect. Since the UVC LED package could achieve uniform irradiance in a 130 mm $\times$ 130 mm area, a sterilisation module could be built just by adding the UVC LED packages with a pitch size of 130 mm, such that the sterilisation area could be made adjustable by adjusting the amount of UVC LED packages. For demonstration, a 2 $\times$ 2 sterilisation module was fabricated, shown in Figure 6.

Figure 4. Uniform irradiance distribution of the UVC LED package in a 130 mm $\times$ 130 mm area.

Figure 5. Irradiance distribution comparison: (a) Commercial UVC LED package; and (b) our UVC LED package.

Figure 6. Sterilisation module consisting of four UVC LED packages.

Since the sterilisation module would be used for an *E. coli* bacteria disinfection test, it was necessary to measure the irradiance so that the dosage could be calculated. Irradiance characterisation (ILT560A, Mini-Spectroradiometer, International Light Technologies, MA, United States) of the sterilisation module was conducted at a distance of 260 mm, with results of $45 \mu\text{W}/\text{cm}^2$ at 200 mA achieved (Figure 7). An optical simulation was performed to characterise the uniformity distribution of the sterilisation module. The result showed that the irradiance was quite uniform, as shown in Figure 8. The irradiance distribution was also characterised by measuring the irradiance in a $130 \text{ mm} \times 130 \text{ mm}$ area at the four corners and the centre, shown in Figure 9. The irradiance at the four corners differed within 5%, while the irradiance at the centre exhibited around 10% higher, due to overlap provided in Table 1.

Figure 7. Relationship of irradiance with different driving currents measured at a distance of 260 mm.

Figure 8. Uniform irradiance distribution of the sterilisation module in a $130 \text{ mm} \times 130 \text{ mm}$ area.

Figure 9. (a) Schematic diagram of the test setup; and (b) positions for irradiance measurement.

Table 1. Irradiance measurement result.

Position	Normalised irradiance
A	92%
B	92%
C	90%
D	91%
E	100%

3. Temperature increase characterisation

The lifetime of the UVC LED chip is related to its junction temperature. For this particular UVC LED chip, the recommended junction temperature was below 90°C , so that L90 (90% initial radiance) of UVC LED chip was greater than 2,000 hours. Therefore, it was necessary to characterise the junction temperature at different driving currents. In terms of measurement approaches, the thermal transient tester method was more accurate than the thermocouple method, because the thermocouple method could only predict the junction temperature by measuring the case temperature, while the thermal transient tester method could precisely measure the junction temperature increase, since the transient cooling curve of the junction could be achieved by measuring the voltage of the junction

in the cooling stage from thermal equilibrium. Therefore, a thermal transient tester (T3Ster 2000/100, Mentor Graphics, Oregon, United States) was adopted to measure the junction temperature increase of the UVC LED package from 100 mA to 600 mA. At 200 mA driving current, the temperature increase of the UVC LED package was 28°C, shown in Figure 10. Since the junction temperature was the sum of the ambient temperature and the temperature increase, an ambient temperature below 62°C should be guaranteed, considering the L90 condition.

Figure 10. Relationship of temperature increase with different driving currents.

4. Sterilisation of *E. coli* bacteria

To demonstrate the sterilisation capability of the sterilisation module, *E. coli* bacteria was used as the benchmark bacteria to evaluate the dosage necessary to achieve 99.99% sterilisation efficiency. The *E. coli* culture was prepared in a standard four-inch agar plate following a standard protocol (Inoculating a Liquid Bacterial Culture, 2018). Different concentrations of *E. coli* bacteria were prepared and the sterilisation test was performed in a bacteria-free chamber. The distance between the sterilisation module and the agar plate was 260 mm, and a 200 mA driving current was applied for one minute, so that the irradiance at the agar plate was 45 $\mu\text{W}/\text{cm}^2$ and the corresponding dosage was 2.7 mJ/cm^2 . A 99.99% sterilisation efficiency was achieved (Table 2) with this small dosage. Compared to the dosage required to achieve the same sterilisation efficiency for a 254 nm mercury lamp, i.e. 50 mJ/cm^2 (Coohill and Sagripanti, 2008), the sterilisation module exhibited superior sterilisation capabilities (Figure 11).

Table 2. Sterilisation test results for the module.

Test conditions	Original concentrations of <i>E. coli</i> bacteria		
	$\sim 45 \times 10^4$	$\sim 45 \times 10^3$	$\sim 45 \times 10^2$
Control sample
200 mA

Figure 11. Comparison of sterilisation capability with different wavelengths for *E. coli*.

5. Cabinet demonstration

For the end product demonstration, a cabinet with dimensions of 1840 mm $\times$ 550 mm $\times$ 570 mm was built for housing multiple sterilisation modules for large-object disinfection, shown in Figure 12. Inside the cabinet, the longest disinfection distance was 260 mm, which was consistent with the distance in the *E. coli* bacteria sterilisation experiment. Compared to the cabinet using 254 nm mercury lamp technology, this cabinet using the novel 265 nm UVC LED packages was a more time-efficient solution.

Figure 12. Cabinet adopting the novel 265 nm UVC LED packages.

6. Conclusion

The novel 265 nm UVC LED packages were used for developing a sterilisation module. Three important characteristics were investigated, i.e. irradiance, junction temperature increase and sterilisation capability. At a distance of 260 mm, $45 \mu\text{W}/\text{cm}^2$ irradiance with around 10% irradiance difference in a $130 \text{ mm} \times 130 \text{ mm}$ area was achieved. Uniform irradiance was achieved by the unique packaging structure of the stacked silicon reflector and secondary optical lens. A 28°C junction temperature increase at operation was measured, which indicated the

L90 requirement of the UVC LED chip could be satisfied. When the distance was 260 mm with an area of $130 \text{ mm} \times 130 \text{ mm}$, only one minute was required to inactivate 99.99% of the *E. coli* bacteria present, with the dosage of $2.7 \text{ mJ}/\text{cm}^2$. Compared with commercial UVC LED sterilisation products, this novel UVC LED sterilisation product could inactivate bacteria on large objects over a longer distance in a shorter time due to its unique UVC LED packaging technologies. Therefore, the sterilisation module was a time-efficient solution for tackling the COVID-19 pandemic.

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