Solid–Liquid Hybrid-State Organic Lens for Highly Efficient Deep Ultraviolet Light-Emitting Diodes

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Deep ultraviolet light-emitting diodes (DUV-LEDs) are considered to be the most promising ultraviolet light sources for effective and fast sterilization under the worldwide spread of the coronavirus disease (COVID-19). However, it reminds challenging to promote the light extraction of DUV-LEDs owing to the strong DUV light absorption of conventional encapsulation materials. Herein, solid–liquid hybrid-state gels (SLHGs) to fabricate organic lenses for DUV-LEDs, which largely enhance the light extraction efficiency without sacrificing the working stability, are proposed. Solid-state cross-linked networks of polydimethylsiloxane are used in the SLHG structure to maintain the liquid components of silicone oil and demonstrate excellent formability, DUV transparency (over 90% transmittance in the UVC range), and thermal stability. The radiant power of DUV-LEDs (275 nm) with the optimized SLHG organic lens is enhanced by 52.5% compared to a commercial quartz lens, achieving a record packaging optical efficiency of 1.31 among solid-state packaging DUV-LEDs. A sterilization evaluation for SARS-CoV-2 demonstrates that the inactivation time can be reduced by \( \approx 25\% \) using the SLHG organic lens. Consequently, herein, a feasible and effective method to enhance the optical performance of DUV-LEDs and advance their promising potential for disinfection applications is provided.

1. Introduction
The spread of the coronavirus disease (COVID-19) has had a tremendous impact on human society, and particularly human health. Thus, an efficient, fast, and safe germicidal program has become extremely important.\[1\] Deep ultraviolet (DUV) light with a wavelength of 180–280 nm has been confirmed to destroy the chemical bonds inside the deoxyribonucleic acid (DNA) or ribonucleic acid (RNA) of microorganisms such as SARS-CoV-2, which causes COVID-19,\[2\] and has been commonly used in hospitals to disinfect objects that cannot be immersed in liquid germicidal agents.\[3\] DUV light is commonly produced using a low-pressure mercury lamp; however, the manufacture of products containing mercury has been prohibited since 2020 by the Minamata Convention on Mercury.\[4\] Thus, DUV light-emitting diodes (DUV-LEDs), which are compact, wavelength-tunable, energy-saving, and environmentally friendly, have been considered to be the most promising ultraviolet light sources for effective and fast sterilization.\[5–8\]

All-inorganic materials with excellent thermal stability, low thermal expansion, and high mechanical strength are widely used in commercial DUV-LEDs.\[9,10\] For instance, these devices can be processed by either directly sealing a chip with a thin quartz plate or forming a sintered monolithic silica from glass frits and have shown superior stability and gas barrier performance under DUV light. However, all-inorganic packaging is often plagued by drawbacks such as limited light extraction, which results from the difference in the refractive indices of air and quartz glass, leading to a severe total internal reflection (TIR) loss and largely reducing the efficiency of DUV-LEDs.\[11–14\] The most common method to address this problem is to use organic polymer to fill the gap between the chip and quartz lens to suppress the TIR loss and enhance the light extraction.\[15,16\] Nevertheless, organic polymers such as thermosetting epoxy and organo-siloxane decompose due to their low DUV resistance, which degrades the efficiency of such devices under DUV light.\[17,18\] Recently, some liquid materials with high DUV resistance have been proposed to fill the gap and maintain better stability, but they have a complicated packaging process and considerable leakage risk.\[19,20\] Organic packaging, as the...
mainstream packaging for visible LEDs, avoids the quartz glass bonding process of the all-inorganic type, reducing the manufacturing cost. Because of their excellent bonding ability and superior properties for lens formation, organic packaging materials can protect a chip from any mechanical damage caused by an impact or humidity while significantly suppressing the TIR loss. However, the light extraction efficiency of DUV LEDs using organic packaging is still restrained by the strong DUV light absorption of conventional organic materials. To overcome this drawback, a fluoropolymer with a stable -CF₃ end group has been proposed, which endows excellent transparency under DUV light. However, the limitations of the evaporative polymer droplet-deposition fabrication method make it difficult to form a curved lens of fluoropolymer, and it is necessary to produce microstructures on the surface of the fluoropolymer coating to improve the light extraction efficiency. However, manufacturing a microstructure is exceedingly complicated, and the corresponding extraction enhancement is often of limited effectiveness. In addition, the fluoropolymer has comparatively poor bonding ability, which may cause unexpected air voids in the interfaces and have a negative impact on the light extraction and thermal stability. Accordingly, it is highly desirable to develop a new type of organic encapsulation for DUV-LEDs, which combines advantages such as excellent formability, DUV transparency, and thermal stability.

Herein, solid–liquid hybrid-state gels (SLHGs) were proposed to fabricate organic lenses for DUV-LEDs, which largely enhance the light extraction efficiency without sacrificing the working stability. Solid-state cross-linked networks of polydimethylsiloxane (PDMS) in the SLHG structure were utilized to maintain the liquid components of silicone oil and exhibited excellent formability, DUV transparency, and thermal stability. The radiant power of DUV-LEDs (275 nm) with the optimized SLHG organic lens is enhanced by 52.5% compared to a commercial quartz lens, achieving a record packaging optical efficiency of 1.31 among solid-state packaging DUV-LEDs. Furthermore, a sterilization evaluation for SARS-CoV-2 was carried out to explore the inactivation ability of these devices.

2. Results and Discussion

The SLHG structure could be obtained through facile and efficient mechanical stirring, and a schematic diagram of the fabrication process is shown in Figure 1a. The liquid components of silicone oil and the solid precursors of PDMS were uniformly mixed during the fabrication process. After curing, the SLHG composite was formed, as shown in Figure 1b. The UV transmittance spectra of SLHG composites with various fluid proportions and commercial composites are shown in Figure 1c. The inserts show the average transmittance changes of SLHG composites during light soaking under UVC source and a photograph of the SLHG composite.

Figure 1. Fabrication method and high DUV transparency of SLHG composites. a) Schematic diagram of the fabrication process for the SLHG composites. b) The UV transmittance spectra of SLHG composites with various fluid proportions and commercial composites. c) The UV transmittance spectra of SLHG composites at a fluid proportion of 85% with various viscosity indices. The inserts show the average transmittance changes of SLHG composites during light soaking under UVC source and a photograph of the SLHG composite.
mixed and then moved to an oven to cure the solid components; thus, SLHG composites could be obtained. Herein, the maximum liquid proportion of the SLHG structure by adjusting the mass ratios of the liquid components to solid precursors is first investigated, ensuring that the solid precursors could be entirely crosslinked and establish a solid-state network after curing. SLHG composites with liquid proportions of 80%, 85%, and 90% were fabricated after curing at 120 °C for 90 min, as shown in Figure S1, Supporting Information. The composites obtained with liquid proportions below 85% maintained their shapes after reversing, while in the case of a liquid proportion of 90%, it could not turn into a solid state and the shape of the composite deteriorated. Therefore, the maximum liquid proportion was set to 85% for subsequent investigations, which was critical for fabricating formable organic lenses for DUV-LEDs.

To investigate the DUV transparency of the SLHG composites, their transmittance spectra are shown in Figure 1b. Herein, the transmittance spectra of commercial composites are used as references, such as silicone of the OE6650 and all-solid-state (AS)-PDMS. It is observed that the transmittance is not significantly different in the UVA and UVB ranges, with all of the composites having transmittance more than 80%. However, the transmittance of the OE6650 suddenly declined from 80% to 0% in the UVC range, while that of the AS-PDMS decreased below 40%, indicating that conventional silicone has a strong DUV absorption ability. This is also one of the reasons why conventional silicone is clearly unsuitable for DUV-LED encapsulation. In contrast, the transmittance of the SLHG composites gradually decreased with the wavelength, exhibiting a higher DUV transparency. The absorption spectra are also provided in Figure S2, Supporting Information, to prove the above discussion.

Furthermore, the SLHG composites exhibited higher DUV transparency values as the liquid proportion of the SLHG composite increased. The composite with the maximum liquid proportion of 85% showed an excellent DUV transparency of more than 90% transmittance in the UVC range, which was twice that of commercial AS-PDMS and similar to that of quartz glass.[41,42] The refractive index and haze spectra of composites are also provided in Figure S3 and S4, Supporting Information, respectively. The haze of SLHG composites is nearly zero in the DUV range, which is attributed to the fact that the SLHG composites are with high DUV transparency and the refractive indexes of components are similar, leading to extremely low haze.[43] Notably, these SLHG composites could easily be fabricated by mechanical stirring without harsh conditions such as the high pressure and temperature needed for quartz glass, ensuring the potential for environmentally friendly and cost-effective mass customization. To enhance the formability of the SLHG structure, the viscosity of the liquid component in the SLHG composites was adjusted, and the DUV transparency was investigated. In these cases, the liquid proportion of the SLHG composites was set to 85%, and the viscosity of the liquid component was adjusted from 50 to 10 000 cs. All of the SLHG composites showed almost identical transmittance spectra, demonstrating that the viscosity of the liquid component had little impact on the DUV transparency, as shown in Figure 1c. However, the viscosity directly affected the geometry of the SLHG structure when in contact with the LED devices. This means that the shape of the SLHG composite could simply be controlled by the viscosity of the liquid component while maintaining high DUV transparency, which provided an alternative for optimizing the lens geometry for high light-extraction efficiency. In addition, the stability test of SLHG composites was carried out, and the transmittance changes of SLHG composites were investigated during light soaking under UVC source (275 nm) as presented in the insert of Figure 1c and S5, Supporting Information. It shows that the SLHG composites still maintain high DUV transmittance over 90% after long-time UV exposure (over 500 h), indicating that the SLHG composites also have excellent DUV stability.

To reveal the mechanism of the excellent DUV transparency of the SLHGs, the chemical structure of the SLHG composites was investigated using the infrared transmittance spectra, as shown in Figure 2a. The infrared transmittance spectra of the solid precursors, liquid components, and cured AS-PDMS were used as references, while the cured SLHG composites had 85% liquid proportions in these cases. The absorption peak of the solid precursors at 3080 cm⁻¹ was attributed to the C=O bond located at the terminated ethylene[44] of the solid precursors, as shown in Figure 1a. After the interaction with the curing agent, the solid precursors were cross-linked by hydrosilylation. Some CH₃ functional groups were added to the main structure, increasing the length of the main chain and the molecular weight. As a result, C—C bonds occurred in the main chain, which had a low bonding energy of 85 kcal mol⁻¹. It was easily broken by UVC and UVB light with high energies of 102 and 91 kcal mol⁻¹, respectively. In contrast, the chemical structure of the liquid components was simple, composed of Si—O and Si—CH₃ functional groups. The main chain of the liquid components was bonded by Si—O, which had a high bonding energy of 108 kcal mol⁻¹; therefore, it was not easily broken and exhibited excellent stability in the DUV range. The corresponding schematic is provided in Figure S6, Supporting Information, to better understand the principle described earlier. However, liquid components with high DUV transparency cannot be directly integrated with DUV-LEDs because of the leakage risk. To ameliorate this drawback, this SLHG structure used solid-state cross-linked networks to maintain the liquid components. The absorption peak of the C=C bonds did not appear in the infrared transmittance spectra of the cured AS-PDMS and SLHG composites, indicating that the solid precursors in the SLHG composites could be entirely cross-linked even when combined with liquid components.

To further confirm this notion, the curing process of the AS-PDMS and SLHG composites was investigated using differential scanning calorimetry (DSC), and the results are shown in Figure 2b. The DSC curves initially increased with the temperature, indicating that the liquid drew heat from the adjacent ambient air to raise the temperature. Subsequently, the cured AS-PDMS showed a large downward peak that represented the exothermic reaction, indicating that the solid precursors formed solid-state cross-linked networks. The downward peak of the SLHG composites was small compared to that of AS-PDMS, which could be attributed to the fact that the liquid components occupied most of the SLHG structure, and only a small portion of solid precursors were cross-linked to form the networks. Consequently, the SLHG structure contained a
large amount of the original liquid components with high bonding energy in its solid networks, thus maintaining a high DUV transparency.

Thermal stability is also an important factor in DUV-LED encapsulation because the heat generated from chips can reduce the efficiency of the device through chemical changes in the polymers. The thermal performance of the SLHG structure was investigated using thermogravimetric analysis (TGA), and the results are presented in Figure 2d. It can be observed that the AS-PDMS and SLHG composites exhibit similar degradations in the temperature range of 30–175 °C, while showing obvious differences as the temperature continues to increase. $T_d(5\%)$ (5% weight loss temperature) is defined as the degradation temperature to show the difference in thermal stability. The $T_d(5\%)$ of AS-PDMS was 293 °C, while that of the SLHG composites reached 405 °C, demonstrating that the SLHG structure had a better thermal performance than the AS-PDMS. This was attributed to the Si-O in the main chain of the liquid components, which had a high bonding energy. Therefore, the excellent thermal stability of the SLHG composites could meet the requirements of DUV-LEDs in practical applications.

Generally, quartz glass, which has excellent DUV transparency, is widely utilized in the encapsulation of DUV-LEDs, but it also leads to limited light extraction attributed to the chip/void interface and chip damage from the high-temperature sintering process.[11,13] For liquid encapsulation with high DUV transparency, quartz glass is still required to avoid the leakage risk.[19,20] Fortunately, the SLHG structure can combine the advantages of quartz and liquid encapsulation, exhibiting excellent DUV transparency, formability, and high thermal stability. Therefore, the SLHG structure is particularly suitable for the encapsulation of DUV-LEDs, while simultaneously serving as

Figure 2. Formation mechanism of SLHGs and their thermal stability. a) Infrared transmittance spectra of solid precursors, liquid components, cured AS-PDMS composite, and SLHG composites with 85% fluid proportion. b) DSC measurements at temperatures of 30–820 °C. The marked circles indicate the degradation temperatures, $T_d$, of the AS-PDMS and SLHG composites. c) Schematic demonstrating the DUV transparency of SLHGs and AS-PDMS. d) Thermogravimetric analysis (TGA) of the AS-PDMS and SLHG composites. The 5% weight loss temperatures, $T_d(5\%)$, are marked by circles.
an organic lens to enhance the light extraction efficiency. In our cases, the viscosity was maintained at 1000 cs, and SLHG organic lenses with various curvatures were fabricated by controlling the dispensing mass, as shown in Figure 3a. The curvature of the SLHG organic lens increased with the dispensing mass and gradually reached the maximum curvature of 0.67 m⁻¹. For convenience, the corresponding fitting curve is given in Table S1, Supporting Information. The curvature of the SLHG organic lens could be precisely adjusted. In the future, the viscosity of the liquid component can be further adjusted to alter the surface tension of the SLHG organic lens because it does not affect the DUV transparency, which will provide a wider curvature range for different applications.

To better understand the influence of the SLHG organic lens on the device efficiency, a ray-tracing simulation was performed, as shown in Figure 3b. Device models that used the SLHG, AS-PDMS, and OE6650 with various curvatures were established, and the two most common DUV wavelengths (275 and 310 nm) were selected to conduct a comprehensive simulation. Note that the material properties of the SLHG, AS-PDMS, and OE6650 were set according to the results in Figure 1. It can be observed that the devices using different organic lenses showed significant differences in radiant efficiency at a wavelength of 275 nm. The radiant efficiency of the device using the OE6650 organic lens was substantially zero, whereas the AS-PDMS organic lens showed a common radiant efficiency, which was due to the strong DUV absorption. In contrast, the SLHG organic lens greatly enhanced the radiant efficiency of the devices (up to 88%) as a result of the high DUV transparency. To gain a better understanding of this issue, the absorption proportion of the organic lens is shown in Figure S7a, Supporting Information. Most of the light emitted from the DUV chips was absorbed by the OE6650 organic lens, and a portion of the chip light was also absorbed in the case using the AS-PDMS organic lens, while the SLHG organic lens had almost no influence on the chip light. It was demonstrated that the SLHG organic lens could efficiently reduce the light absorbed by the encapsulating material to improve the radiant efficiency of DUV-LEDs. Compared to DUV-LEDs with a typical wavelength of 275 nm, the radiant efficiency difference for the different kinds of organic lenses was small in the case of 310 nm, which was mainly because the transparency properties of the SLHG, AS, and commercial material were almost identical at a wavelength of 310 nm.

In addition to the natural absorption loss from the lens materials, the TIR loss at the lens/air interface was also a key factor influencing the radiant efficiency of the DUV-LEDs. To this end, the curvature of the SLHG organic lens was optimized based on the light extraction efficiency of the devices. The radiant efficiency of the devices was enhanced with an increase in the curvature, reaching a peak at a curvature of 0.5 m⁻¹, and then gradually dropped when the curvature continued to increase. The radiant efficiency was only 55% when the organic lens

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**Figure 3.** Optical performance of DUV-LEDs using SLHG organic lens. a) The curvatures of SLHG organic lenses with different masses and the corresponding fitting curves. The inserts show photographs of devices using SLHG organic lenses with various curvatures. b) The radiant efficiencies of DUV-LEDs using SLHG, AS, and a commercial organic lens from optical simulations. c,d) Injection-dependent radiant power values of DUV-LEDs using SLHG, AS, commercial organic, and quartz lenses when the central wavelength of the chips was 275 and 310 nm, respectively. The insert shows a photograph of a DUV-LED with an SLHG organic lens. e) POE comparisons of DUV-LEDs with different packaging types. f) Aging test of DUV-LEDs using SLHG organic lens and quartz lens. The aging condition was a continuous injection current of 40 mA at an environmental temperature of 25 °C.
was almost substantially flat, with little curvature. This was attributed to the light emitted from the chip being reflected at the lens/air interface and absorbed by the substrates, which could be supported by the absorption of the substrates, as shown in Figure S7b, Supporting Information. The increase in curvature reduced the reflected light at the lens/air interface, leading to an enhanced light extraction efficiency. Therefore, a value of 0.5 m−1 was selected for the curvature of the SLHG organic lens to obtain a high light extraction efficiency for DUV-LEDs.

DUV-LEDs with different encapsulations were fabricated, and their radiant efficiency and stability values were investigated. Chips with central wavelengths of 275 and 310 nm were selected as the DUV sources, and the injection-dependent radiant power values of DUV-LEDs using different kinds of encapsulation are shown in Figure 3c,d, respectively. The results indicated that the radiant power values of the devices using commercial organic lenses (OE6650 and AS-PDMS) were low at 275 nm, but were obviously enhanced at 310 nm because of the relatively low absorption ability of commercial organic materials in the UVB range, which was consistent with the simulation results. Nevertheless, the DUV-LEDs with the SLHG organic lens still had the highest radiant power values at 275 and 310 nm under various injection currents. Herein, the most commonly used quartz lens with high DUV transparency and working stability was also used as a reference. It was found that the devices using the SLHG organic lens had a radiant power of 18.3 mW at a typical injection current of 100 mA, while that with a quartz lens only had 12.0 mW, which showed an enhancement of 32.5%, although they both had high DUV transparencies at 275 nm. To investigate this issue, the record POE was used to evaluate the light extraction efficiency enhancement for different packaging types, which was calculated according to the following equation

\[ POE = \frac{P_{\text{packaging}}}{P_{\text{chip}}} \]  

where \( P_{\text{packaging}} \) and \( P_{\text{chip}} \) are the radiant power values of the device with and without packaging, respectively. When the POE was larger than one, it was found that the packaging could enhance the light extraction efficiency of the devices, and the enhancement increased with the POE. In contrast, the packaging exacerbated the light loss in devices if the POE was less than one. For convenience, the POEs of devices with quartz and SLHG organic lenses are marked in Figure 3e for comparison with previous studies using different packaging types. It is observed that the DUV-LEDs with a quartz lens and the devices with all-inorganic packaging have POEs of less than one, meaning that the quartz lens reduced the light extraction efficiency. This was mainly attributed to the increased TIR loss resulting from the air gap between the glass and chip, which was consistent with previous studies.\[^{20,45}\] In contrast, the POEs of devices using SLHG organic lenses reached 1.31, which exceeded the values of most of the devices with solid-state packaging, such as fluoropolymer and nanostructures,\[^{36-49}\] demonstrating that the SLHG structure could significantly enhance the light extraction efficiency of DUV-LED chips.

In addition, an aging test under harsh operating conditions (an injection current of 40 mA) was conducted, and the time-dependent radiant power values are shown in Figure 3f. Almost identical operating stabilities were observed for the devices using the SLHG organic lens and quartz lens. These results confirmed that the DUV-LEDs with SLHG organic lenses preserved the higher radiant power during operation and also exhibited excellent stability in the aging test, which was consistent with the low DUV absorption and high thermal stability discussed above. Therefore, the SLHG organic lens not only had an excellent light extraction performance but also exhibited an excellent working stability comparable to that of a commercial quartz lens.

As a highly efficient sterilization method, the power density is one of the most important performance characteristics of DUV-LEDs, which determines the efficacy of inactivating a virus. In practice, the spatial distributions and distance-dependent power densities of single-packaged DUV-LEDs with optimized SLHG organic lenses were investigated, as shown in Figure 4a. Similarly, a commercial quartz lens was used as a reference. It can be observed that the SLHG organic lens enhanced the light extraction in various directions and expanded the divergence angle of the devices. Subsequently, the spatial distributions of the devices were imported into a ray-tracing model as the DUV light source, and the power densities of the single-packaged DUV-LEDs at various irradiance distances could be obtained. The device with the SLHG organic lens exhibited a higher power density than the case with a quartz lens when the distance was small, which could be attributed to the expanded divergence angle achieved by the SLHG organic lens. In particular, both types of devices had power densities smaller than 1.2 mW cm−2 when the distance reached 2 cm, which could not satisfy the sterilization requirements in an application environment.

To obtain a high and uniform power density, the DUV-LEDs were integrated into a 5 × 5 array as an integrated sterilization light source, and the device pitch (the distance between devices) was optimized via simulations. The sterilization distance was set to 5 cm for daily applications.\[^{35}\] The power densities and uniformities of integrated sterilization light sources with various pitches are shown in Figure 4b. The sources packaged with SLHG organic lenses had a higher power density and uniformity than those with a quartz lens. When the pitch was 9 mm, the source using the SLHG organic lens had a power density of 2.19 mJ cm−2, while that of the source with a quartz lens was only 1.65 mJ cm−2. In addition, the uniformity was characterized using the FWHM values, and it was observed that the source with the SLHG organic lens had a higher FWHM, representing a more uniform DUV energy density. This was mainly attributed to the fact that the SLHG organic lens enhanced the radiant power and expanded the divergence angle of a single-packaged device. With a further increase in the pitch, the power density of the integrated sterilization light sources decreased and the uniformity tended to be stable; for convenience, 9 mm was selected as the optimized pitch to theoretically evaluate their ability in SARS-CoV-2 inactivation. The inactivation performance of the DUV light sources was investigated, as shown in Figure 4c. Generally, continuous treatment with the commonly used ethanol and 2-propanol sterilization solutions at a concentration of greater than 30% (vol/vol) for a period of 30 s can inactivate coronavirus.\[^{31}\] For the DUV-LEDs, the inactivation time was calculated based on a quantitative evaluation in previous research on SARS-CoV-2,\[^{32}\] and the detailed irradiation doses of
DUV light at different wavelengths are given in Table S4, Supporting Information. The results indicated that inactivation times of 1.37 and 1.82 s were required for 275 nm to inactivate 99.9% of SARS-CoV-2 when the sources were packaged with the SLHG organic lens and quartz lens, respectively. The inactivation time could be reduced by \( \frac{1}{4} \times 25\% \) when using the SLHG organic lens, unambiguously demonstrating the remarkable enhancement of the light extraction efficiency. Therefore, the SLHG composites showed great potential for use in highly efficient DUV-LEDs, which could accelerate their application in fast sterilization.

3. Conclusion

Herein, SLHGs were proposed to fabricate organic lenses for DUV-LEDs, which largely enhance the light extraction efficiency without sacrificing the working stability. The infrared transmittance spectra proved that solid-state cross-linked networks of PDMS could be utilized to maintain the liquid components of silicone oil and endowed the SLHG structure with excellent formability, DUV transparency (over 90% transmittance in the UVC range), and thermal stability. Furthermore, an optimized SLHG lens (with an 85% liquid proportion) was applied to a DUV-LED (275 nm), and the results indicated that the radiant power of the device was enhanced by 52.5% compared to a commercial quartz lens, achieving a record POE of 1.31 among solid-state packaging DUV-LEDs. A sterilization evaluation for SARS-CoV-2 demonstrated that the inactivation time could be reduced by \( \approx 25\% \) using the SLHG organic lens. Consequently, herein, a feasible and effective method of enhancing the optical performance of DUV-LEDs and advance their promising potential for disinfection applications is provided.

4. Experimental Section

**Materials:** The DUV-LED devices without encapsulants were purchased from Foshan NationStar Optoelectronics Co. Ltd, China; their peak emission wavelengths were 275 and 310 nm. The liquid components of silicone oil and the solid precursors of PDMS were purchased from Dow Corning, USA.

**Preparation of SLHGs:** The liquid components of silicone oil and solid precursors of PDMS with a specific mass ratio were mixed uniformly by vacuum mechanical stirring and then moved to an oven to cure the solid components. A matrix curing temperature of 90°C was applied for 2 h to ensure that the solid precursors were completely cross-linked to form solid-state networks.

**Device Fabrication:** For the devices with an SLHG organic lens, the liquid components of silicone oil and solid precursors of PDMS were first mixed by vacuum mechanical stirring, and then the prepared SLHG slurry was dispensed onto the DUV-LED chip with a specific mass. Subsequently, the devices were moved to an oven at a temperature of 90°C for 2 h to obtain the devices with SLHG organic lenses with various curvatures. Similarly, devices with commercial organic lenses were prepared following the same procedures. Six samples of DUV-LED devices were used for each experiment.
Characterization: The absorbance and transmittance spectra of the silicone, SLHG composites, and commercial composites were measured using a UV–vis spectrometer (Shimadzu, Japan). The optical performances of the DUV-LEDs were measured using an integrating sphere system from Instrument Systems, Germany, where the injection current was provided by a power source (Keithley, USA). The infrared transmittance spectra of the solid precursors, liquid components, cured AS-PDMS composite, and SLHG composites were measured using a Fourier transform infrared spectrometer (Bruker, USA). DSC and TGA of the SLHG composites were performed using a thermal gravimetric analyzer (NETZSCH, Germany). The temperature program was as follows: heat from 30 to 820 °C at a heating rate of 10 °C min⁻¹ in a nitrogen atmosphere with a purge rate of 10 mL min⁻¹.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available in the supplementary material of this article.

Keywords

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