Linearly polarized GaN micro-LED with adjustable directional emission integrated with a continuous metasurface

Hanbin Zhang; Hancheng Wang; Jian Du; Wenhao Chen; Jin Wang; Junjun Xue; Ting Zhi

J. Appl. Phys. 136, 023106 (2024)
https://doi.org/10.1063/5.0211495
Linearly polarized GaN micro-LED with adjustable directional emission integrated with a continuous metasurface

Hanbin Zhang, Hancheng Wang, Jian Du, Wenhao Chen, Jin Wang, Junjun Xue, and Ting Zhia)

AFFILIATIONS
College of Electronic and Optical Engineering & College of Flexible Electronics (Future Technology), Nanjing University of Posts and Telecommunications, Nanjing 210023, People’s Republic of China

a)Author to whom correspondence should be addressed: zhit@njupt.edu.cn

ABSTRACT
Traditional LEDs emit light that exhibits incoherence and displays a Lambertian distribution. To achieve linearly polarized (LP) light and control the emission direction, a variety of optical components are required to be stacked, which is unsuitable for compact applications and results in low deflection efficiency. Here, we propose and numerically simulate a novel single-chip micro-resonant cavity LED (micro-RCLED) device that generates directional LP light by integrating a continuous metasurface. This device includes a bilayer grating at the GaN layer’s bottom, providing high transverse electric (TE) reflectivity above 89.5% and an extinction ratio exceeds 57 dB at 500 nm. The top distributed Bragg reflector (DBR) and the bilayer grating together constitute a TE mode Fabry–Pérot resonant cavity. This not only promotes the emission of the TE wave, but also guarantees its collimation with the appropriate phase, thereby enhancing its spatial coherence. A functional metasurface above the DBR layer precisely controls the TE wave’s deflection angle. It maintains a low aspect ratio while enabling efficient, large-angle deflection. The simulation results demonstrate that this device provides an effective solution for generating highly spatially coherent directional LP light, with broad potential applications in fields such as polarized light imaging and advanced 3D micro-LED display systems.

I. INTRODUCTION
Micro-LED, a pioneering display technology, boasts a multitude of advantages such as superior brightness, eco-friendliness, and extraordinary stability, thus establishing itself as a highly promising direction for the future of display technology.1–7 leveraging this technology, polarized light emission has found extensive applications across various sectors like 3D displays and polarized light imaging.8–12 Typically, micro-LEDs exhibit a Lambertian-shaped emission pattern, low spatial coherence, and feeble anisotropy.13 Efforts have been made to achieve polarized emission through the application of asymmetric in-plane biaxial stress on quantum wells within LED structures grown on non-polar or semi-polar GaN substrates.14–17 however, these configurations suffer from unsatisfactory extinction ratio (ER) that render them impractical for real-world use. Alternative studies have employed waveplates or bulky birefringent polarizers to manipulate polarization states,18 yet these devices are not conducive to integration.

A sub-wavelength metal grating on the emitting surface of micro-LEDs can facilitate linearly polarized (LP) light emission by fine-tuning its structural parameters to modulate the transmission or reflection of transverse magnetic (TM) and transverse electric (TE) waves.19–22 Despite enabling LP light production, this method encounters challenges with high metal loss and uncontrollable emission direction, making effective regulation and control of polarized light difficult.

To control the angle of the light emitted by the LED, many studies first enhance the spatial coherence of the light beam by integrating a resonant cavity, then achieve the desired angular deflection using a discrete metasurface located above the structure.23–27 While this integration method achieves control of the emission angle of LED light, the light beam exhibits nonlinear polarization. Consequently, it is unable to achieve the directional emission of linearly polarized light. Moreover, the use of discrete, specialized metasurfaces comes with inherent drawbacks: complex fabrication...
processes, reduced robustness, limited deflection angles, and substantial energy loss due to discontinuous phase gradients.\textsuperscript{26–30}

In this study, we introduce a novel micro-RCLED device. A double-layer grating is designed as the bottom reflector of the device instead of the traditional metal reflector for reducing the metal loss, which together with the upper distributed Bragg reflector (DBR) constitutes a TE-mode resonant cavity. This innovative design not only enables control of the micro-LED to emit linearly polarized light with a singular polarization direction but also enhances the spatial coherence of the linearly polarized light, shaping its radiation pattern. After optimization, the nano-grating’s TE wave reflectivity can reach 89.5% and the ER exceeds 57 dB at 500 nm for the micro-LED. In order to precisely control the emission angle of LP light, a continuous metasurface composed of an array of trapezoidal nanoantennas, a simplified structure for suitable fabrication, is designed for a seamless phase shift range from 0 to $2\pi$. In contrast to traditional discrete metasurfaces, this design demonstrates the capability to manipulate light with a fixed polarization direction, achieving substantial angular deflections with high deflection efficiency. The beam deflection efficiencies of the device at 20°, 30°, and 50° are 48.7%, 42.3%, and 30.7%, respectively. The proposed micro-RCLED with integrated a continuous metasurface not only generates TE waves at a designated angle but also showcases potential applications in cutting-edge technologies such as 3D micro-LED displays and polarized light imaging.

II. RESULTS AND DISCUSSION

Figure 1(a) illustrates the schematic of a GaN-based micro-RCLED designed for directional emission of linearly polarized light. The emission properties were meticulously simulated using the finite-difference time-domain (FDTD) method, with the simulation region discretized into three-dimensional grids and perfectly matched layers (PML) incorporated in the $x$, $y$, and $z$ directions as boundary conditions to mimic open-space conditions. The device incorporates a standard vertical LED structure composed of p-GaN, n-GaN, and an active layer featuring multiple quantum wells (MQWs), which emit at a wavelength of 500 nm. Typically, light emitted from micro-LEDs follows a Lambertian distribution, demonstrating limited spatial coherence and non-linear polarization behavior.

Unlike the conventional single-layer sub-wavelength metal grating, our design incorporates a MgF$_2$ layer with a refractive index lower than that of GaN, inserted between the metal grating and the GaN layers to create a transition layer that enhances constructive interference within the nano-grating structure. Figure 1(b) provides a cross-section view of the micro-RCLED, showcasing the structural parameters of the bottom nano-grating. This grating comprises a transition layer made of MgF$_2$ and an aluminium metal grating layer. Key parameters include the nano-grating period ($P_1$), linewidth ($W_1$), thickness of the transition layer ($H_1$), metal grating layer thickness ($H_2$), and duty cycle ($D$), mathematically defined as $D = W_1/P_1$. The reflectivity of the TE wave ($R_{TE}$) and TM wave ($R_{TM}$) from the nano-grating was computed using a 2D FDTD method with a minimum grid resolution of 1 nm. The substrate material used is GaN, characterized by a refractive index around 2.45.

An investigation was carried out to study the effects of $D$ and $P_1$ on $R_{TE}$ and $R_{TM}$, with parameters $H_1$ and $H_2$ fixed at 30 nm and 200 nm, respectively. The working wavelength of the incident light is 500 nm. In Fig. 2(a), $R_{TE}$ steadily rises as $P_1$ increases, achieving a maximum value of 0.91. Figure 2(b) illustrates the relationship between $R_{TM}$, $D$, and $P_1$, where $R_{TM}$ consistently remains lower than $R_{TE}$ across the scanned range. Notably, when $D$ ranges from

![Fig. 1. (a) Schematic diagram of the micro-RCLED structure with an integrated continuous metasurface, which can emit the TE wave directionally. (b) Cross section view of the micro-RCLED.](image-url)
0.6 to 0.7, $R_{\text{TM}}$ tends toward zero, signifying effective suppression. To assess the polarization selectivity of the nano-grating, we employed the reflectivity ER as an indicator of performance: $\text{ER} = 10 \log \left( \frac{R_{\text{TE}}}{R_{\text{TM}}} \right)$. As shown in Fig. 2(c), $R_{\text{TE}}$ maintains a high level throughout the variation range, whereas $R_{\text{TM}}$ remains relatively low. The peak ER performance occurs when $P_1$ is set at 161 nm. With $D$ varying from 0.3 to 0.8, $R_{\text{TE}}$ sustains a relatively large and stable value within the investigated range. Meanwhile, Fig. 2(d) reveals that $R_{\text{TM}}$ reaches its minimum, approaching nearly zero. A peak ER value exceeding 57 dB is achieved when $D$ is set at 0.64, demonstrating the nano-grating’s highly effective polarization selection capabilities.

Figures 3(a) and 3(b) present the two-dimensional simulation charts of $R_{\text{TE}}$ and $R_{\text{TM}}$, respectively, as functions of $H_1$ (spanning 10–100 nm) and $H_2$ (ranging from 80 to 220 nm). In Fig. 3(a), $R_{\text{TE}}$ surpasses the value of 0.85 and can escalate up to a maximum of 0.95, with its performance primarily governed by $D$, $P_1$, and $H_1$, while exhibiting notably low sensitivity to changes in $H_2$. In Fig. 3(b), $R_{\text{TM}}$ exhibits a tendency toward zero when the thickness of $H_1$ varies from 10 to 40 nm and that of $H_2$ spans between 180 and 220 nm. Figure 3(c) shows ER initially increases and then decreases with $H_1$, peaking at an $H_1$ thickness of 30 nm with an ER exceeding 57 dB. In Fig. 3(d), both $R_{\text{TM}}$ and ER attain their minimum and maximum values respectively when $H_2$ is set to 200 nm. Thus, a precisely designed MgF$_2$-Al bilayer grating nano-grating has been configured, with $H_1$ of 30 nm, $H_2$ of 200 nm, $P_1$ of 161 nm, and $D$ of 0.64. The optimized nano-grating design ensures a high $R_{\text{TE}}$ of 89.5% and an exceptional ER exceeding 57 dB at a wavelength of 500 nm.

The bottom nano-grating’s high $R_{\text{TE}}$ and ER performance at 500 nm is confirmed, yet considering the typical 20 nm linewidth of LEDs, the effectiveness of the nano-grating across a broader

![Figure 2](image-url)
spectrum is investigated by examining $R_{TE}$, $R_{TM}$, and ER between 480 and 520 nm. In Fig. 4(a), the dashed line distinctly demonstrates that within this 20 nm linewidth, the ER exceeds the threshold of 20 dB. Concurrently, $R_{TE}$ maintains a value around 0.9, and $R_{TM}$ approaches near-zero levels, which collectively signify a consistently robust and highly polarized output performance. Within a reasonable manufacturing deviation range (10%), the bottom nano-grating reflector also demonstrates notable robustness and a high degree of fault tolerance (see Fig. S2 in the supplementary material). By incorporating a resonant cavity, the collimation of micro-LED light emission can be enhanced, thereby facilitating the reduction of optical crosstalk between neighboring pixels and thus improving display performance. Concurrently, the emitted light attains high spatial coherence, thereby favoring further control in functional metasurfaces applications. The design of the DBR of the resonant cavity is closely related to the absorption characteristics of the micro-LED.\(^{31}\)

Given the absorption losses inherent to micro-LEDs, reflectors with moderate reflectivity should be used on the emitting surface (n-GaN surface) to avoid excessive intra-cavity light reflection and reduce absorption losses. The top DBR is constructed with alternating layers of SiO$_2$ and TiO$_2$, that exhibit high ratio of refractive index within the visible spectrum and exhibit minimal absorption losses. Each layer’s thickness is calculated to satisfy the quarter-wavelength criterion, thereby ensuring an impressive level of reflectance.\(^{32}\) As such, the individual layer thicknesses are set to 66 nm for TiO$_2$ and 94 nm for SiO$_2$. For the non-emitting surface of the LED (p-GaN surface), high reflectivity reflectors should be used to prevent specific light leakage. Combining the designed dual-layer nanograting as the bottom reflector of the LED with the top DBR forms a TE-mode resonant cavity, beneficial for emitting high spatial coherence TE wave in the micro-RCLED, aligning with the targeted functionalities of this
For the cavity length of the FP resonant cavity, it can be derived as

\[ L = \frac{m \lambda}{2n} \]  

where \( L \) represents the cavity length, \( n \) is the approximate refractive index of micro-LEDs, \( m \) is the cavity order which is an integer, and \( \lambda \) corresponds to the emission wavelength which is 500 nm in this study. Ensuring that the length of the resonant cavity aligns with the standing wave requirements within the cavity is crucial for satisfying the resonance conditions. For the achievement of interference enhancement, the electric dipole should be strategically positioned at the antinode of the standing wave electric field. In this study, the dipole’s position, which is the photon generation site...
in the MQW, is approximately at the center of the resonant cavity (see Fig. S1 in the supplementary material). To mitigate the impact of sidewall leakage,\textsuperscript{33} the order of the resonant cavity \((m)\) is set to 4 in simulation. Subsequently, numerical simulations are conducted to investigate the correspondence between far-field emission patterns and the number of DBR stack pairs, with the results presented in Fig. 4(b). As the number of DBR pairs increases below 6 units, the width of the main emission gradually reduces, indicating that a higher number of DBR stack pairs leads to better collimation of the resonant cavity beam. However, when the number of DBR pairs exceeds 6, this upward trend noticeably slows down, implying that extra stack layers in the DBR offer no further advantages, it also results in narrowing bandwidth and thickening of the overall structure as a counter effect.\textsuperscript{27} Therefore, we opted for a configuration composed of six pairs of TiO\textsubscript{2}/SiO\textsubscript{2} stacked DBR layers. This configuration effectively optimizes the spatial coherence and directional collimation of emission light in the micro-RCLED while maintaining a balance between structural complexity and performance advantages.

The micro-RCLED, engineered to emit the TE wave with high spatial coherence, is the subject of our simulation. In the simulation of radiation patterns for various micro-LED structural configurations, the inherent spontaneous emission of electron-hole pairs in the active layer of GaN micro-LEDs is modeled as horizontal and vertical electric dipoles. These correspond to the transmission and emission of TE and TM waves, respectively. The emission wavelength of the electric dipole is 500 nm. To prevent the generation of non-physical coherent effects among different dipole sources, only a single dipole source is permitted to be positioned in the MQW layer during the simulation.\textsuperscript{34} Perfectly matched layer (PML) boundary conditions are applied at the boundaries to absorb outgoing waves. In Fig. 5(a), three distinct configurations of micro-LEDs are presented: a standard micro-LED (a-I), a micro-LED equipped with a bottom nano-grating (a-II), and a micro-RCLED integrated with a resonant FP cavity (a-III). To substantiate the polarization selectivity of the nano-grating and the collimation effect of the resonant cavity on the initial broad Lambertian angular distribution, Fig. 5(b) provides corresponding radiation patterns for each
configuration. To illustrate the emission performance of the three devices, we define the light extraction efficiency ($\eta_{\text{extra}}$) as

$$\eta_{\text{extra}} = \frac{P_{\text{out}}}{P_{\text{source}}},$$

where $P_{\text{out}}$ represents the optical power received by the monitor and $P_{\text{source}}$ denotes the total optical power emitted by the active layer. This study primarily simulates the numerical variations in light extraction efficiency under specific optical structures compared to conventional micro-LEDs, analyzing the influence of various optical components on the efficiency. Figure 5(a-I) schematically portrays the structure of a conventional micro-LED, while Fig. 5(b-I) reveals its radiation pattern that exhibits a classic Lambertian distribution with a half-power intensity angle of 80°, indicating the poor directionality in emission for standard micro-LEDs. $\eta_{\text{extra}}$ of this device is 8.7%. Upon incorporating the bottom nano-grating, the angular distribution of the TE wave shows a significant narrowing along the surface normal, with its half-power angle reducing to about 50°, as depicted in Fig. 5(b-II). Due to the integration of a reflector at the bottom, $\eta_{\text{extra}}$ of the micro-LED increases to 15.5%. Upon constructing a resonant cavity, the micro-RCLED [depicted in Fig. 5(a-III)] shows its TE wave emission predominantly along the surface normal axis. The original Lambertian distribution is thereby transformed into a much narrower angular range, with a significantly reduced half-power angle of approximately 20°, as illustrated in Fig. 5(b-III). Part of the light is confined and modified within the cavity. Even then, $\eta_{\text{extra}}$ can still reach 10.9%. The device integrated with the TE mode FP resonant cavity can significantly emit a highly collimated and coherent TE wave that closely approximates a plane wave, making it an ideal light source for integration with the functional metasurfaces above.

Unlike conventional discrete metasurfaces, the continuous metasurface adopted for device integration boasts not only a more straightforward fabrication geometry but also mitigates energy loss, facilitates large-angle beam steering, and exhibits polarization selectivity. To simplify computational complexity without sacrificing accuracy, periodic boundary conditions are applied along the $x$ and $y$ axes in accordance with the structure’s inherent periodicity, while PML is introduced in the $z$ axis direction to absorb reflections and scattering effects. Considering the high polarization and spatial coherence of the light emitted by the micro-RCLED, TE-polarized plane wave is chosen as the incident light source to accelerate calculation time and streamline the simulation process. The design methodology commences with a discrete metasurface configuration,
progressively transitioning to the continuous metasurface design, thereby allowing for optimization and enhanced performance characteristics.

As depicted in Fig. 6(a), the rectangular nanocolumn serves as the fundamental discrete metasurface, featuring cross-sectional widths ($W_2$) and a unit height ($H_3$) of 280 nm, with a periodicity ($P_2$) of 140 nm. The metasurface material is GaP, characterized by its high refractive index of approximately 3.57, which exhibits low absorption loss and ensures high transmittance within the targeted wavelength spectrum. The substrate material chosen is SiO$_2$, having a refractive index of 1.45, also known for its low absorption and high transmittance in the desired wavelength range. By adjusting $W_2$, it becomes possible to achieve a variety of phase shifts spanning from 0 to 2$\pi$, thereby creating a discrete phase gradient that adheres to the generalized Snell’s law,$^{35}$

$$n_1 \sin \theta_1 - n_2 \sin \theta_2 = \frac{\lambda_0}{2\pi} \frac{d\varphi}{dx},$$  

where a fixed phase gradient can be established at the interface between neighboring nanocolumns, thereby achieving beam deflection. The deflection angle $\theta_2$ is determined by the generalized Snell’s law, which relies on the incident angle $\theta_1$, the refractive indices of the materials $n_1$, $n_2$, the wavelength of the wave in free space $\lambda_0$, and the phase gradient $d\varphi/dx$.

Figure 6(b) presents a period of the discrete metasurface, composed of nanocolumns with varying side lengths $W_2$, where a uniform phase gradient is maintained between adjacent unit, thereby manifesting as a progression of phase shifts spanning from 0 to 2$\pi$ across different nanocolumns. Upon normal incidence of plane waves on this configuration, the beam undergoes deflection according to Eq. (3). Figure 6(c) illustrates that when $W_2$ varies between 20 and 120 nm, the transmittance remains notably high, while the phase shift can span the entire range of 0–2$\pi$. The observed dip in the transmission curve is attributed to the occurrence of FP resonance within the nanocolumns, corresponding to resonance valley. In Fig. 6(d), eight distinct nanocolumns with incremental increases of $\pi/4$ in $W_2$ are chosen to fully cover the required phase shift range from 0 to 2$\pi$, thereby serving as the fundamental building blocks for assembling the continuous metasurface.

A single large isosceles trapezoidal nanocolumn replaces the discrete configuration of eight smaller nanocolumns [Fig. 7(a-II)], as visualized in Fig. 7(a-II). Figure 7(b) outlines the design of the continuous metasurface unit, characterized by an isosceles trapezoidal cross section with upper side length $W_3$, lower side length $W_4$, length $L_\text{x}$, individual nanocolumn height $H_3$, and periodicity $P_\text{x}$ and $P_\text{y}$ along the $x$ and $y$ axes, respectively. By meticulous parameter tuning, a seamless phase shift progression from 0 to 2$\pi$ is achieved across the $P_\text{x}$ dimension of the continuous metasurface.

The deflection angle of the beam can be calculated using the generalized Snell’s law,

$$\theta_2 = \arcsin \left( \frac{m_0 \lambda_0}{P_\text{x}} \right),$$  

where $\lambda_0$ represents the wavelength of the incident light, $P_\text{x}$ is the period of the structural unit, and $m_0$ is an integer indicating the order of the diffracted wave. When $m_0$ equals 0, it denotes zero-order diffraction with no wave deflection, whereas for non-zero values of $m_0$, it signifies high-order diffraction implying a deflected wave. The realization of the maximum deflection angle occurs when the initial zero-order diffraction shifts to the first-order position. Initial design of the continuous metasurface parameters aims to achieve a 30° deflection. The period $P_\text{x} = 1000$ nm is calculated using Eq. (4). Optimization of other parameters yields the final continuous metasurface structure, with the parameters summarized in Table 1.

Subsequent verification confirms that the continuous metasurface unit structure effectively realizes a continuous phase shift from 0 to 2$\pi$, as depicted in Fig. 7(c), which presents the phase shift lines of the transmitted light at various wavelengths of 480/500/520 nm. To visualize the full 2$\pi$ phase shift cycle, the starting point of the line corresponding to 520 nm is adjusted to the phase shift of 2$\pi$. Figure 7(d-I) exhibits the normalized light intensity distribution diagram above the structure, revealing significant beam deflection at 30°. Meanwhile, Fig. 7(d-II) displays the phase distribution of the transmitted light at the micro-LED emission wavelength of 500 nm, highlighting the characteristics of the plane wavefront.

By adjusting the parameters $P_\text{x}$ and $L_\text{x}$ of the trapezoidal nanocolumn unit to enable the incident plane wave to deflect at different angles. To validate the deflection performance of this structured surface, a phase shift diagram above the structure, revealing significant beam deflection at 30°. Meanwhile, Fig. 7(d-II) displays the phase distribution of the transmitted light at the micro-LED emission wavelength of 500 nm, highlighting the characteristics of the plane wavefront.

### Table 1. Unit structure parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$W_3$</th>
<th>$W_4$</th>
<th>$H_3$</th>
<th>$L_\text{x}$</th>
<th>$P_\text{x}$</th>
<th>$P_\text{y}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value (nm)</td>
<td>60</td>
<td>110</td>
<td>273</td>
<td>830</td>
<td>1000</td>
<td>140</td>
</tr>
</tbody>
</table>

The absolute deflection efficiency ($\eta_\text{abs}$) and relative deflection efficiency ($\eta_\text{rela}$) at continuous metasurfaces of 20°, 30°, and 50°.
continuous metasurface, two parameters are introduced: absolute deflection efficiency (\(\eta_{\text{abs}}\)) and relative deflection efficiency (\(\eta_{\text{rela}}\)). The absolute deflection efficiency (\(\eta_{\text{abs}}\)) is defined as the ratio of the light power of the deflected beam (representing +1 order diffraction) to the total incident power. Relative deflection efficiency (\(\eta_{\text{rela}}\)) is defined as the ratio of the light power of the deflected beam (representing +1 order diffraction) to the total transmitted light efficiency, that is, the proportion of the required deflection angle light in the transmitted light power. Figure 8 illustrates that the relative deflection efficiency (\(\eta_{\text{rela}}\)) of this continuous metasurface is 90.35%, 91.8%, and 76.5% when deflected at 20°, 30°, and 50°, respectively, while the absolute deflection efficiency (\(\eta_{\text{abs}}\)) is 66.5%, 76.8%, and 49.4%, respectively. \(\eta_{\text{abs}}\) consistently exhibits lower than \(\eta_{\text{rela}}\) at the same deflection angle, attributable to the influence of the material’s interface reflectivity and absorption. The high-performance continuous metasurface, as we designed, can be integrated above the emission surface of the micro-RCLED to achieve the emission of TE polarized light at a specific angle. The TE mode resonant cavity integrated into the device employs a bottom nano-grating reflector to reflect light emitted by the active layer’s dipoles of the micro-LED and reflected light from the top back to the top, thereby enhancing the spatial coherence and collimation of the emitted TE wave. By strategically arranging continuous metasurface units with varying parameters on the emission surface (the top DBR) of the micro-RCLED, which emits a wavelength of 500 nm, we can modulate the emitted light to angles ranging from 20°, 30°, up to 50°. The numerical simulation results are depicted in Figs. 9(a-I)–9(a-III). To quantify the deflection performance of the micro-RCLED integrated with a continuous metasurface, the beam deflection efficiency (\(E_B\)) of the device is defined as

\[
E_B = \frac{P_0}{P_1},
\]

where \(P_0\) represents the effective radiation power collected within a specific angle range by the micro-RCLED with deflection emission capability, while \(P_1\) represents the total radiation power of the micro-RCLED. For devices with deflection emission angles of 20°, 30°, and 50°, \(P_0\) corresponds to the effective radiation power within the ranges of 15°–25°, 25°–35°, and 45°–55°, respectively. The calculated \(E_B\) for the micro-RCLED at emission angles of 20°, 30°, and 50° are 48.7%, 42.3%, and 30.7%, respectively. As the deflection angle increases, the deflection efficiency decreases, while the light intensity of other diffraction orders gradually strengthens. Furthermore, an aspect ratio, the relationship between the smallest feature size of the nanocolumn unit and the overall height of the structure, is introduced to assess the complexity of the structure.

The micro-RCLED designed in this study can efficiently emit TE waves in different directions by integrating a continuous metasurface with varying structural parameters. Furthermore, it can also achieve a large beam deflection of up to 50°. The performance of the device is intrinsically linked to the size of the micro-LED.
Effective directional TE wave emission can be realized when the device size surpasses 3 μm. Moreover, as the size of the device escalates, the beam deflection efficiency correspondingly enhances (see Figs. S5 and S6 in the supplementary material). And the continuous metasurface has an aspect ratio of only 4.55, and a lower aspect ratio facilitates easier processing and manufacturing.

III. CONCLUSION

In conclusion, GaN micro-RCLED with a continuous metasurface is designed to emit the TE wave directionally, exhibiting significant beam deflection capabilities. The bilayer grating, integrated at the bottom of the structure, functions as a reflector for the TE mode. Through the optimization of the nano-grating structure, the ratio of R_{TE} surpasses 89.5%, and the ER attains a value higher than 57 dB at 500 nm for the micro-LED. The top DBR and the bottom nano-grating form a FP resonant cavity, which makes the micro-RCLED emit the TE wave with good spatial coherence. This results in an effective beam shaping effect, with a half-power angle of merely 20°. To realize the deflection effect of the TE wave, the continuous metasurface is integrated above the top DBR. Boasting an impressively low aspect ratio of 4.55, the continuous metasurface not only features a simple structure and strong robustness (see Figs. S3 and S4 in the supplementary material), but also exhibits exclusive polarization selectivity, effectively deflecting only the TE wave. The innovative device designed in this study combines high levels of integration with superior deflection efficiency, thus presenting promising applications across various sectors including polarized light imaging technologies and advanced 3D micro-LED display systems.

SUPPLEMENTARY MATERIAL

See the supplementary material for the electric distribution of the electric field within the resonant cavity, the influence of parameter variations (height, linewidth) on the nano-grating’s performance, the effect of a reasonable manufacturing deviation (10%) on the transmittance and deflection capabilities of the continuous metasurface, and the light intensity distribution along with the beam deflection efficiency for micro-RCLEDs of various sizes (3, 6, and 10 μm) with a 30° deflection.

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.