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Bidirectional high-speed optical wireless communication enabled by dual-mode blue micro-LEDs: 5.81 Gbps downlink and 1.52 Gbps uplink

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Optical wireless communication (OWC) is an important complement to traditional radio frequency (RF) communication. Micro-LEDs are desirable emitters for OWC, offering high bandwidth and efficiency [1]. Unlike lasers, which require strict alignment and raise safety concerns, micro-LEDs are cost-effective and eye-safe. LEDs can also function as detectors in an OWC system [2], allowing a single device to perform both roles, reducing cost and alignment complexity. Early studies using large LEDs as detectors suffered from low bandwidths [2], whereas micro-LEDs enhance bandwidth due to their lower capacitance, resulting in higher detection bandwidth. Compared to Si-based p-type–intrinsic–n-type (PIN) photodiodes, the narrower absorption spectrum of GaN micro-LEDs can improve signal-to-noise ratio (SNR) by filtering ambient light. Currently, there is still limited research on using micro-LEDs as both the transmitter and receiver in OWC systems.

Here, we report a micro-LED-to-micro-LED system achieving 5.81 Gbps downlink and 1.52 Gbps uplink. The communication system uses violet micro-LEDs ranging from 40 to 100 µm and blue micro-LEDs ranging from 60 to 100 µm. The downlink uses a violet micro-LED to transmit the signal and a blue micro-LED to receive the signal, while the uplink uses a blue micro-LED to transmit the signal, with the optical signal passing through a semi-transparent violet micro-LED and being received by an avalanche photodiode (APD), forming a compact and alignment-friendly duplex link. Detailed configurations and data are provided in Appendixes A–D.

As illustrated in Figure 1, the proposed bidirectional visible light communication system enables everyday light sources, such as automotive headlights and outdoor LED displays, to simultaneously act as data transmitters and receivers. This dual-role capability paves the way for the ubiquitous, low-cost deployment of high-speed optical wireless links in intelligent transportation and smart-city scenarios.

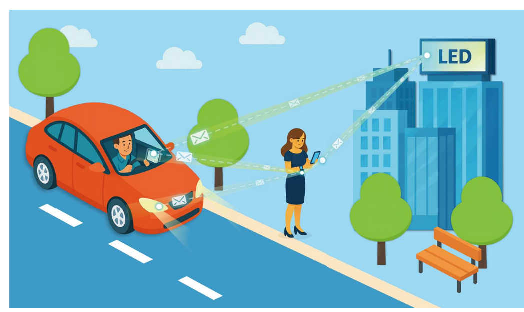

Figure 1 (Color online) LED applications as both detectors and emitters in bidirectional visible light communication.

Device fabrication and characteristics. The epitaxial wafer used for fabricating the micro-LEDs was grown on patterned sapphire substrates via metal-organic chemical vapor deposition (MOCVD). The structure consists sequentially of a GaN buffer layer, n-GaN layer, stress release layer (SRL), multi-quantum wells (MQWs) layer, electron-blocking layer (EBL), p-GaN layer, and indium tin oxide (ITO) layer. A transmission electron microscopy (TEM) image highlights the morphology of the quantum wells and the five-layer stress release structure (Appendix B). This superlattice SRL effectively mitigates the strain resulting from the lattice mismatch, reducing dislocation density. This improvement is pivotal for maintaining high internal quantum efficiency (IQE) and minimizing leakage current, which is critical for detector sensitivity. For the blue micro-LED detector, we designed 11 pairs of quantum wells to reduce its unit-area capacitance [3], whereas the violet emitter incorporates 12 pairs to enhance emission intensity. The peak wavelengths of micro-LEDs were controlled at 450 and 400 nm, respectively. The standard fabrication process of micro-LEDs includes mesa etching, rapid thermal annealing for ohmic contact, SiO_2 passivation via plasma-enhanced chemical vapor deposition (PECVD), and electrode sputtering.

The fabricated devices exhibit excellent optical performance. The 100 µm blue micro-LED detector exhibits a peak response at 380 nm with a full width at half maximum (FWHM) of 59 nm. This narrow detection spectrum enhances the ability to filter out optical noise. The violet emitter maintains a peak output wavelength of 400 nm, with FWHM broadening slightly from 14.1 to

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15.8 nm as current increases from 10 to 100 mA. The significant spectral overlap between the violet emission and blue detection ensures efficient signal transmission. Furthermore, violet micro-LEDs of all sizes achieved output powers exceeding 10 mW, with the 100 µm device surpassing 25 mW, comparable to typical laser diodes (Appendix B).

Link configuration. The experimental setup for the bidirectional link is detailed in Appendix A. For the downlink, the violet micro-LED is driven by an arbitrary waveform generator (Keysight M8190A) via a bias-tee (Mini-Circuits ZFBT-6GW+) and an amplifier (Mini-Circuits ZFL-2500VH+). The optical signal propagates through 45 cm of free space and is focused by a lens onto the blue micro-LED detector. At the receiver, a reverse bias is applied to the blue micro-LED to enhance its bandwidth and responsivity. The detected signal is separated by a bias-tee, amplified by a transimpedance amplifier (70 dBΩ gain, 2 GHz bandwidth), and captured by an oscilloscope for offline orthogonal frequency-division multiplexing (OFDM) demodulation. For the uplink, the blue micro-LED is driven by an arbitrary waveform generator (Keysight M8190A) via a bias-tee (Mini-Circuits ZFBT-6GW+) and an amplifier (Mini-Circuits ZFL-2500VH+). The optical signal is transmitted through a semi-transparent violet micro-LED and propagates to an APD for detection. The detected signal from the APD is captured by an oscilloscope for offline OFDM demodulation. See Appendixes A and C for detailed parameters.

Downlink results and discussion. The bandwidth of the blue micro-LED detectors was measured under varying reverse bias voltages, and the frequency responses at different bias voltages are summarized in Appendix B. At low bias, the bandwidth increases exponentially due to the carrier lifetime in the MQWs layer. However, when the bias exceeds −15 V, the rate of bandwidth increase gradually slows down as the resistance–capacitance (RC) time constant becomes the dominant limitation [4]. At −30 V, the blue micro-LED detectors with mesa sizes of 60, 80, and 100 µm achieved bandwidths of 1.56, 1.22, and 0.95 GHz, respectively (Appendix B). The emission bandwidth of the violet micro-LED emitters is primarily governed by carrier lifetime, which is influenced by the driving current density. As current density increases, the emission bandwidth decreases due to thermal effects and saturation. The 40 µm emitter achieves the highest emission bandwidth, reaching 218.45 MHz at a current density of 4 kA/cm^2, whereas the 100 µm emitter achieves a maximum emission bandwidth of only 110.49 MHz. We systematically tested 12 combinations of emitter and detector sizes using OFDM modulation. The configuration employing a 40 µm emitter and an 80 µm detector achieved the highest data rate of 5.81 Gbps (bit error rate (BER) $< 3.8 \times 10^{-3}$). The relationship between the downlink communication speed and BER is summarized in Appendix D. This speed surpasses the fastest recorded data rate for micro-LED to micro-LED communication to date. Even the slowest 100 µm emitter achieved 3.29 Gbps (Appendix D). The key to achieving the highest communication speed is the balance between bandwidth and optical power. While smaller emitters, such as the 40 µm emitter, sustain higher current densities, leading to higher bandwidths (ranging from ∼100 to ∼200 MHz depending on size), the overall system performance is critically dependent on the detector. Smaller detectors (60 µm) offer higher bandwidth but reduced optical collection area, leading to lower photocurrent and SNR. Larger detectors (100 µm) collect more light but are bandwidth-limited by their capacitance. The 80 µm detector represents the optimal balance, providing sufficient bandwidth (1.22 GHz) while maintaining adequate signal collection, which ultimately results in the highest communication speed when paired with the 40 µm emitter. This demonstrates that co-optimizing emitter bandwidth, detector collection efficiency, and optical power is crucial for maximizing throughput.

Duplex link. One of the key advantages of using micro-LEDs as detectors is that a single micro-LED can handle both emission and detection, which reduces power consumption and cost. For uplink communication, we used the 80 µm blue micro-LED, which had the best performance in downlink tests. Instead of using complex optics with reflectors to separate the uplink and downlink paths [5], we allowed the uplink signal emitted by the blue micro-LED to pass through the violet micro-LED. This setup only required adding a lens and an APD behind the violet micro-LED, simplifying the system.

The transmittance of the violet micro-LED was crucial since the uplink light signal had to pass through it. We improved the transmittance by etching away the non-emitting GaN material and polishing the sapphire substrate, which increased the blue light transmittance by 14%. The light output power of the 80 µm blue micro-LED was 9.13 mW, and after passing through the optical components, 1.94 mW of power was collected at the APD, yielding a transmission efficiency of 21.2% (Appendix C).

Despite lower received power compared to the downlink, the uplink communication achieved a data rate of 1.52 Gbps using OFDM modulation with bit-loading and channel equalization. The relationship between the uplink communication speed and BER is summarized in Appendix C. The SNR was relatively lower, and not every subcarrier could carry signals. However, the data rate was well-matched to the downlink, ensuring balanced overall system performance.

Conclusion. In summary, under identical experimental conditions, we conducted optical communication tests using violet micro-LEDs with mesa sizes of 100, 80, 60, and 40 µm, paired with blue micro-LED detectors of 100, 80, and 60 µm, demonstrating a high-speed bidirectional micro-LED OWC system enabling 5.81 Gbps downlink and 1.52 Gbps uplink. The proposed semi-transparent chip duplex scheme provides a scalable, low-cost solution for future optical networks. By using micro-LEDs as both emitters and detectors, we eliminate the need for discrete photodiodes and lasers, enhancing eye safety and reducing system cost. This work not only proves that laser-free, high-speed communication is feasible but also lays a solid technical foundation for ubiquitous optical wireless communication integrated into everyday displays.

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Supporting information Appendixes A–D. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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