

Review

Recent Progress in GaN-Based High-Bandwidth Micro-LEDs and Photodetectors for High-Speed Visible Light Communication

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Abstract

Visible light communication (VLC) is an emerging communication technology that integrates lighting and communication, offering significant advantages in terms of data transmission rates and broad application prospects. With advancements in semiconductor technology, micro-light-emitting diodes (micro-LEDs) have emerged as one of the most promising light sources for high-speed VLC systems, owing to their high brightness, low power consumption, and high modulation bandwidth. Recent developments have also seen substantial progress in high-bandwidth GaN-based visible light detectors, which complement the transmission capabilities of micro-LEDs. This paper reviews the latest advancements in micro-LEDs as high-speed transmitters for VLC, detailing their capabilities in terms of bandwidth, data rates, modulation techniques, and diverse applications, including structured lighting systems that combine positioning, communication, and illumination. Additionally, the advantages of using micro-LEDs in GaN-based photodetectors (PDs) are discussed, highlighting their potential in enhancing bandwidth and data rates and facilitating high-speed communications across multifunctional applications. Therefore, this review will benefit the further development of micro-LEDs and their application in 6G communication and global interconnect.

Keywords: micro-LED; visible light communication; photodetector; positioning; interconnect

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1. Introduction

With the exponential growth of the internet of things (IoT) devices and applications, traditional radio frequency (RF) communication is facing increasing spectrum resource constraints and will not be able to meet the massive access and demand for high-speed wireless data rates. To broaden the spectrum resources, new spectrum resources, such as visible light, millimeter wave, and terahertz wave, have gained the attention of the academic community. Among these spectrum resources, visible light communication (VLC) can combine lighting and communication and provide very high data rates, so VLC is ideally suited for where humans exist in these indoor spaces [1]. Compared with traditional RF, VLC has the advantages of an unrestricted spectrum, great electromagnetic interference resistance, and a high transmission rate, which is considered to be an important part of the next-generation networks [2–4].

Current research about VLC devices focused on transmitter devices, including light-emitting diodes (LEDs), super-luminescent diodes (SLDs), and laser diodes (LDs). Among them, the technology of gallium nitride (GaN) LEDs is very mature and can provide stable modulated light sources for VLC systems, which can offer almost continuous coverage from

the deep ultraviolet (DUV) through to the red region [5]. However, due to the low inherent modulation bandwidth of LEDs of only tens of MHz, these LED-based VLC systems struggle to achieve higher transmission rates. In addition, due to the low-pass characteristics of the LED channel itself and the existence of inter-symbol interference (ISI) in the channel, the receiver cannot recover the correct signal, resulting in communication quality degradation problems. Different approaches, such as digital equalization/filter [6,7], spectrum-efficient modulation formats [8], and wavelength division multiplexing (WDM) [9], have been proposed to improve the performance of VLC. In addition to these methods, the emergence of micro-LEDs offers a new direction for improving the data rate of VLC systems. The micro-LEDs have a typical size from 1 to 100 μm , which has been widely researched for display applications. The micro-LEDs have the advantages of high brightness, low power consumption, and high modulation bandwidth, and are regarded as one of the most promising transmitters for high-speed VLC systems [10].

As shown in Figure 1, the VLC systems based on micro-LEDs are mainly divided into two categories: one is using micro-LED as the transmitter, and the other is using micro-LED as the receiver. In application scenarios where micro-LEDs serve as the transmitters of VLC systems, the usage can be categorized as high-speed VLC systems based on micro-LEDs, high-precision positioning systems utilizing micro-LEDs, and maskless lithography systems empowered by micro-LED positioning. In VLC-based micro-LED transmitters, due to the high bandwidth of micro-LED, VLC systems can reach a high data rate. The VLC based on the micro-LED transmitter has been widely studied and has achieved good results in both speed and distance. A recently reported VLC link based on a violet micro-LED can achieve data rates of more than 10 Gbps [11].

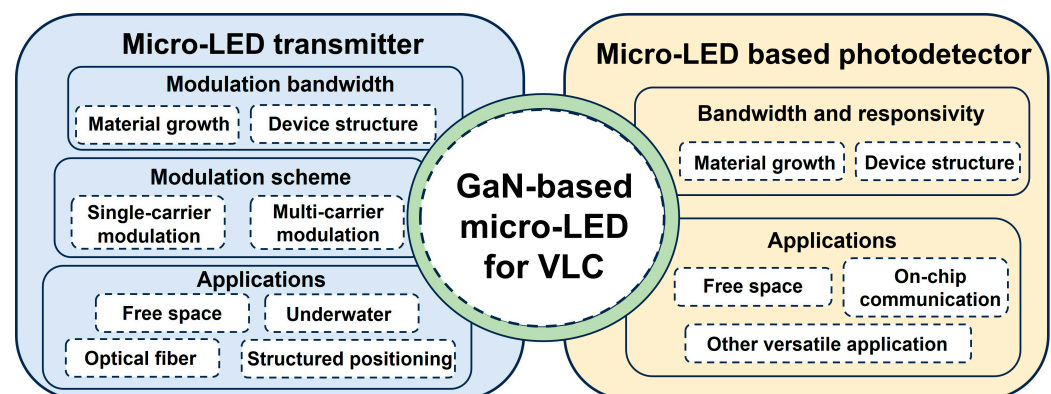


Figure 1. Summary of the recent progress in micro-LEDs as transmitters and receivers.

Micro-LED has achieved significant results in the field of high-speed optical communication and is also continuously developing in other fields. Optical interconnect technology based on micro-LED and optical fiber has a rapid development [12], and the use of high-bandwidth micro-LED can achieve high data rates and low power consumption. Furthermore, the micro-LED can be made into arrays and serve as lighting, making it possible to be used in structured lighting [13]. Structured lighting based on micro-LED can be applied to achieve high-accuracy positioning and can also be used in maskless lithography [14].

VLC transmitters have been researched by lots of groups, but there is still a lack of research on micro-LED as a receiver. Today, most commercial PDs are based on Si or GaAs, and their spectral response ranges are wide, which will lead to high optical noise for VLC application [15]. In addition, the robustness of Si-based PDs is poor for harsh environments in space or salty seawater [16]. Compared with the commercial Si or GaAs-based PDs, GaN or InGaN-based PDs have demonstrated their advantages of wavelength selectivity, low

dark current, and high responsivity, which can improve the signal-to-noise ratio (SNR) of VLC systems [17]. The studies point out that GaN-based PDs commonly are structured with multi-quantum-wells (MQWs), which are also common in LEDs and micro-LEDs [18–21]. The application of micro-LEDs as PDs has been continuously studied in recent years and has made great progress in VLC systems.

In this review, we focus on the recent progress of micro-LEDs in VLC systems and introduce their progress as transmitters and receivers in VLC systems. Furthermore, compared with the previous reviews on micro-LEDs, we also focus on the development of micro-LEDs in structured lighting positioning and optical interconnect technology.

2. High-Speed Communication Systems Based on the Micro-LED Transmitter

2.1. High-Bandwidth Micro-LED Transmitter

Modulation bandwidth is one of the most important indicators of the performance of optical communication transmitter devices, which directly determines the maximum rates that can be achieved by the entire VLC system. The modulation bandwidth of micro-LED can be specified as the signal frequency at which the detected optical power (photocurrent from PD) is half of that at direct current (DC). The modulation bandwidth of micro-LED is also known as -3 dB optical modulation bandwidth or electrical-to-optical bandwidth. Similar to the definition of -3 dB optical modulation bandwidth, the electrical modulation bandwidth is defined as the signal frequency at which the alternating current (AC) power is half of that at DC. Therefore, the optical bandwidth of -3 dB is the same as the electrical bandwidth of -6 dB. Modulation bandwidth is an important factor in VLC data rate, but it is affected by micro-LED characteristics.

The main factors limiting the modulation bandwidth of micro-LEDs are the resistance-capacitance (RC) time constant and the carrier recombination lifetime. As shown in Equation (1), the carrier recombination lifetime includes the radiative recombination lifetime (τ_r) and non-radiative recombination lifetime (τ_{nr}) [22]. As the rate of the carrier recombination increases, the carrier lifetime decreases and the modulation bandwidth can be improved.

$$f_{-3\text{dB}} = \frac{\sqrt{3}}{2\pi\tau} = \frac{\sqrt{3}}{2\pi} \left(\frac{1}{\tau_r} + \frac{1}{\tau_{nr}} + \frac{1}{\tau_{RC}} \right) \quad (1)$$

Figure 2 shows the basic structure of micro-LED and the direction for improving modulation bandwidth. Many research teams improve modulation bandwidth by introducing high-quality substrates, new epitaxial structures, and advanced device technologies.

In terms of material growth, the modulation bandwidth can be improved from the material substrate and quantum well. Some studies have compared polar, nonpolar, and semi-polar micro-LEDs and found that semi-polar and nonpolar micro-LEDs can achieve higher bandwidth at low current densities, with the shorter carrier lifetimes expected in nonpolar and semi-polar active regions due to the larger wave function overlap [23]. A semi-polar micro-LED with a size of $50\text{ }\mu\text{m}$ can achieve a modulation bandwidth of 1030 MHz [33]. Nonpolar orientations can eliminate polarization effects and lead to larger electron and whole wave function overlap and a shorter carrier lifetime. A nonpolar m-plane InGaN/GaN micro-LED can achieve a modulation bandwidth of 1485 MHz at a current density of 1 kA/cm^2 [34]. A blue micro-LED fabricated on a 2-inch c-plane GaN freestanding substrate has been reported. Compared to the sapphire-substrate micro-LED, the GaN-substrate micro-LED has higher crystal quality with lower threading dislocation density (TDD), better heat dissipation, and higher bandwidth [24]. Quantum wells (QWs) can be optimized from ultra-thin quantum wells, quantum dots (QDs), and quantum barrier (QB) thickness. The design of ultra-thin quantum wells has been proven to signifi-

cantly improve the modulation bandwidth of micro-LEDs. Rajabi et al. designed ultra-thin InGaN QWs (1 nm) and GaN barriers (3 nm) to suppress the quantum confined stark effect (QCSE), and achieved a modulation bandwidth of 536 MHz at a current density of 2.5 kA/cm^2 [35]. A high-speed c-plane InGaN/GaN blue micro-LED was obtained by designing an ultra-thin quantum well structure with an InGaN layer of 1 nm, which led to a short differential carrier lifetime and achieved a modulation bandwidth of up to 1530 MHz [27]. Apart from controlling the logarithm and thickness of the quantum well, some researchers fabricated InGaN/GaN-based LEDs on a Si-substrate and optimized the number of superlattice interlayers to 32 for better communication properties. Higher superlattice interlayer period number helps to reduce the carrier lifetime and obtain a higher bandwidth at a lower current [36]. Some research groups used a low-temperature GaN interlayer process to reduce the densities of defects or dislocations related to V-shaped pits and suppress the QCSE. The blue micro-LED arrays they achieved have an improved bandwidth of 220 MHz and a light output power of 2.14 mW [37]. The green micro-LED arrays with 16×16 pixels obtained the 156 MHz bandwidth by designing a modular-architected p-type region including a 60 nm polarization-induced graded p-AlGaIn layer and a 130 nm p-Al_{0.2}Ga_{0.8}N/p-GaN superlattices layer [38]. The use of In_xGa_{1-x}N/In_yGa_{1-y}N MQWs is also an effective way to suppress the QCSE effect and decrease the defect or dislocation density to enhance the luminescence. In_{0.18}Ga_{0.82}N/In_{0.015}Ga_{0.985}N MQWs can be used to fabricate a GaN-based blue micro-LED array with 8.8 mW light output power. This method also has great potential for the improvement of bandwidth [39]. A research group used a pre-strained structure to suppress the QCSE of green micro-LED. The increased thickness of the active region improved the -3 dB bandwidth to 197.3 MHz [40]. In addition, some researchers introduced Si doping content into the first quantum barrier to suppress the QCSE for optimization, and they achieved a c-plane GaN-based vertical-structure micro-LED array with a bandwidth of 578 MHz [41]. Meanwhile, GaN-based quantum dots have also been applied in optoelectronic devices due to their strong three-dimensional quantum confinement abilities. For QDs, the carrier lifetime can be efficiently decreased since the reduced dimensionality of the active region [42]. The designed blue micro-LED with an active region of nano-structured InGaIn wetting layer can significantly suppress QCSE and achieve a modulation bandwidth of 1300 MHz [25]. Based on different diameters of InGaIn quantum dot active regions, micro-LEDs have a modulation bandwidth of 3.6 GHz [43]. In addition, some research groups have also studied the effect of quantum barrier thickness on the modulation bandwidth of micro-LEDs. Under the same current density, the quantum barrier thicknesses of micro-LED are 13 nm, 10 nm, and 5 nm, and the bandwidths are 169 MHz, 226 MHz, and 245 MHz, respectively [26]. In addition, nano-porous GaN distributed Bragg reflectors also enhance the modulation bandwidth and overall performance of the devices [44].

In terms of device preparation, size is one of the important factors affecting the modulation bandwidth of micro-LEDs. Researchers investigated the size and wavelength-dependent properties of ultraviolet, violet, blue, and green micro-LEDs. They found that, as the pixel diameter decreases, the current density and the modulation bandwidth will be higher [29,44,45]. However, the size reduction will lead to a decrease in optical power, which is one of the important factors determining optical communication speed. The size effect on blue GaIn-substrate micro-LEDs had been studied, and the results showed that a 20 μm micro-LED achieves a -3 dB bandwidth of $\sim 2.3 \text{ GHz}$. The maximum data rates of 20, 40, 60, 80, 100, and 300 μm micro-LEDs are 8.294, 8.394, 10.547, 10.019, 9.398, and 7.294 Gbps, respectively. Additionally, a 60 μm micro-LED is more capable of balancing the light output power and modulation bandwidth for higher transmission data rates [46]. Compared to single-pixel structures, the series structures will reduce bandwidth, but

they can effectively increase optical power. Lin et al. fabricated series-connected green micro-LEDs, and their results showed that single-pixel micro-LEDs can withstand higher current densities and thus achieve higher modulation bandwidths than series-connected structures [10]. However, for the parallel structures, the bandwidth increases or stays similar, with the number of parallel arrays increasing at the same current density [47,48]. Under the same current density, the RC time constant becomes an important factor affecting the bandwidth. The capacitance of micro-LED arrays will increase slightly, while the resistance will decrease as the number of parallel pixels increases. Therefore, the RC time constant will decrease or stay similar depending on the actual device characteristics. However, a very large number of parallel micro-LEDs will cause a lower saturation current density because of the heating effect [49]. Therefore, an appropriate number of parallel arrays can obtain the optimal bandwidth. In addition, some researchers focus on the design of the device structure. A research group proposed a micro-LED with an embedded N electrode structure, which has the advantages of better heat dissipation performance and a lower junction temperature. The saturation current density of this micro-LED can be significantly higher. As a result, it can reach a bandwidth of 240 MHz at 8.5 kA/cm^2 [50]. Another research group fabricated a graphene (Gr)/GaN-based micro-LED array and found that a certain number of Gr layers can increase hole injection. Finally, they found that three layers of Gr can reach 610 MHz of -3 dB modulation bandwidth at a current density of 6.7 kA/cm^2 [51]. In addition to reducing the size of LEDs to improve the modulation bandwidth, some researchers have focused on improving the bandwidth of the large chip size of GaN-based LEDs. A research group fabricated an ultrathin vertical-structure LED to decrease the RC time constant for the bandwidth enhancement. The 580-nm-thick vertical-structure LED implemented on a 2-in metal-based bonded GaN-on-silicon wafer can obtain a bandwidth of 45 MHz [52]. Similarly, the method of improving the bandwidth of DUV LEDs can also provide some reference for visible light LEDs. By embedding a SiO_2 -based microcavity, the deep-ultraviolet LED with an aluminum reflector on its top achieves a -3 dB bandwidth of 134 MHz. The reduction in the RC time constant enables an increase in the modulation bandwidth [53]. In summary, in addition to the design of the device size, the connection method and the structure design are also influencing factors.

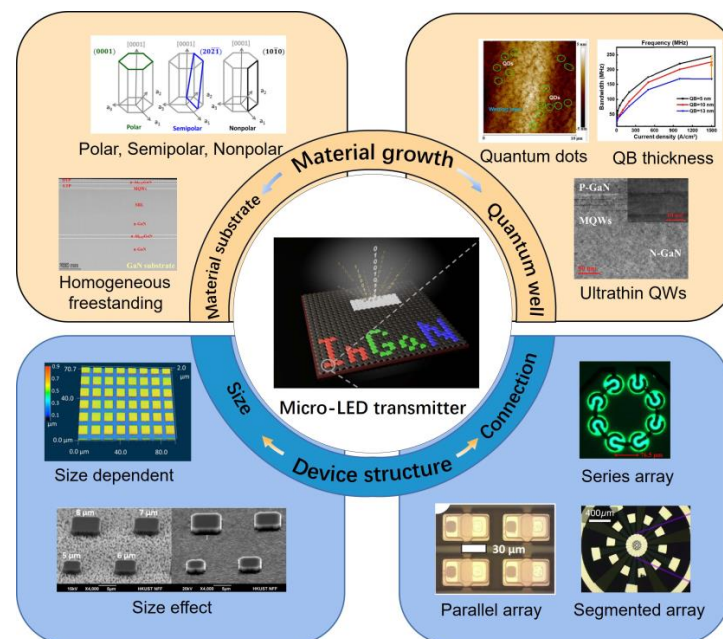


Figure 2. The research progress of modulation bandwidth of micro-LEDs; refs. [10,23–32].

The development of the modulation bandwidth of micro-LEDs as transmitters is shown in Figure 3. The development of blue micro-LEDs is more mature. The red micro-LED has a higher indium content for emission, so they are more affected by QCSE, which is a limitation of modulation bandwidth. Blue and violet micro-LEDs in all wavelengths have the highest modulation bandwidth, and other wavelengths of micro-LED are also under development.

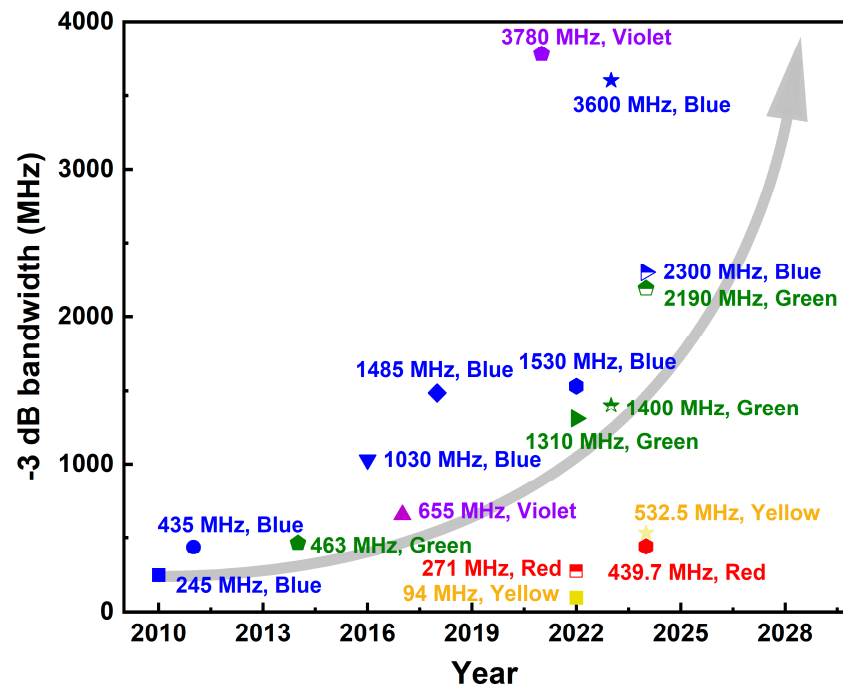


Figure 3. The development of the modulation bandwidth of micro-LEDs as transmitters; refs. [10,27,31–34,43,45,46,54–59].

2.2. Advanced Modulation Schemes

Micro-LEDs have a high modulation bandwidth, which allows them to support very high data rates in VLC. The transmitted bit streams are encoded by different modulation schemes, and then the modulated signals are converted by an arbitrary waveform generator (AWG) or digital-to-analog converted to voltage signals. These signals are amplified by an amplifier and then combined with a DC bias using a bias-tee. The output intensity of the micro-LEDs is modulated by the voltage signals. The optical signals are transmitted over the optical channel, and the optical channel can be free space, optical fiber, underwater, or other environments. The output signals are received by photodetectors after passing through the channel. The photodetectors convert the optical signals into electrical signals. Then, the electrical signals are captured by an oscilloscope and sent back to the personal computer (PC). The PC processes the signals into a bit stream and then compares it with the transmitted bit stream to calculate the bit error rate (BER). To achieve a higher data rate, different advanced modulation schemes are used in VLC systems, and each of them has different complexity, spectral efficiency, and power efficiency [60]. The modulation schemes most commonly used in VLC systems are single-carrier modulation (SCM) and multi-carrier modulation (MCM) [61]. SCM includes on-off keying (OOK), pulse position modulation (PPM), and pulse amplitude modulation (PAM), and MCM includes orthogonal frequency division multiplexing (OFDM) and various forms of OFDM.

OOK is the simplest form of amplitude shift keying (ASK) modulation scheme, which is modulated by turning the LED “on” and “off” corresponding to binary information “1” and “0”. For micro-LEDs of high modulation bandwidths, the data rate of VLC using

OOK modulation can exceed Gbps. Dinh et al. achieved a data rate of 2.4 Gbps by using a semipolar micro-LED with OOK modulation [33]. As the required data rate increases in VLC, SCM techniques such as OOK, PPM, and PAM suffer non-linear signal distortion and ISI [61]. Therefore, MCM is used for high-speed wireless optical communication.

Compared with SCM, MCM is bandwidth-efficient and energy-efficient, but better signal quality is required. In MCM, OFDM is the most common scheme for VLC networks. OFDM transmits multiple parallel data streams simultaneously through a collection of orthogonal sub-carriers. The modulated sub-carriers are combined and transmitted by the LED. In ideal conditions, sub-carriers are typically orthogonal, so bits and power loading techniques can be used on each sub-carrier [61]. Common optical OFDM modulation methods include direct current optical OFDM (DCO-OFDM) and asymmetrically clipped optical OFDM (ACO-OFDM). DCO-OFDM uses a positive direct current bias for the generation of a unipolar signal. ACO-OFDM sets the even subcarriers to zero and transmits data by the odd subcarriers.

Apart from modulation schemes, the design of the VLC system also helps to improve the data rate. The multiple-input and multiple-output (MIMO) based VLC system can use multiple micro-LEDs as transmitters and multiple PDs as receivers. MIMO technology uses spatial multiplexing to increase channel capacity, thereby overcoming the bandwidth limitation of micro-LEDs [62]. The 100 μm GaN-based micro-LEDs can reach 1.34 Gbps in a 2×2 MIMO system [63]. In addition, the WDM system can also improve the channel capacity by using different wavelengths of micro-LEDs to transmit data in parallel [9].

2.3. High-Speed Communication Systems

2.3.1. Free Space

The application of high-bandwidth micro-LED and high-efficiency modulation in a VLC system makes high-speed VLC possible. McKendry et al. first proved that the VLC system with a micro-LED as the transmitter has great potential. A micro-LED with an optical -3 dB modulation bandwidth of 245 MHz was used to achieve a data rate of up to 1 Gbps [54]. In optical communication, there is a direct relationship between optical power and data rate. The designed segmented micro-LED achieved an optical power of 2.3 mW while maintaining a modulation bandwidth of 655 MHz, achieving 7.91 Gbps over short distances using micro-LEDs with a modulation bandwidth of 655 MHz when all the noise sources of the VLC system are present [31]. Due to the limitation of the low optical power of micro-LEDs, the communication distance can hardly be increased, so multi-pixel series or parallel structures of micro-LEDs have been developed to effectively improve optical power. By fabricating a 3×3 series-biased micro-LED array and presenting performance with an optical power and modulation bandwidth of over 10 mW and 980 MHz, respectively, a data rate of 11.74 Gbps has been reached, which is the highest data rate achieved by a monochrome micro-LED for free-space communication. Figure 4 shows their VLC system with a 3×3 series micro-LED as a transmitter. This array achieved data transmission rates of 11.74, 11.72, 10.11, 6.58, 2.84, and 1.61 Gbps at distances of 0.3, 2, 5, 10, 15, and 20 m, respectively [64]. A 3×3 violet series-biased micro-LED array was fabricated to achieve data rates of 10.23, 10.10, and 9.51 Gbps at 0.2 m, 1 m, and 10 m, respectively. The optical power reached 13.4 mW to support long-distance communication [11]. This is the first time that a data rate greater than 9.5 Gbps has been achieved at a distance of 10 m. The bit-loading OFDM with adaptive pre-equalization was used in the VLC system. The application of high-order modulation made the data rate up to 9.51 Gbps at a distance of 10 m, achieving long-distance communication while maintaining high data rates.

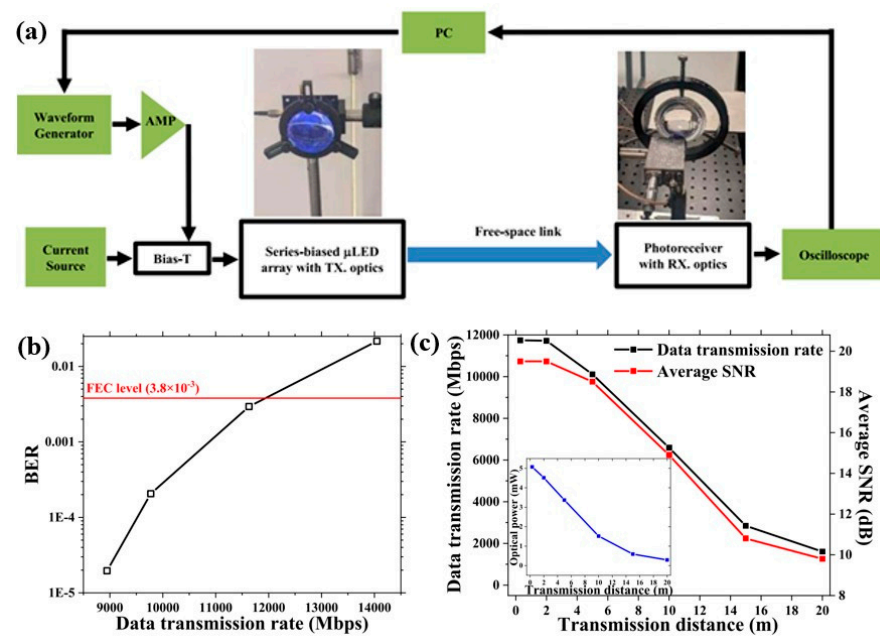


Figure 4. (a) Schematic diagram of the VLC system in free space. (b) BER versus data transmission rate in a 0.3 m free-space VLC system. (c) The data transmission rate, the average SNR, and the optical power at different transmission distances, ref. [64].

For long-distance communication, a research group fabricated a DUV micro-LED for long-distance line-of-sight optical wireless communications. They achieved a data rate of 1.2 Gbps at a 116 m free-space link, which is the first micro-LED-based optical communication system to reach Gbps at distances greater than 100 m [65]. The data rates mentioned above are all based on a single micro-LED device. Using multiple micro-LEDs with multiple wavelengths can also significantly improve the data rate. By using WDM, blue and green micro-LEDs and RC-LEDs could achieve a data rate of 11.28 Gbps at a distance of 1.5 m. The sum of the data rate of blue and green micro-LEDs reached 7.28 Gbps [66]. Subsequently, a WDM optical wireless communication system with a free-space distance of 13 m was constructed, and the total data rate was 15.78 Gbps by using four different wavelengths of micro-LEDs [57]. In the same year, an aggregated data rate of up to 25.20 Gbps over 25 cm free space was achieved through a WDM system, and micro-LEDs offered a data rate of up to 18.43 Gbps [9]. In summary, the data rate of micro-LEDs in free space can be improved by fabricating series or parallel structures or using multiple wavelengths.

2.3.2. Underwater

Compared with free space, the underwater environment is more complex. Substances such as chlorophyll, Maalox, and sea salt in the water may affect communication performance [67]. The underwater communication technology mainly includes underwater RF, hydroacoustic communication, and underwater wireless optical communication (UWOC). UWOC with high data rate and long communication distance is a promising underwater communication technology [21]. The existing transmitter devices of underwater wireless optical communication are mainly based on lasers and LEDs. An LED has the characteristics of a wide emission angle, low power consumption, and high human security compared with LD, but its maximum achievable data rate is not as good as that of a micro-LED due to the limitation of modulation bandwidth [68]. A micro-LED has excellent communication performance in free space, but only a few research reports have explored its application in the underwater environment. For the first time, a data rate of 800 Mbps was obtained by using micro-LEDs as transmitters for communication in a UWOC system over 0.6 m [69],

and then the data rate was increased to 933 Mbps [67]. After that, a single-layer quantum dot blue micro-LED with a modulation bandwidth of up to 1.03 GHz can reach a data rate of 2 Gbps at a 3 m air-underwater channel [70]. Due to the problem that micro-LEDs may have insufficient optical power for long-distance underwater transmission, an array of six series-connected blue micro-LEDs increased the optical power while maintaining high bandwidth, achieving a data rate of 4.92 Gbps in a 1.5 m underwater link [71].

Furthermore, the upcoming 6G communication network is expected to integrate space/air/underwater networks. A double-sided emission micro-LED array is reported to achieve free-space communication on one side and underwater communication on the other side. This report also demonstrated the feasibility of pattern display and communication and provided a good direction for research and application in 6G communication [72]. Figure 5 shows the schematic diagrams of the double-sided communication system based on the green double-sided emission micro-LED. Data rates of 1.55 Gbps at a 3 m free-space link and 1.11 Gbps at a 3.4 m underwater link were achieved.

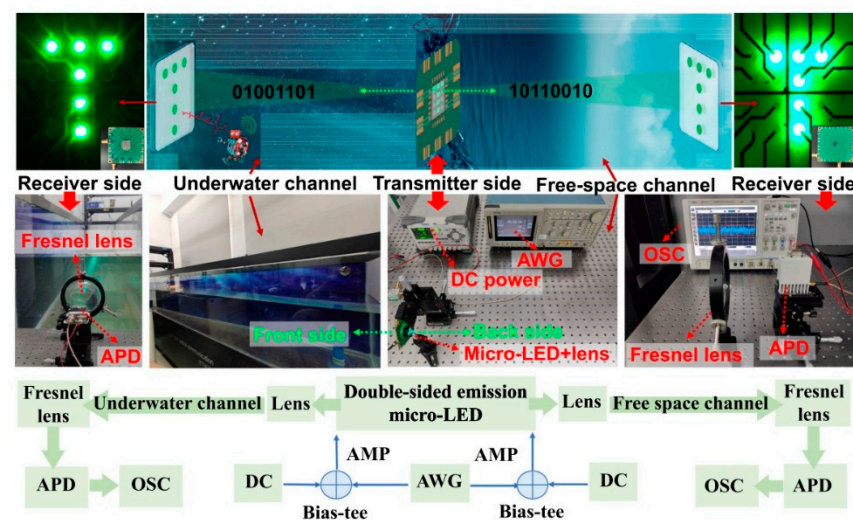


Figure 5. Schematic diagrams and experimental setup of the double-sided optical communication system; ref. [72].

2.3.3. Optical Fiber

The optical interconnect technology based on micro-LED and optical fiber coupling offers advantages such as high speed, low power consumption, and low latency. As the demand for computing power continues to grow, the transmission power consumption of traditional wires is facing increasingly high costs. Currently, copper cable-based links operate at approximately 25 pJ/bit, optical module-based links typically exceed 10 pJ/bit, and even the most advanced silicon photonic links are around 5 pJ/bit [73]. However, micro-LED-based optical interconnect technology can reduce the energy consumption per bit to as low as 0.1 pJ, which is highly attractive for short-distance data transmission. Optical interconnect is now widely used in data centers, with technology giants like Facebook, Google, and Microsoft adopting it to accelerate communication speed and reduce transmission costs in their data centers. In 2012, McKendry et al. reported progress in the use of micro-LED arrays for plastic optical fiber (POF) and achieved a data rate of 1.5 Gbps [74]. Three years later, Li et al. used 4-channel micro-LEDs of the wavelength of 450 nm to achieve a single-directional data rate of 6.25 Gbps in POF at a distance of 10 m [75].

Using micro-LED and fiber coupling methods, a new data communication architecture called LightBundle™ [76] integrates a large number of micro-LEDs on a silicon chip to send optical data in a parallel format. This architecture can use a separate optical transceiver

array chip or an optical transceiver array directly integrated into a complex system-on-chip. Each optical transceiver array consists of several hundred light emitters and receivers, with each light emitter consisting of a driver circuit and a micro-LED, and each receiver consisting of a photodetector integrated with receiver circuitry onto a silicon IC.

Recently, a research team demonstrated low-energy optical interconnects (0.6 pJ/bit at 10^{-4} error rate and 1.3 pJ at 10^{-12}) using a custom 32-channel micro-LED-based optical link with each channel data rate of 2 Gbps [12]. Then, this team showed another transceiver IC with a micro-LED array-based transmitter and a hybrid silicon detector array with 304 channels at a data rate of 3.3 Gbps per channel, for a total data rate of 1 Tbps [77].

The above discusses the progress of VLC in free space, underwater and optical fiber. In addition to these three environments, micro-LEDs can also be applied in various environments, and their development is progressing rapidly. We have organized the progress of monochromatic micro-LED and multi-color micro-LED applications in VLC systems and shown the results of micro-LED-based VLC in terms of speed and distance in Figure 6.

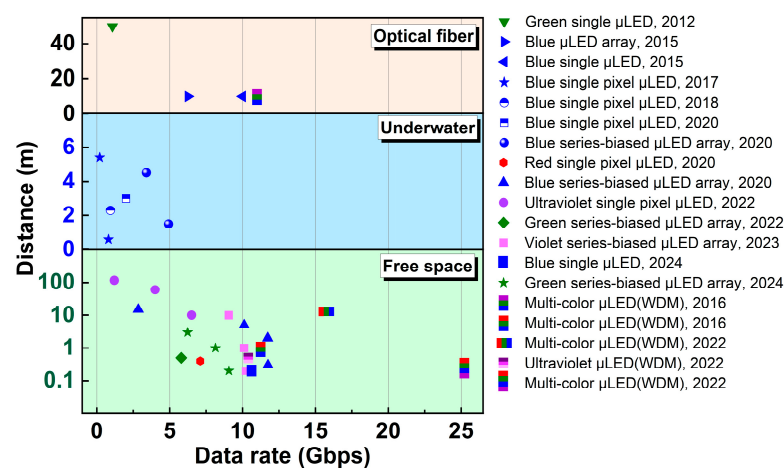


Figure 6. The development of a VLC system based on micro-LED transmitters; refs. [9–11,30,46,57,59, 64–66,69,71,74,75,78–82].

2.4. Structured Micro-LED Array System

As technology advances, the application scenarios for positioning technology continue to expand, and the demand for positioning accuracy is ever-increasing. Consequently, research into visible light position (VLP) has garnered significant attention. Traditional positioning technologies, such as the Global Positioning System (GPS), Wi-Fi, Bluetooth, radio-frequency identification (RFID), and acoustic positioning, all have their respective limitations [83]. For instance, GPS has a relatively low positioning accuracy and cannot penetrate concrete for indoor positioning [84]. Wi-Fi and Bluetooth technologies are susceptible to RF interference and pose security concerns. RFID technology has a limited transmission range (5–6 m) and consumes more power [85]. Acoustic positioning relies on energy-intensive amplifiers and loudspeakers [86]. In contrast, VLP can support indoor positioning scenarios, provide high positioning accuracy, and offer benefits similar to those of optical communication, such as the absence of RF interference and integration with solid-state lighting (SSL). Using micro-LEDs as light sources offers significant advantages for building VLP systems. This is due to the small size and high modulation bandwidth of micro-LEDs. The small size allows for higher positioning accuracy, while the high modulation bandwidth enables faster positioning speeds. Herrnsdorf et al. first proposed using a micro-LED array as a light source to achieve visible light positioning [87]. Other researchers further advanced this technology by integrating ghost imaging algorithms, enhancing the positioning accuracy and precision of micro-LED array-based VLP systems [13]. By

adjusting the effective positioning range, micro-LED-based VLP systems can be applied to various scenarios. In this section, we will introduce various VLP technologies based on micro-LED arrays and their different application scenarios.

2.4.1. Technologies for Realizing Visible Light Positioning

VLP can be differentiated based on the measured parameters. Common positioning techniques include received signal strengths (RSSs), time of arrival (ToA), time difference of arrival (TDoA), phase of arrival (PoA), phase difference of arrival (PDoA), angle of arrival (AoA), trilateration, structured light, fingerprinting, etc.

VLP methods include fingerprint positioning, which modulates each pixel in an array individually, causing them to emit unique light signals. The position of the detector is determined by the fingerprint information obtained by the detector, and the detection accuracy of this scheme directly depends on the size of the light spot. Figure 7 demonstrates the feasibility of employing a micro-LED array for precise visible light positioning. As depicted in Figure 7a, a micro-LED array was utilized as the light source, with each pixel's illumination being modulated based on the rows of a Hadamard matrix, independently controlled by a field-programmable gate array (FPGA). This modulation resulted in each frame of the array displaying a structured light pattern derived from the Hadamard matrix. A detector collected the projected light spots through a lens from the micro-LED array, and after demodulating the sampled signals, a second-order correlation reconstruction algorithm was employed to determine the specific spot where the detector was positioned, thereby achieving accurate localization. Since positioning accuracy is directly influenced by the size of illuminated spots, utilizing a micro-LED array as the light source significantly enhances precision in positioning. The experimental setup is shown in Figure 7b, resulting in high-precision positioning with sub-millimeter accuracy (<1 mm). The positioning speed reached 1.3 ms, thus demonstrating notable advantages offered by micro-LEDs for visible light-based localization.

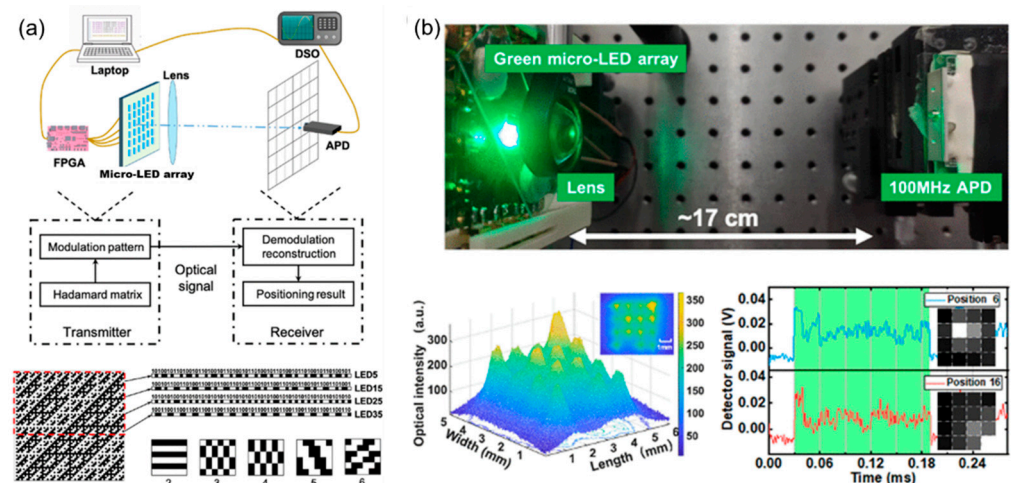


Figure 7. (a) Schematic diagram of structured illumination-based visible light positioning system and modulation scheme based on Hadamard matrix. (b) Experiment based on a micro-LED array; ref. [13].

2.4.2. Application of Visible Light Position

VLP technology offers a diverse array of applications across various fields. Its high accuracy, low cost, and immunity to electromagnetic interference make it an ideal solution for indoor positioning, vehicular positioning, IoT applications, high-precision positioning, and more. By leveraging existing lighting infrastructure and integrating VLP with other technologies, it is possible to create intelligent, efficient, and personalized environments.

For example, some researchers use micro-LED arrays as structured illumination sources. By projecting preset patterns onto the target object and then capturing the pattern deformation through image sensors, the three-dimensional morphology of the target object can be reconstructed [88]. Furthermore, VLP is also applied in advanced processes such as automatic alignment in maskless lithography. Automatic alignment is a crucial technology in maskless lithography that ensures the precise matching of the processing position with the design position during actual processing. The accuracy and stability of automatic alignment directly determine the quality of the products produced. Due to its small size advantage, micro-LED-based structured lighting is highly suitable for positioning and aligning fluorescent markers in maskless lithography, making it an attractive option for high-precision manufacturing processes in the field of microelectronics. Figure 8 presents maskless lithography systems containing micro-LED arrays [14,89]. The system in Figure 8a,c achieves alignment to red-emitting fluorescent markers at any position on the exposure plane through 450 nm spatial-temporal modulated illumination using CdSe/ZnS colloidal QDs microstructures or dye-doped microspheres [14]. Then, the resist pattern is aligned with the markers through the programmable movement of the micro-LEDs in the array and the XYZ platform. The micro-LED technology enables self-alignment and multi-step lithography capabilities using fluorescent markers for alignment.

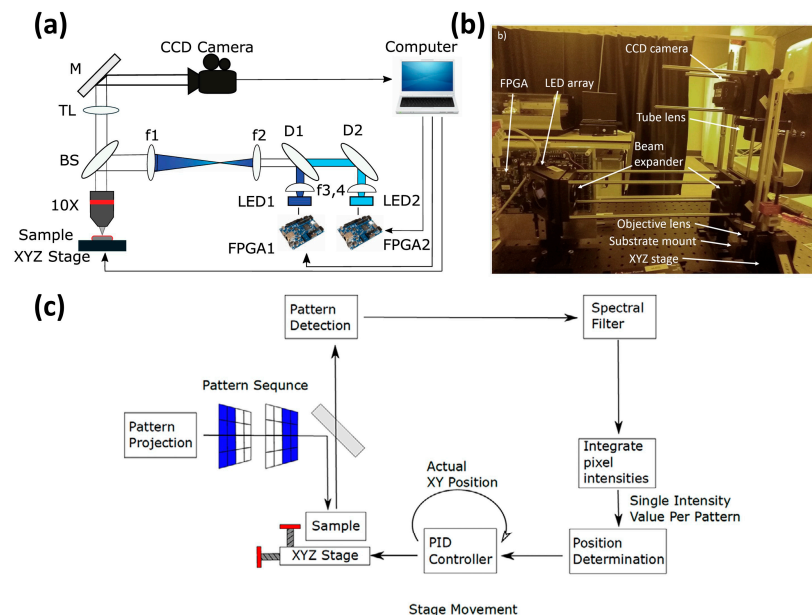


Figure 8. (a) Schematic diagram of the maskless lithography optical system. (b) Simple maskless lithography experimental platform. (c) Principle of pattern sequence analysis; ref. [14,89].

Furthermore, the current state of VLP development is introduced, including commonly used algorithms for VLP and typical application scenarios. Special emphasis is given to the VLP systems based on micro-LED technology; by leveraging the small size and high bandwidth characteristics of micro-LEDs, high-speed and high-precision positioning has been achieved.

2.5. Summary of Micro-LEDs as Transmitters for VLC

This section gives an overview of high-speed communication systems based on micro-LED transmitters. The data rates of high-speed VLC systems are increasing in a variety of environments, and high-speed VLC systems have developed rapidly in the last decade. To maximize VLC data rates, various strategies, such as increasing the modulation bandwidth of micro-LEDs and using advanced modulation methods are discussed. Now, the

modulation bandwidth of micro-LED has reached 3.6 GHz, and the data rate has reached over 10 Gbps with a single micro-LED device. In the future, VLC based on micro-LED will inevitably be investigated towards high bandwidth, high-power micro-LED, long-distance, and high-speed communication, and may play a crucial role in future 6G communication.

3. GaN Micro-LED-Based Photodetectors

Most commercial PDs today are based on Si or GaAs due to their high performance, proficient integration technology, and large-scale production, but their receiving spectrum covers a wide range, which can lead to high optical noise in VLC applications [90,91]. In addition, the robustness of Si-based PDs is poor, so they cannot adapt to harsh environments in space or salty seawater [16]. These issues significantly impair the performance of Si-based PDs and impede the advancement of high-quality VLC systems utilizing Si-based PDs. Group-III nitride semiconductor materials possess favorable physical and chemical properties, thus proposing their utilization in the fabrication of PDs [92]. InGaN-based PDs also offer high breakdown voltage and low intrinsic noise compared to Si-based PDs due to the wide band gap [93]. PDs based on GaN or InGaN materials have the characteristics of wavelength selectivity, and they can detect short-wavelength signals, which improves the SNR of VLC systems. Furthermore, III-nitride-based PDs exhibit exceptional robustness in diverse environments, indicating their great potential for high-speed VLC systems. Similarly, micro-LED-based PDs, a type of III-nitride-based PD, also have the advantage of wavelength selectivity, which can only receive light with wavelengths lower than their own, so they have natural filter characteristics [94]. Furthermore, micro-LED-based PDs can be employed for the dual functions of photon emission and photon detection compared to commercial Si or GaAs-based PDs, and have the advantages of wavelength selectivity, low dark current, high responsiveness, and high sensitivity, attracting a great deal of academic attention and interest [95].

The works on high-bandwidth micro-LEDs described above illustrate that micro-LEDs have made great progress in VLC applications, particularly using micro-LEDs as transmitters for VLC systems. In contrast, the development of optical receivers in VLC systems is still lagging compared to the advances in high-speed transmitters for VLC systems. Current research indicates that GaN-based LEDs possess not only a light emission function but also a photon detection function, thereby enabling versatile applications in VLC systems [17]. Directly adopting LED for both Tx and Rx is a low-cost solution [96]. Similar to LED, micro-LEDs can also be used as photodetectors and are more suitable for high-speed communication scenarios. In this section, we will introduce the historical progress and important performance characteristics of GaN micro-LED-based PDs and introduce the breakthrough progress in the field of VLC based on micro-LED-based PDs. The current study shows that micro-LEDs not only offer advantages in VLC transmitters but also act as receivers. It is because of this feature of micro-LED-based PD that transmitter and photodetector functions can be integrated into a micro-LED array. Such integrated micro-LED enables multi-functional applications and provides a new solution for full-duplex VLC communications.

3.1. Historical Progress of GaN Micro-LED-Based Photodetectors

LED-based photodetectors have been investigated as receivers in VLC systems. Giustino et al. implemented an LED-to-LED VLC link with a data rate of only 870 bit/s [97]. Then, an LED-to-LED communication system using the OOK technique reached a data rate of 15 Mbps [98]. Later, another LED-to-LED communication system was implemented, linking with a data rate of up to 110 Mbps, where the LED detector operates at -30 V [99]. In addition, a single LED could both emit and detect light, so we can use an LED as a

transmitter and a receiver at the same time for VLC [100]. In contrast to the development of LED-based PDs described above, the use of micro-LEDs as optical receivers has hardly been investigated previously, but with advances in micro-LED technology, micro-LEDs have been proposed as optical receivers for VLC systems. Due to the advantage of wavelength selectivity of GaN-based PDs, InGaN/GaN MQW-based micro-photodetectors (micro-PDs) were proposed as high-speed optical receivers for VLC. A VLC system based on InGaN QW micro-PDs used OFDM modulation to achieve a data rate of 3.2 Gbps [16]. This study shows the great potential of III nitride-based micro-PDs as optical receivers in VLC links. However, this work only uses a single micro-PD, whereas an array of micro-PDs can enable multi-user communication and increase data rate compared to a single micro-PD. Since micro-LEDs have the same structure as the above-mentioned InGaN MQW-based micro-PDs, the photodetection function of micro-LEDs has also been discovered and applied. A GaN micro-LED array was proposed as a photodetector to achieve a MIMO parallel high-speed VLC system of up to 350 Mbps using OOK modulation at a bias of -5 V [17]. This work reports for the first time on the application of micro-LED-based PDs as the optical receiver of VLC systems, and micro-LED-based PDs have the advantages of low cost, ease of mass production, and wavelength selectivity without the need for additional optical filters, which demonstrates the potential of micro-LEDs as photodetectors for high-speed VLC. Inspired by the above research, more and more GaN-based micro-PDs and micro-LED-based PDs are used in VLC systems to realize high-speed VLC links. A semipolar InGaN/GaN MQW micro-PD has been used in a VLC system to achieve a remarkable rate of 7.4 Gbps combined with bit and power loading OFDM [101]. Later, the underwater application of micro-LEDs for transmitters, PDs, and solar cells had been demonstrated [21]. In the same year, a work also demonstrated the micro-LED-based PD's duplex VLC performance and integration with display and SSL [102].

Then, a few research groups aim to achieve very high-speed applications based on micro-LED-based PDs. Recently, researchers proposed an InGaN/GaN MQW vertical structure micro-LED-based PD array and used the micro-PD array to achieve a VLC system with a data rate of more than 10 Gbps, which showed its great potential for high-speed VLC links beyond 10 Gbps [103]. In the studies of micro-LED-based PDs discussed above, the devices operated in reverse-biased or zero-biased states. Similarly, a blue mini-LED was proposed that can be used as both a PD and a light source. Furthermore, the mini-LED-based PD could simultaneously act as an uplink photodetector and a downlink transmitter in the same full-duplex VLC system, achieving an uplink transmission rate of 300 Mbps and a downlink transmission rate of 225 Mbps at a transmission distance of 1.5 m [15]. This work enables the use of the same mini-LED as a display, VLC transmitter, and VLC receiver at the same time, which greatly simplifies the architecture of full-duplex communication systems and proves the potential of mini-LEDs for miniature IoT and multifunctional display applications.

3.2. Bandwidth and Responsivity Characteristics of GaN Micro-LED-Based PDs and Micro-PDs

Previous studies have shown that III-nitride-based micro-PDs have excellent performance in VLC links as optical receivers. So, micro-LED-based PDs with a similar structure to micro-PDs as an optical receiver in VLC links have gained the attention of researchers in recent years. Recent studies have shown that micro-LED-based PDs possess excellent bandwidth and responsivity characteristics, which can achieve multifunctional applications with integrated light emission and photodetection functionalities. How to improve the bandwidth and responsivity of micro-LED-based PDs is one of the hot topics in current research. Here, we summarize the benchmark of the -3 dB bandwidth versus reverse bias voltage for GaN-based micro-PDs, as shown in Figure 9. Currently, the reported micro-PDs

are mainly divided into single PDs and PD arrays. A high-speed PIN micro-photodiode with a -3 dB bandwidth of 300 MHz was proposed. This study offered the possibility to work toward GaN-based micro-PD [104]. Later, a micro-PD for VLC systems was proposed, with a -3 dB bandwidth of 71.5 MHz [16]. Then, it was discovered that the bandwidth of micro-PDs could be increased by reducing the thickness of the QB in InGaN/GaN MQW micro-PDs, and a -3 dB bandwidth of 700 MHz at a reverse bias of -6 V was eventually achieved [93]. Furthermore, another research group designed semi-polar InGaN/GaN MQW micro-PD arrays, which were able to achieve a -3 dB bandwidth of 170 MHz [105] and 228 MHz [106], separately. Recently, a green micro-LED on sapphire substrates was fabricated, which can reach a record modulation bandwidth of 878.8 MHz [107]. The high-bandwidth characteristics of micro-LED-based PDs will be of great help in increasing the data rates of communication systems.

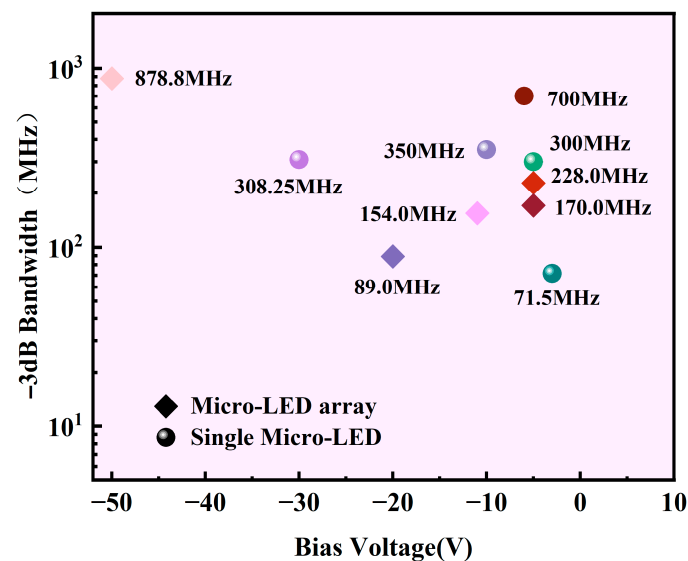


Figure 9. Benchmark of -3 dB bandwidth versus reverse bias voltage for GaN micro-LED-based PDs and micro-PDs; refs. [16,20,93,103–109].

Micro-PDs can have various structures, such as micro-LED, PIN, and APD structures. Due to the advantages of GaN-based photodetectors, including wavelength selectivity, low background noise, and high quantum efficiency, they have become one of the key types of research focuses. To meet the high-speed requirements of 6G communications, it is essential to develop high-performance photodetectors. Currently, researchers have studied various types of GaN-based photodetectors, which can be classified into different structures, including metal-semiconductor-metal (MSM) PDs, PIN structure PDs, 2D structure PDs, and quantum well structure PDs, among others. Some novel device structure designs also help to improve the modulation bandwidth performance of GaN-based MQW photodetectors and their transmission speed in VLC systems. In 2019, Kang et al. proposed a semi-polar InGaN/GaN quantum well micro-PD. This device exhibited a responsivity of 0.191 A/W and a -3 dB bandwidth of 347 MHz at a bias voltage of -10 V, achieving a data rate of 1.55 Gbps based on OOK modulation [20]. This is currently the highest OOK data rate achievable by GaN-based MQW structure micro-PDs. In 2020, Chow et al. designed a small-sized GaN-based micro-PD device with dimensions of 20×20 μm . By thinning the GaN quantum barrier layer in the MQWs during epitaxial growth, they successfully increased the device's -3 dB modulation bandwidth to 700 MHz [93].

Compared with studies on the bandwidth characteristics of micro-PDs, fewer studies have been conducted on the responsivity characteristics of micro-PDs. The responsivity characteristic of micro-PD proposed by Ho et al. was 70.7 mA/W at $\lambda = 392$ nm [16].

Afterward, the responsivity of micro-PD was improved, and micro-PDs with a responsivity of up to 0.191 A/W were reported [20]. Micro-LED-based PDs have higher responsivities compared with micro-PDs. Another research group investigated the responsivity characteristics of micro-LED-based PDs of different sizes [17]. Micro-LED-based PDs at 100 μm , 60 μm , and 40 μm had high responsivities of up to 0.27, 0.31, and 0.24 A/W at -5 V bias, and 0.24, 0.29, and 0.21 A/W at 0 V bias, respectively. The mini-LED-based PD proposed by Lu et al. also had high responsivities of up to 0.243 A/W [15]. These results suggest detectors based on GaN-micro-LED arrays are competitive candidates for the development of PD arrays that enable high-speed VLC.

3.3. Multiple Applications Using GaN Micro-LED-Based Photodetectors in VLC

We can find that the GaN micro-LED-based photodetectors have the advantages of low cost, high responsivity, and wavelength selectivity from the above studies. We can also find that GaN micro-LED-based PDs have integrated functions in multiple applications. The most significant function of micro-LED-based PDs is serving as high-bandwidth optical receivers in high-speed VLC systems. Furthermore, the micro-LED-based PDs can also achieve multifunctional applications such as integrated optoelectronic chips and show great potential for applications in miniature IoT.

3.3.1. GaN Micro-LED-Based Photodetectors in High-Speed VLC

The micro-LED-based PDs with excellent optoelectronic performance and high bandwidth are applied to the high-speed VLC link, which not only further improves the data rate but also provides a solution for MIMO VLC systems as well as full-duplex VLC systems. In this section, we will introduce multiple applications using micro-LED-based PDs in VLC.

A self-powered, high-performance, and wavelength-selective GaN micro-LED-based PD array was proposed in 2019, which enabled MIMO parallel high-speed VLC using micro-LED-based PD [17]. This research shows that micro-LED-based VLC has huge potential to supplement present Wi-Fi or wired networks. Another piece of research reported the size-dependent photocurrent, bandwidth, and VLC performance of GaN micro-LED/LED-based PDs [18]. A typical structure of micro-PDs is shown in Figure 10a, b. This paper proved that the optimal size of micro-LED-based PDs is 80 μm because of the potential to balance photocurrent and bandwidth. Furthermore, the micro-LED-based PD array has the potential to be used in MIMO VLC, with a potential data rate of beyond tens of Gbps, which opens a new way to achieve ultra-high-speed communication. Figure 10c shows the bandwidth of an 80 μm micro-LED-based PD at different bias voltages. Figure 10d displays the data rate tests of LEDs of different sizes, providing a reference for selecting the size of micro-LED-based PDs in the future construction of MIMO communication systems.

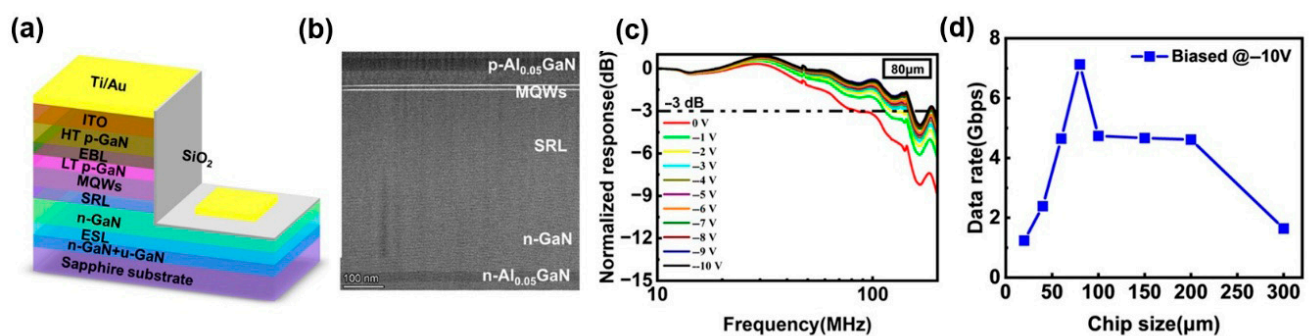


Figure 10. (a) Schematic diagram of the micro-LED structure for photodetector array. (b) The cross-sectional TEM image of the micro-LED. (c) The -3 dB bandwidth of micro-LED-based PD at different reverse bias voltages. (d) The data rate of micro-LED/LED-based PDs with different sizes, ref. [18].

Furthermore, another higher modulation bandwidth and data rate of InGaN-based micro-PDs were reported [103]. A 4×4 micro-LED-based photodetector array was proposed. This micro-LED-based photodetector array was fabricated on a Si substrate. Si substrates are a promising option to grow GaN-based micro-PDs with the advantages of low cost, high crystal quality, better conductivity, and high thermal conductivity. The VLC system using a micro-LED-based photodetector array implemented in the experiment is shown in Figure 11a. Figure 11b shows the -10 and -20 dB bandwidth changes with reverse bias voltages for three sizes of micro-PD arrays. The -3 dB bandwidths were 89.0 MHz, 88.8 MHz, and 43.0 MHz at -20 V for $10\ \mu\text{m}$, $50\ \mu\text{m}$, and $100\ \mu\text{m}$ micro-LED-based PD arrays. Figure 11c illustrates the relationship between the baud rate and data rate. As the baud rate increases, the data rate gradually reaches its highest point and then starts to decrease, and the maximum data rate is 10.81 Gbps with 1.9 Gbaud for the $50\ \mu\text{m}$ micro-PD array using bit and power loading OFDM modulation. These results show that micro-LED-based PDs have significant potential for ultra-high-speed VLC links beyond 10 Gbps.

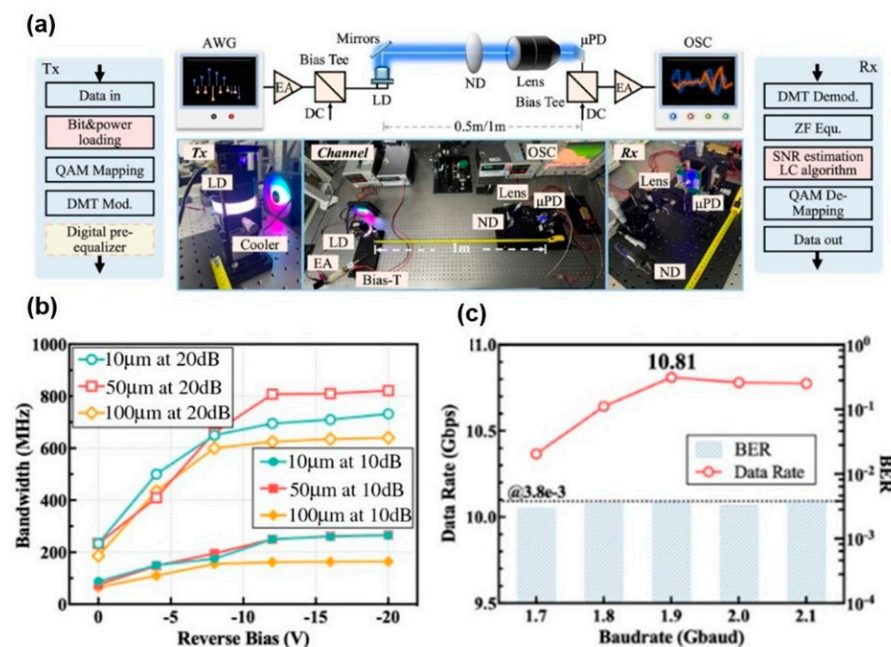


Figure 11. (a) Experimental setup of a VLC system utilizing a micro-LED-based photodetector. (b) The bandwidths of micro-LED-based PD arrays versus reverse bias. (c) Maximum data rate and BER versus baud rate at 0.5 m for $50\ \mu\text{m}$ micro-LED-based photodetectors, ref. [103].

The current VLC systems using micro-LED-based PDs mainly use OOK and OFDM modulation methods. The data rate with OFDM modulation is much higher than with OOK modulation. The single GaN micro-LED based PD has achieved a record data rate of 15.64 Gbps by using OFDM modulation scheme and bit-loading algorithm [109]. Kang et al. achieved the data rate of the VLC system based on micro-PD by using OOK modulation [20]. A high data rate of up to 1.55 Gbps was achievable by utilizing a semipolar InGaN/GaN MQW micro-PD. The same research group also reported an 8.205 Gbps VLC transmission over a 0.5 m free-space link based on a 4×4 Si-substrate InGaN/GaN MQW micro-LED-based photodetector array [108]. The same research group used the device structure of the PD with super-lattice interlayer to cope with the lattice mismatch and compressive strain, and fabricated a series of high-speed Si-substrate GaN-based PDs. They eventually realized a VLC system with a data rate of 15.26 Gbps by using one unit of the 4×4 micro-LED-based PD array [96].

3.3.2. GaN Micro-LED-Based Photodetectors in On-Chip Communication and Other Versatile Applications

We can find the application of GaN-based micro-PDs not only as high-sensitivity photodetectors but also in photonic integration for on-chip optical communication. A research group studied the characteristics of an integrated monolithic system on a GaN-on-Si wafer, which included LEDs, PDs, and waveguides [110]. The InGaN/GaN multi-quantum wells, responsible for blue light emission in the LEDs, were also utilized as PDs for light detection. The overall structure is shown in Figure 12a,b. Later, another research group studied a UV interconnect system to explore the multiplexing between emission and absorption modulation on a single optoelectronic chip, as shown in Figure 12c,d. All on-chip components, transmitters, monitors, waveguides, modulators, and receivers share the same quantum well structure [111].

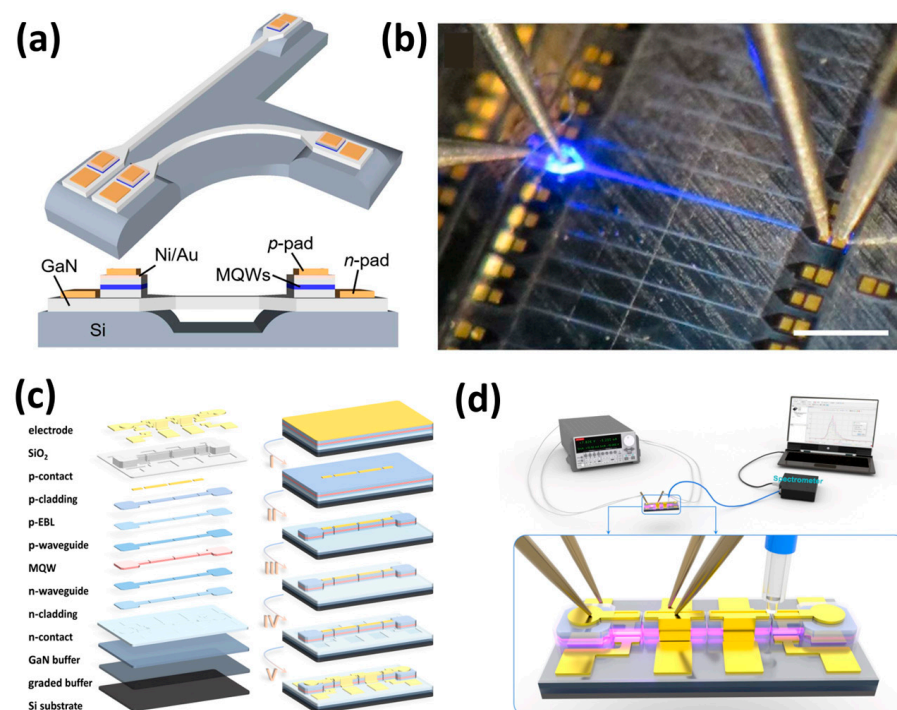


Figure 12. (a) The integration of LEDs, PDs, and waveguides on a GaN-on-Si wafer. (b) The image of the integrated monolithic system on a GaN-on-Si wafer. (c) The layered structure of the on-chip optoelectronic system. (d) The schematic diagram of the on-chip optoelectronic system's operation; refs. [110,111].

In addition, the GaN micro-LED-based photodetector can offer significant scalability, allowing it to be combined with other innovative applications. A multifunctional ultraviolet-C (UVC) micro-LED with a monolithically integrated PD was fabricated [112]. Figure 13a shows the I–V curve of a 300 μm GaN-based PD under different injection currents. This study shows that the photocurrent generated by one micro-LED can well reflect the light output power of the adjacent micro-LEDs, which can improve stability for diverse applications. Another research group introduced a GaN-based photodetector system for acoustic sensing, as depicted in Figure 13b. By directly measuring changes in power due to membrane deformation, this system could simply detect sound vibrations, offering a feasible solution for miniaturization and cost reduction in sensing systems [113]. Furthermore, another research group developed an integrated thermopile in a large-area MQW LED for on-chip temperature and power monitoring, as shown in Figure 13c. The results indicated that integrating a thermopile into the LED enhanced temperature and power monitoring capabilities; we can find the stability of the light output power of the

LED at various temperatures under a 200 mA injection current. Additionally, this integrated approach could potentially enable real-time temperature management and control in LEDs [114]. Furthermore, the underwater applications of micro-LED in light emission, optical detection, and solar cells were demonstrated [21]. The schematic diagram and experimental setup of the duplex UWOC system are shown in Figure 13d. They studied the photovoltaic characteristics of micro-LED based on the duplex UWOC system. This study made a breakthrough in the duplex UWOC system based on a micro-LED array and showed the significant potential of micro-LED application in the field of duplex UWOC and underwater charging.

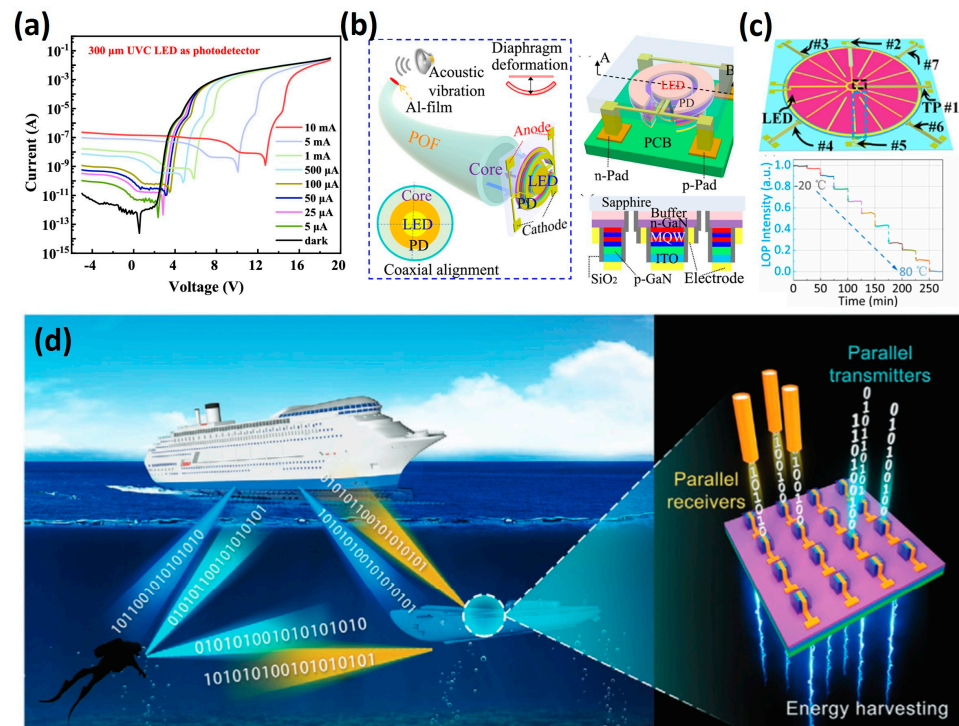


Figure 13. (a) The current-voltage characteristics of a 300 μm LED, functioning as a PD, were recorded in the dark and while exposed to 40 μm micro-LED irradiation at various injection currents. (b) The integrated acoustic sensing system. (c) The structure of the thermopile-integrated LED chip and the stability of the light output power of the LED at various temperatures under a 200 mA injection current. (d) Depiction of application scenarios for dual UWOC and power-delivery technologies utilizing a micro-LED array; refs. [21,112–114].

Moreover, along with the on-chip communication supported by GaN-based micro-PDs, other components can be integrated. A three-terminal diode that consists of a traditional two-terminal GaN-based diode with a monolithically integrated third terminal (Tt) composed of metal/ Al_2O_3 dielectric layer directly on the p-layer was fabricated [115]. Figure 14a shows the schematic structure of the three-terminal diode (TTD). When the three-terminal diode operates as a transmitter, the light intensity can be adjusted by modulating the bias applied to the third terminal. Additionally, since the third terminal features an integrated bias tee, its modulation bandwidth can increase from the original 160 MHz to 263 MHz. Figure 14c shows that, when it functions as a photodetector, both the external voltage applied to the third terminal and the incident light serve as signal inputs that control the output photocurrent, providing reconfigurable photonic NAND and NOR logic gates. This study demonstrates the enormous potential of GaN-based micro-PDs in building optical interconnect chips.

GaN-based micro-PDs can be developed with more different structures to achieve many other applications. This paper focuses on the material issues of III-nitride quantum-structure optoelectronic devices. It employs dopant-free polarization-induced doping with linearly graded AlGaIn to create a p-type layer and fabricates p-down p-i-n photodiodes based on InGaIn/GaN MQWs, as shown in Figure 15a [116]. Another paper fabricates visible-light heterojunction phototransistors (HPTs) using a dopant-free p-type base and an InGaIn/GaN superlattice absorber, achieving a high I_{ph}/I_{dark} ratio, a high responsivity (37 A/W at 1 V, 470 A/W at 3 V), a rise time of ~ 3.4 ns, and bias-controlled wavelength selectivity (narrowband at ≤ 1.0 V, broadband at ≥ 1.5 V) due to polarization effect without optical filter [117]. Another paper deals with InGaIn-based blue-light PDs for VLC systems, as shown in Figure 15b. Their application is limited by InGaIn's poor crystalline quality. With high responsivity and speed, InGaIn-based MSM blue-light PDs are fabricated on Si substrates via low-temperature pulsed laser deposition (LT-PLD) and high-temperature metal organic chemical vapor deposition (HT-MOCVD) combination. LT-PLD suppresses interfacial reactions, and HT-MOCVD improves film quality. The PDs have a high responsivity of 0.49 A W^{-1} and short rise/fall times of 1.25/1.74 ms at 3 V bias, outperforming previous ones [118].

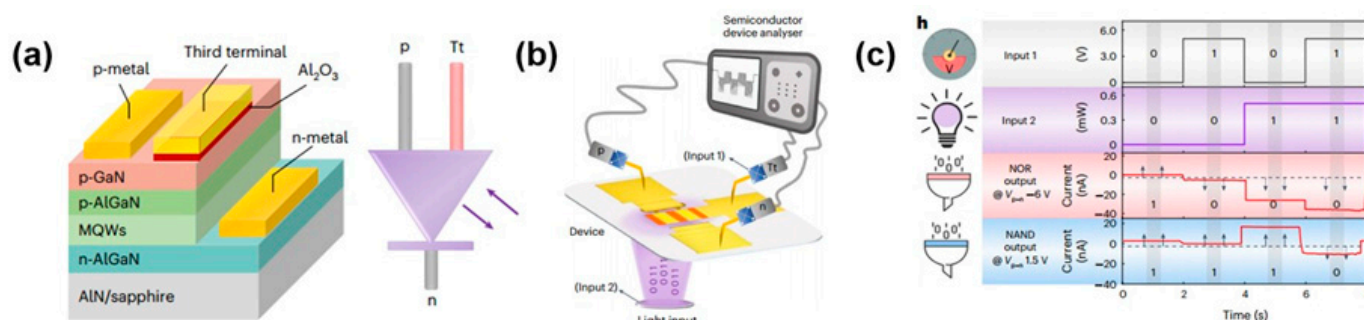


Figure 14. (a) The schematic structure of the three-terminal diode. (b) The system setup for testing the optoelectronics functionality of three-terminal PDs. (c) The logic of the TTD with inputs; ref. [115].

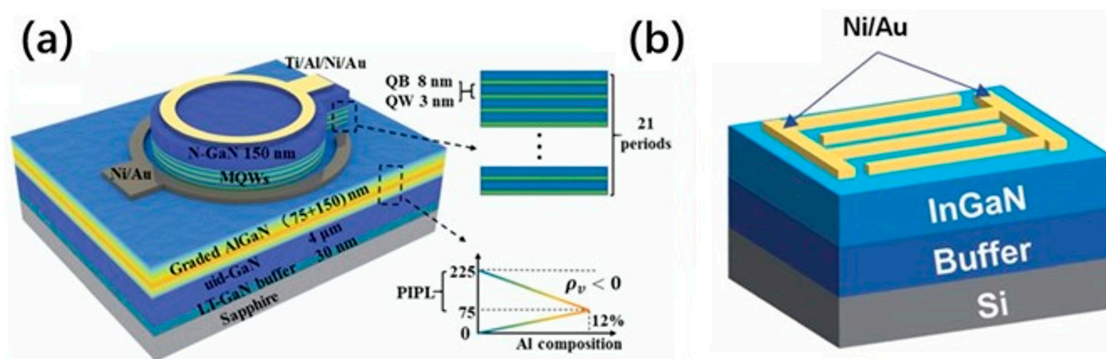


Figure 15. (a) Schematic diagram of the structure of the visible-light photodiode, along with the depiction of the variation in the aluminum (Al) composition and the thickness of the polarization-induced p-type layer (PIPL). (b) Schematic diagram of epitaxy InGaIn film; refs. [116,118].

3.4. Summary of Micro-LED-Based Photodetectors in VLC

The micro-LED-based PDs discussed above have excellent characteristics of responsivity, a high bandwidth, and a high data rate. Considering the relationship between transmission distance and data rate, we summarize the benchmark of the data rate versus reverse bias voltage for VLC systems of micro-LED-based PDs, as shown in Figure 16.

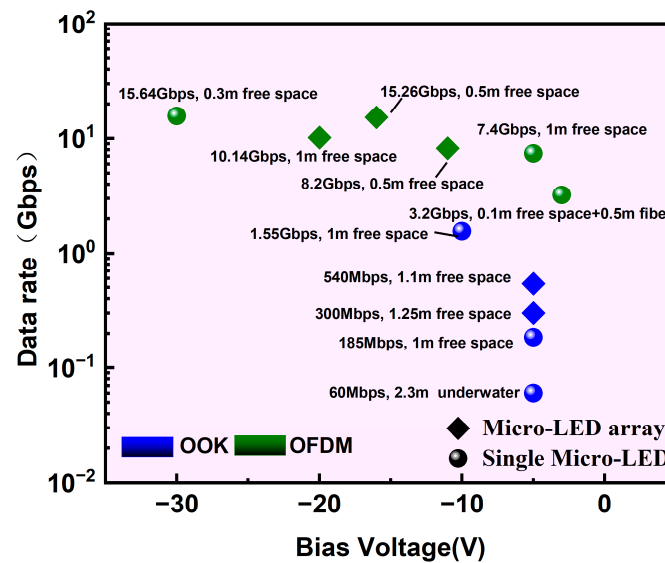


Figure 16. Benchmark of the data rate versus reverse bias voltage for GaN micro-LED-based PDs and micro-PDs; refs. [16,17,20,96,101,103,105,106,108,109].

In summary, GaN micro-LED-based PDs show great potential in VLC, underwater charging, and multifunctional displays. In the future, how to make micro-LED-based PDs with higher bandwidth and higher responsivity is still an important research topic.

4. Conclusions

In this paper, we focused on recent progress in the application of GaN-based high-bandwidth micro-LEDs and photodetectors, and also reviewed the current status of research and challenges in micro-LED-based PDs. In addition, we briefly summarized the wide range of micro-LED applications, especially focusing on the latest applications of micro-LEDs in structured positioning and optical interconnect technology. The outstanding performance of micro-LEDs in luminescence and photodetection functions will drive the rapid development of integrated chips and will also broaden the application scenarios of micro-LEDs. The pursuit of high-speed optical communications has led to further enhancements in the bandwidth and speed of GaN-based micro-LEDs and photodetectors. At the same time, new applications derived from GaN-based micro-LEDs, such as on-chip optical communications, high-speed optical interconnects, and structured light positioning, are diversifying the future development of optical communications. The above micro-LED-based high-speed communication systems will promote the development of communication technology, so that VLC is expected to become a powerful technology in the 6G.

Looking ahead, future research and development in this field hold several promising directions.

1. The promotion of GaN-based high-bandwidth micro-LEDs will further enhance the development of VLC. The introduction of new substrates and the optimization of QWs will further shorten the carrier recombination lifetime and improve the modulation bandwidth of the micro-LED. The research on field-effect transistors, heterojunction memory devices, and perovskite solar cells can inform the bandwidth design of micro-LED through shared technological approaches such as band structure engineering, interface optimization, and multidimensional structural design [119–121]. For the design of devices, size, connection methods, and device structure are the main focuses of researchers. The future of the micro-LED needs to better balance the relationship between the modulation bandwidth and the optical power. High bandwidth combined with high optical power will further improve the data rate of

VLC. In addition, the introduction of new fabrication processes will also improve the efficiency of micro-LED manufacturing. By simultaneously innovating in materials, structure, and manufacturing processes, it is possible to break through the limitations of bandwidth and optical power, achieving low-energy, high-speed communication performance to meet the increasing demand for data transmission.

2. The improvement of micro-LED-based PDs can be divided into three parts. Firstly, the epitaxial optimization of high-performance micro-LED-based PDs featuring GaN-based MQW structures is significant. Through further meticulous optimization of the device architecture, it is feasible to fabricate PDs that simultaneously exhibit high responsivity and high bandwidth, thereby substantially augmenting the performance of these photodetectors across diverse applications. Some researchers achieve room-temperature broadband mid-infrared detection through vertical Schottky junction integration, thereby providing technical insights for the design of micro-LED-based PDs [122–125]. Secondly, the design of high-speed arrays of micro-LED-based PDs with GaN-based MQW structures must be meticulously optimized for MIMO-VLC systems. The large divergence angle of the LED causes the light to directly illuminate the adjacent PD, resulting in signal aliasing and a decrease in SNR. Furthermore, each pixel in the micro-LED array requires an independent driver, which restricts the high-density integration of micro-LED-based PDs. Therefore, the design of the micro-LED array must avoid optical crosstalk by precisely configuring the number, size, and spacing to ensure compatibility with high-speed LED arrays. This accomplishment will facilitate more efficient and dependable data transmission within VLC systems, thereby broadening the application fields of VLC in domains such as high-speed indoor communication networks and IoT.
3. The integration of micro-LED-based PDs with GaN-based MQW structures and micro-LED light-emitting devices harbors substantial potential. By synergistically combining functions encompassing lighting, display, and communication, it is possible to realize sophisticated applications such as intelligent lighting systems and smart displays with multifunctional integration. This integration will not only confer enhanced convenience to people's daily living experiences but also provide novel opportunities for the advancement of smart cities and other cognate fields.

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