A Prospect of Novel Devices for Visible Light Communication in Future 6G Networks Applications

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***Abstract*—Over the past two decades, advances in materials science and electronics have greatly supported the progress of the communication industry, and the emergence of new materials has made it possible to design higher performance communication modules. As a potential key technology for future 6G networks, the standardisation and industrialisation of visible light communication (VLC) cannot be separated from the improvement of the communication devices. In this paper, we first analyse and summarise the performance enhancement of new materials and designs of VLC devices. Then the support of improved capabilities of novel VLC devices for 6G new services is prospected. As device performance improves, VLC is expected to support more scenarios in 6G.**

***Index Terms*—Visible light communication, materials, devices, 6G**

I. Introduction

Visible light communication (VLC) is a kind of wireless optical communication (OWC) that integrates the functions of illumination and communication. It has the advantages of rich spectrum resources, easy deployment and good electromagnetic compatibility, and is considered as an effective complement to 6G radio frequency (RF) communications. VLC uses visible light source to transmit information by emitting the optical signal that is hard to distinguished, and then converts the received light signal into electrical signal to obtain information via photoelectric converter, such as photoelectric detector (PD) [1]. The parameters such as bandwidth and sensitivity of transmitting light source device and receiving detector device determine the upper limit of the communication data rate and the actual transmission distance, which affects the design of the physical and link layers of the optical network.

Light source devices typically include light-emitting diodes (LEDs), laser diodes (LDs) and others [2]. LEDs consist of a PN junction with unidirectional conductivity, while LDs consist of a PN junction and a resonant cavity. The core light-emitting layer of LEDs and LDs is typically composed of compounds of elements such as Gallium (Ga), Arsenic (As), Phosphorus (P) and Nitrogen (N), which can efficiently convert electrical energy into optical energy, and the light source made of different materials excites light at different frequencies, such as blue light, red light and green light. Most current VLC systems use LEDs as the emitting light source. However, limited by carrier lifetime and resistance-capacitance (RC) parasitic parameters, the modulation bandwidth of current commercial LEDs is few MHz, making it difficult to support 6G GBit/Tbit-level throughput [3]. In contrast, LDs operate in excited radiation mode, which is not limited by carrier lifetime and therefore have a larger modulation bandwidth. Currently, the modulation bandwidth of blue LDs can reach over 1GHz [4]. However, the light beam emitted by LDs is narrow, which requires a strict alignment between transmitter and receiver, making it difficult to ensure wide network coverage.

Receiving devices for VLC are dominated by a variety of semiconductor PDs using materials such as Silicon (Si), Germanium (Ge), Silicon Carbide (SiC) and Gallium Nitride (GaN). Common commercial PDs include silicon-based PIN, APD and CMOS imaging sensors [5]. The basic operating principle of PD is the photoelectric effect, so the indicators such as field of view (FOV), sensitivity, light-sensitive area and dark current will determine the performance of devices, including the transmission distance and rate. Moreover, the PD receiving bandwidth has become one of the potential limitations for future high speed communication. As the performance of the transmitter device improves, further improvement of the receiving bandwidth of the PD becomes a direction to consider.

Motivated by our research on 6G requirements, VLC application scenarios and VLC devices, we explore the future application of novel devices. Specifically, we summarise the potential application scenarios of VLC in 6G networks and the researches on VLC devices of our team, then we analyse the prospect of new devices for future applications in 6G networks.

The rest of this paper is organised as follows. Section II presents the current state of research on VLC devices. In Section III, the current state of 6G research and potential application scenarios are briefly introduced. In Section IV, new materials and designs of novel VLC devices are described. Then the application prospects of new devices in future 6G networks is analyzed in detail, including complementing and enhancing existing applications, and supporting future

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applications. Finally, the future challenges for VLC devices is outlined in Section V.

II. Related Works

In order to enable the VLC in future 6G networks, transceiver devices need to be investigated to meet various strict requirements for 6G. In recent years, several research teams have made efforts to improve the performance of VLC devices. In 2013, S. Watson et al. used LDs to achieve 2.5Gbps data rate [6]. Latter in 2017, Islim constructed a miro-LED based VLC system and achieved a rate of 11.95Gbps by using OFDM and adaptive bit energy loading [7]. In 2020, Y. Huang et al. developed blue-emitting GaN micro-LED arrays with pixels from 1×1 to 6×6. The optical output power of the 6×6 matrix array reached 356.7mW [8]. Chang extended the modulation bandwidth of mirco-LED array to 1.1GHz and built a VLC test environment [9]. In 2022, Hai-Han Lu et al. implemented a three-wavelength RGB VLC-underwater wireless laser transmission (UWLT) and a laboratory illumination fusion system, achieving a total transmission rate of 30Gbps and laboratory-grade white illumination of 752 lux [10].

Since 2021, China Mobile Research Institute and Fudan university have conducted several researches on VLC devices, including micro-LED, LD and SLD. The newly designed devices break through the rate of 700Mbps, 3.7Gbps, 4.57Gbps to 14Gbps, respectively [4], [15]–[17]. The team also designs a LD structure with a wide FOV that exceeds 150 degrees and explore the design of arrayed waveguide grating [17], [18].

III. Requirements of Future 6G Networks

A. Key Point Indicators, New Application Scenario of 6G Networks

With the commercialisation of 5G, the industry has begun to explore the next generation of mobile communication systems. Compared to 5G, 6G has more complex application scenarios, including holographic communication, extended reality (XR), unmanned aerial vehicle (UAV) communication, intelligent transportation and global ubiquitous connect-ability, all of which place a higher demand on network key point indicators (KPIs). Therefore, 6G requires higher in various aspects such as capacity, reliability, delay, mobility and energy consumption [11]. In order to support the existing and potential multiple services, the 6G network needs to achieve KPIs such as peak rate over 1Tbps, traffic density per unit area over 1Gbps/m2, airport delay less than 0.1ms, and positioning accuracy up to 1cm.

The solutions for 6G KPIs can be divided into two categories, one is to increase the communication bandwidth by using the higher frequency such as the visible light band and the terahertz band. The other is to increase the spectral efficiency and spatial freedom through new coding and modulation waveforms [12].

B. Application of VLC in 6G Networks

VLC is expected to support high-speed data transmission due to its huge available frequency bandwidth, and the simple deployment makes it possible to meet high traffic density requirement of 6G networks. Thus, VLC can support multiple scenarios of 6G, as shown in Fig.1.

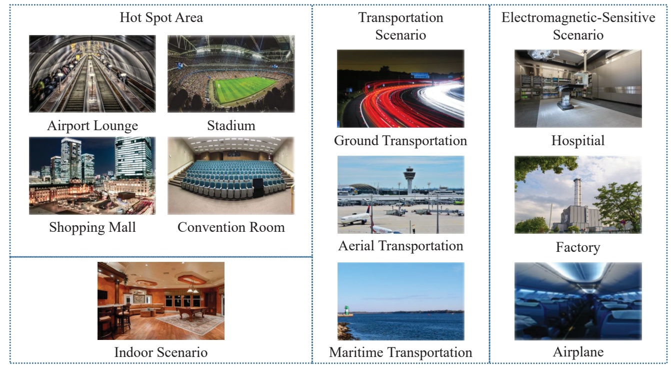

Fig. 1. Application scenarios of VLC in 6G networks.

In terms of deployment, the VLC application scenario can be divided into hot spot scenarios and indoor scenarios, where the former covering a large area with dense traffic, and the latter mainly concentrating on a small area with limited mobility. Combined with the vertical industry, VLC can also be applied in three transportation scenarios after integration with lighting: ground, aerial and maritime. In addition, due to the electromagnetic characteristics of visible light, it can also be used in a variety of electromagnetic sensitive environments such as hospitals, factories and aircraft interiors, which can simultaneously provide the necessary illumination and effectively avoid electromagnetic interference. Therefore, VLC can further build a safe and reliable wireless communication environment.

IV. New Materials and Designs for VLC Devices

Overall, 6G-oriented VLC applications place high requirements on equipment, the new generation of VLC transceivers need to meet the KPIs of large bandwidth, wide coverage, low cost, convenient coupling, good security, high sensitivity and so on. Therefore, the development of device materials, structures and manufacturing processes is of great significance to the standardisation and industrialisation of VLC.

A. New Materials for VLC Devices

The above mentioned materials used in the LEDs and LDs primarily serve solid-state lighting and are not primarily aimed to support communications. Therefore new materials are required to be explored to fulfill both requirements. In recent years, group III–Nitride materials, mainly (In, Ga, Al)N, have been mostly studied for light emitters, including LEDs, superluminescent diodes (SLDs), and LDs [13].

GaN is a type of direct bandgap semiconductor, which has a wide direct bandgap, strong atomic bonds, high thermal conductivity, good chemical stability (almost not corroded by any acid) and strong resistance to irradiation. Therefore, GaN has a wide prospect in the design of optoelectronic, high temperature high power devices and high frequency microwave devices.

GaN-based emitters are currently a hot research topic, which can significantly improve the communication performance of light source. For example, the modulation bandwidth of LEDs prepared with GaN materials can be increased from several MHz to several hundred MHz [14]. Compared to silicon-based PDs, GaN-based PDs are more flexible in spectrum selection. Due to the superior thermal and chemical stability of GaN materials, GaN-based PDs are more resistant to irradiation, more reliable and suitable for long-term operation.

InGaN/AlGaIn is a fouth-generation semiconductor and is the most important material used in red light devices. InGaN/AlGaIn further increases the modulation bandwidth of red LEDs in RGB-LED systems while maintaining stable illumination. In addition, the production of this material is green and environmentally friendly, adapting to the future development of 6G.

B. New Design of Modules for VLC Devices

1) Micro-LED Array: Recently, micro-LEDs have attracted growing attention due to their excellent current spreading, high efficiency, and large modulation bandwidth. Micro-LEDs greatly increase the density of current carriers in the active area by reducing the active area, which can reduce the carrier lifetime. At the same time, the smaller active area reduces the junction capacitance of the devices, further reducing the RC parameter. The micro-LEDs based VLC systems can increased the modulation bandwidth up to several hundred MHz, extend coverage and increase the output power [15].

Fig.2 shows a proposed micro-LED arrays designed in our previous work [15], [16]. Fig.2(a) and Fig.2(b) are the micro-scope image and lighting effect of green micro-LED grown on a c-plane sapphire substrate by metal organic chemical vapor deposition (MOCVD) technique, where its epitaxial structure consists of different thickness of undoped U-GaN, N-AlGaN, P-AlGaN, P-GaN and MQWs active layer. Fig.2(c) and Fig.2(d) are the performance of proposed micro-LED arrays. These devices can support communication rates from 700Mbps to 3Gbps.

2) Superluminescent Diode: The III-Nitride superluminescent diode (SLD) has emerged as a promising light emitter in VLC systems. The SLD is fabricated through grinding and polishing of laser diode on submount. Compared to LEDs, SLDs have an extended modulation bandwidth due to the enhanced spontaneous emission mechanism. Meanwhile, SLDs have relatively low speckle noise and are friendly to human eyes. Fig.3 depicts a proposed blue SLD, which is also prepared by the MOCVD technique [14]. It is fabricated based on a conventional laser epi-structure, consisting of InGaN/GaN quantum wells, together with AlGaN cladding layers, GaN waveguiding layers and an AlGaN electron blocking layer. The proposed blue SLD can achieve communication rates of up to 4.57Gbps.

3) Ultra-Wide FOV Design: Since the light beam produced by LD is highly directional, the link between the transceiver needs precisely aligned, which limits the application of VLC. To meet different scenarios, VLC devices require enough FOV

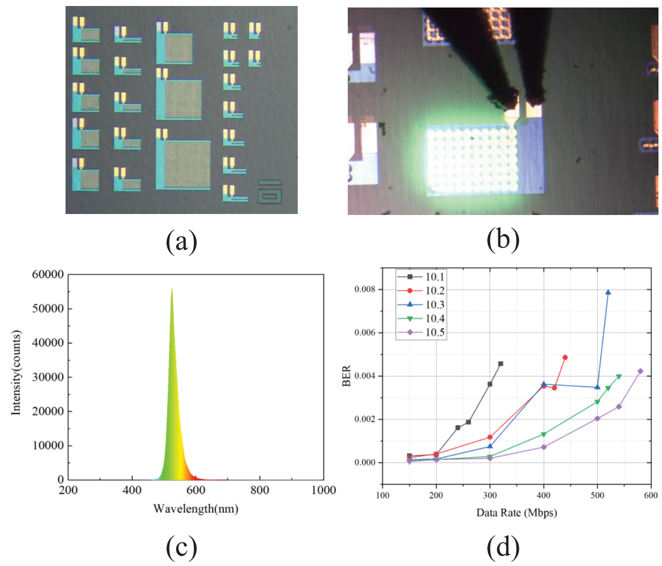

Fig. 2. The schematic structure and lighting effect of the proposed micro-LED arrays [15], [16]. (a) Optical microscope image of the micro-LED arrays collected using a CCD camera. (b) Green micro-LED array as transmitter in high-speed VLC system. (c) Electroluminescence (EL) spectrum of InGaN/GaN micro-LED. (d) Bit error ratio (BER) vs transmission data rate measured from micro-LED array with different number of 10μm diameter pixels using on-off keying (OOK) modulation.

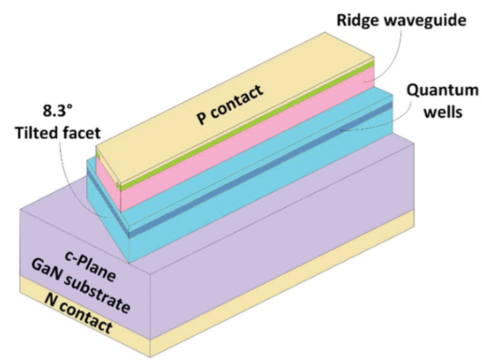

Fig. 3. Schematic illustration of the SLD on the GaN substrate [14].

for communication. In [17], we design a white LD transmitter integrated with an engineered diffuser. An ultra-wide FOV exceeding 150 degree with data rates over 200 Mbps is achieved in this design, demonstrating the possibility to further advance researches and applications of VLC technologies.

C. New Devices Support 6G New Service and Scenarios

1) Multi Frequency Band Converged Networking: The 6G network will be a deeply integrated network consisting of a full range of spectrum resources such as the sub-6GHz band, the mid-frequency band, the millimetre wave band, the terahertz band and the visible light band, etc. Multiple network formats such as WiFi, 5G, LTE, and multi-dimensional deployment scenarios such as air, space, and ground will exist simultaneously in the network. Among them, VLC networks

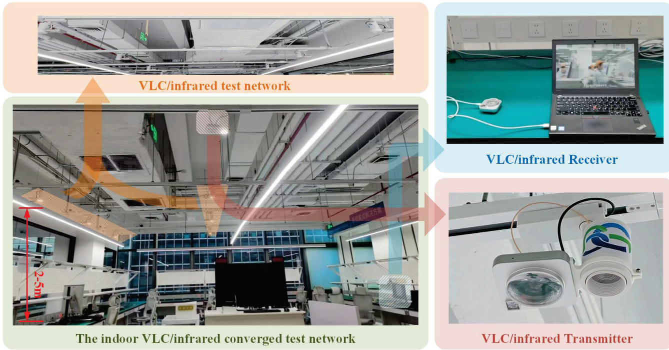

Fig. 4. The indoor VLC/infrared converged test network, built by China Mobile Research Institute (China Mobile Information Port, Beijing, China), where the network contains multiple LED transmitting nodes and PD receiving nodes. The visible light band is used for the downlink and infrared band is used for the uplink. The system is based on WiFi protocol and can support two-way real-time communication with a radius of about 2m at a height of 5m. And the peak real-time rate of up to 50MB/s can be achieved.

are mainly used as a complement to RF networks to further enhance the user experience [19]. Fig.4 shows a typical VLC converged network.

The modulation bandwidth of the new devices is tens of times greater than that of LED, and its frequency response curve will be smoother. This is expected to reduce the difficulty of device adaption, simplify the complex signal processing, and achieve a generalised VLC baseband signal design. As a result, the new devices can meet the requirements of 6G universal baseband processing, accelerate the convergence of VLC networks with other formats and frequency bands, and achieve 6G universality. More stable illumination and longer device lifetime make VLC converged networks easier to maintain, which will be a major advantage for ultra-dense deployed VLC nodes. The promoted transmitter's coverage area and improved receiver's sensitivity are expected to reduce the shadow areas in the network, reduce the number of nodes used to compensate for blindness, and further reduce the cost of network deployment. The new devices could also increase the edge access probability of the cell, and the support capacity of multi-user will also increase serval times, which can provide a solution for the hot spot area in 6G.

2) In-Flight Communications: With the development of beamforming technology, air-to-ground (ATG) communication has become a hot research topic in 5G. At present, the information transmission between the ground and the aircraft is mainly achieved by establishing an ATG base station on the ground. After the on-board communications equipment of aircraft converts the signals from ATG base station into WiFi signals, passengers will be able to access the internet. Some of relevant network operators have gradually began the test of 5G-ATG communications in recent years [20]. However, WiFi signals are still electromagnetic signals, which will complicate the electromagnetic environment on the aircraft. In addition, the changes in the electromagnetic environment during flight will also make WiFi signals unstable [21]. With stability of transmission, VLC is able to achieve the "last metre" on the aircraft, providing a high-speed and reliable downlink transmission.

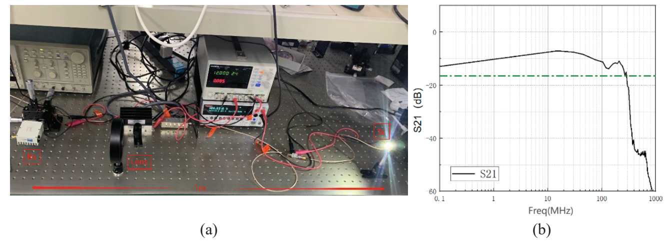

Fig. 5. The novel miniaturised visible white light transmitter, where the 3 dB bandwidth is over 700MHz.

By adopting new materials and new structural designs, VLC transmitters can be miniaturised in size and be able to operate at a low power level. Fig. 5 illustrates a designed novel miniaturised visible white light transmitter of our previous work. Miniaturised devices can reduce the difficulty of installing equipment on aircraft, while meeting the high traffic density requirements of the access network. Lower power devices can better meet the requirement of aircraft interior illumination. In addition, the mechanical failure rate of smaller, more integrated devices is significantly lower when considering the bumps during the flight.

3) Smart Home: Smart home is an emerging 5G indoor internet of things (IoT) service that utilises network communication technology to enhance people's living experience. Currently, the communication of smart home devices is mainly based on RF links or power line links, and the emergence of new devices has also made VLC one of the solutions for smart home. The VLC transmitters will be combined with indoor lighting to replace WiFi access points (APs) in current application. Compared to WiFi APs, the advantages of new devices have obviously improved the downlink transmission rate to Gbps level. In addition, the propagation characteristics of optical signals also reduce the downlink signal interference and indoor electromagnetic radiation at the same time. The probability of eavesdroppers accessing the network is also reduced, ensuring the privacy of the user's home network.

4) Extended Reality: As 6G research progresses, higher transmission rate, lower latency, and multiple connections will push the extended reality (XR) user experience to the top [22]. The current XR technology creates a believable experiential environment in the form of head-mounted display (HMD) via wired and WiFi. It adopts multi-sensory technology to capture and model the surrounding environment in real time, and then transmits the results to the cloud for AI processing. By visually and audibly mapping the surrounding environment, the cloud will provide feedback to the user with the information of visual, auditory, and haptic senses. Then the interaction experience between the virtuality and reality of the user will be completed. Thus, the XR places higher requirements on the delay, transmission rate, connection, coverage and reliability of the current wireless network.

Depends on its advantages of large bandwidth, high rate,

Fig. 6. Application of VLC in XR.

low latency, and multi-connectivity, VLC can be applied to XR to meet the above requirements. By adopting new materials and optical structure design, the VLC transmitters are able to realize miniaturization, wide coverage and high integration at the same time. And the highly sensitive and responsive receivers can replace the current devices on XR. While satisfying the low latency and high rate access in high traffic density scenarios, it can also realize centimeter-level positioning through cloud-based AI data interaction [23], as shown in the following Fig.6.

The left side in Fig.6 shows the new miniaturized, wide coverage, high rate VLC transceiver in our previous work. The center shows a scenario where VLC is used in multi-user XR, and the right side shows the processing of VLC after data receiving. In the multi-user XR scenario, different bands in VLC can be used in the uplink and downlink to transmit data, and the VLC receiver will distribute the data received through the 6G base station to the AI edge cloud and the center cloud to compute, model, and locate the data. The final modeling results and location information will be sent from the VLC transmitter to different users. The modeling results will show the users the fusion of real and virtual scene information, while the location information will show the users the movement of the characters in the current virtual scene, and make a decision on whether or not to switch to a different VLC transmitter to optimize the network transmission.

V. Future Challenges of VLC Devices

The development of future VLC devices is facing two main challenges: the growing demand for 6G services and the evolution of semiconductors. With the improvement of devices, VLC initially has the ability to serve some application scenarios in 5G, B5G and 6G. However, for the requirements of 6G common KPIs, it is still necessary to develop devices with larger bandwidth, wider coverage and more responsive. As 6G services are still evolving, some potential new services are emerging, such as ultra-scale UAV communications and L5-level intelligent driving, which will require a sufficient design margins of devices in the future. Meanwhile, since a large-scale infrastructure that may be deployed in the future, not only the communication metric needs to be considered, but also the physical structure, operational stability, and power consumption of devices.

In addition, the materials, models and tape out of the devices are limited by the development of the semiconductor industry, making it difficult to achieve an obvious progress in a short period of time. The experimentation of new materials and the exploration of fabrication processes take years of time and cost a lot of money. As a result, the speed of device update iteration is difficult to match the development of potential 6G applications.

VI. Conclusions

This paper investigates the application of novel VLC devices for future 6G networks. Based on 6G requirements and VLC application scenarios, the third-generation semiconductor materials and model design of novel VLC devices are presented. These improvements enhance the performance of VLC devices. Then the support of devices to 6G different scenarios are drawn, and the challenges of next-generation VLC devices are described. This work provides a guidance for the standardisation and industrialisation of VLC.

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