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A Review on Infrared Light-Emitting Diodes for Optical Communication

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Abstract. As a core light source for optical communication systems, infrared light-emitting diodes (IR-LEDs) demonstrate significant advantages in visible light communication (VLC), free-space optical communication (FSO), optical wireless communication, and infrared remote control, owing to their low power consumption, electromagnetic interference immunity, and invisibility to the human eye. This article systematically reviews the working principles of IR-LEDs and their performance in optical communication systems, with a focus on recent research advances in structural optimization (e.g., reflective transparent structures, vertical LEDs, micro-LED arrays), novel materials (e.g., quantum dots, III-V semiconductors), and advanced modulation techniques (e.g., OFDM, WDM, polarization/mode multiplexing). Studies reveal that micro-LED arrays enhance modulation bandwidth, quantum dot materials achieve >20% external quantum efficiency (EQE), and heterogeneous integration of III-V materials with silicon photonics substantially overcomes the bandwidth and efficiency limitations of conventional IR-LEDs. Future multi-technology collaborative innovations will further drive the evolution of IR-LEDs for high-speed, high-capacity optical communication.

Keywords: Infrared light-emitting diodes, Optical communication, Visible light communication, Free-space optical communication

1. Introduction

Infrared light-emitting diodes (IR-LEDs), serving as the core light source in optical communication systems, continue to expand their application scenarios in visible light communication, free-space optical communication, and other fields due to their inherent advantages, including electromagnetic interference immunity, low power consumption, and invisibility to the human eye. Although current research has achieved significant progress in areas such as bandwidth enhancement of micro-LED arrays, breakthroughs in the external quantum efficiency of quantum dot materials exceeding 20%, and III-V/silicon photonic heterogeneous integration, notable gaps persist. Key challenges include insufficient device-level compatibility with CMOS processes, scarce research on the stability of quantum dot materials, lagging development of communication modules for specialized scenarios, and an unclear fusion mechanism at the system level between polarization/mode multiplexing technologies and IR-LEDs. This review focuses on three key improvement pathways: device

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structure optimization, novel material systems, and advanced modulation techniques. It systematically explores synergistic strategies for overcoming the bandwidth bottleneck and nonlinear limitations inherent in conventional IR-LEDs. Specifically, it scrutinizes the mechanisms by which material band engineering influences carrier recombination efficiency, the impact pathways of micro-nano structures on light extraction characteristics, and the capacity-enhancement logic of multi-dimensional multiplexing techniques. Through a systematic comparative analysis of multidisciplinary literature and synthesis of technical roadmaps, this review aims to provide reference points for future research on IR-LEDs for optical communication, ultimately aiming to propel future innovations in this direction.

2. Application context of infrared light-emitting diodes in optical communication

2.1. Fundamental principles of IR-LEDs

The basic structure of an IR-LED resembles that of a conventional visible-light LED, both operating on the p-n junction principle. When current flows through the semiconductor material, electrons and holes recombine in the p-n junction region, releasing energy. A portion of this energy is radiated in the form of photons. For IR-LEDs, the emitted photons fall within the infrared spectrum (typically 780–1000 nm), which is invisible to the human eye—granting unique advantages in communication applications. Gallium arsenide (GaAs) and aluminum gallium arsenide (AlGaAs) constitute the primary material systems for mainstream IR-LEDs. By precisely controlling material composition and quantum well structures, emission at wavelengths critical for optical communication—such as 850 nm, 940 nm, and 1550 nm—can be achieved.

2.2. Structure and workflow of infrared optical communication systems

The infrared light-emitting diode (IR-LED) optical communication system mainly consists of a transmitter, a transmission medium, and a receiver. The transmitter drives the IR-LED through a modulated signal to emit optical signals carrying information. These signals are transmitted through optical fibers or free space. The receiver uses a photodetector to receive and convert the optical signals into electronic signals, which are then restored to information by a decoder to achieve data transmission. In addition, there is usually a feedback control part after signal processing to ensure the system's regulatory performance, such as stabilizing optical power and reducing bit error rate.

3. Application performance of infrared light-emitting diodes in optical communication

As a light source, IR-LED plays an important role in various optical communication systems, especially in visible light communication, free space optical communication, optical wireless communication and infrared remote-control systems.

3.1. Application performance in visible light communication

Visible light communication (VLC) is an emerging wireless communication technology that takes advantage of the dual benefits of LED lighting and communication. Although VLC mainly uses the visible light band, IR-LED can provide additional communication channels in hybrid systems or serve as a supplement in scenarios where visible light is not suitable. Infrared LEDs can be used for covert indoor wireless communication, especially in scenarios where lighting functions are not required, which makes IRED have unique advantages in creating secure communication links

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without radio frequency interference. For example, one proposal introduces a dual-band modulation scheme that operates simultaneously in the visible and infrared spectra, leveraging the ubiquity of existing visible-light infrastructure while exploiting infrared's immunity to dimming.

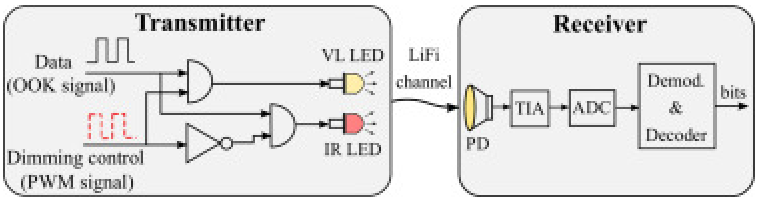

Figure 1. Block diagram of visible light communication system [1]

3.2. Application performance in free space optical communication

Free Space Optical Communication (FSO) utilizes lasers or LEDs for data transmission through atmospheric or aquatic channels. Recent studies have demonstrated real-time transmission of text, images, and audio over FSO and Underwater Wireless Optical Communication (UWOC) channels, while quantitatively analyzing the impacts of atmospheric/oceanic attenuation and turbulence on system performance [2]. Notably, IR-LEDs exhibit significant competitive advantages in short-range applications due to their low atmospheric attenuation in specific wavebands (780-950nm) and invisibility to the human eye, highlighting their critical application potential in FSO systems.

3.3. Application performance in optical wireless communication

Optical wireless communication uses light waves (including infrared light, visible light and ultraviolet light) as information carriers for wireless transmission. The low cost and easy availability of infrared LEDs and the ability of photodetectors to directly convert electrical energy into infrared radiation and vice versa make them the first choice in the near-infrared region for data communication. Studies have proposed a low-speed uplink system that uses surveillance cameras on the ceiling to communicate with infrared LEDs below to avoid glare and interference in visible light uplinks or radio frequency uplinks [3].

3.4. Application performance in infrared remote control

Infrared LEDs are most widely and maturely used in remote control systems. Such systems use infrared light for short-distance wireless control and data transmission. They usually adopt simple modulation and demodulation technologies, such as on-off keying, to encode data signals by quickly switching infrared LEDs on and off. Since infrared light is invisible, this communication method will not interfere with the human eye and has low power consumption. For example, remote controls for home theater systems, air conditioners and various smart home appliances generally use infrared LEDs as transmitters [4]. In automotive applications, infrared remote-control systems are also used for secure access control, providing flexible programmability and a variety of data encoding and carrier modulation technologies [5].

4. Current improvement directions for infrared light-emitting diodes

The performance of infrared optical-communication systems hinges on the transmitter, typically an infrared light-emitting diode. Yet conventional IR-LEDs are constrained for high-speed use by their narrow modulation bandwidth and pronounced nonlinearities [6]. Therefore, improvement directions

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mainly focus on device structure optimization, application of new materials, and combination with advanced modulation technologies.

4.1. Device structure optimization

4.1.1. Reflective transparent structure

The reflective transparent structure enhances the performance of IR-LEDs by optimizing light extraction efficiency. Incorporating a reflector or transparent electrode into the LED architecture redirects internally generated light outward, minimizing absorption and markedly boosting external quantum efficiency (EQE). Some studies have successfully reflected downward-emitted light upward by integrating a reflector at the bottom of the LED, increasing light output [7]. This structural optimization can reduce light loss inside the device and improve optical output power.

4.1.2. Vertical structure LED

Vertical structure LEDs (Vertical-LEDs) have multiple advantages over traditional planar structures. In vertical structures, current passes vertically through the active region, resulting in a more uniform current density distribution and reducing current crowding effects. In addition, substrate stripping technology can optimize the heat dissipation path, bringing the high-heat-generating active region closer to the heat sink, thereby reducing operating temperature, extending device lifespan, and increasing output power. For visible light LEDs, vertical structures have been proven to effectively improve luminous efficiency and reduce operating voltage, and these advantages can be adapted to IR-LEDs with improvements.

4.1.3. Miniaturized LED (Micro-LED) arrays

Micro-LED arrays, especially for visible light communication (VLC) and infrared optical communication, have significant advantages. Miniaturization can greatly increase the modulation bandwidth of the device because small-sized LEDs have lower parasitic capacitance and resistance. In addition, Micro-LED arrays can achieve higher integration. By driving each micro-unit independently, advanced modulation schemes—spatial multiplexing and pixel-level brightness control—become feasible, unlocking μ-LED displays that deliver high color fidelity, minimal crosstalk, ultrahigh resolution, and low cost for XR, MR, AR, and VR applications [8].

4.2. Application of new materials

The application of new materials provides new approaches to break through the performance limitations of traditional semiconductor materials, especially in expanding the emission wavelength range and improving luminous efficiency.

4.2.1. Quantum dots

Quantum dots (QDs) have become highly promising new materials in the field of IR-LEDs due to their characteristics, such as size-tunable emission wavelengths, narrow-band emission, and high quantum efficiency. Colloidal quantum dots, a type of solution-processable semiconductor, have been successfully applied in near-infrared LEDs, with device external quantum efficiency (EQE) exceeding 20% [9]. Quantum dots can not only be used to achieve high-purity red and green light

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emission and improve color gamut but also can be combined with existing blue Micro-LED arrays to construct full-color Micro-LED displays and realize gigabit (Gbps)-level multi-channel visible light communication [8].

4.2.2. III-V group semiconductor materials

III-V group semiconductor materials (such as GaAs, InP, InGaAs, etc.) have natural advantages in the field of optoelectronic devices due to their direct bandgap characteristics and are key to achieving efficient light emission and high-speed modulation. The heterogeneous integration of III-V group materials with silicon photonics can combine the efficient light emission of III-V group materials with the low cost and high integration advantages of silicon photonics, enabling optical communication and sensing applications in the wavelength range from 850 nm to 3.85 μm [10].

4.3. Advanced modulation technologies

4.3.1. Orthogonal Frequency Division Multiplexing (OFDM)

Orthogonal Frequency Division Multiplexing (OFDM) is a multi-carrier modulation technology that can effectively cope with the nonlinear characteristics and frequency-selective fading of LEDs. Researchers have proposed various solutions, such as non-redundant PAM-coupled U-OFDM systems, which reduce signal distortion caused by LED nonlinearity by utilizing the inherent empty signals in U-OFDM blocks [11].

4.3.2. Wavelength Division Multiplexing (WDM)

Wavelength Division Multiplexing (WDM) technology significantly increases the capacity of communication systems by simultaneously transmitting optical signals of different wavelengths in the same optical fiber or free space. For IR-LEDs, combining WDM can achieve multi-channel parallel transmission, thereby improving overall data throughput. In visible light communication, WDM schemes combining red/green/blue laser diodes (R/G/B-LDs) with yellow LEDs have been used for high color rendering index lighting and high-speed optical wireless communication, realizing compact white light communication systems [12].

4.3.3. Polarization Multiplexing (PM) and Mode Division Multiplexing (MDM)

Polarization Multiplexing (PM) and Mode Division Multiplexing (MDM) are important components of spatial domain multiplexing technologies. They use the polarization state or spatial mode of light as independent communication channels to further improve data capacity. In wireless optical communication, multi-channel data transmission can be achieved by controlling the polarization state of the light beam or exciting different spatial modes in multi-mode optical fibers. For example, in 5G/6G mobile fronthaul networks, fiber radio frequency (RoF) technology combined with dual-polarization MZM (Mach-Zehnder Modulator) and dual-polarization BPSK (Binary Phase Shift Keying) modulators can achieve multi-band full-duplex transmission, effectively mitigating nonlinear distortion [13], which provides a reference for the application of IR-LEDs in high-speed communication.

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5. Conclusion

This paper comprehensively analyzes the application status and technical challenges of infrared light-emitting diodes (IR-LEDs) in the field of optical communication: in terms of application scenarios, IR-LEDs provide covert communication channels in Visible Light Communication (VLC), achieve stable transmission by leveraging the characteristic of low atmospheric attenuation in Free Space Optical Communication (FSO), and occupy a dominant position in infrared remote control systems with mature and low-power solutions. In terms of performance optimization, the device performance has been significantly improved through reflective transparent structures to enhance light extraction efficiency (with External Quantum Efficiency (EQE) > 20%), vertical structure LEDs to improve heat dissipation and current distribution, and micro-LED arrays to break through the modulation bandwidth limit (reaching the GHz level). In terms of technological innovation, quantum dot materials enable efficient near-infrared emission with tunable wavelengths, the heterogeneous integration of III-V group semiconductors and silicon photonics expands the communication wavelength bands, and modulation technologies, such as Orthogonal Frequency Division Multiplexing (OFDM) and Wavelength Division Multiplexing (WDM) effectively overcome the nonlinear distortion of LEDs and improve system capacity. Future research should focus on the following directions: at the device level, develop new wide-bandgap semiconductors (such as GaN-on-Si) to be compatible with CMOS processes and reduce costs; deepen the research on the stability of quantum dot infrared LEDs and promote the industrialization of solution-based preparation processes; and optimize the driving circuit design of Micro-LED arrays to achieve high-precision spatial light modulation. At the system level, explore the application of Polarization Multiplexing (PM) and Mode Division Multiplexing (MDM) technologies in IR-LED multi-channel transmission; construct an integrated intelligent optical network integrating "lighting-communication-sensing"; and dynamically regulate optical signals in combination with artificial intelligence algorithms. In terms of application expansion, develop infrared optical communication modules suitable for special scenarios such as underwater and medical fields; promote the integrated application of IR-LEDs in emerging fields such as 6G air-ground integrated communication and quantum key distribution.

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