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Full-duplex ultraviolet light communication network for space-chip interconnection

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Silicon-based photonic integrated on-chip interconnects enable miniaturized, high-density, and cost-effective photonic integration, which is an ideal solution to address the power consumption, bandwidth, and latency challenges faced by integrated circuit technology in the post-Moore era [1]. However, since silicon cannot emit light independently, it hinders the development of silicon photonic integration. Gallium nitride (GaN) materials have been widely used in energy-efficient and high-power light-emitting diode (LED) fabrication in recent years, and the emerging GaN-on-silicon platform has great potential in photonic integration. Owing to the spectral overlap between the electroluminescence (EL) and responsivity (RS) spectra, III-nitride multiple quantum well (MQW) diodes can function not only as light transmitters to emit light but also as light receivers to detect light from light sources that have the same MQW structure. Therefore, when linked by a waveguide, a multifunctional photonic integrated circuit (PIC) can be developed by integrating multiple MQW devices with the same MQW structure on a tiny silicon-substrated chip without high-cost and complex heterogeneous integration processes.

There has been increasing interest in PICs in recent years. Especially, we first reported a monolithic full-duplex light communication system in 2018, in which full-duplex audio light communication was completed [2]. Since ultraviolet (UV) light has lower background noise compared with visible and near-infrared counterparts, it attracts more interest in PIC. He et al. [3] reported a deep-ultraviolet (DUV) PIC that supports analog video communication via composite video broadcast signals (CVBS). However, previous studies without network protocols cannot integrate with the existing network architecture, while the ideal on-chip light communication network (LCN) will support multiple network nodes for real-time information exchange. Until now, offline PICs are still separate without network interconnections and cannot satisfy the increasing demand for sophisticated on-chip optical interconnection networks.

Here, we make a full-duplex real-time on-chip light communication system and interconnection network debut. In this study, an on-chip light communication link is established by integrating a light transmitter, a waveguide, and a light receiver on a single GaN optoelectronic integrated chip. By combining two waveguide channels, full-duplex on-chip light communication is achieved under transmission control protocol/Internet protocol (TCP/IP), which supports multiple real-time services and can be integrated with other existing networks via Ethernet gateways.

Architecture. A light interconnection communication network architecture is demonstrated in Figure 1(a), which integrates a 408-nm on-chip LCN, a Wi-Fi network, and a 275-nm free-space DUV wireless light communication network (WLCN). As shown in Figure 1(a), the personal computer (PC), web camera, and wireless module are concentrated on the same Ethernet switch (ES), which is simultaneously wire-connected to the physical layer of an on-chip light communication system through network drivers. The on-chip LCN is established by two waveguide channels of GaN optoelectric integrated chips. When full-duplex light communication links are established, network equipment on both sides can communicate via TCP/IP. At the same time, users can upload or download files from the backbone network, interacting with the on-chip LCN for real-time resource sharing and information transmission.

In Figure 1(a), an integrated scheme of the interconnection communication network is demonstrated. As shown in Figure 1(a), the DUV WLCN can connect with the on-chip LCN in wired and wireless manners. On the one hand, two light communication systems can be directly connected by concentrating them on the same ES, as shown in Switch 2 of Figure 1(a). On the other hand, a wireless bridge can be established by two wireless modules, in which wireless module 2 operates at 2.4 GHz in follow mode with wireless module 1. When wireless module 2 and the DUV WLCN are connected, the two LCNs are connected by the wire-

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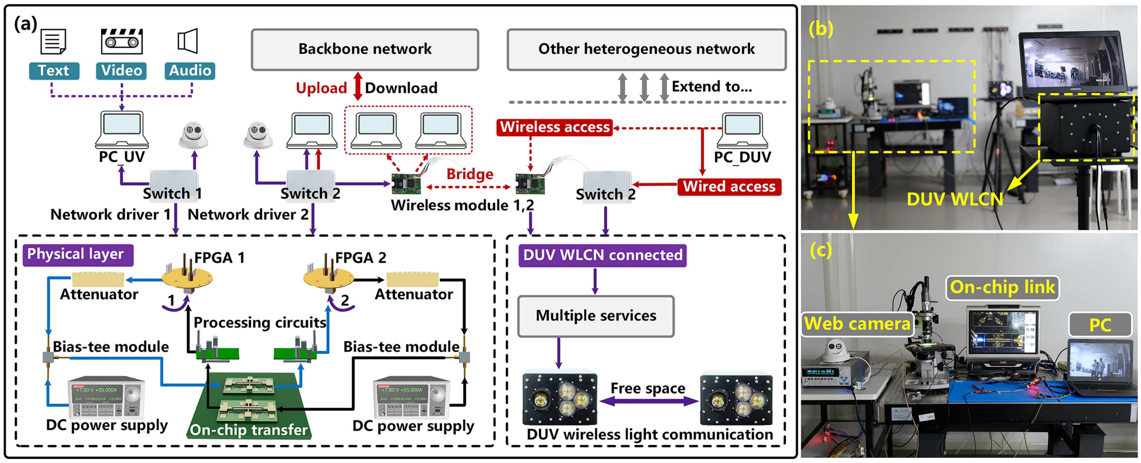

Figure 1 (Color online) (a) Architecture of the integrated UV light interconnection communication network; (b) experimental demonstration of the interconnection communication network; (c) full-duplex on-chip light communication system.

less bridge. Finally, a connection is established between PC_DUV and PC_UV.

In detail, the physical layer of the on-chip LCN consists of the GaN optoelectronic integrated chip and peripheral circuits. The detailed characterization of the GaN chip is presented in Appendix A. The 38-nm EL-RS spectral overlap leads to an on-chip data transmission. The software section, the driving circuit, and the receiving circuit of the physical layer are mainly designed by a field-programmable gate array (FPGA), a bias-tee module, and a signal processing circuit. The information from the upper computer is modulated by an on-off keying (OOK) modem and directly modulated to the on-chip transmitter for transmission. The overall schematic diagram of the physical layer is presented in Figure B1 in Appendix B.

Experiment. An experimental demonstration is shown in Figure 1(b). As shown in Figure 1(b), the DUV WLCN and the on-chip LCN are connected in a wired manner by an ES. A web camera is used as the message source, and both PC_UV and PC_DUV display the same real-time video from the camera. The full-duplex on-chip light communication system is highlighted in Figure 1(c). Two waveguide links establish full-duplex on-chip light communication, and one link is enlarged in the optical microscope. Both LEDs of the two communication links are directly modulated by the live-video signal and constant-current driven at 10 mA by the Keithley 2636B SourceMeter. Then, part of the light from the illuminated LED is laterally coupled into the waveguide across the isolation trench, except for the scattered light into the free space. The guided light propagates along the waveguide to arrive at the receiver, while part of the light is scattered again at the isolation trench between the waveguide and the receiver. The photodiodes (PDs) of both communication links are biased at 0 V for light detection. Using 5000 32-byte Internet Control Message Protocol (ICMP) request messages to characterize the network connection quality, the packet loss rate (PLR) is measured as 1.46%, whereas the delay and jitter are measured as 5.02 and 7 ms. A real-time video communication demonstration is uploaded in the supplemental materials. Benefiting from the low background noise of the UV light, the demonstrated network is observed to be immune to indoor ambient light noise.

Furthermore, owing to their EL-RS spectral overlap, MQW diodes inherently exhibit dual functionalities of light emission and detection. Therefore, two identical MQW diodes, which are monolithically integrated into a tiny monolithic GaN photonic circuit, can be separately self-defined as a transmitter and a receiver to establish an in-plane light communication system via a single waveguide. Therefore, the proposed network architecture is decentralized, and all nodes have equal and complete mapping characteristics within this communication architecture. Bidirectional data transmission can be achieved using the same waveguide under the time-division multiplexing (TDM) scheme. A single-channel TDM duplex communication demonstration is uploaded in the supplemental materials.

In summary, we integrate an on-chip LCN and a free-space DUV WLCN, consequently proposing a completely light-based interconnection communication network, with which real-time video communication is experimentally demonstrated. On-chip and free-space light communication are achieved respectively in waveguide and wireless manners. Based on TCP/IP, the network can be merged with the existing network architecture, supporting real-time services such as video, text, and audio, and providing seamless connectivity across space and chip environments. This work offers significant potential for developing sophisticated on-chip optical interconnection networks for advanced information processing and computing systems.

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Supporting information Appendixes A and B and videos 1 and 2. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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