Silicon Photonic Front-end Module in Support of both mmWave and THz Wireless Transmission for B5G/6G Fronthaul

Jiao Zhang [1,2]†, Liang Tian[1]†, Min Zhu[1,2]*, Qingsong Wang[2], Junhao Zhang[2], Bingchang Hua[1], Mingzheng Lei[1], Yuancheng Cai[1], Yucong Zou[1], Jinbiao Xiao[1,2]*, Jianjun Yu[1,3]

(1) Purple Mountain Laboratories, Nanjing, Jiangsu 211111, China
(2) National Mobile Communications Research Laboratory, Southeast University, Nanjing 210096, China
(3) Fudan University, Shanghai, 200433, China
* author e-mail address: minzhu@seu.edu.cn, jbxiao@seu.edu.cn
† equal contribution

Abstract *A silicon photonic front-end module with 3-dB bandwidth > 25 GHz is presented for B5G/6G fronthaul that can support diverse use cases. We further demonstrate 28 GHz mmWave and 320 GHz THz wireless link with line rates up to 8.625 Gbps and 25 Gbps, respectively.*

Introduction

With the growth of mobile services and usage scenarios, the telecommunication society have commenced research on high carrier frequencies, including the millimeter wave (mmWave) and terahertz (THz) bands [1-3]. The B5G mmWave in the 28 GHz band has already been partially rolled-out commercially, and the THz-band up to 300 GHz or higher are envisioned as a promising candidate for 6G. In parallel, the evolution of radio access networks with stringent demands on throughput, latency, and power consumption will pose major challenges to the B5G/6G fronthaul network [4]. Several seamless convergence of fiber-optic and wireless schemes have been proposed to support “mmWave + THz” diverse applications. An RoF-based indoor distributed antenna system that can support mmWave and THz services was demonstrated [5]. An optical fronthaul system for the transmission of multiple radio signals in different frequency bands was proposed based on a subcarrier-multiplexing intermediate frequency-over-fiber system [6]. However, the proposed architectures in these works are relied on discrete photonic devices.

Thanks to the fast advancement in photonic integrated circuit (PIC) technology, silicon photonics can realize highly integrated, low cost and small footprint systems to support cost sensitive optical fronthual [7-9]. Here, as shown in Fig.1, we propose an optical fronthaul architecture using silicon photonic front-end module for B5G/6G diverse services. For mmWave macro cell, distributed unit (DU) is combined with remote unit (RU) to achieve ultra-reliable and low latency communications (uRLLC), such as smart transportation, smart factory, and industrial IoT [10]. Furthermore, THz has high frequency, high path loss, severe molecular absorption and extremely narrow beam. To cope with THz coverage issues, the fiber-optic is deeply embedded. For THz micro cell, another fronthaul fiber from silicon photonic front-end module can be integrated with THz RU to support enhanced mobile broadband (eMBB) services, e.g., dense scene communications, holographic video conferences, metaverse, and 8K/10K video [11-13]. This B5G/6G fronthaul enabled by silicon photonic can simultaneously meet bandwidth and latency requirements.

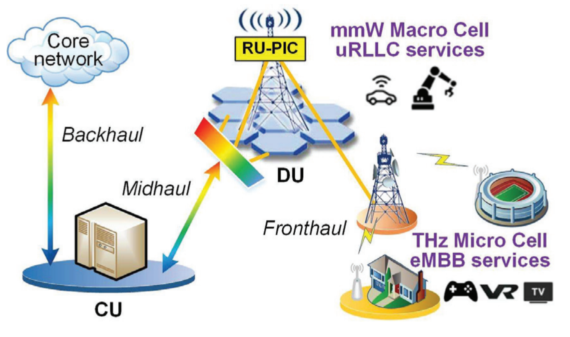

Fig. 1: Proposed optical fronthaul architecture using silicon photonic front-end module for B5G/6G diverse services.

In this work, we design and fabricate a silicon photonic front-end module based on a silicon-on-insulator platform by using optical, electrical, thermal, and mechanical packaging processes. The principle, fabrication and characterization before and after packaging are introduced in detail. The packaged module has > 25 GHz 3-dB bandwidth. The transmission performance of 28 GHz mmWave and 320 GHz THz wireless link are validated with a broadband various formats.

Chip fabrication and characterization

The schematic of silicon photonic front-end chip is given in Fig. 2(a). This PIC is mainly composed of a Mach-Zehnder modulator (MZM), a photodetector (PD), a variable optical attenuator (VOA), a 2×2 optical coupler (OC), and three grating couplers (GCs). The MZM is used to modulate a digital baseband signal onto an

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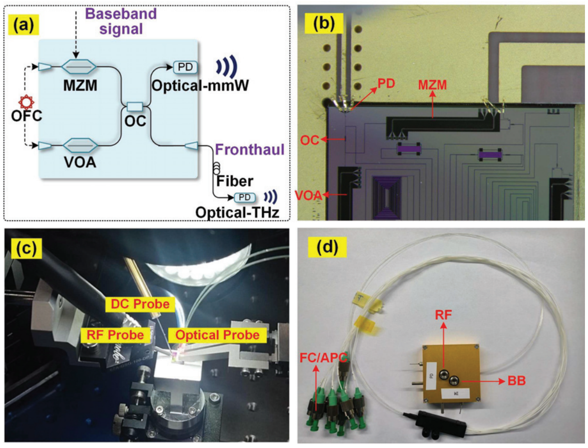

Fig. 2: (a) PIC schematic; (b) Optical microscope of the fabricated chip; (c) Photograph of probe station for chip testing; (d) Packaged silicon photonic front-end module.

optical carrier, and the VOA is utilized to control optical power from optical local oscillator (LO) to achieve the optimal signal-to-noise ratio (SNR). Subsequently, the 2×2 OC realizes a 180° optical hybrid of two optical signals. Finally, the PD implements the up-conversion function from the baseband signal to the mmWave signal by optical heterodyne beating. Moreover, the optical output GC is responsible for the THz fronthual.

The optical microscope of the fabricated chip is shown in Fig. 2(b), and and the overall size of the chip is 5.15×5.15 mm. A thermo-optically tunable phase shifter is used to change the working point of the MZM, and four load resistors are used for terminal matching. The VOA is mainly composed of an MZI structure, a TiN heater electrode above a phase-shift waveguide, and a lead electrode for connecting the TiN heater electrode and metal pads. The length, width, and square resistance of the TiN heater electrode were 400 μm, the width was 2.5 μm, and its square resistance was 10.5 Ω/sq. The 2×2 OC operates at a wavelength of 1550 nm, its working mechanism is based on the multimode interference effect in a multimode waveguide, and the power splitting ratio is designed to be 50:50. The PD is mainly

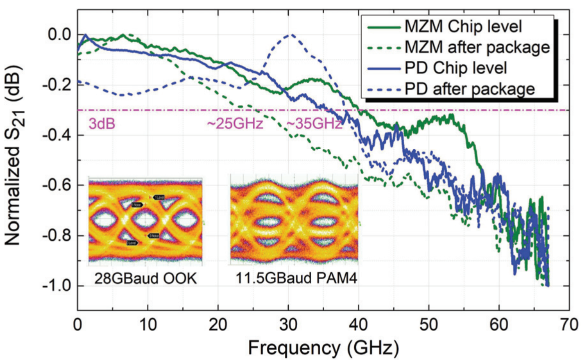

Fig. 3: Normalized S21 parameter for the MZM and PD before and after packaging.

composed of an intrinsic Ge absorption layer, and a P-type silicon layer and an N-type silicon layer formed by boron and phosphorus doping on an intrinsic silicon film.

By using the SPIC measurement platform with an optical probe, direct current (DC) probe, and RF probe, as shown in Fig. 2(c), the key performance parameters are tested. Furthermore, for practical application, the silicon photonic front-end module was fabricated using a series of optoelectronic integrated packaging processes. As shown in Fig. 2(d), the overall size of this frond-end module is 4×4 cm. Two 1.85 mm connectors are responsible for the baseband signal input of the MZM and mmWave signal output of the PD. Two DC connectors used to control the bias point of the MZM and VOA. Three polarization-maintaining fiber channels with FC/APC are used as the inputs of the two optical carriers and the output of an optical signal for THz communication. The normalized S21 of the MZM and PD was tested before and after packaging, as shown in Fig. 3. The 3-dB bandwidth of the packaged MZM is around 25 GHz, which is reduced by about 15 GHz compared with that of the on-chip test. The 3-dB bandwidth of the packaged PD is about 35 GHz, nearing the on-chip test. The insets show the eye diagram with 28 GBaud OOK and 11.5 GBaud PAM4 signals by using packaged module.

mmWave and THz link experiments

The schematic of the experimental setup for the 28 GHz mmWave and 320 GHz THz wireless transmission is shown in Fig. 4. We firstly use intensity modulator to generate an optical frequency comb (OFC), and then is fed into a wavelength selective switch (WSS) to select two tones with 28 GHz line spacing as optical baseband carrier and optical local oscillator (LO) for photomixing to generate RF signals. One arbitrary waveform generator (AWG) is used to

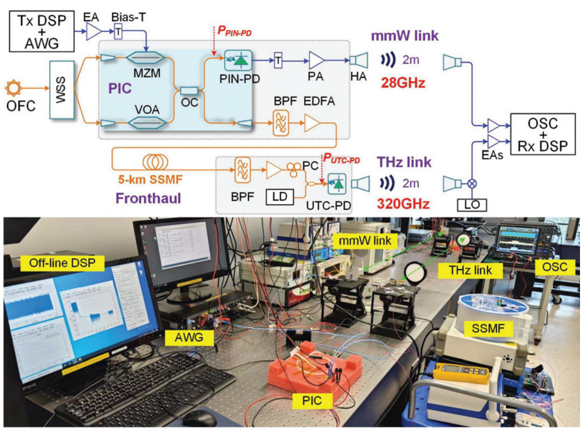

Fig. 4: Schematic of the experimental setup for the 28 GHz mmWave and 320 GHz THz wireless transmission.

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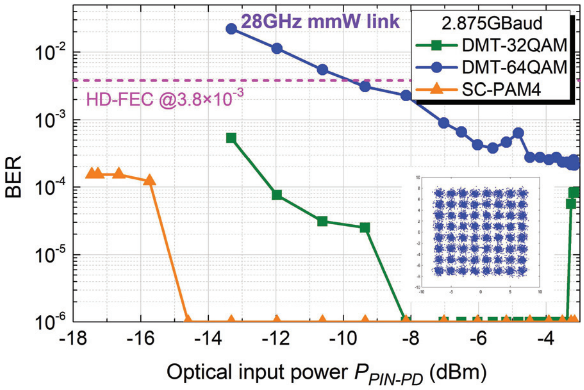

Fig. 5: BER versus optical input power $P_{PIN\text{-}PD}$ for 28 GHz mmWave over 2 m wireless link.

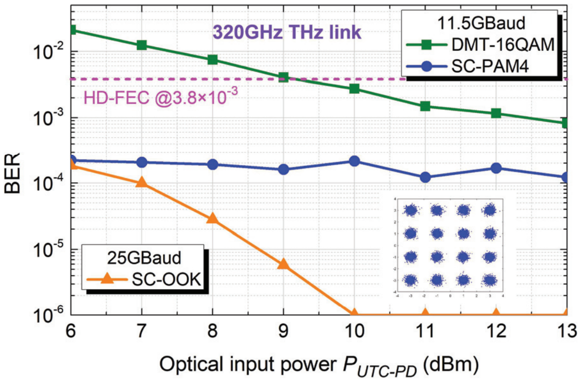

Fig. 6: BER versus optical input power $P_{UTC\text{-}PD}$ for 320 GHz THz over 5 km fiber and 2 m wireless link.

generate digital baseband signals. At the receiver, RF signals are boosted by electric amplifiers (EAs) and captured by the 256 Gsa/s digital storage oscilloscope (OSC) with a 59 GHz bandwidth for offline DSP demodulation. Here, discrete multitoned (DMT) and coherent single-carrier four-level pulse amplitude modulation (SC-PAM4) modulation formats are considered.

For mmWave link, 28 GHz mmWave signal from front-end module PD connector is amplified by a power amplifier (PA), and then fed into horn antenna (HA) to transmit over 2 m wireless link. The OSC can directly capture 28 GHz RF signal. In parallel, two optical carriers from another 2×2 OC output port of front-end module are firstly filtered out optical baseband carrier by an optical band-pass filter (BPF) for THz link. After 5 km SSMF transmission, the optical signal and optical LO with 320 GHz frequency space are coupled by an optical coupler (OC), and then up-converted to the THz-wave signal by UTC-PD. Over 2m wireless link, the THz receiver has an IF output bandwidth of 28 GHz and is driven by a 12-time frequency multiplied electrical LO signal. Inset shows the photo of the experimental setup.

Results and discussions

Based on the optimized system parameters, we firstly investigate the BER versus optical input power $P_{PIN\text{-}PD}$ for 28 GHz mmWave over 2 m wireless link, as shown in Fig. 5. A BER performance below the 7% overhead (OH) hard-decision FEC (HD-FEC) limit of 3.8×10^{-3} is achieved with 2.875 GBaud DMT-32, -64QAM and Nyquist SC-PAM4, resulting in line rates of 7.1875 Gbps, 8.625 Gbps and 5.75 Gbps, respectively. Moreover, DMT-32QAM and SC-PAM4 can realize “error free” transmission when higher optical power into PD.

Then, we evaluate the BER versus optical input power $P_{UTC\text{-}PD}$ for 320 GHz THz over 5 km fiber and 2 m wireless link without using THz amplifier, as shown in Fig. 6. The BER of broadband 11.5 GBaud DMT-16QAM, SC-PAM4, and 25GBaud SC-OOK can achieve under 7% HD-FEC, corresponding to line rates of 23 Gbps, 23 Gbps and 25 Gbps, respectively. Due to the typical responsivity of UTC-PD is 0.15 A/W, higher optical power is needed.

Here, mmWave and THz link is separately measured. Time-division multiplexing (TDM) can be used for the transmission of mmWave and THz signals over the same optical fronthaul system. Furthermore, THz amplifier, massive multiple-input multiple-output (MIMO) and beamforming will lever THz wireless transmission distance. This proposed silicon photonic front-end module bears great potential to offer low-cost solutions for B5G/6G fronthual.

Conclutions

An optical fronthaul architecture using silicon photonic front-end module for mmWave URLLC and THz eMBB use cases is proposed. We designed and tested the module following fabrication and encapsulation. An MZM, a PD, a VOA, a 2×2 OC, and three GCs were monolithically integrated to realize complete front-end functions. The 3-dB bandwidth of the packaged MZM and PD was beyond 25 GHz under the reverse bias voltage of 2 V. We also experimentally validated the functionality of the 28 GHz mmWave and 320 GHz THz wireless transmission. This PIC module can meet bandwidth and latency requirements in high-frequency bands for B5G/6G with low cost, footprint and power consumption.

Acknowledgements

This research was supported in part by the National Natural Science Foundation of China (62101121, 62101126, 62201397, 62201393, 62271135), the project funded by China Postdoctoral Science Foundation (2021M702501, 2022T150486).

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