Integrated Multi-Channel Millimeter Wave Photonic Generation Based on A Silicon Chip with Automated Polarization Control

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Abstract *We propose and experimentally demonstrate multi-channel millimeter wave (MMW) generation on a silicon chip. Automated polarization-control function is demonstrated, and 5 channels of 28-GHz MMW carrying 2-Gb/s on-off-keying signals are generated.*

Introduction

To meet the requirements of rapidly increasing mobile data rates, large-scale millimeter-wave (MMW) antenna arrays have been intensively studied for 5G mobile networks to increase the system capacity[1]. Thanks to the wide bandwidth and low loss offered by modern photonics, MMW generation based on photonics has attracted much attention. Various photonic techniques, such as heterodyning of two wavelengths, external intensity modulation and four-wave mixing[2,3], have been demonstrated. Heterodyne, which is typically implemented by beating two free-running continuous-wave (CW) lights at a photodetector (PD), has been widely employed for its simplicity and large frequency tunability. Based on this approach, MMW band fiber-wireless-integration (FWI) transmission systems have been demonstrated[4,5]. However, these demonstrations have relatively low level of integration in the MMW generation modules, making the wireless transmit-receive ends bulky and high power consuming.

Due to the compact footprints and CMOS compatibility, silicon photonic integrated circuits have the great potential to provide an integrated solution towards MMW generation for large-scale antenna arrays. In this paper, we propose an on-chip silicon-based multi-channel MMW generation scheme, to generate 5 channels of 28-GHz signals with each carrying 2-Gb/s data. Two functions are demonstrated in our work: 1) multi-channel MMW signal generation by beating a local oscillator (LO) light with 5 channels of optical baseband data carried by an identical optical carrier; 2) automated silicon polarization control (SPC) developed based on the work reported in Ref. [6], to align the polarization directions of the optical baseband signals with the optical LO light. To the best of our knowledge, this is the first demonstration of an integrated solution for multi-channel MMW generation on a compact silicon photonic chip.

System architecture

Fig. 1 shows the schematic diagram of a FWI transmission system, in which our proposed on-chip silicon multi-channel MMW generator is placed in the base station (BS). At the central office (CO), optical baseband signals on optical carriers with an identical wavelength are generated and delivered via a multi-core fiber (MCF), a technique widely known as space division multiplexing (SDM). Only a single laser source is required at the CO. After fiber transmissions, the baseband signals are coupled into a silicon photonic multi-channel MMW signal generator. To compensate for the

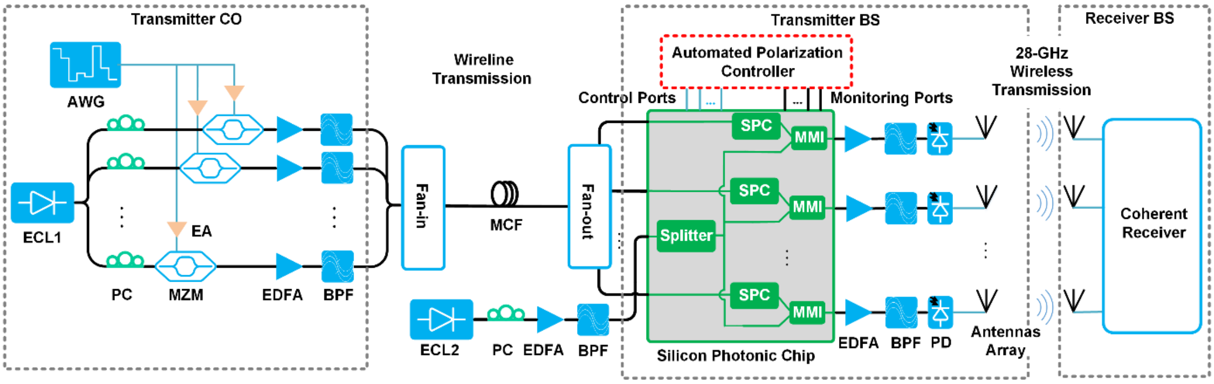

Fig. 1: Proposed multi-channel FWI system architecture based on integrated silicon photonic MMW generator

random polarization shifts created during fiber transmissions, silicon polarization controllers (SPCs) are implemented with on-chip polarization tuning units[6] and off-chip control circuits. Each of the polarization-compensated optical baseband signals is combined with a LO light and then coupled to its corresponding output port, and each output signal is sent into a broadband PD to beat the optical baseband signal with the LO light, to generate the desired MMW signal. The multi-channel MMW signals are transmitted over a wireless link by large-scale antennas and received at the receiver BS.

Experimental setup and results

We perform a proof-of-concept experiment to verify the feasibility of the proposed on-chip MMW generation scheme, with the experimental setup illustrated in Fig. 2(a). At the CO, a CW light at 1550.273 nm from an external cavity laser (ECL) (Koheras BASIK C15), with a <15-kHz linewidth and 10-dBm optical power is sent to a 25-GHz Mach-Zehnder modulator (MZM) (FTM7939EK) driven by a 2-Gb/s pseudo-random bit sequence (PRBS) data. An arbitrary waveform generator (AWG) (Keysight M8195A) with a sampling rate of 60-GSa/s is used to generate the electrical baseband signal, which is then boosted by an electrical amplifier (EA). Note that the baseband signal is resampled to mitigate the sidelobes and therefore minimize the occupied bandwidth. The output optical signal of the MZM is amplified by an erbium-doped fiber amplifier (EDFA) and coupled into a multi-channel silicon MMW generator via edge coupling with ~5-dB coupling loss. Due to the lack of a fiber array for edge coupling, only one channel is tested at a time. A LO light at 1550.497 nm from another free-running ECL (Koheras BASIK C15) is injected into the chip via vertical coupling with ~7-dB loss. On-chip 5-channel MMW signal generation is demonstrated. The micrograph of the fabricated device is shown in Fig. 2(b), which has a footprint of 1.1 × 2.1 mm^2. To align the polarization state of the input signal light with that of the LO light, we realize the SPC for each channel. The schematic of a polarization tuning unit[6] is shown in Fig. 2(c). A polarization splitter and rotator (PSR)[7] is adopted to divide the TE and TM portions of the randomly polarized signal light, and simultaneously rotate the TM polarized light to TE mode. Two Mach-Zehnder interferometers (MZIs) containing two micro-heaters and two 2 × 2 multi-mode interferometers (MMIs) are then used to adjust the phases and amplitudes of the two lights, which are sent to the output port and the monitoring port, respectively. At the monitoring port, the converted electrical signal is amplified, sampled and processed by a control sub-system.

Fig. 2(d) and (e) show the schematic and photograph of the polarization control sub-system. We develop a global minimum searching algorithm, which is different from that in the previous work[6]. The proposed algorithm consists of two minimum searching sub-processes in sequence by tuning one micro-heater over a large phase-shift range at a time, instead of switching between the two micro-heaters with small steps. This algorithm can effectively prevent the control system being trapped into local minima where the monitored signal is buried in noise. Usually one iteration can finely obtain a desired extinction ratio

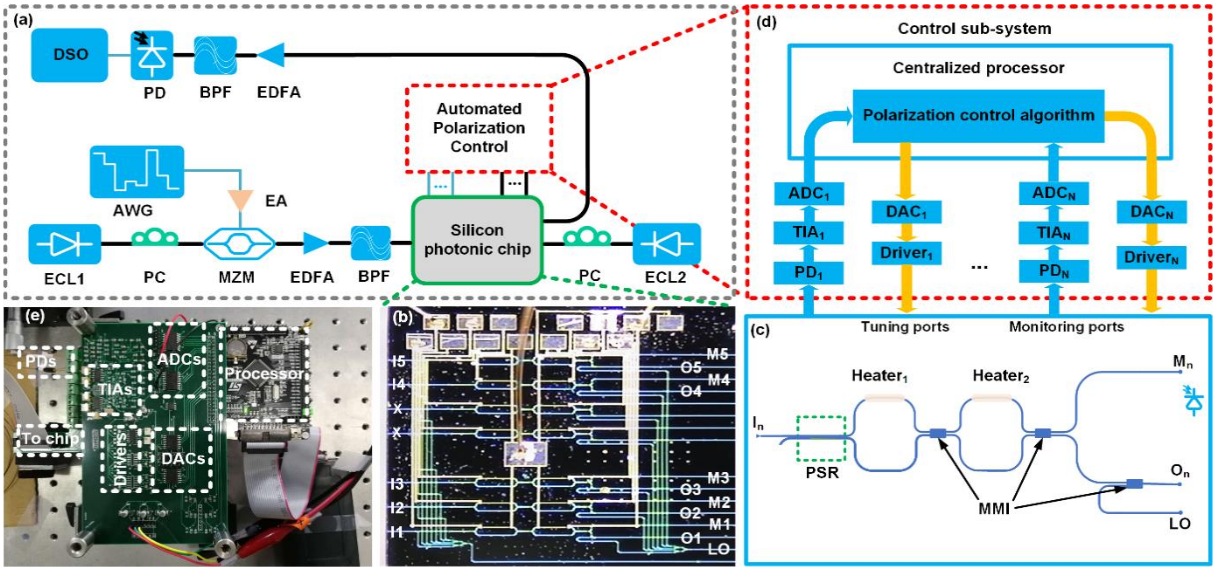

Fig. 2: (a) Experimental setup. (b) Micrograph of the fabricated chip. (c) Schematic diagram of a polarization tuning unit. (d) Schematic diagram of the control sub-system. (e) Photograph of the control sub-system.

between O_n and M_n. After executing the two sub-processes, the signal light is efficiently converted to the TE mode and aligned with the LO light. The two lights of each channel are combined by a MMI and coupled to the designated output port by vertical coupling. All the vertical coupling ports are connected to a fiber-array coupler. The output signal of the tested channel is then amplified, filtered and detected to generate a ~28-GHz MMW signal by an EDFA, an optical bandpass filter (BPF) and a 40-GHz PD (XPDV2120R), respectively. At the output of the PD, we sample the MMW signal by an 80-GSa/s digital storage oscilloscope (LeCroy 10-36Zi-A). Demodulation and eye diagram measurement are subsequently realized by offline digital signal processing (DSP). Note that a 28-GHz RF source can perform the demodulation and significantly lower the requirement of the sampling rate.

One channel of the tuning process is demonstrated in Fig. 3(a), with the photocurrent waveforms of the monitored signal at M_2 and the output signal O_2 in the progress of one iteration of the polarization control plotted. Note that the optical power at M_2 is ~3-dB higher than that at O_2, which is caused by a MMI at O_2 for heterodyne beating. A 27-dB extinction ratio between O_2 and M_2 and ~7-ms tuning time are demonstrated. The signal-to-noise ratios (SNRs) of the two waveforms are different because of different probe cables used. Fig. 3(b) and 3(c) show the optical spectrum and the electrical spectrum of channel 2 before and after the heterodyne beating, respectively. Fig. 3(d) provides the waveforms and the demodulated eye diagrams of the 5 channels of the MMW signals. The inter-symbol interference is mainly caused by the resampling process of the AWG.

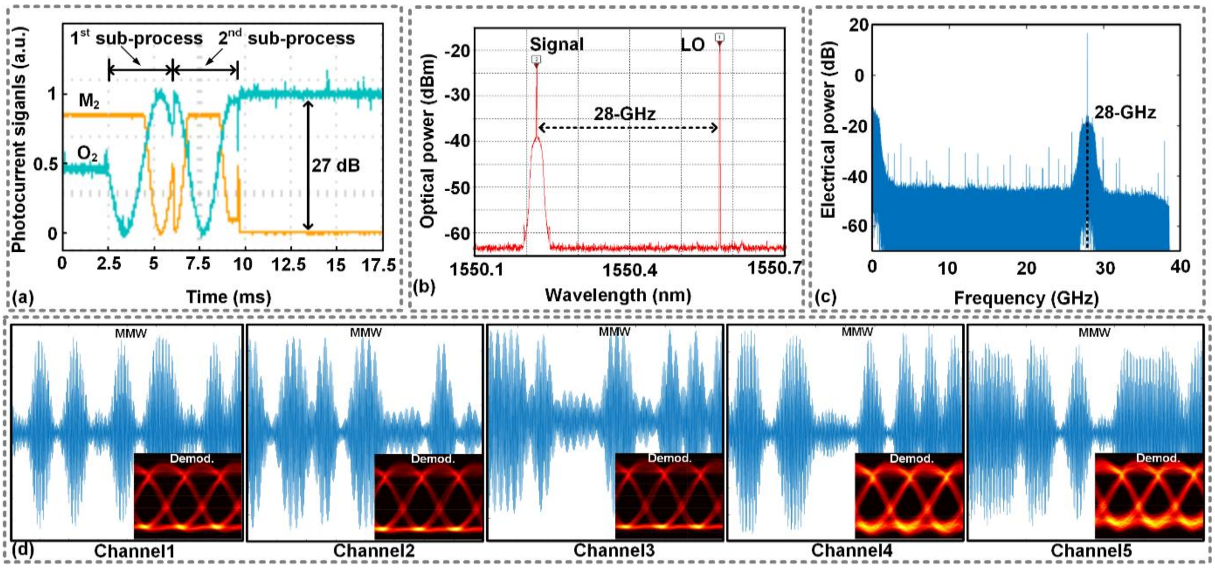

Fig. 3: (a) Automated polarization tuning of channel 2. (b) Optical spectrum of channel 2 before heterodyne beating. (c) Electrical spectrum of channel 2 after heterodyne beating. (d) Waveforms and demodulated eye diagrams of the generated 5-channel MMW signals.

Conclusion

We experimentally demonstrated an integrated multi-channel silicon photonic chip to generate 5 channels of 28-GHz MMW carrying 2-Gb/s OOK signals. Automated silicon on-chip polarization control was achieved with ~7-ms tuning time and 27-dB extinction ratio.

Reference

[1] S. Han et al., "Large-scale antenna systems with hybrid analog and digital beamforming for millimeter wave 5G," IEEE Commun. Mag., Vol. **53**, no. 1, p. 186 (2015).

[2] R. Guzmán et al., "Millimeter-wave signal generation for a wireless transmission system based on on-chip photonic integrated circuit structures," Opt. Lett., Vol. **41**, no. 20, p. 4843 (2016).

[3] Q. Wang et al., "Millimeter-wave frequency tripling based on four-wave mixing in a semiconductor optical amplifier," IEEE Photon. Technol. Lett., Vol. **18**, no. 23, p. 2406 (2006).

[4] X. Li et al., "Bidirectional delivery of 54-Gbps 8QAM W-band signal and 32-Gbps 16QAM K-band signal over 20-km SMF-28 and 2500-m wireless distance," Proc. OFC, Th5A.7, Los Angeles (2017).

[5] J. Zhang et al., "Multichannel 120-Gb/s data transmission over 2× 2 MIMO fiber-wireless link at W-band," IEEE Photon. Technol. Lett., Vol. **25**, no. 8, p. 780 (2013).

[6] M. Ma et al., "Silicon photonic polarization receiver with automated stabilization for arbitrary input polarizations," Proc. CLEO, STu4G.8, San Jose (2016)

[7] K. Tan et al., "Ultra-broadband fabrication-tolerant polarization splitter and rotator," Proc. OFC, Th1G.7, Los Angeles (2017).