# Silicon Photonic Integrated Circuit-Based Terahertz Wireless Signal Generator and Performance Analysis for Signal Distortion Recovery Using Histogram Statistics

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**Abstract** *We report silicon photonic integrated circuit-based coherent terahertz signal generation and signal distortion recovery performance for transmission capacity expansion and reliable mass production. The experimental results demonstrate 16QAM optical signal transmission up to 100 Gbps and error-free 1-m terahertz wireless transmission up to 50 Gbps.*


## Introduction

In 6G wireless networks, where radically new services such as holographic teleportation, autonomous systems, and digital twins are introduced, terahertz (THz) frequency band from 0.1 to 10 THz plays an important role in achieving high-rate wireless communications [1].

A photonics-based approach for THz signal generation is generally to use photomixing, where two lasers with closely spaced frequencies are mixed in an ultrafast photodetector, generating a photocurrent with a frequency that is equal to their frequency difference in the THz bandwidth. However, the photonics-based THz approach can easily tune the frequency of the THz signal by adjusting the spacing of the laser, but it is expensive due to bulky equipment and requires high driving forces for efficient operation. The integration of all these bulky components at the chip level further improves device reliability and mass-manufacturability. Hence, silicon photonics technology can serve as an effective alternative to reduce both the power consumption and cost of the THz systems [2].

In the coherent THz wireless communication for transmission capacity expansion, coherent detection with subsequent digital signal processing (DSP) not only alleviates system complexity by relieving the need for hardware phase-locking and polarization tracking, but also compensates for free-space transmission impairments. Recently, advanced DSP methods have been studied to effectively address in-phase and quadrature (IQ) imbalances [3].

In this study, we report the implementation of a silicon photonic integrated circuit-based THz wireless signal generator with 100 Gbps IQ modulation and a performance analysis for phase noise and IQ imbalance compensation of digital signal processing using histogram statistics.

## Silicon Photonic Integrated Circuit-Based THz Wireless Signal Generator

A conceptual description of a silicon photonic integrated circuit-based THz wireless signal generator is shown in Fig. 1(a). The THz wireless signal generator is responsible for efficient IQ modulation using a dual-parallel Mach-Zehnder modulator (MZM) and high-quality THz signal generation by optical heterodyning. The silicon photonic integrated circuit (SiPIC) in the THz wireless signal generator offers coherent modulation schemes, including quadrature

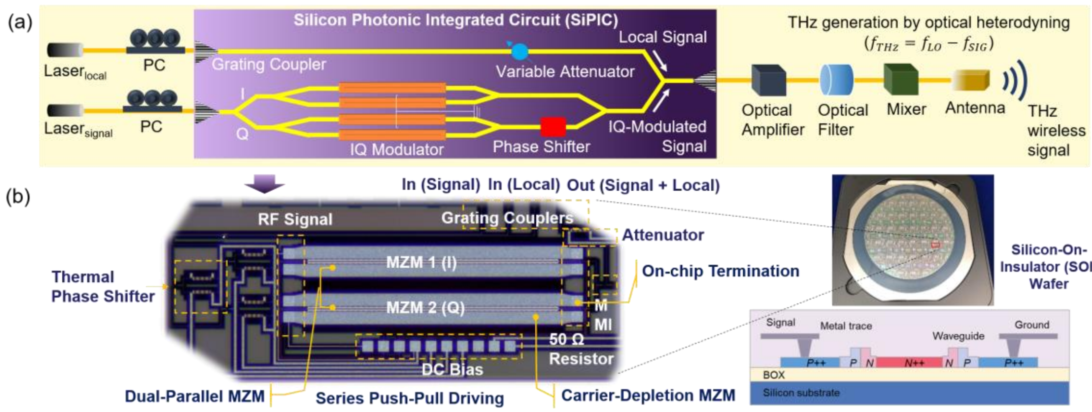


Fig. 1: (a) Conceptual description of THz wireless signal generator with an IQ modulator based on a SiPIC for coherent THz wireless transmission, (b) Microscope image of the fabricated SiPIC.

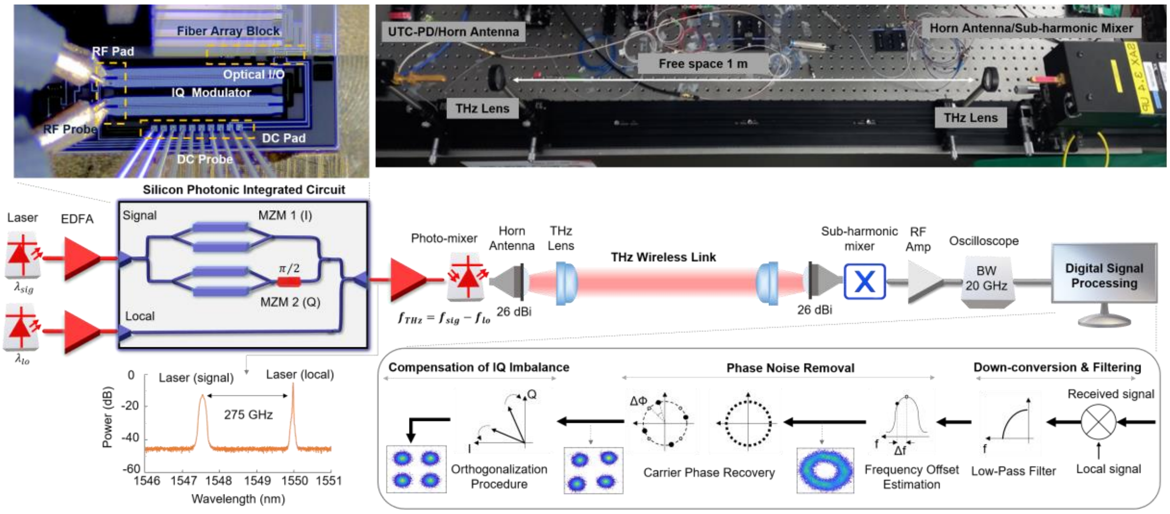


**Fig. 2:** Experimental setup of QPSK optical signal transmission up to 80 Gbps, 16QAM optical signal transmission up to 100 Gbps, and coherent THz wireless transmission using the SiPIC-based THz signal generator.

phase-shift keying (QPSK) and multilevel quadrature amplitude modulation (m-QAM) with high spectral efficiency, and low-loss on-chip combination of modulated signals and local signals. Figure 1(b) exhibits a photograph of a SiPIC fabricated on a 200 mm silicon-on-insulator platform. The dual-parallel MZM consists of two carrier-depletion MZMs, which employ a series push-pull driving configuration to reduce losses and improve the modulation bandwidth and linearity. The performance of the fabricated SiPIC was measured in the following: The total loss of the SiPIC was 18 dB at 1550 nm including a grating coupler loss of 4 dB, a rib waveguide propagation loss of 6 dB/cm, a thermal phase shifter loss of 0.2 dB. Regarding the dual-parallel MZM, the modulation efficiency ($V_\pi \cdot L$) was 2.25 V·cm at a 2 V reverse bias, and the PN length was 2.4 mm.

The performance of high-quality IQ modulated signal generation in the SiPIC was confirmed by experimentally transmitting QPSK signals up to 80 Gbps and 16QAM signals up to 100 Gbps on back-to-back optical links. Furthermore, the SiPIC-based coherent THz wireless transmission was experimentally demonstrated by transmitting the THz signal over a 1-m free space and measuring the bit error rates (BERs), error vector magnitudes (EVMs), and constellation diagrams of the received QPSK signals, as shown in Fig. 2. The optical QPSK signal from a laser at a 1547.8 nm center wavelength with an optical SNR of 40 dB was generated by the IQ modulator within the SiPIC. The local signal from a laser at a 1550.0 nm was separated from the QPSK signal by 2.2 nm, corresponding to 275 GHz. The unitraveling-carrier photodiode (UTC-PD) integrated with a WR-3.4 waveguide generated THz signals with a frequency of 275 GHz via the heterodyne beating method. After 1-m free-space transmission, the THz signals received from the WR-3.4-based corrugated horn antenna were frequency-down-converted by a sub-harmonic mixer and captured using a 50-GS/s digital sampling oscilloscope.

The DSP in the THz receiver is essential for achieving higher bit rates, higher-order modulation format, and better transmission performance. After down-conversion to the base band in the DSP, the frequency offset and the carrier phase from phase noise due to transmission impairment were estimated using the Viterbi and Viterbi phase recovery algorithm. Decision-direct least mean square-based carrier phase estimation tracks the carrier phase

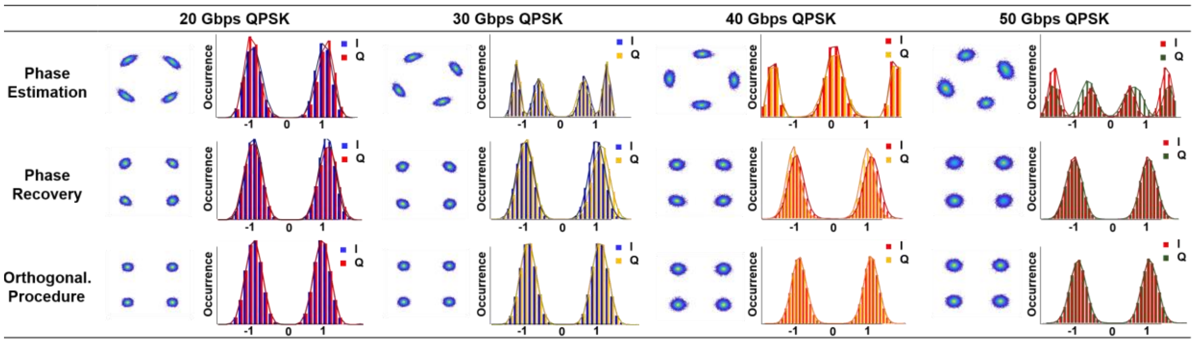


**Fig. 3:** Recovery performance of the digital signal processing using constellation diagram and histogram statistics for signal distortion of 20 Gbps to 50 Gbps QPSK signals on a back-to-back optical link

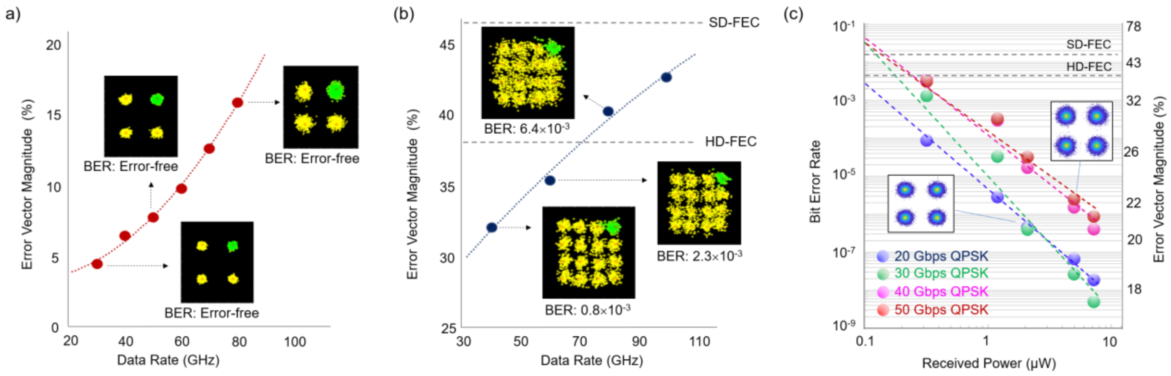


**Fig. 4:** (a) The error-free transmission of QPSK signals over a back-to-back optical link for data rates of up to 80 Gbps, (b) 16 QAM optical signaling for data rates of up to 100 Gbps, (c) The BER performance after a 1-m THz wireless transmission

fluctuation to recover the carrier phase. IQ imbalance is effectively resolved by an orthogonalization procedure which orthogonally decouples the IQ components in the frequency domain, and reconstructs noise-robust signals in the time domain.

## Experimental Results

Figure 3 displays the signal distortion recovery performance of the DSP for 20 Gbps to 50 Gbps QPSK signals stepped by using constellation and histogram statistics. The experimental results show that after the carrier phase recovery and the orthogonalization procedure, the constellation shape of the QPSK signals is cleared into four circular points corresponding to the four phases and the occurrence difference of histogram statistics between I and Q components is eliminated, thereby improving the Q factor.

The error-free transmission of QPSK signals over a back-to-back optical link for six data rates of 30, 40, 50, 60, 70, and 80 Gbps was demonstrated by error counting the received signal using knowledge of the transmitted pseudorandom pattern; its length was $2^{15}$-1, as shown in Fig. 4(a). No bit errors were detected within our record length of $10^6$ symbols, indicating error free signals with BER<$10^{-6}$. The experimental result of Fig. 4(b) displays that the SiPIC-based THz wireless signal generator enables 16QAM signalling with BERs below the threshold for soft-decision FEC (SD-FEC) with 20 % overhead at symbol rates of 25 Gbaud, corresponding to data rates of up to 100 Gbps on a single wavelength and in a single polarization. Figure 4(c) describes the measured BERs and constellations of QPSK signals after a 1-m THz wireless transmission for various data rates from 20 to 50 Gbps. In the 1-m wireless transmission, the BERs for 20 to 50 Gbps were obtained below the hard-decision FEC (HD-FEC) threshold.

## Conclusions

This study has successfully demonstrated a coherent THz wireless transmission for 50 Gbps QPSK signals and 16QAM signalling up to 100 Gbps using a chip-scale SiPIC and digital signal processing for phase noise and IQ imbalance compensation. The SiPIC-based THz signal generator consists of the dual-parallel MZM, which employs carrier-depletion mode on a series push-pull driving configuration. We have experimentally analyzed the signal distortion recovery performance of the DSP by comparing shapes of histogram statistics between I and Q components. As a result, the experimental results clearly demonstrated that our approach achieves error-free transmission of QPSK optical signals up to 80 Gbps and transmission of 16QAM optical signals up to 100 Gbps with BERs below the SD-FEC threshold, and error-free 1-m THz wireless transmission with BERs of $10^{-6}$ or less at a data rate of 50 Gbps. This approach to SiPIC-based THz generation and DSP-based signal distortion recovery will contribute to substantial capacity expansion and cost reduction in coherent THz wireless systems.


## Acknowledgements

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## References


[1] K. B. Letaief, W. Chen, Y. Shi, J. Zhang, and Y.-J. A. Zhang, "The Roadmap to 6G: AI Empowered Wireless Networks," *IEEE Communications Magazine* vol. 57, pp. 84-90, 2019, DOI: 10.1109/MCOM.2019.1900271.

[2] W. Lee, S. Han, S.-R. Moon, J. Park, S. Yoo, H. Park, J.-K. Lee, K. Yu, and S.-H. Cho, "Coherent terahertz wireless communication using dual-parallel MZM-based silicon photonic integrated circuits," *Optics Express*, vol. 30, pp. 2547-2563, 2022, DOI: 10.1364/OE.446516

[3] Li X, Geng T, Gu Y, Tian R, Gao S. "Compensation for In-Phase/Quadrature Phase Mismatch in Coherent Free-Space Optical QPSK Communication Systems," *Applied Sciences*, vol.11, no. 6, 2021, DOI:10.3390/app11062543