



Integrated multi-functional silicon photonic engine for long-range FMCW laser ranging

Jing Wang^{1,2} · Lin Zhu² · Yan Zuo² · De Zhou² · Rui Zhu² · Hongsong Xu² · Hao Wang² · Xiong Jiang² · Zhiheng Yue² · Daohui Pan² · Qifeng Liu² · Dechuan Zhang²

Received: 14 November 2024 / Revised: 4 February 2025 / Accepted: 10 February 2025
© The Author(s) 2025

Abstract

We present an integrated multi-functional silicon photonic engine tailored specifically for long-range frequency-modulated continuous-wave (FMCW) laser ranging systems. The engine integrates a parallel four-channel dual-polarization coherent detection module, an on-chip optical splitting system, a laser nonlinearity calibration module utilizing a large-scale optical delay line (DL), and an on-chip local light optical splitting unit on a single chip. Key components, including germanium-silicon photodetectors, were optimized to achieve high responsivity (1.09 A/W) and low dark current (3.6 nA). The on-chip delay line design achieves an optical time delay of 5.74 ns with improved loss, enabling nonlinearity calibration that enhances signal-to-noise ratio (SNR) and spectrum linewidth. The packaged silicon photonic engine, with a chip size of 2.8 mm × 2.7 mm, demonstrates ranging capabilities up to 200 m with SNR exceeding 10 dB across all four channels. This study represents a new integration solution for the FMCW laser ranging system, providing a robust platform for automotive and other high-precision ranging applications.

Keywords Silicon photonics · FMCW · Coherent receiver · Nonlinearity calibration · Integration

1 Introduction

The frequency-modulated continuous-wave (FMCW) laser ranging system, in contrast to traditional time-of-flight (ToF) techniques, exhibits advantages such as direct velocity measurement, robust anti-interference capability, and reliable ranging performance, thereby being regarded as the primary development direction for next-generation light detection and ranging (LiDAR) technology. However, traditional FMCW laser ranging systems, constructed with numerous discrete components, suffer from large size and high cost, rendering them unsuitable for automotive applications [1]. To address these challenges, silicon photonics technology has been applied to enhance the integration of the system [1–4]. Over the years, the FMCW laser ranging system based on silicon photonics technology has made

remarkable progress, including the utilization of optical phased arrays (OPA) for all-solid-state scanning [5–10], which reduces the volume and cost of scanning systems, and the employment of silicon-based external cavity lasers for ultra-narrow linewidth and wide tuning range [5, 11–13]. Additionally, a single-channel FMCW receiver chip on a 3-μm-thick silicon platform has been demonstrated with a 120-m ranging capacity for a target with 80% reflectivity [14]. A four-channel dual-polarization FMCW coherent receiver based on silicon photonics has been reported, achieving a ranging distance of 81 m with a wall as the target [15]. Despite these advancements, there has been limited research on integrating the nonlinearity calibration and parallel multi-channel coherent detection functionalities onto a single chip [14–16]. These functionalities play a crucial role in all FMCW ranging system architectures. They help to reduce the number of external fibers and discrete components, minimizing the required hardware boards. Additionally, they enable co-packaging of the receiver and calibration module, significantly decreasing the overall volume. Integrating the nonlinearity calibration functionality of the FM signal on the chip facilitates real-time calibration and improves the stability of nonlinearity calibration. This is

✉ Jing Wang
wangj8@sustech.edu.cn

¹ School of Microelectronics, Southern University of Science and Technology, Shenzhen, Guangdong 518055, China

² Suteng Innovation Technology Co., Ltd. (RoboSense), Shenzhen, Guangdong 518000, China

attributed to the fact that the on-chip delay line waveguide operates in the transverse electric (TE) mode, whereas traditional fiber loops are susceptible to polarization effects caused by environmental changes, resulting in degraded calibration performance. In the automotive application domain, to achieve high-precision detection of small targets, a high point cloud frequency is required, making single-channel coherent detection insufficient, thus emphasizing the significance of multi-channel parallel coherent detection. Furthermore, previous reports have primarily focused on the chip level and simple chip-on-board (COB) packaging, with no reports on advanced packaging forms such as hermetic packaging. Therefore, exploring hermetic packaging for FMCW laser ranging can provide a foundation for subsequent co-packaging with lasers or semiconductor optical amplifiers (SOA) [17].

In this work, we present a silicon photonic engine tailored for long-range FMCW laser ranging applications. The engine integrates multiple functionalities on a single chip and represents a significant advancement in the field. Key design optimizations have been implemented to enhance performance, and the chip has been packaged in accordance with automotive LiDAR requirements. Additionally, a hardware board with multi-channel signal amplification has been developed and packaged with the engine. The engine demonstrates good performance characteristics, including high responsivity, common-mode rejection ratio (CMRR), and bandwidth (BW). Furthermore, it has been successfully employed in an FMCW ranging system, achieving good ranging capabilities of 200 m.

2 Analysis of coherent receiver in long-range FMCW laser ranging system

The BW of the receiver in an FMCW ranging system should be greater than the maximum frequency of the difference frequency signal of the target at the maximum distance ($R_{\max}$) and maximum velocity ($v_{\max}$) which can be expressed as follows [18]:

$$BW \geq \max(df) = f_{R_{\max}} + f_D = \frac{2R_{\max}}{c} \cdot \frac{2B}{T} + \frac{V_{\max}}{\lambda_{\text{laser}}} \quad (1)$$

Here, df represents the frequency of the difference frequency signal. The frequency difference arising from the distance delay $R_{\max}$ is denoted as $f_{R_{\max}}$, while f_D signifies the frequency difference induced by the Doppler shift with a maximum velocity of $v_{\max}$. Additionally, B stands for the frequency modulation BW of the modulated light source, c is the speed of light, T represents the frequency modulation period, and λ_{laser} designates the wavelength of the

laser. When considering a standard application of a long-range FMCW ranging system, such as the one employed in vehicular LiDAR, and disregarding the necessity for velocity measurement (whereby the second term becomes zero), specific parameters emerge. For instance, with $R_{\max}$ set at 250 m, B at 5 GHz (which corresponds to a ranging resolution of 5 cm, as determined by $f \geq 0.89 c/\sigma$, where σ signifies the resolution), and T at 36 μs , the receiver's BW can be achieved to be a minimum of 463 MHz. If the ranging distance increases to the current demand of 500 m, with a ranging resolution of 3 cm suitable for applications like autonomous trucking, the receiver's BW exceeds 900 MHz. Furthermore, it is evident that for alternative uses of the FMCW ranging system, particularly in short-range settings where velocity measurement is not required, the second term of Eq. (1) becomes irrelevant. Given that $R_{\max}$ is diminished in these scenarios, the receiver's BW can be significantly reduced. However, it is important to note that this particular scenario lies beyond the scope of this paper. Considering the primary elements of the entire receiver chain, which include the BW of the transimpedance amplifier (TIA) and the analog-to-digital converter (ADC), typically ranging from 500 MHz to 1 GHz, the photodetector's BW is estimated to exceed 500 MHz. This ensures that the BW requirements of the receiver chain are adequately met.

The signal detection capability and signal-to-noise ratio (SNR) of the FMCW ranging system exhibit a strong correlation. In the field of vehicular LiDAR, a target board with a reflectivity of 10% and an SNR of 10 dB are used as criteria for judging ranging capability. Here the SNR can be expressed as follows [18]:

$$\begin{aligned} \text{SNR} &= \frac{2\eta^2 P_E P_L e^{-\frac{4\pi\Delta\nu R}{c}}}{N(\text{shot}) + N(\text{Heat}) + N(\text{TIA}) + N(\text{ADC})} \\ N(\text{shot}) &= 2q\eta P_L B_e \\ N(\text{heat}) &= \frac{4KT B_e}{R_F} \\ N(\text{TIA}) &= \text{NEP}^2 \eta^2 B_e \\ N(\text{ADC}) &= \left(\frac{V_{\text{ADC}}}{R_F} \right)^2 \frac{1}{12(2^N - 1)^2 f_{\text{ADC}}} B_e \end{aligned} \quad (2)$$

The noise level of the FMCW LiDAR system is composed of four main elements: photodetector shot noise (labeled $N(\text{shot})$), thermal noise (represented by $N(\text{heat})$), TIA noise (designated as $N(\text{TIA})$), and ADC quantization noise (indicated by $N(\text{ADC})$). Here R denotes the target range, c is the speed of light, η represents the photodetector's responsivity, P_L refers to the optical power of the local oscillator (LO) at the mixing port, P_R signifies the received optical power at the mixing port, $\Delta\nu$ is the effective linewidth of the laser source, R_F stands for the transimpedance gain of the TIA, B_e denotes the electrical BW used for signal processing, K is the Boltzmann constant, T is the temperature, NEP represents the noise equivalent

power of the TIA, V_{ADC} is the ADC input voltage range, N designates the ADC effective number of bits (ENOB), and f_{ADC} is the ADC BW.

To improve the SNR, there are primarily four strategies. Firstly, one can increase the optical power incident on the photodetector by optimizing the overall optical path loss, enhancing coupling efficiency, expanding the receiving aperture, and raising the transmitted power. Secondly, reducing B_c can be effective, although this may lead to increased signal processing delays and demanding hardware requirements, possibly not meeting the high frame rate (≥ 10 Hz) needs of vehicular LiDAR point clouds. Thirdly, focusing on increasing the responsivity of the photodetector is another approach. Lastly, the linewidth of the laser, or coherence length, significantly impacts the SNR, with increased distance leading to greater SNR degradation due to laser decoherence. Utilizing a narrow linewidth laser can further enhance performance. In our research, we aim to boost the responsivity of the photodetector and optimize the receiving link's loss. For instance, we plan to enhance the coupling efficiency between the single-mode fiber and the silicon photonic chip by selecting suitable glue and optimizing the process.

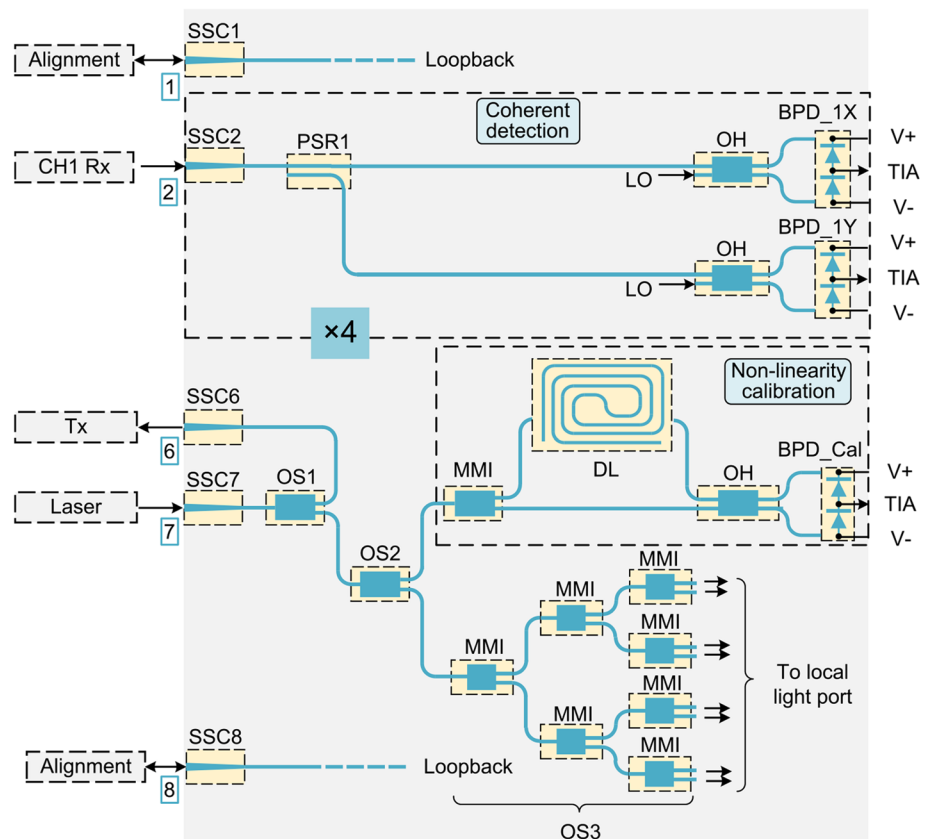
Additionally, from a photodetector architecture perspective, despite the complexity of a balanced photodetector (BPD) compared to a single photodetector, such as requiring

twice the number of photodetectors and additional passive mixers, it offers a 3-dB SNR improvement. This significantly extends the detection range. Hence, we have chosen to adopt BPD in our work. Moreover, considering the variety of actual targets that can differentially affect the polarization state of reflected light, we have implemented a polarization diversity mechanism. This allows for independent processing of distinct polarization signals from each channel, ensuring efficient target detection.

3 Chip architecture design and key device verification

Figure 1 illustrates a comprehensive schematic of the innovative silicon photonic chip tailored for FMCW laser ranging, showcasing its diverse functionality. The chip architecture encompasses four primary functional modules: a parallel four-channel dual-polarization coherent detection module, an integrated on-chip optical splitting module, a laser nonlinearity calibration module leveraging a large-scale optical DL, and an on-chip local light optical splitting unit. Within the coherent detection module, we take the first receiving channel as a representative example to elucidate its operation. Here, the spot size converter 2 (SSC2) adeptly couples incoming signal light into the silicon photonic

Fig. 1 Schematic diagram of the silicon photonic chip architecture with multiple functions. Optical crossings are not shown here. Ports 2–5 represent the individual ports of the coherent detection module



chip, ensuring efficient energy transfer. Subsequently, the polarization splitter-rotator 1 (PSR1) precisely divides this coupled light into two TE-mode beams, facilitating polarization diversity detection. These beams then undergo processing by optical hybrids (OHs) and balanced photodetectors (BPD_1X and BPD_1Y) to achieve coherent detection. The remaining three receiving channels operate analogously, sharing similar operational principles, and are thus omitted here for brevity. The on-chip optical splitting module, consisting of an SSC and optical splitters (OS), carefully divides light from an external FM light source. Light initially enters the chip via SSC7 and is bifurcated into two beams by OS1. One beam subsequently exits the chip through SSC6, serving as the transmitted signal, while the other beam is further divided by OS2. This division ensures that one beam is directed toward the nonlinearity calibration module, while the other enters the on-chip local light optical splitting unit. The nonlinearity calibration module includes essential components such as an OS, a significant DL, a 3-dB coupler, and a balanced photodetector (BPD_Cal). These components form an optical interferometer structure with a fixed delay. The BPD_Cal generates a beat signal that is acquired by a data acquisition (DAQ) board. Subsequently, the instantaneous frequency of the laser is calculated using the Hilbert transform, and the nonlinearity is determined by comparing it with the ideal frequency of the laser. If the nonlinearity meets the requirement, the calibration process stops; otherwise, a new laser drive waveform is generated, and the calibration is repeated. The on-chip local light optical splitting unit employs a cascading arrangement of multiple 1×2 multi-mode interference (MMI) couplers in a 1-to-8 configuration, generating eight identical local optical signals. These signals are then routed to the local light input ports of the OHs, ensuring uniformity across detection channels. Additionally, SSC1 and SSC8 are interconnected via waveguides, forming a loopback configuration that facilitates active alignment of the fiber array (FA). It is worth noting that, for clarity and conciseness in the schematic representation, certain optical crossings (OCs) within the chip have been deliberately omitted.

The germanium-silicon photodetector is a key component within the multi-functional silicon photonic engine. The photodetector needs to have high responsivity, minimal dark current, substantial saturation current, and a suitable BW. Despite advancements in high-performance germanium-silicon photodetectors, we selected a proven platform, accounting for the challenges posed by multi-channel integration yield. Specifically, we opted for a lateral PN junction germanium-silicon photodetector, featuring an intrinsic germanium layer sandwiched between P+- and N+-doped silicon regions. Fabricated on a 220-nm silicon-on-insulator (SOI) substrate, this photodetector leverages germanium as the light-absorbing material, grown atop the silicon waveguide.

Subsequent oxide growth, selective opening, and metal deposition processes culminate in the formation of metal electrodes. Careful doping profiles were adopted, with the P+-doped region featuring a light doping concentration of $2 \times 10^{18}/\text{cm}^3$ and a heavy doping of $5 \times 10^{20}/\text{cm}^3$, while the N+-doped region exhibits light and heavy doping concentrations of $7.5 \times 10^{17}/\text{cm}^3$ and $5 \times 10^{20}/\text{cm}^3$, respectively.

Figure 2 presents a comprehensive analysis of the photodetector's performance characteristics, examining both simulation and experimental results. Figure 2a, b demonstrates the influence of germanium region length and gap on dark current, respectively, at varying doping concentrations. As the germanium region lengthens, dark current escalates, attributed primarily to enhanced Shockley–Read–Hall (SRH) and band-to-band tunneling (BBT) recombination mechanisms [19]. Notably, heavy doping exacerbates this trend, with BBT dominating, resulting in significantly higher dark currents. Conversely, incorporating a germanium region gap effectively mitigates dark current by minimizing BBT recombination, rendering SRH the primary contributor. Figure 2c, d illustrates the relationships between responsivity, saturation current, and germanium region dimensions. The responsivity was tested under an input optical power of ~ -10 dBm. Responsivity initially increases with germanium length, plateauing once a saturation point is reached, influenced by both waveguide absorption and silicon doping-induced absorption. The gap does not change responsivity much because it does not block light absorption. The saturation current remains stable across variations in spacing and length, primarily governed by the space charge screening (SCS) effect, though lightly doped photodetectors exhibit lower saturation currents due to enhanced SCS sensitivity [20]. Based on our findings, we selected a photodetector with light doping, a 0.5- μm gap, and a 20- μm germanium length, achieving a responsivity of 1.09 A/W, a dark current of 3.6 nA, and a saturation current of 6.3 mA. This optimized photodetector has been integrated into our multi-channel coherent receiver, underscoring its suitability for FMCW laser ranging.

To achieve on-chip nonlinearity calibration functionality, the implementation of an on-chip DL with a considerable length is imperative. Here, we opt for a spiral waveguide structure to minimize the overall area occupied by the DL. It was developed in rib waveguides with a top silicon layer of 220 nm, 3 μm upper/bottom oxide cladding, and a slab height of 150 nm to minimize propagation loss owing to sidewall roughness. For the straight waveguide section, we employ a wider rib waveguide to mitigate the impact of sidewall roughness. For the curved waveguide section, a hybrid approach combining conventional curved waveguides and sine-shaped curved waveguides is adopted to minimize bending loss. Our design is inspired by our previous work, but we have further enhanced the delay to exceed 5.5 ns [16].

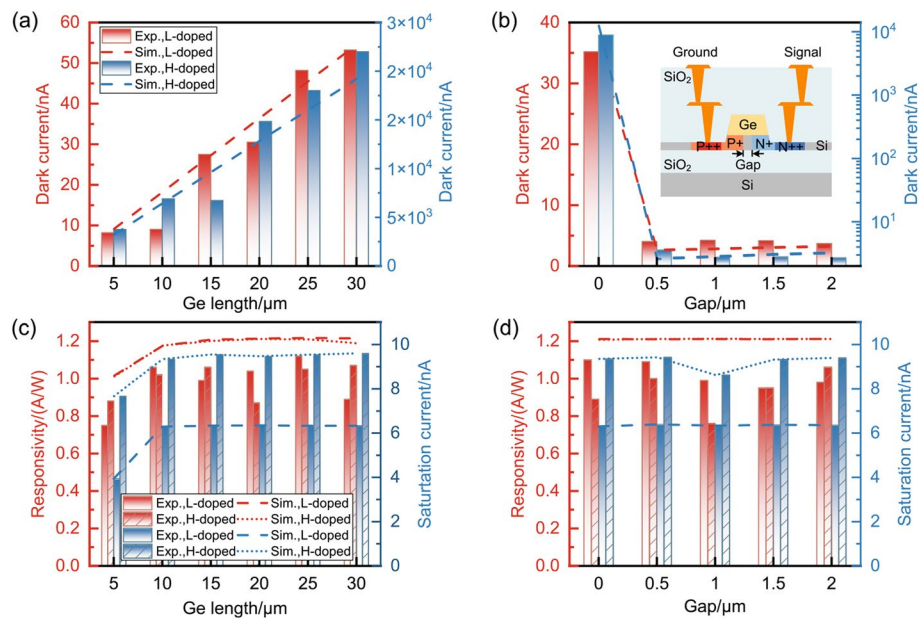


Fig. 2 **a** Relationship between dark current and germanium region length at two doping concentrations. Here the gap is 0 μm . **b** Correlation between dark current and germanium region gap under two doping conditions. Here the length of the Ge region is 20 μm . The inset figure provides a schematic representation of the waveguide cross-section of the germanium-silicon photodetector. **c** Relationship

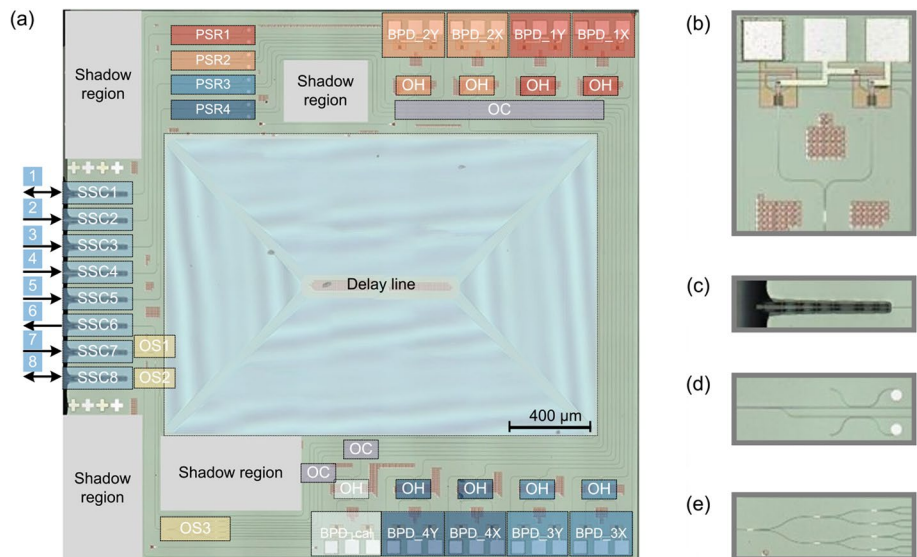
between responsivity and saturation current with germanium region length at two doping concentrations. Here the gap is 0 μm . **d** Dependence of responsivity and saturation current on the germanium region gap at two doping concentrations. Here the length of the Ge region is 20 μm . **a** and **b** share the same color bar as shown in **a**, while **c** and **d** utilize a common color bar as depicted in **c**

4 Chip processing and device packaging

The silicon photonic chip was manufactured using a 130-nm complementary metal–oxide–semiconductor (CMOS) process. Figure 3 annotates various functional units for a comprehensive understanding of the chip's architecture. Eight SSCs serve as crucial optical interfaces that integrate the silicon photonic chip with external optical fibers.

Four distinct dual-polarization coherent receiver sections are incorporated, each comprising a PSR, two OHs, and two BPDs, enabling efficient coherent detection. A notable aspect of the chip design is the integration of a large-scale on-chip optical DL positioned at its core, optimizing the chip's layout for compactness. This DL, in conjunction with a 50:50 OS, an OH, and a calibration BPD (BPD_cal), constitutes an innovative on-chip calibration module,

Fig. 3 **a** Microscopic image of silicon photonic chip processed under 130 nm CMOS technology. We use shaded areas to cover the chip parts that are not related to our work. Further magnifications of internal device units are presented as follows: **b** BPD. **c** SSC. **d** PSR. **e** OS3



facilitating real-time nonlinearity correction. To maintain focus on the chip's essential functionalities, non-pertinent regions are shaded, providing a concise visual representation. In comparison to the chip architecture diagram, this silicon photonic chip incorporates OCs that interconnect the various functional units, ensuring signal propagation. The chip dimensions, measuring $2.8 \text{ mm} \times 2.7 \text{ mm}$, demonstrate the successful miniaturization of complex functionalities within a compact footprint. A series of tailored testing structures were designed and evaluated to characterize the performance of the chip's constituent components at a wavelength of 1550 nm . The SSC, when coupled with a single-mode fiber, exhibited a coupling loss of 2.5 dB/facet , indicating good alignment and minimal loss, with potential for further reduction through the application of a refractive index-matching liquid. The OS demonstrated an insertion loss below 0.1 dB . The OH exhibited an insertion loss of 0.15 dB with an unbalanced loss of 0.1 dB . The OC introduced a negligible crosstalk of -45 dB while maintaining an insertion loss of 0.1 dB . The PSRs, critical for polarization control, exhibited an insertion loss of 0.3 dB , validating their design and fabrication. Lastly, the DL, spanning 40 cm in length, achieved an optical time delay of 5.74 ns with an average loss per length of 0.8 dB/cm . To further reduce the loss of the DL, a more advanced SiN-on-SOI integration platform can be utilized in the future. This approach not only takes full advantage of the low-loss characteristics of SiN waveguides but also enables the integration of other active functional components [21]. Meanwhile, efforts will continue to optimize the performance of the germanium-silicon photodetector, further enhancing its responsivity and dynamic range [22].

In contrast to conventional COB packaging, box-level (BOX) packaging offers a hermetically sealed environment, isolating the device from the external surroundings and thereby enhancing product reliability and longevity, positioning it as the preferred packaging format for commercialization. Furthermore, detailed packaging design is required to reduce optical insertion loss and minimize the electrical link loss of the receiver. Given the configuration of our silicon photonic chip, which incorporates nine BPDs distributed across both sides, each equipped with three pads, we have devised an aluminum nitride (AlN) substrate featuring 15 pads on each of its upper and lower surfaces. This design ensures a seamless connection to each BPD pad, adhering to the connectivity requirements. Based on the simulation results of high-frequency transmission lines, the crosstalk between channels is less than -45 dB when the pad spacing is $100 \mu\text{m}$. The metal tube housing, which encapsulates the chip, aligns its pads one-to-one with those of the AlN substrate. This makes it easier for electrical signal transmission between the BPDs, AlN substrate, and housing via metal lead wires. To ensure optimal performance, we

have undertaken joint simulations of our custom-designed ceramic substrate and metal tube housing, considering the electrical characteristics of the backend TIA. Specifically, we employ a TIA with a 3-dB BW of 500 MHz and a gain of $2 \text{ k}\Omega$. Upon amplification by the TIA, the output current signal from the BPDs is converted into a voltage signal. This voltage signal is then enhanced through a voltage amplifier (VA) to elevate its amplitude, meeting the needs of downstream processing. To maintain signal integrity, we have strict rules on parasitic capacitance. The TIA adds 0.8 pF , the printed circuit board (PCB) adds 0.5 pF , and the package housing's S signal to ground path also contributes. The total parasitic capacitance must not exceed 1.2 pF . Through careful layout and routing of the AlN substrate, we have managed to restrict its contribution to parasitic capacitance to below 0.42 pF . Further simulations of the tube housing have validated that its parasitic capacitance remains under 0.76 pF , adhering to our design specifications. Ultimately, comprehensive joint simulations of the ceramic substrate and tube housing at a frequency of 500 MHz have yielded promising results, with an insertion loss of 0.7 dB , and a crosstalk suppression of -45 dB between adjacent channels. These outcomes underscore the effectiveness of our packaging design in preserving signal quality and minimizing interference, positioning our silicon photonic chip as a reliable and high-performance solution for FMCW laser ranging applications.

Upon successful completion of the design and fabrication of all individual components, we embark on the packaging of the integrated device. As an initial step, each component undergoes plasma cleaning to ensure a contamination-free interface. Subsequently, we meticulously affix the silicon photonic chip to its designated position on the ceramic substrate, positioning the FA through the tail tube of the tube housing. This delicate assembly process involves coupling and dispensing an optimized glue. The glue is used to attach the FA to the silicon photonic chip. Careful glue selection and procedure optimization help minimize coupling loss during the coupling and curing process. Once the FA is securely bonded, we insert the ceramic substrate into the tube housing. The ceramic substrate now houses the silicon photonics chip. We then create a hermetic seal between the FA and the tail tube. This ensures a robust and leak-proof connection. Following this, we meticulously perform wire bonding to the electrical pads located on the silicon photonic chip, ceramic substrate, and tube housing, facilitating electrical interconnection. The lid and body of the tube housing are then fused using a parallel sealing technique, further reinforcing the package's integrity. Figure 4a showcases the completed packaged silicon photonic device, offering a clear view of the internal arrangement of its various components and the silicon photonic chip. After the packaging, we integrate the device with a multi-channel receiver hardware

board, designed to amplify up to 10 signals simultaneously. This capability aligns perfectly with the requirements for comprehensive device performance characterization. Additionally, the hardware board provisions individual bias voltages to each photodetector, ensuring optimal operational conditions. The circuits of each channel are spatially separated enough to ensure sufficiently low channel crosstalk. Figure 4b depicts the hardware board hosting the packaged silicon photonic devices, underscoring the modularity and scalability of our approach. Further reliability validation will be conducted in our subsequent work.

5 System verification of multi-functional silicon photonic engine

We devised and implemented an experimental setup to evaluate and characterize the nonlinearity calibration capability of the engine, as depicted in Fig. 5a. In this setup, a distributed feedback (DFB) laser diode (LD) with a 100-kHz linewidth serves as the source of FM signals, which are driven by an arbitrary waveform generator (AWG). The current injection changes the carrier concentration in the active region of laser and then the frequency modulation is achieved. A variable optical attenuator (VOA) is positioned

to precisely control the output power of the LD. Subsequently, a 10:90 OS efficiently directs a portion of the light toward our silicon photonic engine for on-chip nonlinearity calibration, while the remaining light is further divided by a 50:50 OS into two beams. One beam traverses a 200-m optical fiber to simulate the signal light, while the other serves as the LO light. Both beams ultimately converge at a coherent receiver, which incorporates a 3-dB coupler and an external discrete BPD. The BPD_cal within the nonlinearity calibration link of the silicon photonic engine is amplified and interfaced with a DAQ card. Upon capturing the BPD signals from this link, the DAQ processes these signals through a dedicated nonlinearity calibration algorithm. This algorithm then generates refined driving signals, which are subsequently fed back to the LD via the AWG, implementing a closed-loop feedback control mechanism. Figure 5b depicts the frequency spectrum of the beat signal, as obtained through fast-Fourier transformation (FFT), before and after nonlinearity calibration, following its transmission through a 200-m optical fiber. Prior to calibration, the beat signal generated by the LD's FM signal traversing the 200-m optical fiber exhibits a reduced SNR and a broader linewidth, indicative of compromised ranging accuracy. In contrast, enhancement in SNR is observed after calibration, accompanied by a narrowed-spectrum linewidth, signifying

Fig. 4 **a** Image of silicon photonic devices after packaging, including metal tube shells, FA, silicon photonic chip, and ceramic substrates. **b** Image of packaging silicon photonic devices on a hardware board

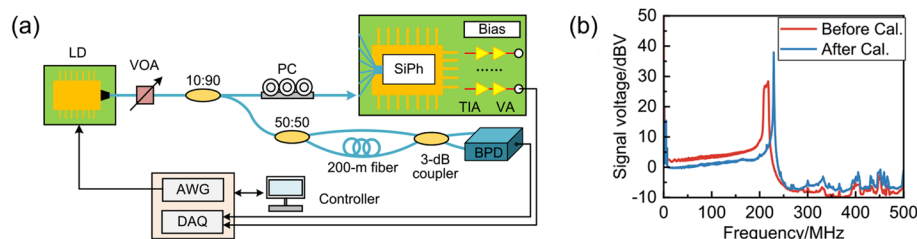
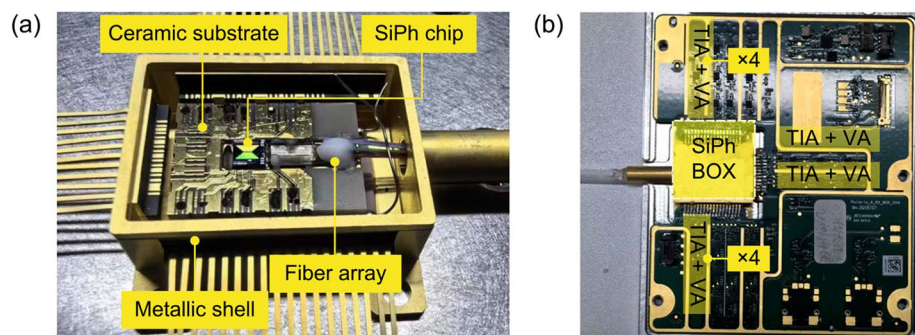


Fig. 5 Verification outcomes of the on-chip nonlinearity calibration capability of the silicon photonic engine. **a** The experimental configuration designed to authenticate the on-chip nonlinearity calibration functionality of the silicon photonic engine. **b** The correlation

between the voltage amplitude of the difference frequency signal post-FFT, transmitted through a 200-m fiber, and the frequency variations before and after applying the on-chip nonlinearity calibration. PC: polarization controller

higher ranging precision. This improvement highlights good nonlinearity calibration capability of our silicon photonic engine, confirming its effectiveness in reducing the inherent nonlinear distortions in FM signals. In subsequent work, we will further investigate the relationship between the delay amount in nonlinearity calibration module and the calibration results, providing a basis for chip design.

In our investigation, we conducted a thorough evaluation of key performance metrics for each channel of the receiver at a wavelength of 1 550 nm. Figure 6 shows the test results of various photodetectors in the silicon photonic engine in terms of responsivity of each photodetector, CMRR of each BPD, and 3-dB BW of the receiving link where each BPD is located, including the impact of the backend circuit. Our analysis revealed that all 18 photodetectors integrated within the engine exhibited a stable responsivity range spanning from 1.01 A/W to 1.06 A/W, underscoring their reliability and uniformity. To ensure the accuracy of our measurements, we adopted a direct probing technique on the pad areas of each photodetector, thereby minimizing any potential interference from the backend circuitry. Regarding the CMRR, our results indicated that nine of the BPDs achieved values approximating 33–37 dB, showcasing good manufacturing consistency across the device. This level of CMRR is crucial for minimizing interference and enhancing signal fidelity. Furthermore, we assessed the 3-dB BW of the entire receiver link for each BPD. The intrinsic BW potential of the germanium-silicon BPDs is substantial. However, the backend amplification circuit limits the observed BW range to 475–495 MHz per link. Nevertheless, this BW capacity is more than adequate to fulfill the demands of long-range detection in FMCW laser ranging applications.

To comprehensively evaluate the performance of the silicon photonic engine, we constructed an FMCW ranging

system. Figure 7a illustrates the experimental setup of this system, detailing the flow of signals from generation to detection. A laser source with a 100-kHz linewidth emits an FM triangular wave signal with a period of 36 μ s and a modulation BW of 4.1 GHz. Upon entering the engine, it is partially directed toward an on-chip nonlinearity calibration module for precise calibration. The processed signal exiting the engine is subsequently amplified by an erbium-doped fiber amplifier (EDFA) and transmitted through an optical circulator and collimator to a target plate with 10% reflectivity positioned at a distance D . Here the collimator had a waist diameter of 7 mm and a waist distance of 37.2 mm. The beam waist diameter at 200 m is 56.8 mm, satisfying the application requirements for detecting small targets at long distances. The reflected light then retraces its path back into the engine, where it is sampled by a DAQ card and processed via FFT to extract the frequency response of the beat signal. To assess the receiving performance of each channel, we connected both polarization outputs of each channel to the DAQ card and selected the path exhibiting the higher SNR as the representative signal for that channel. By adjusting the LD and VOA, the LO optical power entering each BPD was maintained between 1 and 2 mW. Figure 7b shows the actual testing environment. Here, we have chosen a standard target plate with a reflectivity of 10% as the detection target, which is often used in the testing of LiDAR products to provide more objective judgment criteria. While previous studies have reported good ranging capabilities using high-reflectivity targets (e.g., 90%), our choice of a 10% reflectivity target underscores the robustness and practicality of our system under more challenging conditions.

Figure 7c shows the relationship between the beat signal power and frequency for the first channel. It demonstrates that targets at varying distances generate distinct frequency

Fig. 6 Test results of various photodetectors in the silicon photonic engine. **a** Responsivity of each photodetector. **b** CMRR of each BPD. **c** 3-dB bandwidth of the receiving link where each BPD is located, including the impact of the backend circuit

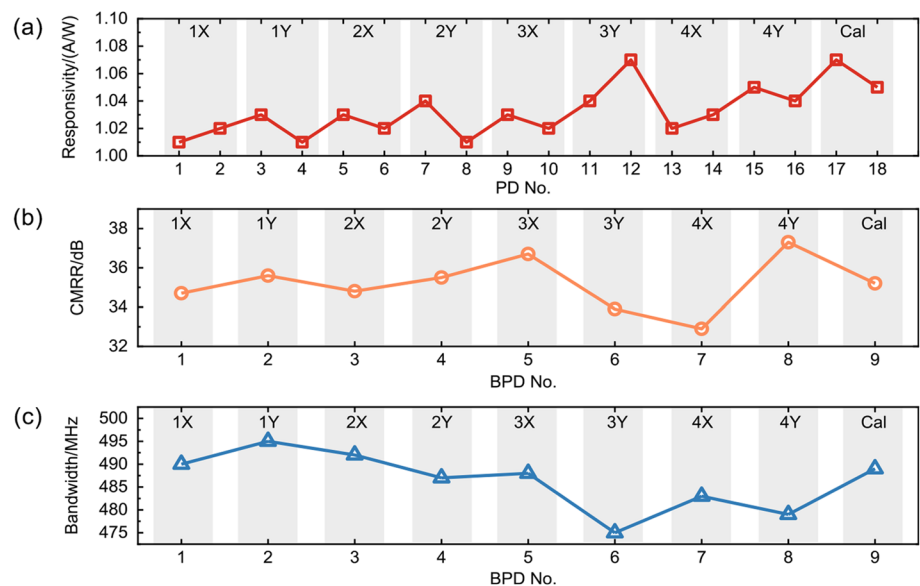
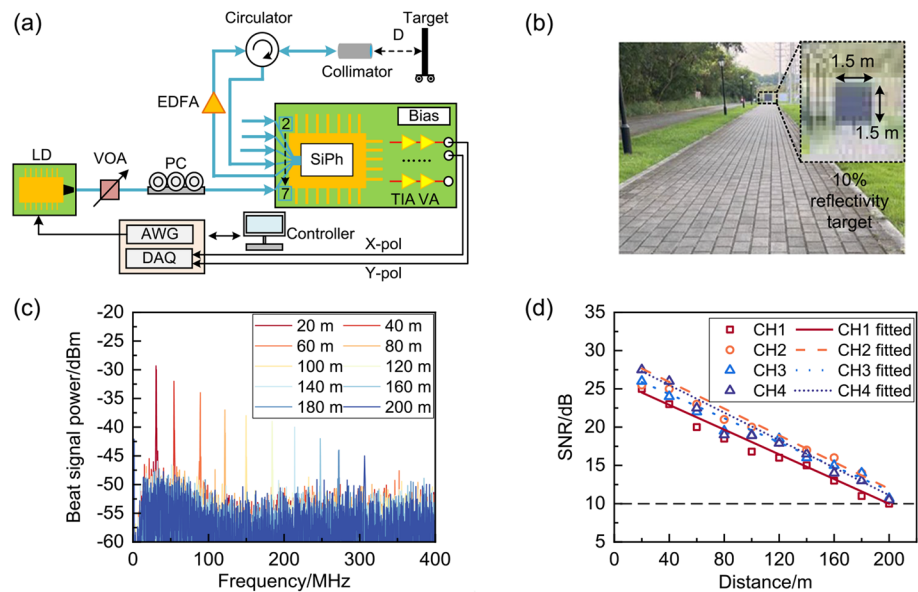


Fig. 7 Verification results of the ranging capability of the silicon photonic engine. **a** An experimental setup devised for characterizing the ranging capability of the silicon photonic engine. **b** The actual testing environment, alongside the utilization of a standard reflectivity panel with a reflectance of 10% and dimensions of 1.5 m × 1.5 m. **c** Correlation between the power and frequency of the beat signal within the first receiving channel. **d** Dependence of the SNR of each receiving channel on the target distance, where the higher SNR among the two polarization signals within each channel is taken as the representative SNR for that channel



signatures, with peak power and SNR declining as distance increases. Evidently, the SNR deteriorates rapidly with increasing distance. This decrease in SNR can be attributed to two primary factors: firstly, the reduction in optical power of the echo from distant targets, and secondly, the phase noise of the laser that accumulates as the distance increases, leading to a reduction in signal coherence and subsequently a decrease in SNR. Despite the use of specially fabricated narrow linewidth lasers in this experiment, an additional SNR degradation of 3.6 dB is evaluated within a ranging distance of 200 m. In the experiment, we will use the SNR of the two polarization state signals in the receiving channel with the larger SNR value as the SNR of this receiving channel. To further quantify ranging performance, Fig. 7d presents the SNR versus distance profiles for all four receiving channels, accompanied by linear fits to highlight the underlying trends. Here, we estimate the SNR based on the spectrogram of the beat signal. For instance, considering CH1 (as shown in Fig. 7c), we use -55 dB as the noise level (N) and the power of the peak signal (S) to conduct a simple SNR estimation, $SNR = S/N$. For channel 1, within a range of 200 m, the SNR gradually decreases from a peak of 25 dB to approximately 10 dB, with minor fluctuations likely attributed to environmental instabilities. Comparable trends are observed across all channels, indicating consistent ranging performance. Assuming a threshold SNR of 10 dB as the criterion for reliable target detection, all four channels exhibit a ranging capability exceeding 200 m. The SNR can be enhanced by utilizing higher transmission power, boosting the LO power, increasing the aperture size of the collimator, and refining the filtering algorithm

further. Additionally, the time-varying free-space optical channel may impact signal reception, which can be improved by investigating corresponding algorithms in future work.

6 Conclusion

In this work, we have successfully demonstrated an integrated multi-functional silicon photonic engine tailored for long-range FMCW laser ranging. The engine encapsulates various functionalities on a single chip, including parallel four-channel dual-polarization coherent detection, on-chip optical splitting, nonlinearity calibration with an extended optical DL, and local light splitting. Through meticulous design and optimization of key components, particularly the germanium-silicon photodetectors, good performances are achieved, such as high responsivity (1.09 A/W) and low dark current (3.6 nA). The on-chip nonlinearity calibration module, leveraging the optical DL, demonstrated an improvement in SNR and linewidth. Experimental validation of the packaged silicon photonic engine within an FMCW ranging system showed ranging capabilities up to 200 m with consistent SNR across all four channels, indicating its suitability for demanding applications such as automotive LiDAR. The integration of multiple functionalities onto a single chip minimizes the required external components and hardware boards, reducing system complexity and cost. This study not only advances the state of the art in silicon photonics-based FMCW laser ranging technology but also paves the way for its widespread adoption in various long-range and high-precision ranging applications.

Acknowledgements Not applicable.

Authors' contribution Writing—review and editing, funding acquisition, supervision: Jing Wang. System design and test: Lin Zhu and Hongsong Xu. Chip design: Yan Zuo, De Zhou, Rui Zhu, and Hao Wang. Hardware circuit design and test: Zhiheng Yue and Daohui Pan. Packaging: Qifeng Liu, Dechuan Zhang, and Xiong Jiang.

Funding This study was supported by the National Key Research and Development Program of China (Grant No. 2021YFB3202201), Shenzhen Science and Technology Program (Grant Nos. JSGG20220831094200001, JCYJ20241202125420027, and CJGJZD20240729141700001), and Southern University of Science and Technology (SuSTech) Startup Fund.

Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate Not applicable.

Competing interests The authors have no relevant financial or non-financial interests to disclose.

Consent for publication Not applicable.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

1. Rogers C, Piggott AY, Thomson DJ, Wiser RF, Opris IE, Fortune SA et al (2021) A universal 3D imaging sensor on a silicon photonics platform. *Nature* 590(7845):256–261. <https://doi.org/10.1038/s41586-021-03259-y>
2. Riemensberger J, Lukashchuk A, Karpov M, Weng W, Lucas E, Liu J et al (2020) Massively parallel coherent laser ranging using a soliton microcomb. *Nature* 581(7807):164–170. <https://doi.org/10.1038/s41586-020-2239-3>
3. Shekhar S, Bogaerts W, Chrostowski L, Bowers JE, Hochberg M, Soref R et al (2024) Roadmapping the next generation of silicon photonics. *Nat Commun* 15(1):751. <https://doi.org/10.1038/s41467-024-44750-0>
4. Chen R, Shu H, Shen B, Chang L, Xie W, Liao W et al (2023) Breaking the temporal and frequency congestion of LiDAR by parallel chaos. *Nat Photonics* 17(4):306–314. <https://doi.org/10.1038/s41566-023-01158-4>
5. Liu C, Guo Y, Xu R, Lu L, Li Y, Chen J et al (2024) Highly-linear and wavelength-tunable frequency-modulated continuous-wave hybrid-integrated laser. *Laser Photonics Rev* 18(7):2300882. <https://doi.org/10.1002/lpor.202300882>
6. Fu Y, Chen B, Yue W, Tao M, Zhao H, Li Y et al (2024) Target-adaptive optical phased array lidar. *Photonics Res* 12(5):904–911. <https://doi.org/10.1364/PRJ.514468>
7. Qiu H, Liu Y, Meng X, Guan X, Ding Y, Hu H (2023) Bidirectional high sidelobe suppression silicon optical phased array. *Photonics Res* 11(4):659–668. <https://doi.org/10.1364/PRJ.479880>
8. Poulton CV, Byrd MJ, Russo P, Moss B, Shatrovov O, Khandaker M (2022) Coherent LiDAR with an 8,192-element optical phased array and driving laser. *IEEE J Sel Top Quantum Electron* 28(5):1–8. <https://doi.org/10.1109/JSTQE.2022.3187707>
9. Li C, Cao X, Wu K, Qiu G, Cai M, Zhang G et al (2021) Blind zone-suppressed hybrid beam steering for solid-state Lidar. *Photonics Res* 9(9):1871–1880. <https://doi.org/10.1364/PRJ.424393>
10. Fukui T, Tanomura R, Komatsu K, Yamashita D, Takahashi S, Nakano Y et al (2021) Non-redundant optical phased array Optica 8(10):1350–1358. <https://doi.org/10.1364/OPTICA.437453>
11. Wu Y, Shao S, Tang L, Yang S, Chen H, Chen M (2024) Hybrid integrated tunable external cavity laser with sub-10 Hz intrinsic linewidth. *APL Photonics* 9(2):021302. <https://doi.org/10.1063/5.0190696>
12. Wu Y, Deng L, Yang K, Liang W (2022) Narrow linewidth external cavity laser capable of high repetition frequency tuning for FMCW LiDAR. *IEEE Photonics Technol Lett* 34(21):1123–1126. <https://doi.org/10.1109/LPT.2022.3203063>
13. Lukashchuk A, Yildirim HK, Bancora A, Lihachev G, Liu Y, Qiu Z et al (2024) Photonic-electronic integrated circuit-based coherent LiDAR engine. *Nature Commun* 15(1):3134. <https://doi.org/10.1038/s41467-024-47478-z>
14. Xu C, Liu C, Ding Y, Wang R, Wu A (2024) FMCW LiDAR with a coherent receiver chip based on 3 μm SOI photonics platform. *Results Phys* 57:107327. <https://doi.org/10.1016/j.rinp.2024.107327>
15. Liu C, Qi F, Cai P, Li S, Zhao J, Duan Y et al (2024) Silicon photonic four-channel dual-polarization coherent receiver module for FMCW LiDAR application. *Optical Fiber Communication Conference. Paper M4J.1*. <https://doi.org/10.1364/OFC.2024.M4J.1>
16. Wang J, Zhu L, Niu B (2023) Integrated nonlinearity calibration optical-electrical engine for FMCW LiDAR application. *Opt Lett* 48(23):6100–6103. <https://doi.org/10.1364/OL.504530>
17. Sayyah K, Sarkissian R, Patterson P, Huang B, Efimov O, Kim D (2022) Fully integrated FMCW LiDAR optical engine on a single silicon chip. *J Light Technol* 40(9):2763–2772. <https://doi.org/10.1109/JLT.2022.3145711>
18. Kim T (2019) Realization of integrated coherent LiDAR. Ph.D. dissertation, University of California, Berkeley.
19. Zuo Y, Yu Y, Zhang Y, Zhou D, Zhang X (2019) Integrated high-power germanium photodetectors assisted by light field manipulation. *Opt Lett* 44(13):3338–3341. <https://doi.org/10.1364/OL.44.003338>
20. Jiang Z, Yu Y, Wang Y, Zhou D, Deng W, Zhang X (2021) High-power Si-Ge photodiode assisted by doping regulation. *Opt Express* 29(5):7389–7397. <https://doi.org/10.1364/OE.417165>
21. Siew SY, Li B, Gao F, Zheng HY, Zhang W, Guo P et al (2021) Review of silicon photonics technology and platform

- development. *J Light Technol* 39(13):4374–4389. <https://doi.org/10.1109/JLT.2021.3066203>
22. Yan T, Li L, Zhang Y, Hao J, Meng J, Shi N (2024) High-performance Ge photodetectors on silicon photonics platform for optical interconnect. *Sens Actuators A Phys* 376:115535. <https://doi.org/10.1016/j.sna.2024.115535>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Jing Wang graduated from the Department of Electronic Engineering, University of Science and Technology of China in 2010, and received his Ph.D. from the Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences in 2015, during which he studied jointly at Purdue University from 2013 to 2014. From 2015 to 2018, he was engaged in the research and development

of advanced optoelectronic chips at Huawei Technologies Co., Ltd. Since 2018, he has served as a senior R&D expert at Suteng Innovation Technology Co., Ltd. (RoboSense), responsible for the research, development, and management of vehicle-mounted solid-state LiDAR systems, chips, and components. As the project leader, he has presided over six large-scale government technology research projects and participated in nearly 10 other government projects. In July 2024, he joined the School of Microelectronics in Southern University of Science and Technology (SusTech) as an associate professor. So far, he has applied for over 130 patents, with more than 50 authorized, published over 20 papers, authored one English monograph, and holds seven copyrights for integrated circuit layout designs. His research interests include high-speed silicon-based optical modulators, photodetectors and their large-scale integrated chip design, LiDAR optoelectronic chip design, and complex optoelectronic system design based on silicon photonic chips.