SCIENCE CHINA
Information Sciences

• LETTER •

January 2026, Vol. 69, Iss. 1, 119405:1–119405:2
https://doi.org/10.1007/s11432-025-4513-x

A reconfigurable 8 × 8 SPAD array LiDAR receiver with on-chip noise suppression and reflectivity compensation for high-frame-rate applications

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Received 2 January 2025/Revised 14 April 2025/Accepted 2 July 2025/Published online 4 January 2026

Citation Wei Z C, Liu D S, Yu Y. A reconfigurable 8 × 8 SPAD array LiDAR receiver with on-chip noise suppression and reflectivity compensation for high-frame-rate applications. Sci China Inf Sci, 2026, 69(1): 119405, https://doi.org/10.1007/s11432-025-4513-x

In high-frame-rate 2D LiDAR applications, achieving fast, accurate, and robust ranging under strong ambient light and variable target reflectivity remains a major challenge. This work presents a reconfigurable 8 × 8 SPAD (single-photon avalanche diode) array LiDAR receiver that addresses four critical issues: (1) background noise from ambient light and SPAD dark counts [1], which is mitigated by dynamically reconfiguring the SPAD detection area to match the laser focal point, and by applying photon-coincidence detection to suppress non-laser triggers; (2) the need for high-precision time-of-flight (TOF) measurement, met by a custom 31.25 ps-resolution TDC with multi-echo recording capability and a synchronizer that ensures accurate fine-coarse timing alignment under jitter; (3) the demand for high frame rates in real-time scanning scenarios, fulfilled by a three-stage on-chip histogramming engine [2] that supports output rates up to 10 kHz while maintaining low hardware overhead; and (4) walk error caused by reflectivity-dependent variations in SPAD trigger timing, which is corrected using a novel reflectivity compensation method based on SPAD multiplicity, reducing ranging error to within ±2% across 10 m. These integrated innovations enable precise and reliable LiDAR sensing under complex environmental conditions, with validated performance at 1k fps under 92 klux sunlight and total power consumption of only 160 mW. The proposed LiDAR receiver IC, illustrated in Figure 1, integrates multiple subsystems optimized for speed, accuracy, and robustness. At the core lies a reconfigurable 8 × 8 SPAD array, where each pixel is equipped with independently controlled enable and output paths, allowing dynamic activation of the region that aligns with the laser's focal point. This targeted activation significantly reduces background noise and improves signal integrity [3]. A delay-locked loop (DLL) and a phase-locked loop (PLL) provide timing reference and clock generation for the system's high-resolution timing architecture. The integrated multi-echo time-to-digital converter (TDC) achieves 31.25 ps resolution and supports recording of multiple photon arrival events per laser cycle. It also captures the number of simultaneously triggered SPADs, which is essential for photon-coincidence-based noise filtering and for estimating signal intensity related to reflectivity. The decoded time-of-flight and intensity data are processed by a three-stage on-chip histogramming engine, which performs peak extraction with minimal hardware complexity. The histogram engine utilizes a partial accumulation strategy that narrows the TOF range progressively across coarse, mid, and fine timing bins. This reduces memory usage and power consumption while retaining peak selection accuracy. The extracted TOF peak and associated SPAD count are further used for reflectivity-aware compensation, enhancing measurement precision under diverse lighting and surface conditions.

The 8 × 8 SPAD array serves as the core optical sensing front-end, where each pixel is equipped with independently controllable enable and output lines. This per-pixel configurability allows the system to dynamically reconfigure its active detection area to match the focal spot of the incoming laser echo. During system alignment, the SPAD enable signals are sequentially activated to scan the array and identify which subset of SPADs responds to the focused laser spot. Only these focal-point SPADs are kept active, while the rest are disabled to suppress false triggers from ambient light and dark counts [2, 4]. This targeted SPAD activation significantly reduces the contribution of out-of-focus SPADs, which typically only respond to background noise, thereby enhancing the signal-to-noise ratio and reducing the optical precision requirement of the lens system. Furthermore, the individual SPAD outputs are aggregated to extract both TOF and photon intensity information. The number of simultaneously triggered SPADs provides a strong indicator of valid laser returns, enabling photon coincidence detection and intensity-aware reflectivity estimation. Overall, this adaptive SPAD selection mechanism is crucial for maintaining measurement precision under wide dynamic lighting conditions and varying reflectivity, especially when operating outdoors or in high ambient light environments.

The TDC adopts a multi-echo architecture with 31.25 ps resolution, capable of recording multiple TOF events within a single laser cycle. By incorporating fine-coarse interpolation and synchronized data capture, it ensures accurate timing while minimizing data loss from overlapping or closely spaced echoes. In parallel,

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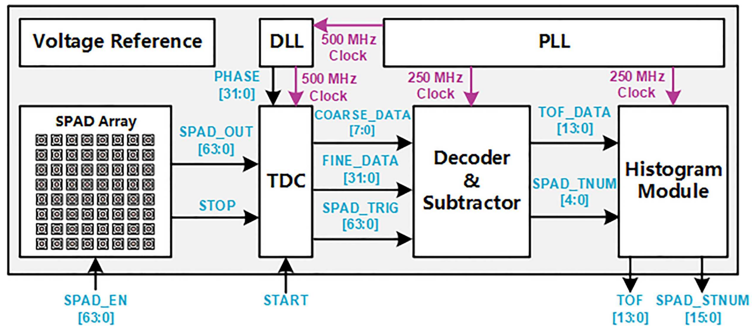

Figure 1 (Color online) Architecture diagram of the proposed single point receiver for 2D LiDAR.

the TDC records the number of triggered SPADs for each event, enabling simultaneous extraction of both temporal and intensity information. This design significantly improves measurement reliability in multi-path and high-noise scenarios, enhances signal discrimination under strong ambient light, and provides essential input for reflectivity compensation.

Different from [1], the histogram engine adopts a three-stage partial accumulation strategy to efficiently extract the TOF peak from incoming data. It directly interfaces with the TDC, receiving 14-bit TOF values (composed of 9-bit coarse and 5-bit fine timing) along with 5-bit SPAD trigger counts after each laser cycle. By splitting the 14-bit TOF data hierarchically, the engine first performs coarse-level binning on the upper 5 bits of the coarse field (TOF[13:9]), then refines the search over the next 5 bits (TOF[8:4]), and finally resolves the peak using the remaining 4 bits (TOF[3:0]). This three-stage narrowing process minimizes the number of histogram bins required at each stage, thereby significantly reducing logic and memory overhead while retaining peak selection precision. In parallel, the engine accumulates SPAD trigger counts associated with each TOF sample, enabling simultaneous generation of intensity metrics. This intensity data is critical for downstream reflectivity compensation, which uses the number of triggered SPADs to estimate reflectance-induced timing errors. The histogram engine's tight integration with the TDC and its dual-output functionality-TOF peak and average SPAD multiplicity-ensure both speed and robustness, supporting flexible output frame rates up to 10 kHz even under strong ambient light conditions.

We designed and fabricated a chip in 180 nm BCD technology, integrating a reconfigurable 8×8 SPAD array, a multi-echo TDC, photon coincidence detection, and a three-stage on-chip histogram engine. A LiDAR module was then built around this chip to validate system performance. Under direct sunlight at 92 klux, the system maintained stable distance measurements at 10 m without any data loss, demonstrating strong robustness against ambient light interference. Compared to traditional single-trigger acquisition, the adoption of full multi-echo recording and intensity-based filtering improved the signal-to-noise ratio from -11.36 to 3.03 dB. These results confirm that the receiver supports high-speed and high-precision operation even in harsh lighting environments, making it well-suited for outdoor real-time LiDAR applications.

To address the walk error, which is reflectivity-induced ranging error [5], the system implements an off-chip compensation method based on the number of triggered SPADs per measurement. Since higher reflectivity leads to more simultaneous SPAD activations and thus faster OR gate response, the resulting TOF shifts are corrected using a calibration curve that maps SPAD trigger count to compensation distance. The calibration is derived from empirical measurements across varying reflectance targets at known distances, and applied in the MCU post-processing pipeline. This approach effectively reduces reflectivity-dependent timing errors, enabling consistent ranging accuracy within $\pm 2\%$ across targets with diverse surface properties.

In summary, the proposed LiDAR receiver IC integrates a reconfigurable SPAD array, multi-echo TDC, on-chip histogramming, and reflectivity compensation to address key challenges in high-speed, high-accuracy ranging. Module-level testing under strong sunlight confirms its robustness, achieving stable operation, improved SNR, and $\pm 2\%$ accuracy across varying reflectivity, demonstrating its suitability for real-world, light-intensive environments.

Acknowledgements This work was supported by Wuhan National Laboratory for Optoelectronics, and Hubei Provincial Natural Science Foundation (Grant No. 2025AFA039).

Supporting information Appendixes A–E. 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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