High-Precision High-Efficiency Multi-Photon Sensing Architecture to Unlock Real-Time TCSPC

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Life-science research increasingly relies on light-based imaging techniques capable of mapping intracellular and extracellular architecture while providing fluorescence signatures with minimal invasiveness. In this context, Time-Correlated Single-Photon Counting (TCSPC) emerges as a compelling technique for measuring weak and fast biosignals through high-precision timestamping of millions of photons over repeated excitation cycles. However, when real-time operation is required, classic TCSPC faces an intrinsic bottleneck: statistically reliable reconstruction requires long acquisition times while increasing the photon count rate leads to pile-up distortion due to the detector dead time. This trade-off has been overcome by a constraint-less TCSPC measurement strategy, demonstrating that distortion-free photon histograms can be obtained by continuously tracking the detector activity state [1]. Once distortion is no longer the limiting factor, the main challenge shifts to maximizing the photon count rate, minimizing detector dead time. To this aim, we introduce a large-area sensing architecture that exploits the dynamic range of SiPMs through replicated detector tiles, without compromising the intrinsic timing performance of SPADs. The optimized number of cells in each tile balances fast temporal response with photon-collection efficiency approaching its theoretical limit [2] (red circles in Fig. 1 (Left)). Furthermore, by exploiting the synchronous reactivation of fired cells at each excitation cycle, we demonstrate full compatibility with the pile-up correction strategy, tracking the activity state while accounting for the finite number of cells per tile, guaranteeing physical feasibility. The identification of the optimal number of cells in the tile guided the design of a 9-cell prototype with a 400 ps dead time (Fig. 1 (Middle)). By combining single-cell timing performance, near-optimal efficiency across the operating space (Fig. 1 (Right)), compatibility with the pile-up correction strategy, and straightforward scalability through tile replication (Fig. 1 (Middle)), the proposed architecture potentially records multiple photons per period per tile, bringing TCSPC closer to real-time deployment while placing its intrinsic precision at the service of advanced clinical applications.

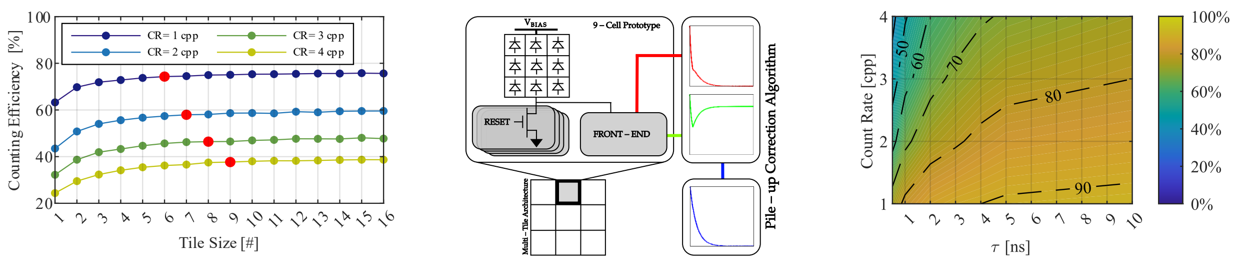

Fig. 1: *(Left) Efficiency vs. tile size for different counts per period (CR) with T_{dead} = 400 ps and τ =500 ps; (Middle) 9-cell prototype architecture; (Right) Efficiency map in the CR - τ space for the 9-cell protoype with T_{dead} = 400 ps.*

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References

[1] Rech, I. et al. (2023). Toward Constraintless Time-Correlated Single-Photon Counting Measurements: A New Method to Remove Pile-Up Distortion. *IEEE Journal of Selected Topics in Quantum Electronics*, 30(1), 1-12.

[2] Cominelli, A. et al. (2025). Speed-optimization strategies for time-correlated single photon counting experiments. *Optics Express*, 33(11), 22270-22295.