

5.7 A 20ch TDC/ADC Hybrid SoC for 240x96-Pixel 10%-Reflection <0.125%-Precision 200m-Range Imaging LiDAR with Smart Accumulation Technique

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Long-range and high-pixel-resolution LiDAR systems, using a Time-of-Flight (ToF) information of the reflected photon from the target, are essential upon launching safe and reliable self-driving programs of Level 4 and above. 200m long-range distance measurement (DM) is required to sense proceeding vehicles and obstacles as fast as possible on a highway situation. To realize safe and reliable self-driving in city areas, LiDAR systems uniting wide angle-of-view and high-pixel resolution are required to fully perceive the surrounding events. Moreover, these performances must be achieved under strong background light (e.g. sunlight), which is the most significant noise source for LiDAR systems. To accomplish a 100m-range DM, an accumulation of the DM results through several pixels is utilized to improve the S/N ratio with 70klux background light [1]. Here, S is the number of photons reflected from the target and N as the number of background light photons. However, if the range is extended to 200m under similar condition of the laser power and frame rate (FPS), 16x more pixel accumulation will be required. Such number of pixel accumulation leads to blurring the range image, hence, a serious oversight in the surrounding events, such as a flying-out pedestrian, may occur; not suiting self-driving applications. Furthermore, the Time-to-Digital Converter (TDC) based ToF measurement is activated only when 2 or more photons are detected simultaneously [1], and thus, is not suitable for the 200m long-range DM where few photons are reflected from the target. On the other hand, ToF measurements using ADCs, which can continuously quantize the silicon photomultiplier (SiPM) output and can sense single-photon events, suits long-range measuring purposes well [2]. However, still a number of accumulation should be required to accomplish 200m-range DM, and hence, low resolution is inevitable. In addition, the SoC cost is critical. To enhance the short-range DM resolution by using ADCs, the required sampling rate is over 10GS/s; upon realizing a 20ch AFE, such ADC array alone may occupy an area of over 10mm² and consumes huge power [3].

A TDC/ADC hybrid LiDAR SoC with Smart Accumulation Technique (SAT) is proposed to achieve both 200m and high-pixel-resolution range imaging for reliable self-driving programs. SAT recognizes and accumulates only the target reflection data by utilizing the intensity and background light information from the ADC, which enhances 4x the effective pixel resolution compared to the conventional accumulation. The proposed TDC/ADC hybrid architecture relaxes the ADC sampling rate requirements for short-range DM precision, and moreover, the proposed residue-quantizing noise-shaping (RQNS)-SAR ADC further downscales the ADC cost. The proof-of-concept 200m range LiDAR system achieves a 2x wider DM-range compared to the conventional designs, and also realizes 240x96 pixel resolution and 0.125% DM precision.

Fig.1 shows the proposed TDC/ADC hybrid LiDAR SoC block diagram. The SoC consists of an ADC-based long-range (LR) DM block (20-200m), a TDC-based short-range (SR) DM block (0-20m), and a digital block for range image construction including SAT. DM is carried on by measuring ToF of the round-tripped photon captured via SiPM and the laser scanning is applied by mechanical mirror. The ADC is an essential block for the proposed LiDAR SoC upon realizing 200m-range DM with higher effective pixel resolution. However, to obtain 0.1%-DM precision for SR measurement closer than 20m (corresponding to 2cm at 20m), ADC sampling rate of over 10GS/s is required, which is unrealistic due to chip cost and power consumption. The proposed TDC/ADC hybrid architecture releases this dilemma. The 12bit 40ps-LSB TDC can easily achieve 1cm-precision and moreover, the proposed hybrid architecture significantly relaxes the ADC sampling rate to 400MS/s. The reflected photon from the target is injected to two kinds of (LR/SR)SiPM customized for each LR/SR requirement where the SR-SiPM has higher input-photon-saturation tolerance than LR-SiPM. In virtue to the above techniques, a SoC essential to 200m-range, 0.125%-DM-precision, 240x96-pixel-resolution LiDAR system for >Level 4 self-driving program is realized with satisfactory cost.

Fig.2 shows the main concept of SAT. SAT recognizes the target reflection data and conducts a smart accumulation by utilizing the intensity and background light information from the ADC; S/N ratio is efficiently improved and long-range high-pixel-resolution DM is achieved. Since few photons are reflected from 200m-range 10%-reflectivity target, the S/N ratio can be < 0dB at the worst case condition with the background light of 70klux. In such conditions, M-times accumulation of the DM results through surrounding M pixels is necessary for the S/N improvement. However, if the pixels "watching" a different target are used for the accumulation, both S/N ratio and pixel resolution degrade [1]. In Fig.2, we will assume that E is the measuring pixel (MP) and the surrounding pixels are candidates for accumulation. Note that accumulation of the pixels D,F,G,H,I "watching" the same target (a car) as E will contribute to the S/N improvement. On the other hand, by accumulating pixels A,B,C "watching" a non-target object (an electric pole), the ToF-measurement can easily fail. To prevent this problem, SAT pre-processes the ADC results and tags the peak level (PL) and floor level (FL). Note that the amplitude swing of the ADC depends on the number of captured photons, and hence PL has a strong correlation with the reflectivity and the distance of the target. Moreover, FL also has a strong correlation with the target, where the reflected photon source is the sunlight. SAT accumulates the corresponding pixel only when the correlations of both PL and FL at MP exceeds appropriate value (e.g. 70%). Also SAT enhances not only the accuracy but the environmental robustness; PL is effective for nighttime and FL for daytime imaging, depending on the amount of the background light. Simulation results show that compared to the conventional simple accumulation [1], SAT can detect 1/4-size objects, hence, SAT enhances 4x the effective pixel resolution and thus, suits longer-range DM.

Fig.3 shows the 400MS/s RQNS-SAR ADC. Generally in a SAR ADC, the C-DAC area is dominating because it increases exponentially with the ADC bit. Moreover, SAR conversion cycles also increase with the ADC bit. Hence, to enhance the sampling rate up to our target, 400MS/s, area-consuming time-interleaving technique will be required. Therefore, SAR ADC with noise-shaping (NS) technique [4] is used for our LiDAR SoC, which enhances the conversion accuracy per cycle by NS, hence, fewer cycle and ADC bit, smaller area. On top of that, a 2nd-order residue-quantizing NS (RQNS) technique is proposed for further area reduction. In the conventional NS-SAR ADC, the residue signal processing required a number of area-consuming analog circuits, such as sampling circuits and amplifiers. The proposed RQNS shifts the residue processing to the digital-domain, where the signal processing is low area cost and; the amplification can be conducted by bit-shifts and sampling circuits by a single flip-flop. This enables the NS order enhancement with minimum area penalty. The residue quantizer composed of SAR ADC samples and quantizes the residue prior to the next conversion in a pipelined fashion. Finally, the 2nd-order NS reduces the ADC bit by 3 and greatly reduces C-DAC area by 80%. Since the ADC sampling rate is crucial for DM precision rather than the input bandwidth, over-sampling is acceptable. The measurement results confirm the 2nd-order NS effect: SNDR=37.7dB at OSR=2 and achieves the smallest area among previously reported ADCs at ISSCC with SNDR>35dB and BW 50-400MHz.

The proposed TDC/ADC hybrid LiDAR SoC was fabricated in 28nm CMOS (Fig.7). Fig.4 shows the LiDAR DM performance, where the 10%-reflectivity target was moved through 20 to 220m under 100-klux sunlight (70klux at the target surface). The DM succession rate of 100% up to 180m and 92.7% at 200m was achieved. Moreover, the σ error of DM was constantly under 0.125% within 20-200m range; a very high precision at wide range. The range images captured by the LiDAR w/ SAT, w/o accumulation, and w/ simple accumulations, are shown in Fig.5(a),(b),(c), respectively. Fig.5(a) proves that SAT significantly improves the pixel resolution and can recognize the pedestrian, suitable for self-driving applications. Fig.6 shows the LiDAR performance comparison. The proposed LiDAR using the proposed hybrid SoC and SAT achieves 2x longer DM and 4x higher effective pixel resolution than conventional designs with almost equivalent FPS. Even if the same laser power was used as in [1], our proposed LiDAR can achieve 1.4x longer range DM due to the hybrid architecture and SAT.

References

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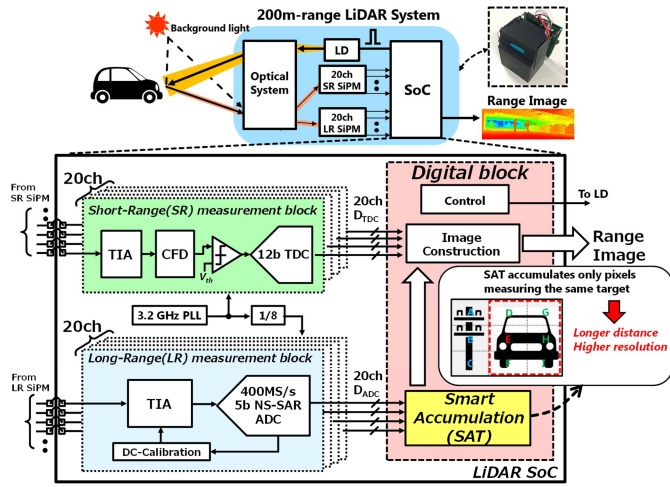


Figure 5.7.1: Block diagram of the proposed 200m range Hybrid LiDAR SoC.

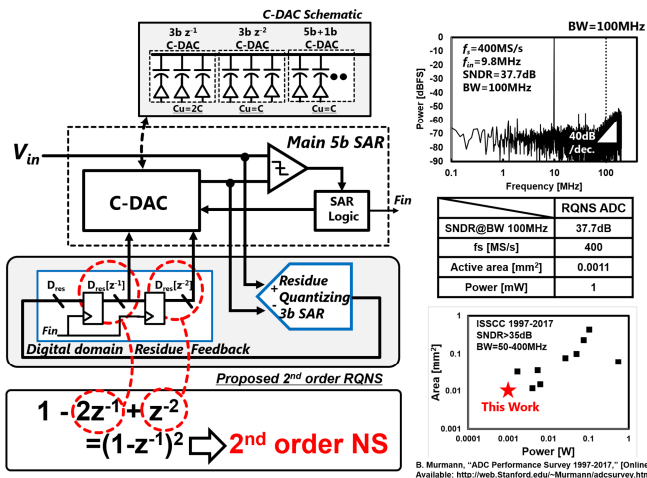
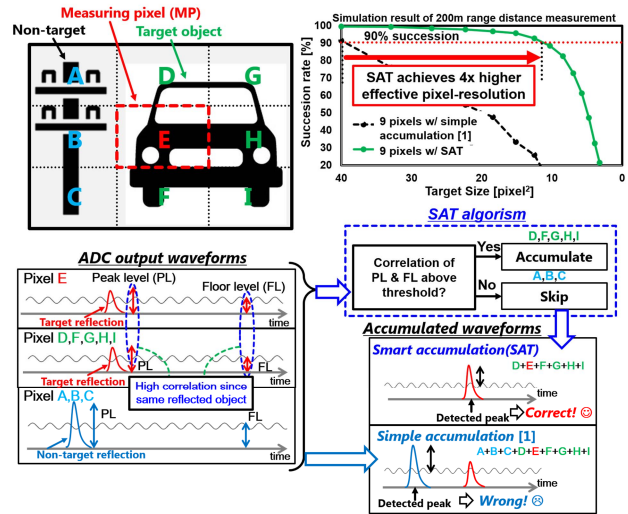
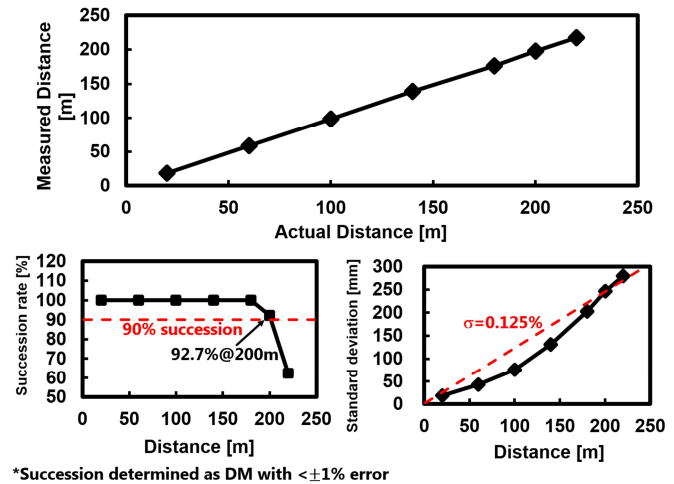
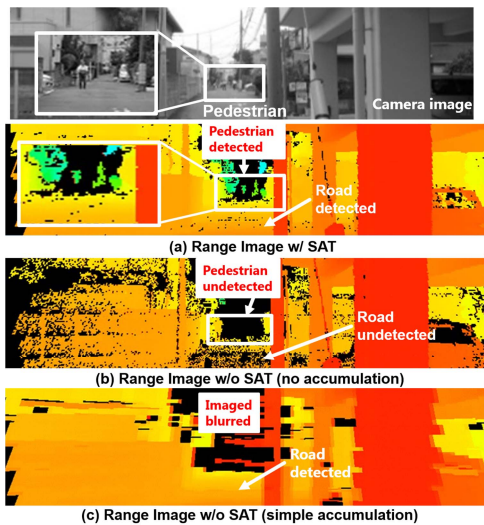


Figure 5.7.3: Block diagram and measured result of the 400MS/s



*Succession determined as DM with $\leq \pm 1\%$ error

Figure 5.7.4: Measured LiDAR Distance Measurement (DM) performance for 10%



	This Work	[1]	[5]
Technology	28nm	180nm	180nm
SPADs	Off-chip	On-chip	On-chip
Optical System	Mechanical Mirror	Mechanical mirror	MEMS mirror
Pixel-Resolution	240x96	202x96	N.A.
Effective Pixel-Resolution w/ accumulation	4x	1x	N.A.
Laser Wavelength [nm]	905	870	870
Laser power [mW]	50	21	N.A.
FPS	10	10	N.A.
Target Reflectivity	10%	9%	10%
Background light [klux]	70	70	75
Distance range [m]	200	100	20
1 sigma error @max distance	0.125%	0.14%	0.5%

Figure 5.7.6: Comparison results with the recently published LiDAR systems.

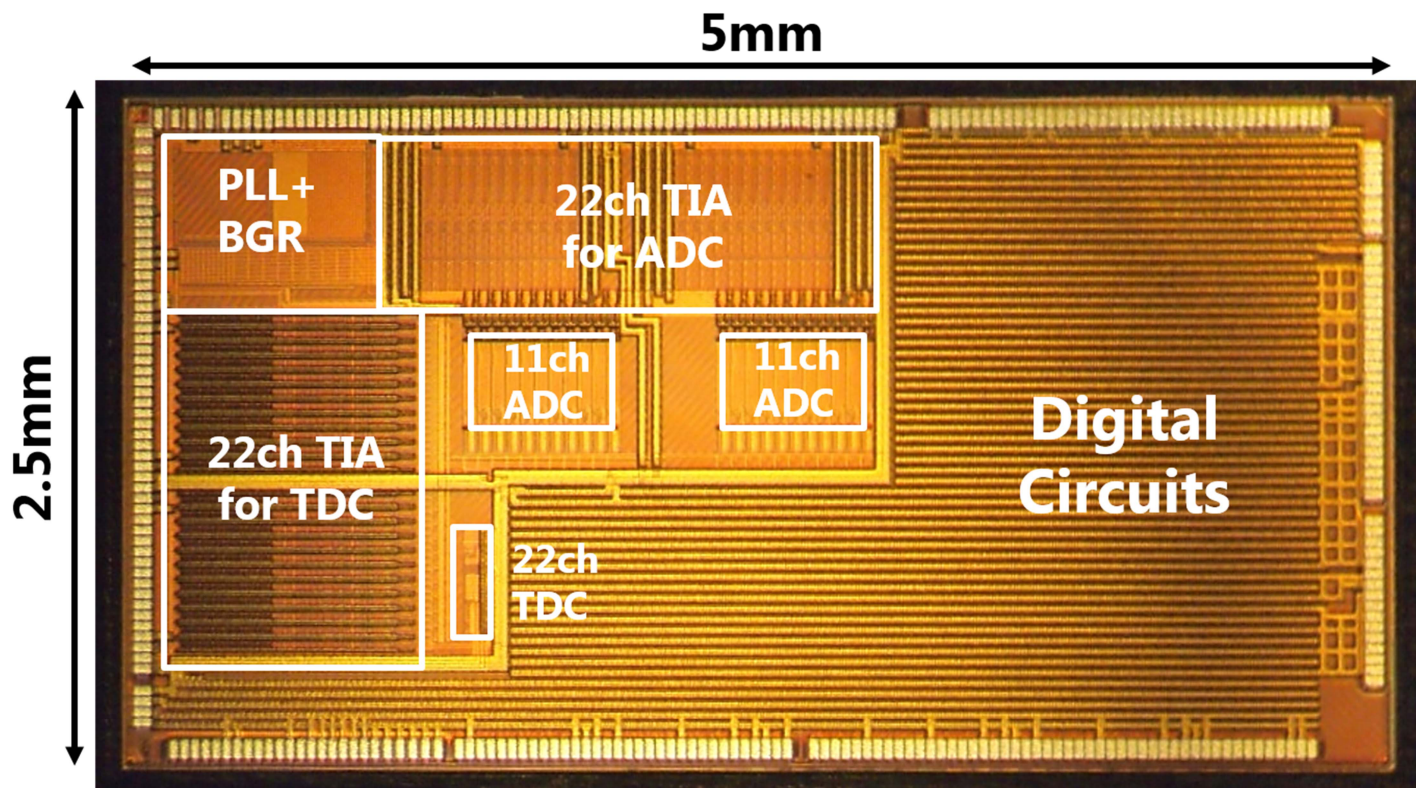


Figure 5.7.7: Chip photo.