A Direct TOF Sensor with In-Pixel Differential Time-to-Charge Converters for Automotive Flash LiDAR and Other 3D Applications

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One of the core technologies for advanced driver assistant systems (ADAS) and autonomous driving is remote sensing technology. Light detection and ranging (LiDAR), which is based on the direct time-of-fight (D-TOF) principle, employs laser light for distance measurement, is one of the prevailing solutions. There are two types of LiDAR systems, scanning LiDAR and flash LiDAR. Scanning LiDAR uses highly collimated laser beams to scan the space with MEMS mirrors or solid-state scanners. Flash LiDAR typically uses an expanded beam to illuminate a scene over a wider FOV, and capture the range data of the whole scene simultaneously. The light source should generally be low coherence and high power but may have low brightness when compared to the highly collimated sources used for scanning LiDAR, making it safer to human eyes [1].

Most scanning LiDARs on the market employ sensors with a single photon avalanche photodiode (SPAD) array and time-to-digital converter(s) (TDC) running at multi-GHz. Due to the size of the TDC, one TDC is usually shared by multiple pixels when non-stacking process is used. Distributing ultra-high speed clock to a large array with minimum skew is also very challenging. Thus, the spatial resolution of such sensors is usually low [2,3,4]. The data rate of scanning LiDARs is usually around 1M points per second. Flash LiDAR using SPAD arrays may potentially have higher spatial resolution and higher data rate than scanning LiDAR if the size of the TDC can be reduced and the clock distribution problem can be alleviated. One approach to reduce the size of the TDC and avoiding high speed clock is to use pixel-wise time-to-analog converters (TAC) [5,6,7,8]. However, due to its vulnerability to PVT variations, the TAC is not a reliable solution for automotive products. Here we introduce a differential time-to-charge converter (TCC) which addresses these drawbacks.

In this paper, a D-TOF sensor based on SPAD technology with a differential TCC in each pixel is presented. The TCC converts the TOF information into two amounts of charge, and stores them in each pixel independently. The stored charge can be read out like a regular CMOS image sensor (CIS). This eliminates the need for distributing high speed clock to the whole array and thus reduces power and circuit complexity. The differential design makes it less sensitive to PVT variations. The time resolution and measuring range can be easily varied by altering the charge transfer speed and shutter opening duration. A proof-of-concept test sensor of 112x128 pixels was implemented, fabricated in a 0.18um CMOS process and characterized for a linear range of 90m. The range resolution is about 1.6cm/lsb, which is equivalent to that of a D-TOF sensor with 9.4GHz TDCs. The sensor is then characterized with a diffused laser source which has a FWHM pulse width of 1ns at a frame rate of 30fps.

The principle of operation of a TCC is shown in Fig.1. There are three storage sites, Cc, Ca and Cb, in each pixel. A certain amount of electronic charge is stored at Cc during reset, while Ca and Cb are emptied. When the shutter is open, the TCC starts counting by transferring charge from Cc to Ca at a constant rate. A laser pulse can be project to the scene before or after the shutter is open. Once the reflected pulse is detected by a photon detector, e.g. SPAD, the TCC switches the charge transferring direction from Ca to Cb at the same rate. The charge transferring stops at the end of a pre-defined transfer period when shutter is closed. Thus, when charge transfer is complete, the differential charge is linearly proportional to the TOF of the object detected. The charge on Ca and Cb can then be read out by the typical image sensor readout method. The TOF of the point being measured can be calculated as $D = A/(A + B) * T_{tx} - T_{dly}$, where A is the voltage readout of charge on Ca, B is the voltage readout of charge on Cb, and Ttx is the shutter duration and Tdly is the laser pulse delay. Unlike the single-ended TAC solution in [7,8], in which the accuracy is affected by the current source variation, our calculation is not related to the slope of Vtx, so the accuracy is not sensitive to PVT induced Vtx variations.

Since this TCC detects the very first photon that triggers avalanche after shutter starts, when ambient light is strong or when dark noise is large, the real return signal might be ignored. To solve this problem, we included a coincidence detection (CD) circuit similar to [2] in each pixel. It monitors 2x2 neighboring SPADs. Only when multiple SPADs trigger at the same time, the TCC stops charge transferring. Fig.2 shows the pixel array architecture with TCCs and shared SPADs. Each TCC has a CD circuit inside.

A test chip of 112x128 pixels with analog output was designed, fabricated and tested to prove the concept of the above theory using a 0.18um CIS process. The major building blocks of the sensor are the SPAD pixel array with in-pixel TCC and CD circuit, row decoder and high speed shutter driver array, column decoder array and column parallel readout circuit array. The SPAD core is 25um in pitch and the total pixel pitch is 30um. The control signals are generated by an FPGA on the test board. One 16-bit ADC on board is used to convert the analog output into digital values. A DPSS laser of 532nm with a diffuser is used to illuminate the scene. The laser pulse width is around 1ns. The sensor was first calibrated for fixed pattern noise (FPN) removal. The FPN is mainly due to transfer gate threshold variations. After FPN is removed, the linear range and temporal noise of the pixels are characterized with controlled laser pulse delay. Five thousand frames of image were collected at each delay setting and the photon arrival time was calculated per frame and per pixel. A histogram-less peak detection algorithm was developed to find TOF information with confidence. Fig.3 shows the characterization results in which fifty frames were used to obtain one range measurement with peak detection. The linear range is about 90m and the RMS noise is less than 0.7% throughout the linear range. The RMS noise can be further reduced by including two memory nodes in pixel for true correlated double sampling (CDS) readout. Fig.4 shows a comparison between our results and several previously published results.

A demo was setup to demonstrate the capability of the sensor. Fig.5 shows the demo setup and the captured 3D image. The distance from the boards and the wall to the camera is 0.5m, 4.2m, 11.7m and 7m to 7.7m, respectively. The average optical power is about 6mW. The 3D image is generated with FPN removal and oversampling rate of 20 for peak detection algorithm. The ranging resolution is about 1.6cm, which is degraded by the two source follower buffers in the analog readout chain. The ranging resolution can be further improved by increasing the slope of the Vtx signal.

In summary, we have proposed and prototyped a D-TOF sensor for automotive flash LiDAR and other 3D applications. It consumes low power, has high angular resolution and has low motion blur. It will be a very good candidate for the next generation ADAS system and other 3D imaging systems.

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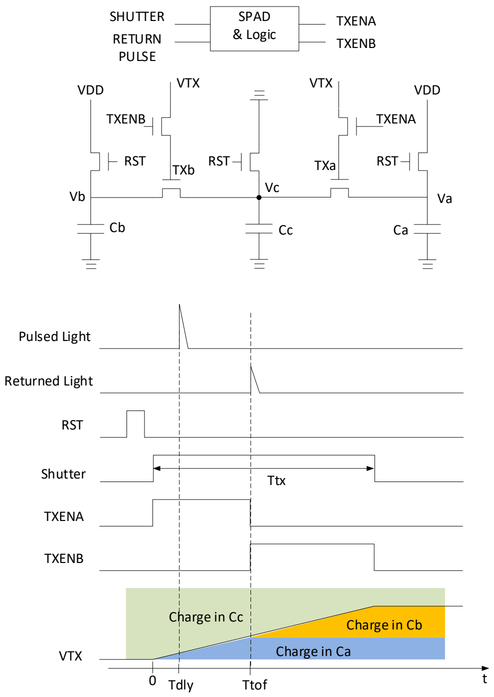

Fig. 1. Operating principle of a differential TCC.

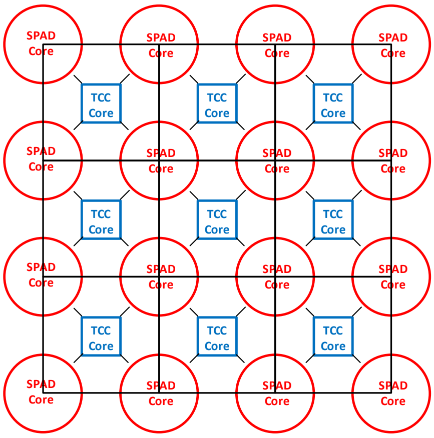

Fig. 2. Pixel array architecture with TCCs and shared SPADs. Each TCC has a CD circuit inside to detect coincident photons of 2x2 neighboring SPADs.

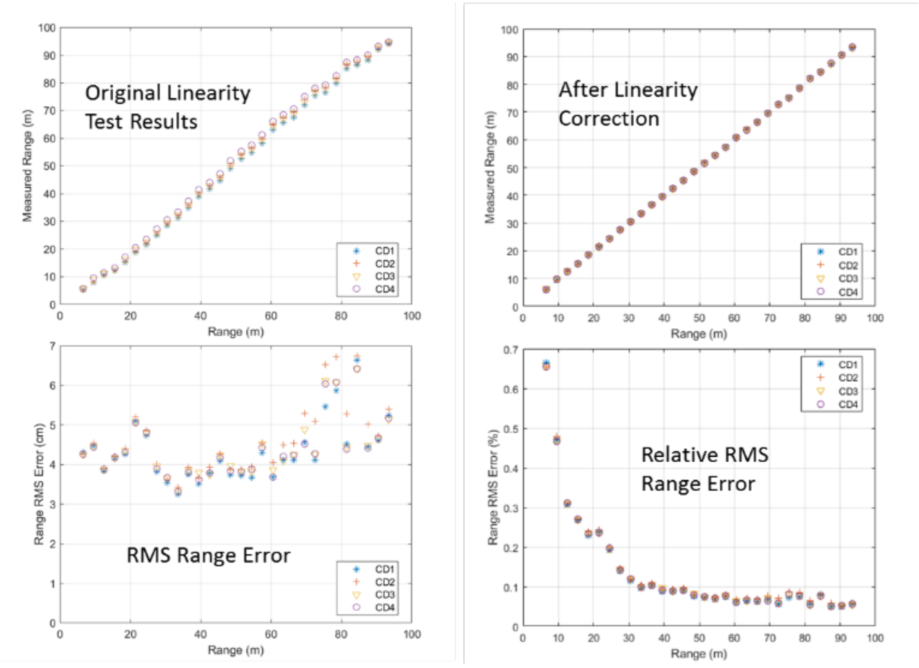

Fig. 3. Characterization result. The linear range is from 5m to 95m and the RMS error is less than 7cm.

	This Work Differential TCC	[3] TDC	[4] Single-ended TAC	[5] Differential TAC	[6] Single-ended TAC
Technology	180nm	180nm	130nm	350nm SiGe	130nm
SPAD Array	113 x 129	340 x 96	32 x 32	-	256 x 256
Effective Measurement Points per Laser Pulse	112x128	32 x 1	32 x 32	-	256 x 256
Linear Range	5 - 95m	10 - 100m	3m (20ns)	1.875, 3,75, 7.5 or 15m (12.5, 25, 50 or 100ns)	7.5m (50ns)
RMS Error	< 7cm	< 10cm	< 2.4cm (160ps)	-	5.5cm (368ps)
Frame Rate	30 fps	10 fps	-	-	10 fps
Pixel and/or TDC/TAC Size	30um x 30um (TCC in-pixel)	~800um x 60um (TDC only)	50um x 50um (TAC/AEC in-pixel)	440um x 650um (TAC+ADC only)	8um x 8 um (TAC in-pixel)
Optical Fill Factor	45%	-	15%	-	19.63%
Coincident Detection	Yes	Yes	No	No	No

Fig. 4. TAC and TDC comparison.

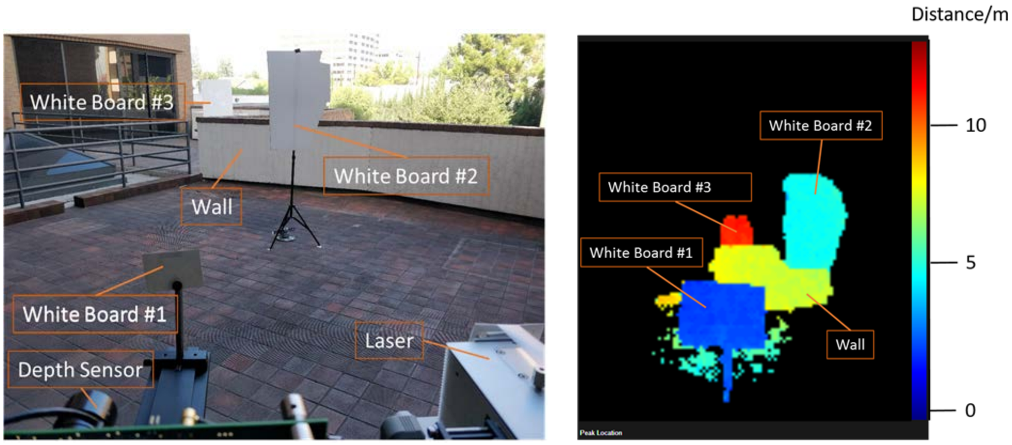

Fig. 5. Demo setup and the 3D image captured.