An 8-tap CMOS Lock-in Pixel Image Sensor for Short-Pulse Time-of-Flight Measurements

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I. INTRODUCTION

Indirect Time-of-flight (TOF) range image sensors are expected to be used for various attractive applications such as AR/VR/MR, security systems, drone and robot vision. In order to expand the application range of TOF imagers, improvements for range resolution (depth noise) under aggressive conditions like longer distance (>5m) and stronger ambient light (>20klux) are necessary. Toward this goal, an indirect TOF measurement technique using short-pulse (SP) modulation and a multiple-tap lock-in pixel CMOS imager will be an attractive candidate. This paper discusses effectiveness of the proposed 8-tap (7 signal taps and 1 drain tap) lock-in pixel image sensor for SP-TOF measurements [1].

II. IMPROVEMENT OF RANGE RESOLUTION WITH MULTIPLE-TAP LOCK-IN PIXEL CMOS IMAGER

Figure 1 shows the operation timing diagram of (a) 7 signal taps for 6 gating time windows for TOF measurements, (b) 4 taps for 3 time-windows and (c) 3 taps for a single time-window[2][3]. In this figure, LP area (green) drawn to be same in three timing diagram means that the signal charge is the same. As increasing the number of signal taps in lock-in pixels, shorter and more energy-concentrated light pulse can be used under the same average light power and the ratio of signal light charge to ambient light charge is increased. This leads to better signal-to-noise (ambient light shot noise) ratio as can be seen from the thick bidirectional arrow, resulting better range resolution under strong ambient light condition. Theoretically, a 6-window TOF measurement using the 7-tap pixel has $6^{1.5}$ =14.7-times better range resolution can be expected if the ambient light shot noise is dominant when compared with a conventional signal-window TOF measurement using 3-tap pixel [3]. Fig. 2

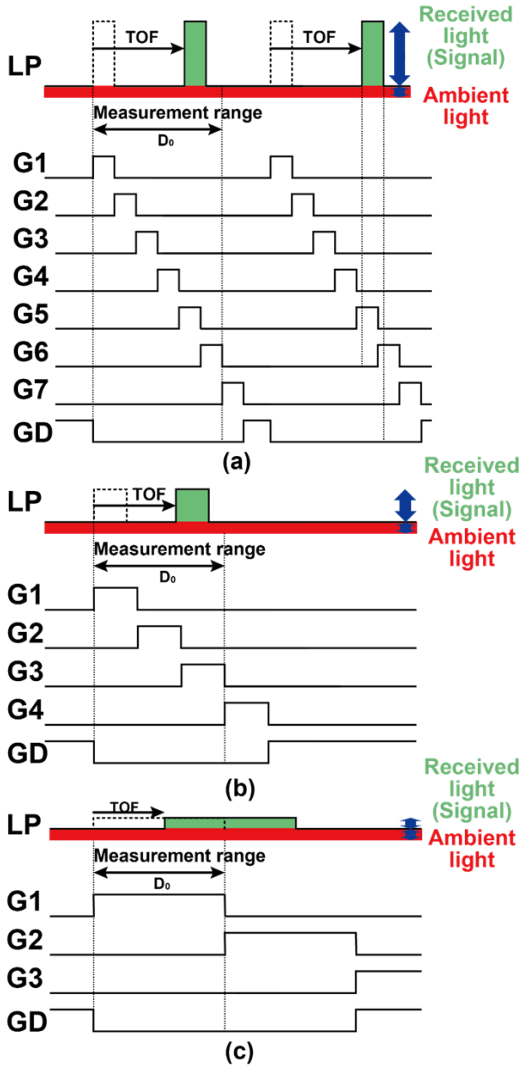
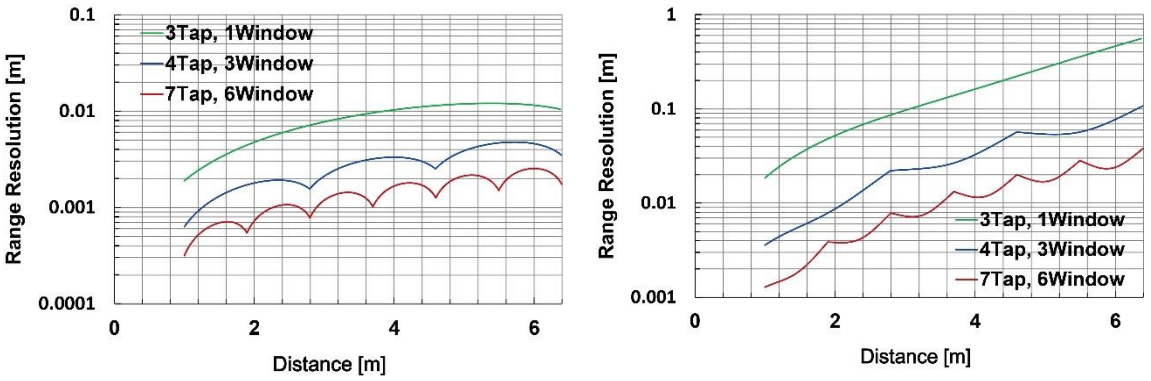


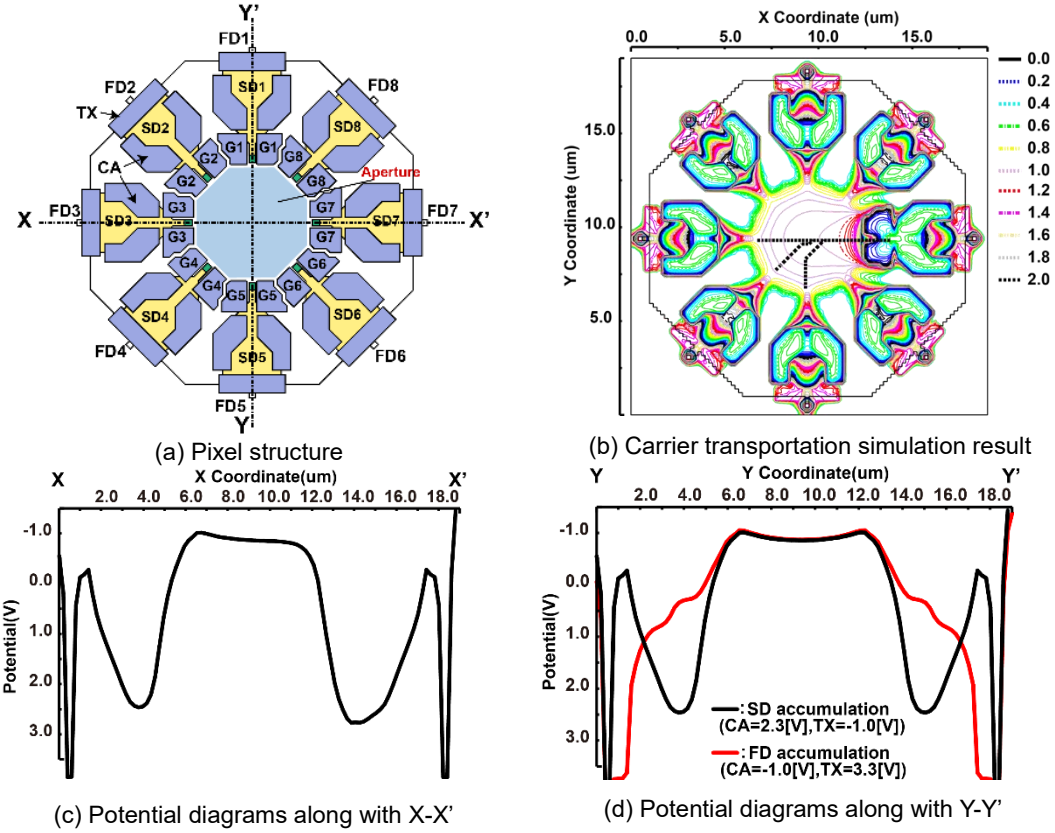
Fig. 1 Short Pulse TOF measurement Using Multiple-Tap Lock-in Pixel Imager. (a) 7Tap, 6Window, (b) 4Tap, 3Window, (c) 3Tap, 1Window.



(a) No Ambient Light

(b) with Ambient Light (20klux)

Fig. 2 Calculation examples of range resolutions versus distance for short-pulse TOF measurements using multiple-tap Lock-in Pixel Imager for no ambient light and strong ambient light conditions.



(a) Pixel structure

(b) Carrier transportation simulation result

(c) Potential diagrams along with X-X'

(d) Potential diagrams along with Y-Y'

Fig.3 Structure and Simulated Potential Diagrams of the Designed 8-Tap Pixel.

shows calculation examples of range resolution for 3 types of implementations of TOF pixels with 7taps, 4taps and 3taps for 6, 3 and 1 time-windows, respectively under two ambient light conditions; (a) 0lux and (b) 20klux. An operating condition of 0.6W average light power, FOV of 40 (V) x 60(H) degrees and a QVGA imager with 22.4μm pixel, QE=40%@870nm and 30fps is assumed. Using a 7-tap pixel (6 time-windows) at 6m and 20klux, for instance, the range resolution (σ) of 4cm is expected while σ with a 3-tap pixel (a single time-window) is 60cm.

III. THE PROPOSED 8-TAP LOCK-IN PIXEL IMAGE SENSOR FOR SP-TOF MEASUREMENTS

A proof-of-concept TOF imager chip (Fig. 4) with 8-tap lock-in pixels has been designed and implemented with a DBH 0.11μm CIS technology. The sensor chip has an 8-tap CMOS lock-in pixel array(80(H)×128(V)). Fig.3 shows the structure of the designed 8-tap CMOS lock-in pixel and simulation results for the potential diagrams along with X-X' and Y-Y' for a setting of the generated

charges in the PD to be transferred to the SD7 by applying Low to G1, G2, G3, G4, G5, G6 and G8 and HIGH to G7 in the LEFM (lateral electric field modulator) gates. [4]

IV. MEASUREMENT RESULTS

Fig. 5 shows a measurement result of the response of 7 signal-tap outputs to the light pulse delay. The incident laser pulse width and pixel gating pulse width are 6.0ns. An 850nm laser diode with a pulse width of 6.0ns is used. Fig. 5 demonstrates that the response of the designed 8-tap pixel is excellent as the response curve (triangular shape) is quite close to ideal response where it is rising linearly in 6ns and falling linearly in 6ns. Using the normalized response of Fig. 5(b), the differences of two signal-tap outputs (S1-S3, S2-S4, S3-S5, S4-S6, S5-S7) are calculated as shown in Fig. 6. 5 piecewise-linear response curves two of which are overlapped each other are obtained and these are used for the TOF range measurements by switching these 5 curves properly. Fig. 7 shows a curve of the calculated pseudo distance versus calculated distance by the delay time of light pulse which corresponds to the twice TOF. Other characterizations of the TOF pixel and imager including the distance measurement, the range map generation and evaluation of the range resolution and tolerance to ambient light are now being carried out.

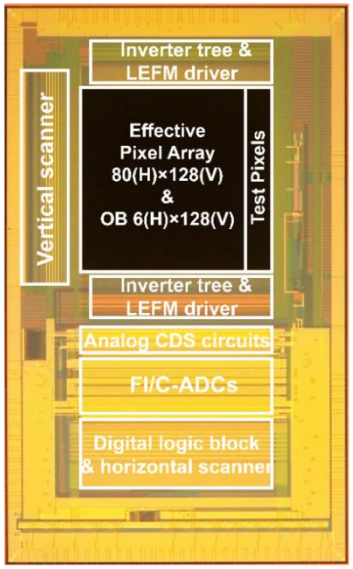
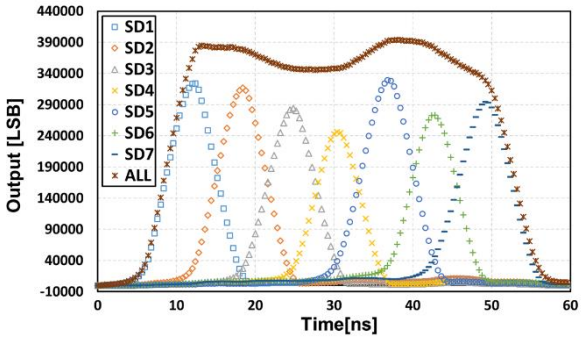
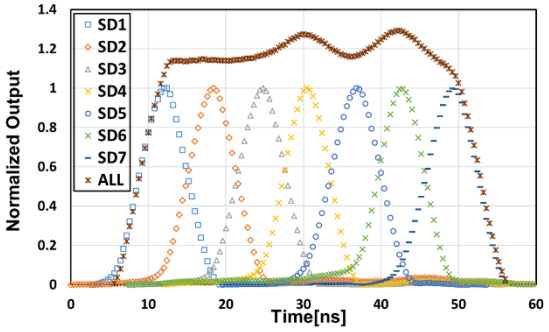


Fig. 4 Implemented Sensor Chip.



(a) Raw Output



(b) Normalized

Fig. 5 Measurement result of the response of 7 signal-tap outputs.

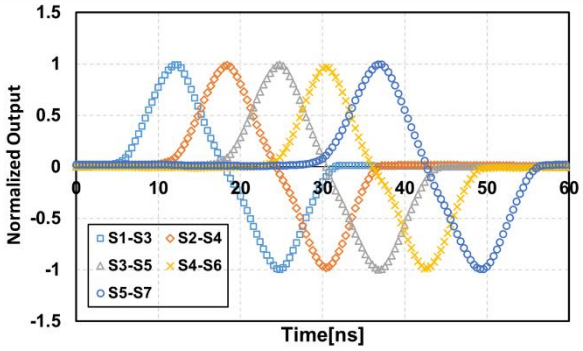


Fig. 6 Differences of two signal-tap outputs.

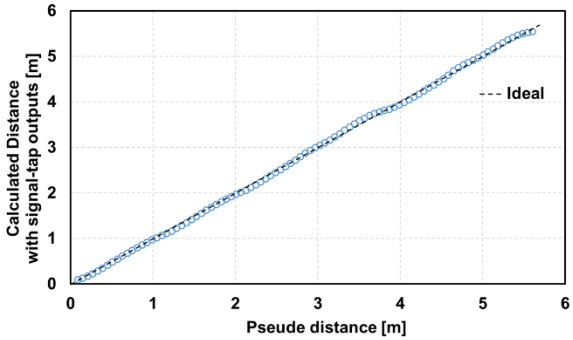


Fig. 7 Calculated distance with signal-tap outputs versus pseudo distance.

V. CONCLUSIONS

This paper proposes an 8-tap CMOS lock-in pixel image sensor for short-pulse time-of-flight measurements and that using the multiple-tap lock-in pixel CMOS imager is useful for improving the TOF range resolution. The basic operation of an 8-tap lock-in pixel image sensor is evaluated. The measurement result of the response and calculated distance with signal-tap outputs are quite close to ideal response. Therefore, the range map is also expected to be able to generated for real distance with high range resolution as the number of taps increases.

ACKNOWLEDGMENTS

This work was supported in part by the Japan Society for the Promotion of Science (JSPC) KAKENHI, the Grant-in-Aid for Scientific Reserch (S) under Grant 18H05240 through the Ministry of Education, Culture, Sports, Science and Technology (MEXT), the MEXT/JST COI-STREAM Program, and the MEXT Regional-Innovation Ecosystem Program. The authors also would like to thank DB HiTek for CIS chip fabrication.

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