A Hybrid Indirect ToF Image Sensor for Long-Range 3D Depth Measurement under High Ambient Light Conditions

Kunihiro Hatakeyama[1], Yu Okubo[1], Tomohiro Nakagome[1], Masahiro Makino[2], Hiroshi Takashima[2], Takahiro Akutsu[3], Takehide Sawamoto[3], Masanori Nagase[3], Tatsuo Noguchi[1], Shoji Kawahito[3,4]
[1]Toppan Inc., Tokyo, Japan, [2]TOPPAN TECHNICAL DESIGN CENTER CO., LTD., Tokyo, Japan,
[3]Brookman Technology, Inc., Hamamatsu, Japan, [4]Shizuoka University, Hamamatsu, Japan

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Abstract

A new indirect time of flight (iToF) sensor realizing long-range measurement of 30 m has been demonstrated by a hybrid ToF (hToF) operation, which uses multiple time windows (TWs) prepared by multi-tap pixels and range-shifted subframes. The VGA-resolution hToF image sensor with 4-tap and 1-drain pixels, fabricated by BSI process, can measure the depth up to 20 m in outdoor and under high ambient light of 100 klux. The new hToF operation with overlapped TWs between subframes improves accuracy. The sensor works at 120 fps for a single subframe operation. Interference between multiple ToF cameras in IoT systems is suppressed by a technique of emission cycle-time random modulation.

Keywords: iToF, hToF, Multi Tap, Long-Range Measurement, Short Pulse, Drain Gate, Ambient Light, Multi TW, Subframe.

Introduction

For 3D depth sensing, the iToF sensors are one of promising technologies to realize module downsizing, high depth resolution and high-speed operation, simultaneously. To expand their applications to fields such as slow-speed vehicles, AGV and drone, an extension of the measurement range and high ambient light tolerance are indispensable. In recent IoT systems where multiple 3D sensors are operated, providing interference suppression mode in iToF sensor itself is essential [1].

Widely-used continuous wave (CW) iToFs [2] have an issue of long-range measurement under strong ambient light, particularly if the pixel is downsized. To improve the ambient light tolerance for the CW iToFs with small pixels, a binning technique is often used [6, 7]. However, the binning sacrifices the depth-image resolution. In contrast, the short pulse (SP) iToFs [3, 4] have advantages of mitigating the above issues because its pixel equipped with a drain gate and operated with small duty ratio can avoid saturation in high ambient light by draining unwanted signal. These features are emphasized by using the hybrid ToF (hToF) [5] operation, which uses multiple time windows (TWs) prepared by multi-tap pixels and range-shifted subframes, although no real hToF imagers with competitive small pixel size have been reported.

This paper presents a VGA-resolution hToF sensor with BSI-based 5.6µm pixels that realizes seamless long-range measurement of 30 m and 20 m in indoor and outdoor, respectively, for the first time and interference suppression by using newly proposed techniques of overlapping TWs and changing the emission cycle time (Tc) in SP modulation.

Pixel Circuit

Fig.1 shows our hToF pixel circuit. It has four transfer gates (G1, G2, G3 and G4) and one drain gate (GD). Photodiode (PD) charges are transferred and integrated into each MOS Cap type floating diffusion (FD) labeled as CAP1–CAP4. To suppress signal saturation under strong sunlight, each capacitor has high full well capacity (FWC) of 100ke-.

Principle of Depth Measurements in hToF

Fig.2 shows the principle of hToF measurements, including the basic timing diagram of each subframe and the entire timing diagram for hToF using 3 subframes. In each subframe, if the light pulse arrives when G1–G4 are opened, the signals S1–S4 respond to the time of flight (T_D) [Fig.2 (left)]. Then, the T_D can be measured by two steps: 1) finding the signal tap at which the light pulse arrives and 2) calculating the T_D finely using the slope of signal as a function of T_D. Using the 4-tap pixel, the T_D can be measured in the range of $3T_0$ in each subframe, where T_0 is the width of one TW. To expand the depth range, the other two subframes range-shifted with $3T_0$ and $6T_0$ are used, and then the T_D can be measured in the total range of $9T_0$. By assigning integration times in subframes such that shorter integration for short-range and longer integration for long-range, wide working range can be realized by avoiding signal saturation in close objects while improving the signal-to-noise ratio in far objects. This hToF technique is very effective for high-precision depth measurement for outdoor use using short light pulse while extending the measurable range ($9T_0$ in Fig.2) using multiple TWs. Compared with a technique reported in [5], the proposed hToF operation with multiple subframes, each of which has 3 TWs by overlapping the TW between adjacent subframes provides improved accuracy, particularly if the target objects are moving.

The interference in multiple ToF-camera operations is quite effectively suppressed by the proposed technique of randomly changing the emission cycle time (Tc) in the SP iToFs. This is advantageous over the CW iToF [1] because of less acquisition of interference itself using small duty cycle in addition to its cancellation behavior by randomization.

Measurement Results

Fig.3 shows demodulation characteristics of the signal taps (G1–G4) to the delay of light pulse, showing excellent responses, which are almost ideal rectangular shapes. A demodulation contrast of 94% is obtained. As shown in Fig.4, the indoor depth characteristics has good linearity ranging in 1–30 m, and a depth resolution of less than 0.6% is obtained. Fig.5 shows the depth maps under sunlight (100klux) and night (<1 lux). Good depth maps in the range of 1–20 m are obtained at 15fps under the strong ambient light. This sensor can also work at 120fps in single subframe mode for high-speed 3D imaging. Fig.6 shows the interference suppression in 3 ToF-camera operations. The interference between cameras is successfully suppressed by the proposed technique. A high quantum efficiency (QE) of 32% at 940nm is obtained as shown in Fig.7. Table 1 summarizes the performance comparisons with other iToFs.

References

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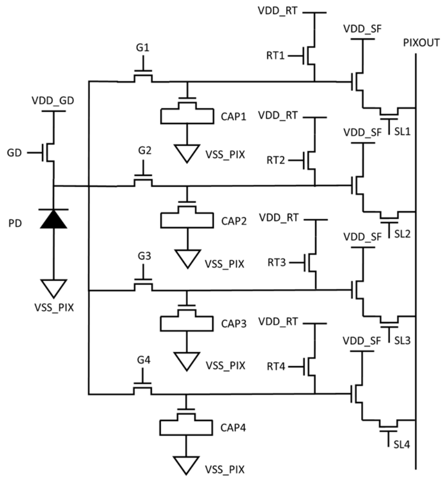

Fig.1 Pixel circuit.

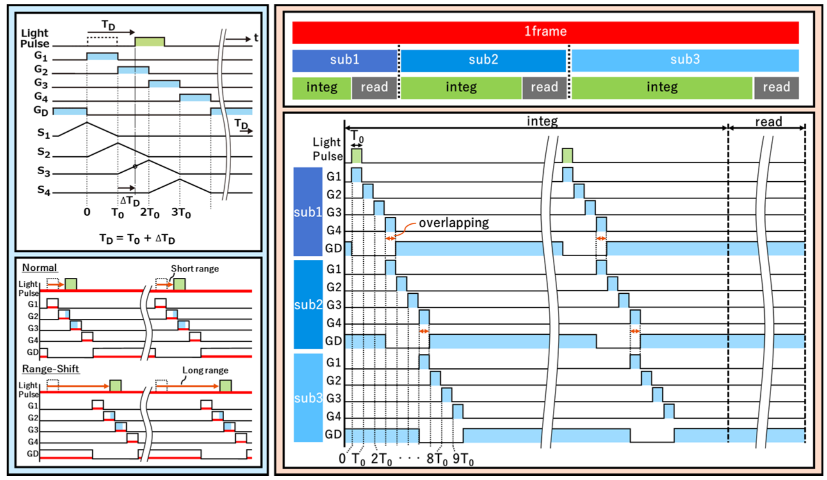

Fig.2 Timing diagrams of each subframe and hToF operation using 3 subframes.

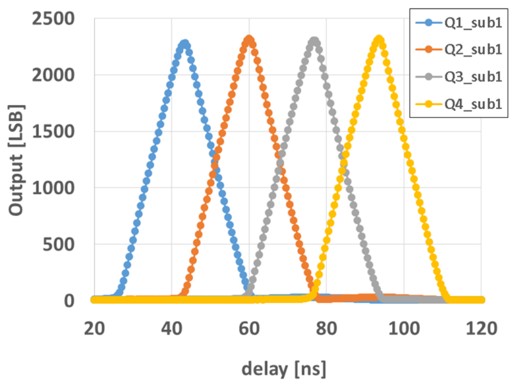

Fig.3 Measured demodulation characteristics.

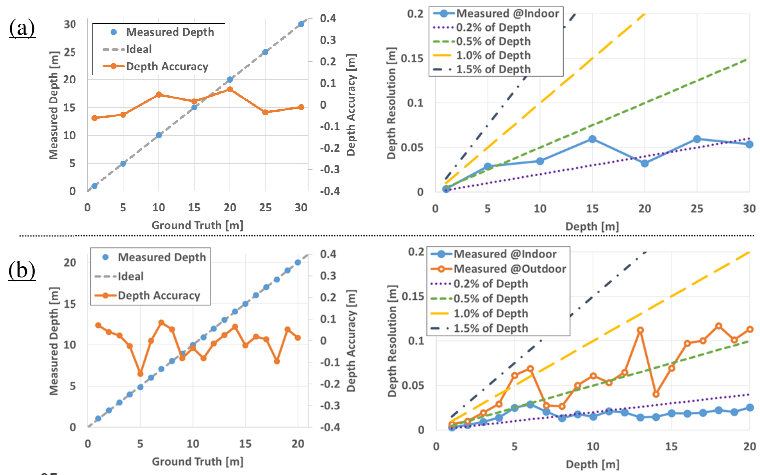

Fig.4 Depth measurements in indoor (a) and outdoor (b). The indoor depth resolution in 1–20 m is also included in (b) for comparison.

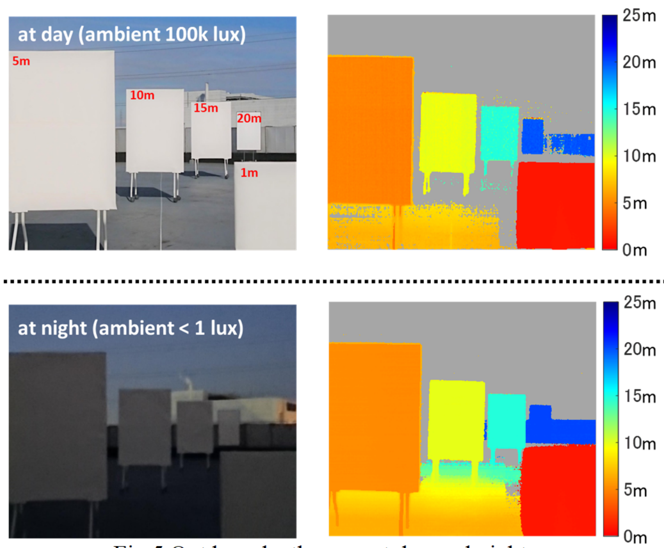

Fig.5 Outdoor depth maps at day and night.

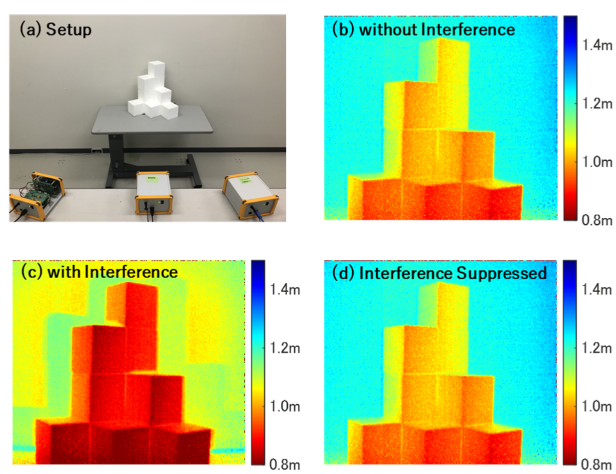

Fig.6 Interference suppression in multiple hToF cameras.

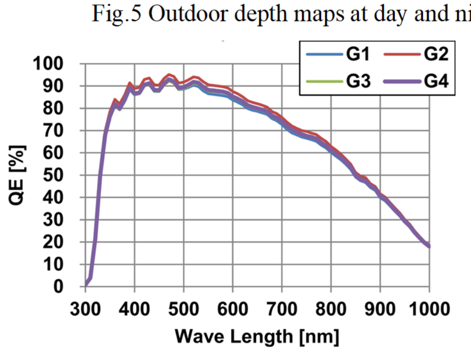

Fig.7 Quantum efficiency.

Table.1 Comparison table.

	This Work	ISSCC'21[1]	IEDM'20[7]	ISSCC'18[6]
Process	110nm BSI	65nm/65nm Stacked BSI	90nm/65nm Stacked BSI	65nm BSI
Pixel Pitch	5.6um	3.5um	3.5um	3.5um
Pixel Array	640 x 480	1280 x 960	1280 x 960	1024 x 1024
Full well capacity	100,000e−	–	18,000e−	–
Number of Tap	4	4	2	2
Responsivity	0.243A/W @940nm	0.288A/W @940nm	0.243A/W @940nm	0.343A/W @860nm
Demodulation Contrast	94% Pulse Width:17ns	96% @100MHz, 80% @200MHz,	–	87% @200MHz
Depth Range	0.5–30m	0.4–4m	0.3–10m	0.4–4.2m
Depth Resolution(wo/ambient)	< 0.6% @1–30m	<1.52%(full) @0.4–4m	<1.0%(full) @0.3–3m	<0.2% @0.4–4.2m
Depth Resolution(w/ambient)	< 1.3% @100klux @1–20m	–	<2% @80klux(QVGA) @–10m	<0.75% @25klux(262K) @0.4–4.2m
Ambient light tolerance	100klux @VGA	–	80klux @QVGA (4x4 binned)	25klux @262K (2x2 binned)