Long-Range iToF Sensing with Hybrid Pulsed-CW Operation enabling High Dynamic Range, Ambient Light Rejection, and In-Chip Depth Calculation

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Abstract

This paper presents a novel mode of operation for indirect-Time-of-Flight (iToF) sensors utilizing high peak power and low duty cycle pulsed illumination. The proposed hybrid mode mimics the response of conventional Continuous-Wave (CW) operation while providing extended dynamic range and doubling ambient light rejection. We demonstrate a 30m indoor and 20m outdoor operation with an eye-safe system using four vertical-cavity surface-emitting lasers (VCSELs). The depth calculation is done on-chip using the same algorithm pipeline that is used in normal iToF operation, and includes dual-frequency calculation for anti-aliasing.

Motivation

The increasing demand for short-to-medium-range depth sensing in applications such as Autonomous Mobile Robots (AMRs), Automated Guided Vehicles (AGVs), and Augmented/Virtual Reality (AR/VR) highlights the need for improved depth sensing solutions that support indoor and outdoor operation while maintaining compact size and simple system integration. Indirect Time-of-Flight (iToF) technology meets these demands by leveraging advancements in CMOS Image Sensor technology, including small pixel sizes and high Near-IR quantum efficiency (QE). Our iToF sensor technology introduces an additional advantage by incorporating voltage-domain in-pixel four-frame storage, enabling efficient depth calculation directly on-chip. This eliminates the need for external computation and significantly reduces motion artifacts, enhancing the overall system efficiency for real-time applications.

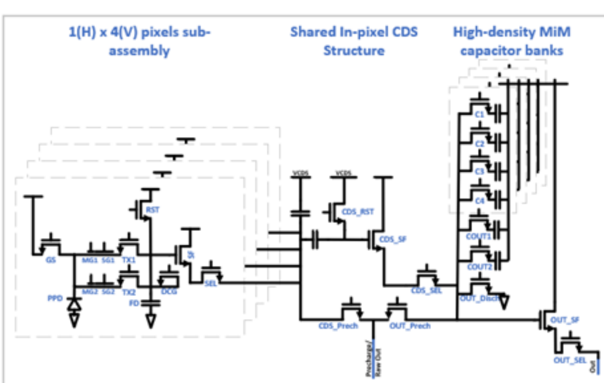

Fig. 1. Schematic of an iToF pixel with global shutter gate and in-pixel voltage domain storage.

Sensor Operation

We introduce an iToF sensor capable of operating in a Hybrid Pulsed-CW mode. Unlike conventional CW iToF sensors, where modulation gates cycle continuously with each illumination pulse, our approach generates an illumination pulse only once every Nth modulation cycle. To increase dynamic range and improve ambient light rejection the pixel is required to be able to halt integration and drain photogenerated electrons in synchronization with the pulsed illumination. This is enabled by adding a dedicated global shutter gate to the pixel.

The pixel structure is detailed in Fig. 1. The main part of the pixel includes a pinned photodiode (PPD) connected to two storage nodes (SG1, SG2) via modulation gates (MG1, MG2). The global shutter gate (GS) links the PPD to the drain, halting the integration of new signals when engaged. This unique feature, combined with flexible modulation control logic, enables the Hybrid mode operation.

Every four pixels share a Correlated-Double-Sampling (CDS) stage that connects every pixel to 4 high-density metal-insulator-metal (MiM) capacitors. Overall, this structure allows for voltage domain storage of the 4 phases required for iToF depth estimation in the pixel. By binning 2 horizontally adjacent pixels using the auxiliary capacitors COUT1 and COUT2, it allows storage of up to 8 signals, or 4 phases of two different modulation frequencies, to remove ambiguity due to wrap around

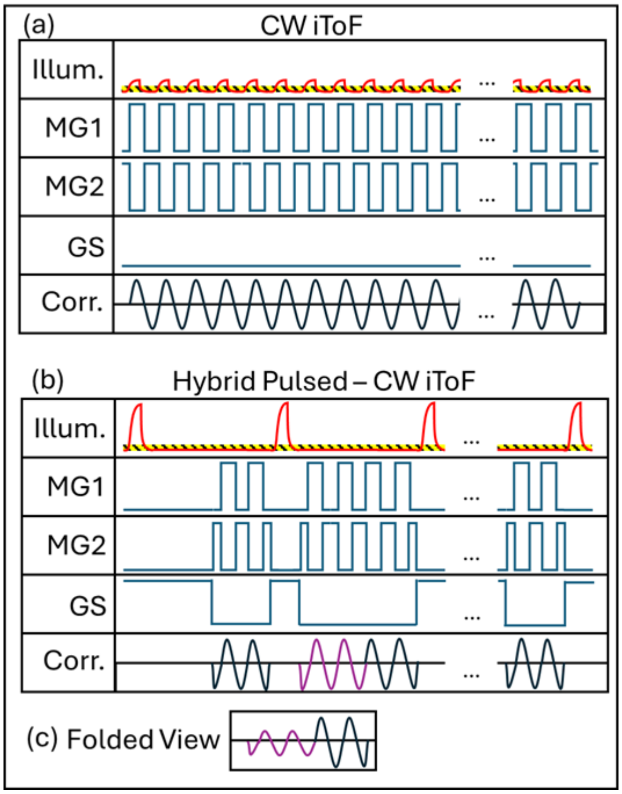

Fig. 2. Pixel timing for (a) Continuous Wave (CW) operation, (b) Hybrid operation, (c) Folded view of hybrid operation, where cyclic signals are superimposed.

in long range depth measurements. The availability of all the data in the pixel allows us to run efficient depth calculation algorithms using hardware pipelines without the need for inefficient frame memories and embedded ISPs.

One of the main advantages of Hybrid mode over CW operation is its ability to block over 50% of the ambient light using the GS gate, as depicted in Fig. 2. In conventional CW mode, each modulation cycle consists of a single illumination pulse, and the returning signal is integrated into one of the two

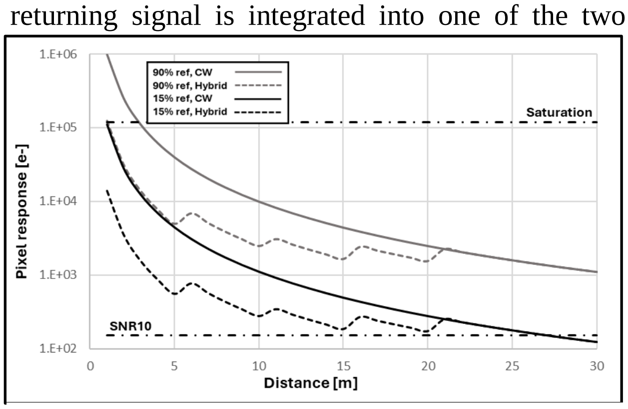

Fig. 3. Illustration of the extended dynamic range depth measurement enabled by hybrid mode

storage gates (SG1/SG2). However, in Hybrid mode, additional degrees of freedom allow for improved system operation: the illumination is pulsed at a reduced duty cycle—only once per N modulation cycles—but with proportionally higher peak power to maintain consistent overall illumination energy. This lower duty cycle enables suppression of modulated signals through the GS, significantly reducing the amount of integrated ambient light. The effect is clearly visible in the "folded view" illustration (Fig. 2c), which demonstrates how this approach compensates for the natural $1/r^2$ illumination falloff from a point source, effectively extending the sensor's dynamic range. To further illustrate the dynamic range benefits, Fig.3 presents a simulated plot of calculated pixel response versus target distance for two target reflectivities (90% and 10%). The plot highlights the sensor's dynamic range between the saturation threshold for a binned pixel (~120Ke⁻) at the high end and an SNR10 (~150e⁻) at the low end. The solid lines depict the response for CW operation, where high-reflectivity targets reach saturation at approximately 3m. In contrast, the Hybrid mode response (dashed line) demonstrates superior dynamic range by suppressing signals from close-range targets, ensuring saturation free operation up to 1m. This capability significantly improves performance in environments where objects at varying distances need to be detected simultaneously.

Results

A detailed laser delay scan, obtained using a picosecond delay generator, is presented in Fig. 3. The scan illustrates the response of our sensor operati4ng in Hybrid mode under two different modulation frequencies and patterns. The left panel shows a scan with an illumination pulse occurring every five modulation cycles, employing a mix of the following eight modulation patterns: {"11110", "01110", 2×"00110", 4×"00010"}. The right panel demonstrates a scan using the patterns: {"11111", "01111", "00111", 2×"00011", 3×"00001"}. These scans highlight the superposition of modulation patterns and the selective suppression of signals from near-range targets. Notably, the sequence of four modulations at 20MHz results in an active sensing range of 30m, while the sequence of five modulations at 24MHz extends the active range to 31.25m. The unambiguous range, determined by the greatest common divisor of the two frequencies (4MHz), is calculated as 37.5m. However, the practical operational range of the system is defined

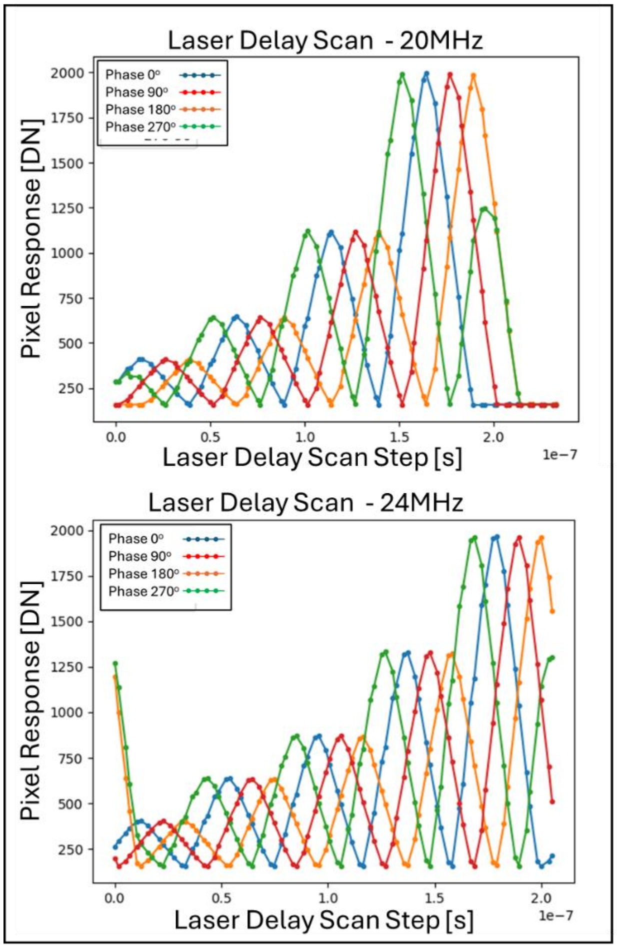

Fig. 4. Measurement results of pixel response to a pulsed laser.

by the shortest of these values, establishing a working range of 30m.

The effectiveness of the Hybrid mode is validated through real-world depth captures, as shown in Fig. 5. The figure presents indoor depth frames obtained from a single exposure, and with the depth extraction algorithm, including anti-aliasing, is computed entirely in-chip, with no external processing. The system utilizes four 940nm VCSELs operating at Class-1 optical power levels, with a total exposure time of 16ms (2ms × 4 phases × 2 frequencies). The Hybrid mode depth frame captures both a non-saturated target at 1m and another target at 30m simultaneously. In contrast, the CW mode frame shows significantly higher signal levels at shorter ranges, leading to saturation at 1m due to the lack of suppression. This clearly illustrates the effectiveness of Hybrid mode in extending dynamic range, ensuring accurate depth measurements across a broad range of distances.

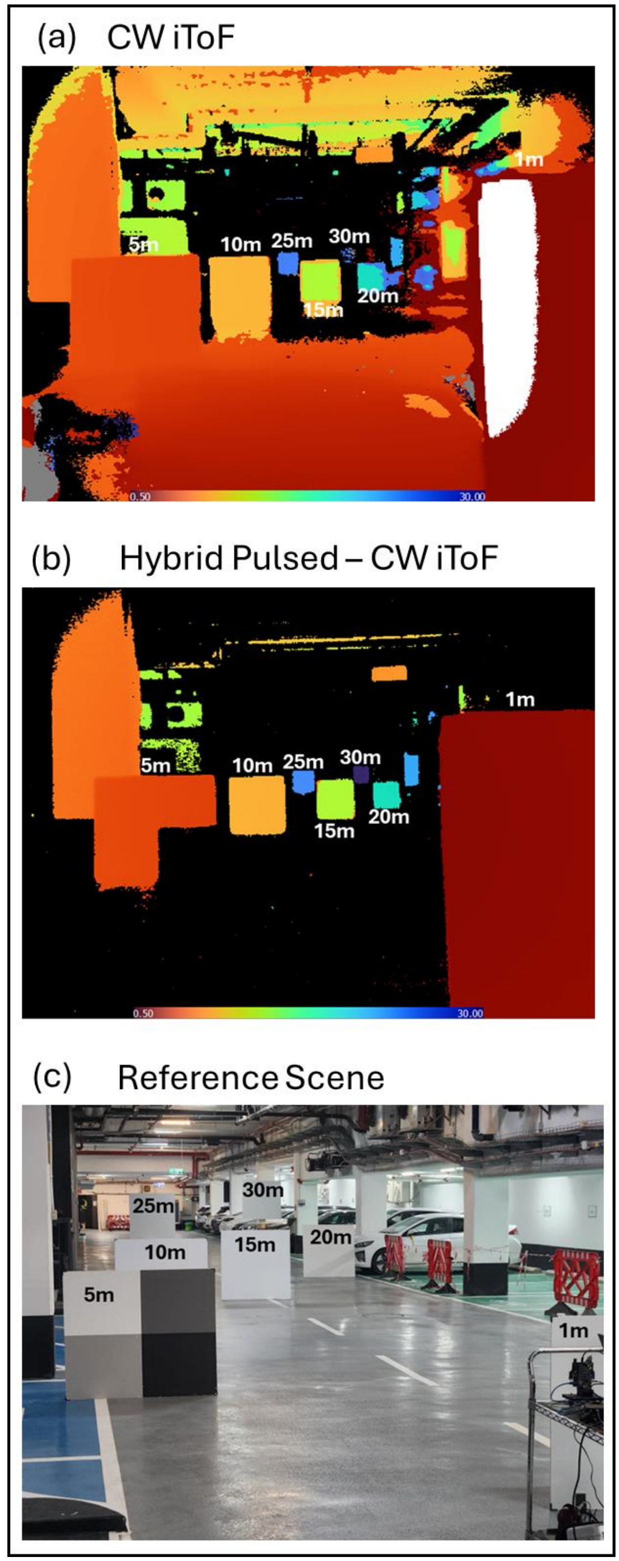

Fig. 5. Comparison between the dynamic range of (a) CW iToF and (b) Hybrid iToF in an indoor scene.

The other significant advantage of hybrid mode, which is working under strong ambient illumination, is demonstrated in Fig. 6. The captured scene is

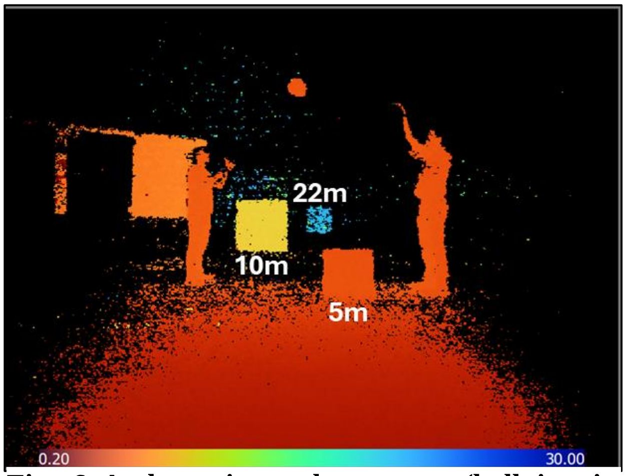

Fig. 6. A dynamic outdoor scene (ball in air, ~75Klux sunlight) showing simultaneous depth capture of <1m and >20m range with no motion artifacts.

dynamic, capturing a basketball mid-flight, combined with strong sunlight of ~75Klux, and a large depth dynamic range with scene elements closer than 1m, and further than 20m. The system used for this capture used VCSELs with peak power of ~50W, but in a much shorter integration time of 250usec per phase, so the overall system still operated under Class-1 limit. Similar to the indoor scenes, the entire depth calculation, including filters and invalidation of noisy pixels was done in-chip.

Summary

This paper introduces a novel hybrid mode for indirect-Time-of-Flight (iToF) sensors, leveraging high peak power and low duty cycle pulsed illumination. This mode mimics conventional Continuous-Wave (CW) operation while enhancing dynamic range and ambient light rejection. The system, demonstrated with four vertical-cavity surface-emitting lasers (VCSELs), achieves 30m indoor operation and 20m outdoor operation with eye-safe levels, performs on-chip depth calculation using standard iToF algorithms, and is able to capture dynamic scenes without introducing significant motion artifacts. A summary of key features of the pixel and of the hybrid mode presented in the paper can be found in the table below.

	This Work	[1]	[2]
Pixel Pitch	3.5um (binned to 7um)	16.8um	5.6um
Sensor Resolution	1280 x 960 (binned to VGA)	VGA	VGA
Mod. frequency	20+24MHz used for 30m range (200MHz max.)	45MHz	28MHz
Modulation Contrast	95% @ 100MHz	-	94%
Full Well Capacity	120ke-/binned pixel tap	-	100ke-
940nm QE	42%	18.6%	32%
Depth Range	30m (single frame)	20m	30m

References

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[2] K. Hatakeyama *et al*., "A Hybrid Indirect ToF Image Sensor for Long-Range 3D Depth Measurement under High Ambient Light Conditions," *2022 IEEE Symposium on VLSI Technology and Circuits*