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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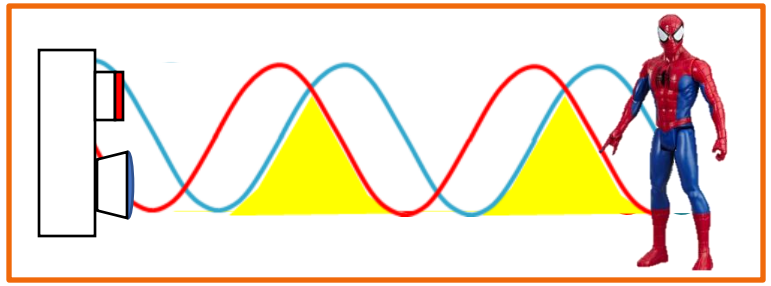
6/2/25

indirect Time of Flight - Background

- iToF sensors calculate depth D from the phase between reflected light and pixel response modulation:

$$D = \frac{C}{2}\left(\frac{\Delta\varphi}{2\pi f_m}\right)$$

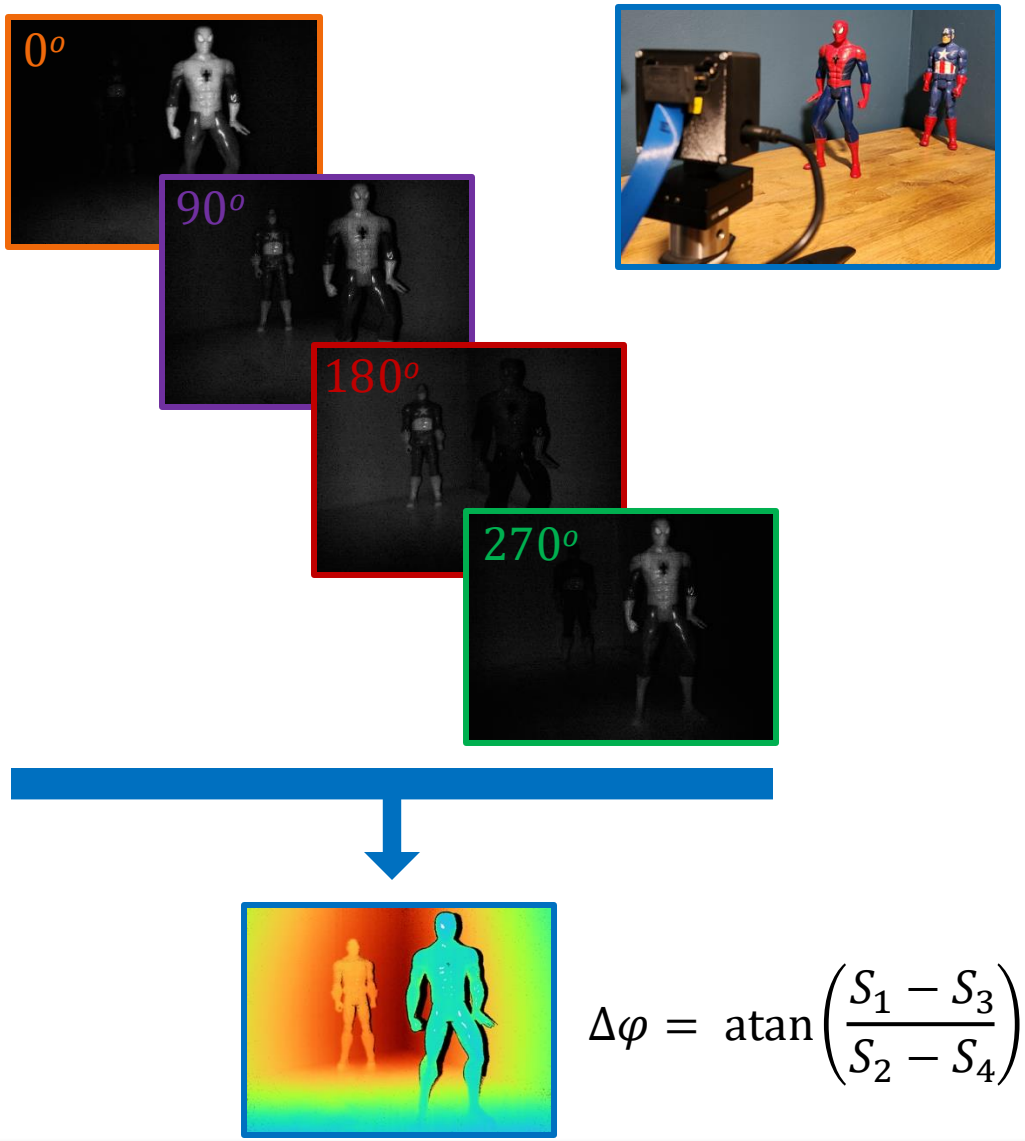
{ f_m = modulation frequency, C = speed of light }



- The phase $\Delta\varphi$ can be resolved from 4 frames with different delay ϕ between pixel and illuminator modulation:

$$S_1 = A\sin(\Delta\varphi) + C \qquad \{\phi = 0^o\}$$
$$S_2 = A\cos(\Delta\varphi) + C \qquad \{\phi = 90^o\}$$
$$S_3 = -A\sin(\Delta\varphi) + C \qquad \{\phi = 180^o\}$$
$$S_4 = -A\cos(\Delta\varphi) + C \qquad \{\phi = 270^o\}$$

- If longer ranges are required, phase unwarping algorithms may require 8 raw frames or more (4delays x2 frequencies).

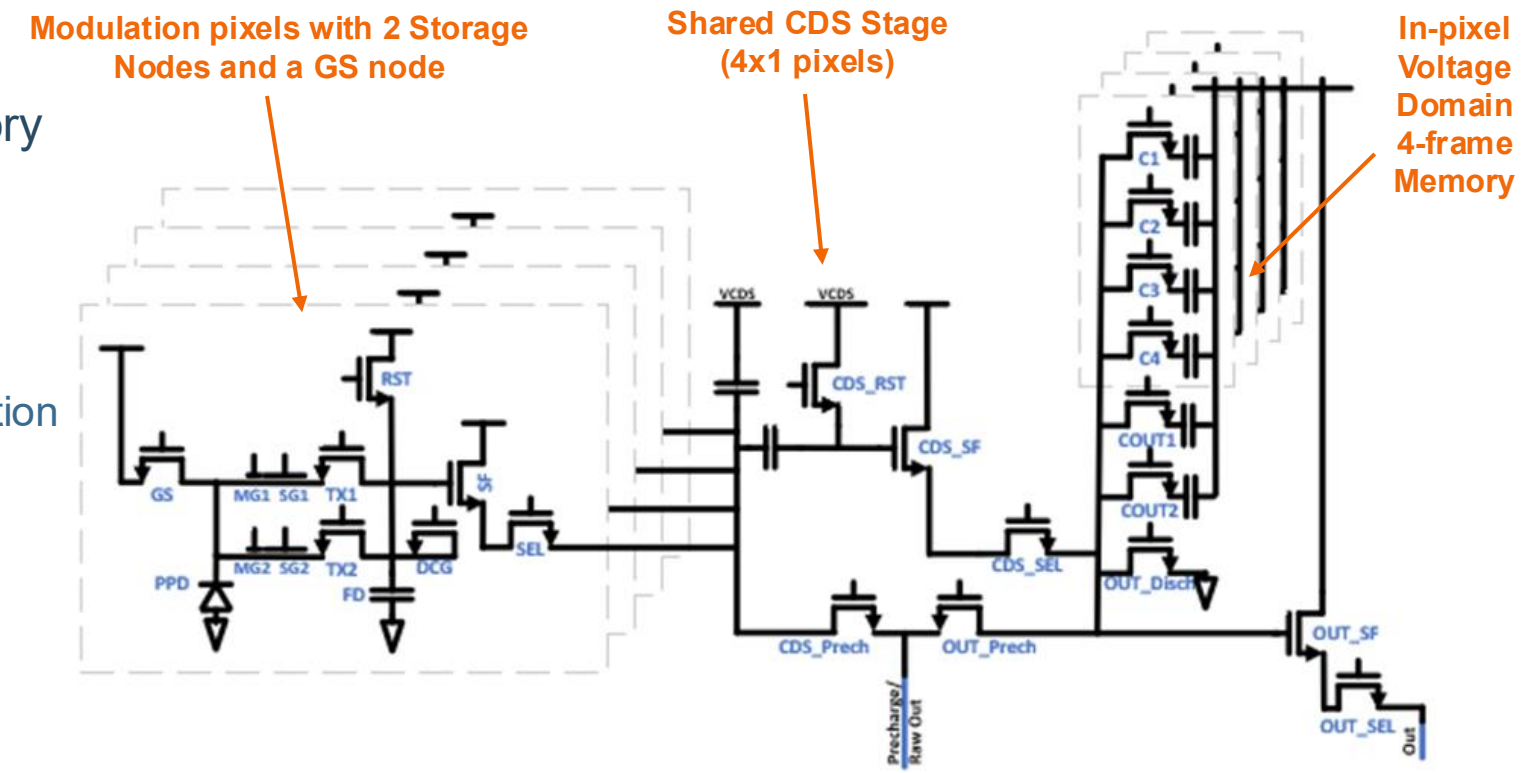


$$\Delta\varphi = \operatorname{atan}\left(\frac{S_1 - S_3}{S_2 - S_4}\right)$$

3.5um iToF pixel with in-pixel 4 frame storage

- Non-stacked, 3.5um iToF pixel
- In-pixel CDS and 4 frame analog memory

- Enables:
  - >50% Motion artifact reduction
  - Easy to implement in-chip depth calculation
  - Reduced data bandwidth and system complexity



Motion Artifacts in standard iToF camera

Reduced Motion Artifacts with in-pixel storage

Results - Mode 175MHz + 200MHz, on-chip depth calculation

Modulation Frequency:

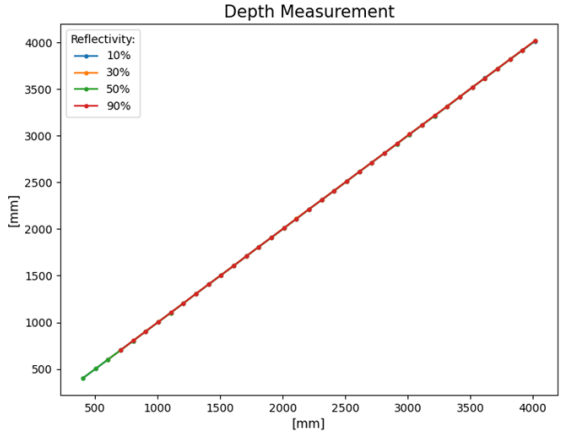
- 175MHz + 200MHz
- Unambiguous up to 6m

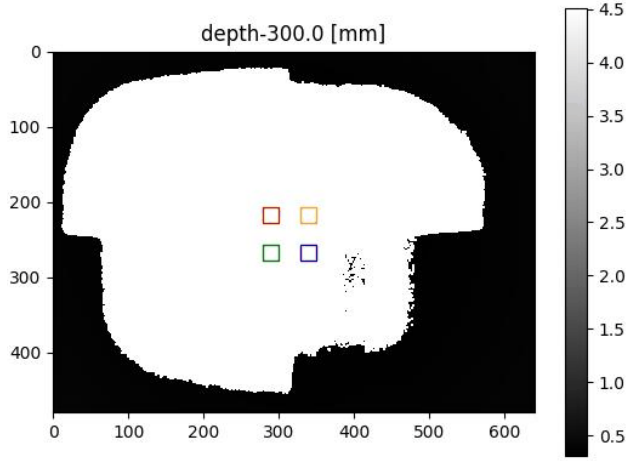
VCSEL Power:

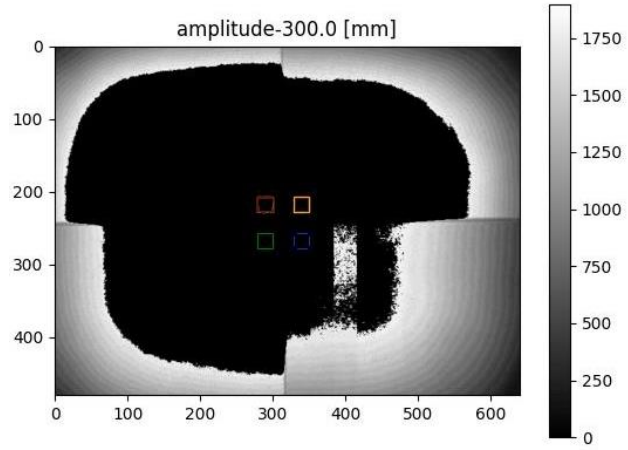
- 4 x 1.75mW Avg.

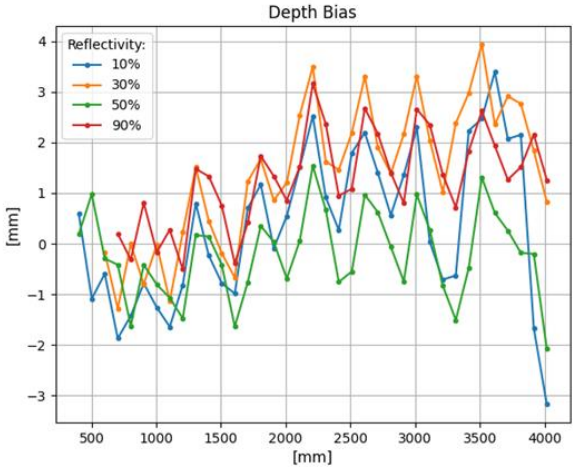
- Tested range 0.5 - 4m
- Max. Depth Bias < 0.2%
  - 50% ref < 1.5mm
  - 10%-90% ref < 4mm

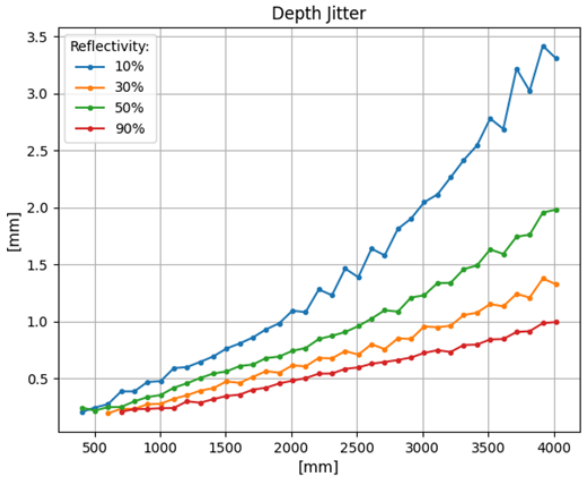
- Max Depth Jitter < 0.1%
  - 50% ref < 2mm
  - 10% ref < 3.5mm

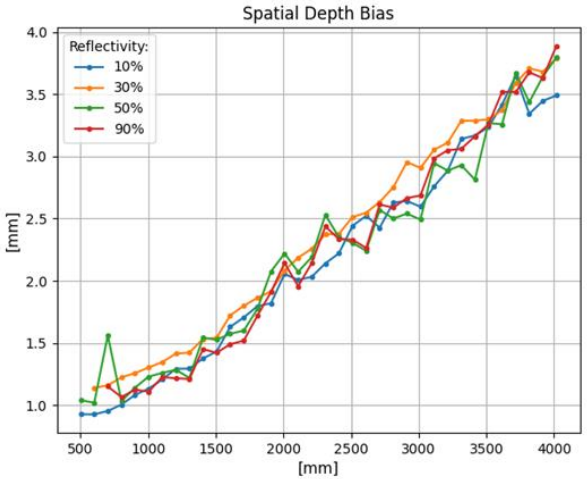






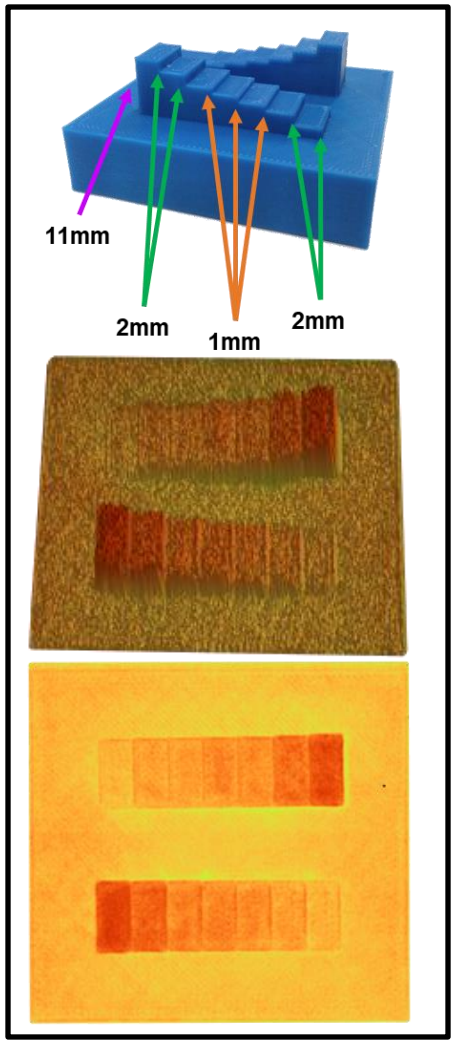




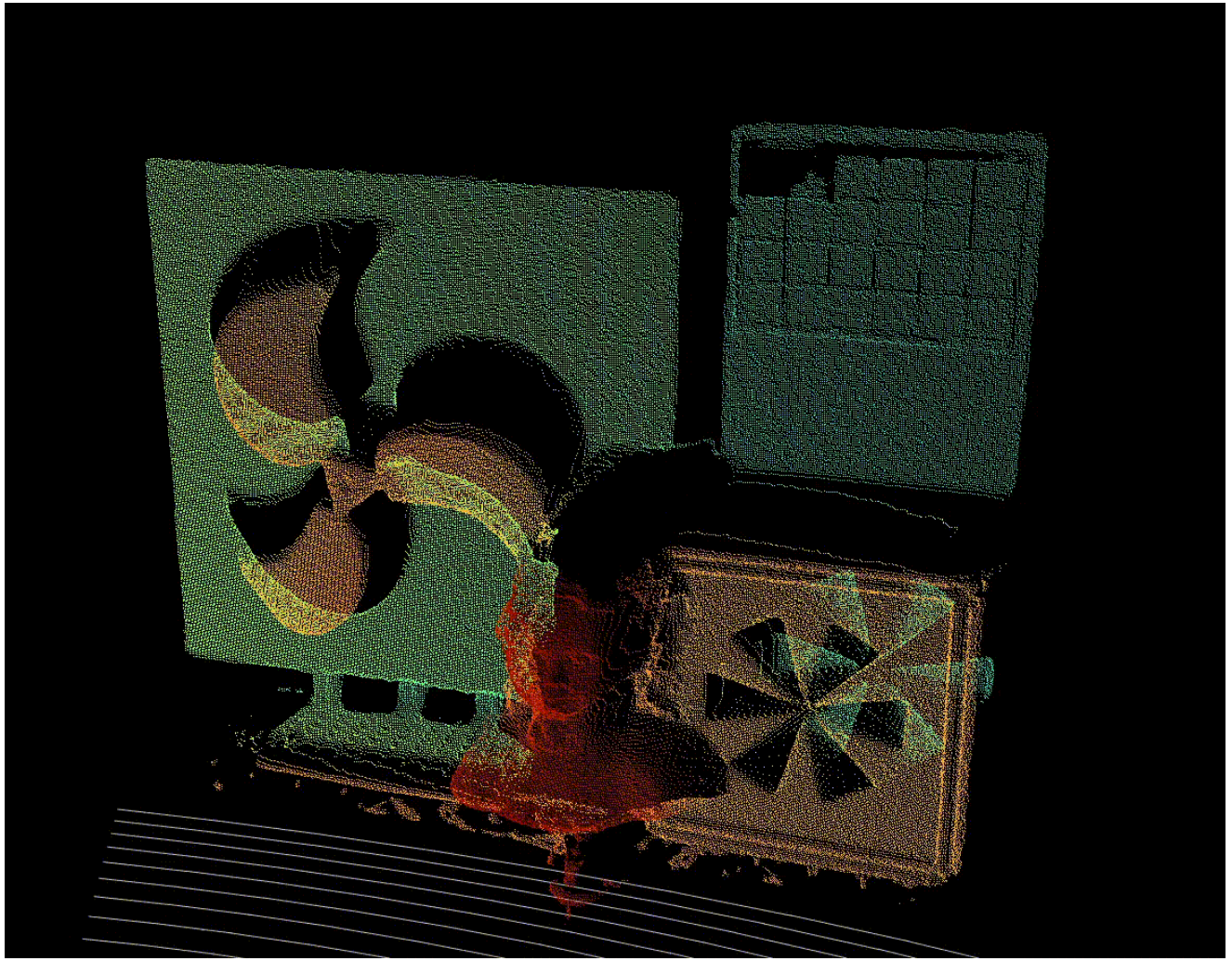


Results - Mode 175MHz + 200MHz, on-chip depth calculation

1mm Accuracy



Fan Speed 440 RPM, No pixel offset correction



Hybrid iToF - Introduction

Traditionally, iToF sensors can be classified as:

CW / Phased iToF:

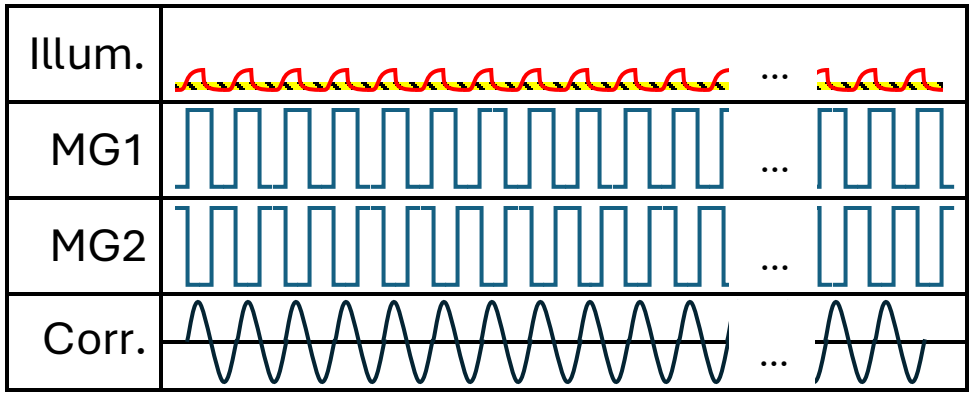
- Continuous illumination & pixel modulation
- Pixel response is a harmonic function of target distance
- Robust, efficient, analytic, easy to calibrate

Pulsed iToF

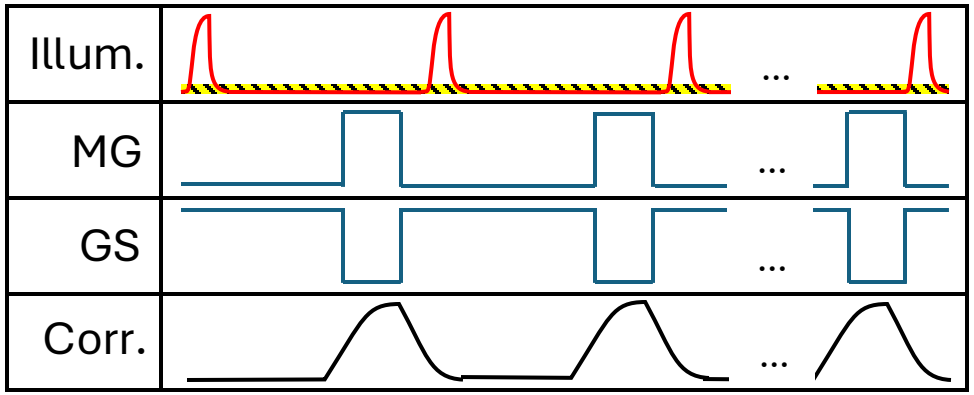
- Pulsed illumination & pixel modulation
- Pixel response is an arbitrary function of target distance
- Higher flexibility and potential for optimization

With Hybrid mode, we aim to combine advantages from both types

CW iToF

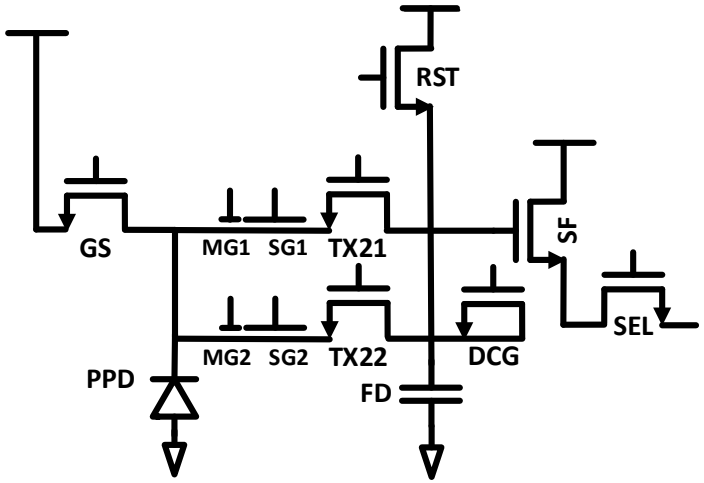


Pulsed iToF

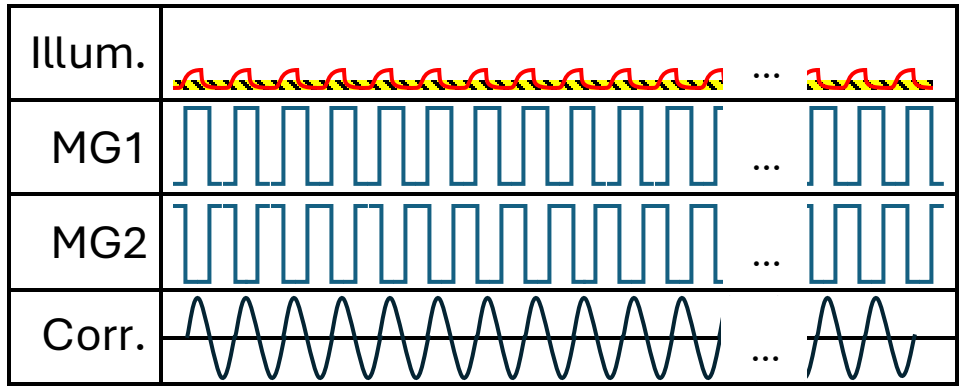


Hybrid iToF - Introduction

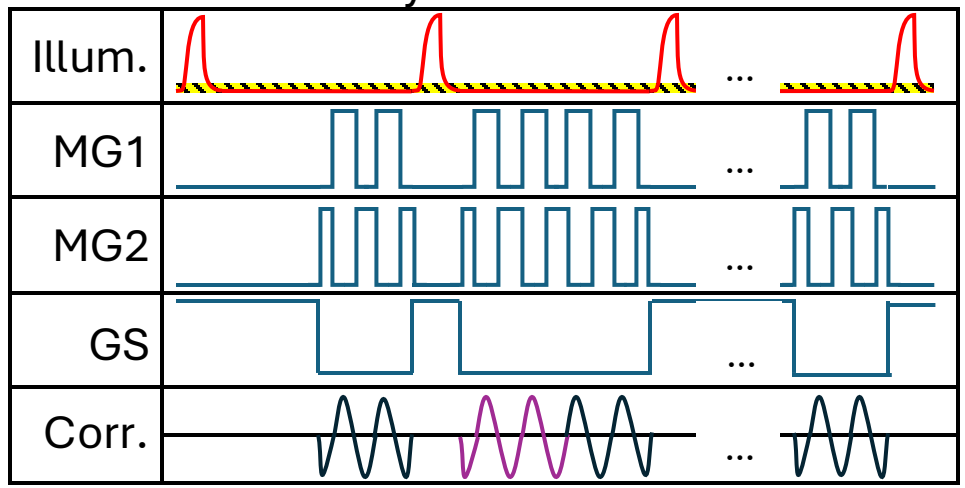
- Our proposed Hybrid iToF is enabled having **2 modulation gates** and **a fast global shutter gate** connected to the photodiode.
- The pixel operates in CW mode but has the added capability of stopping integration by closing MG1&2 and opening GS.



CW iToF

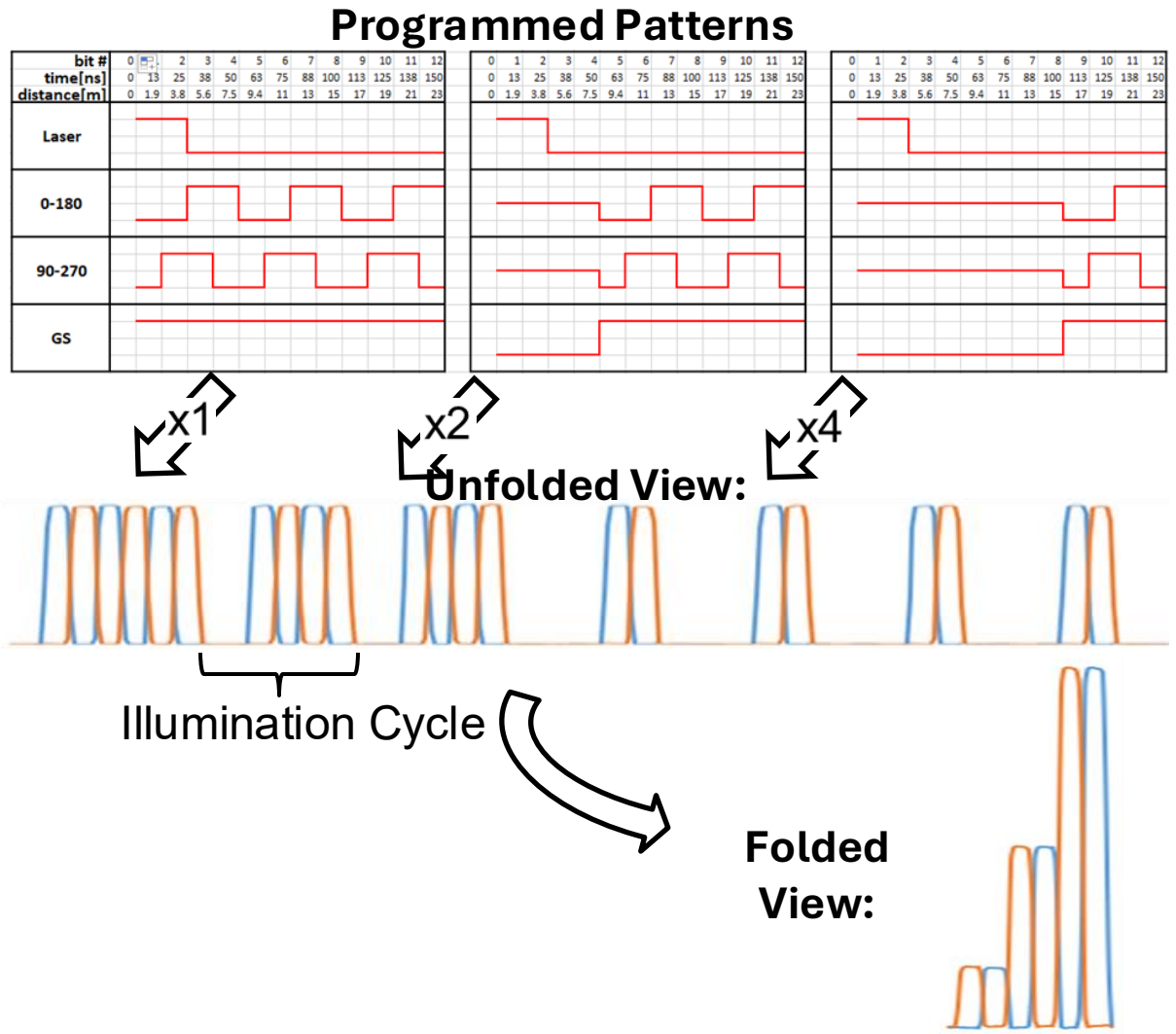


Hybrid iToF



Hybrid iToF - Implementation

- On top of the unique pixel, our iToF sensor includes a flexible pattern generator that allows generation of different patterns for each illumination cycle.
- Since the iToF pixel integrates signal over thousands of illumination cycles it is possible to synthesize an almost arbitrary response waveform.
- The “folded view” is the super position of many “unfolded” illumination cycles and represents the sensor response to laser pulse that is coming from different distances.

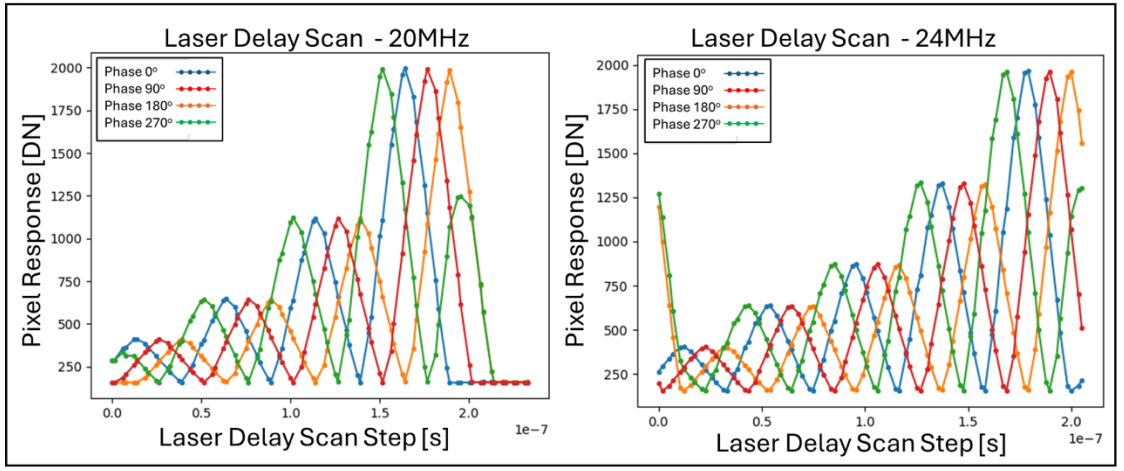


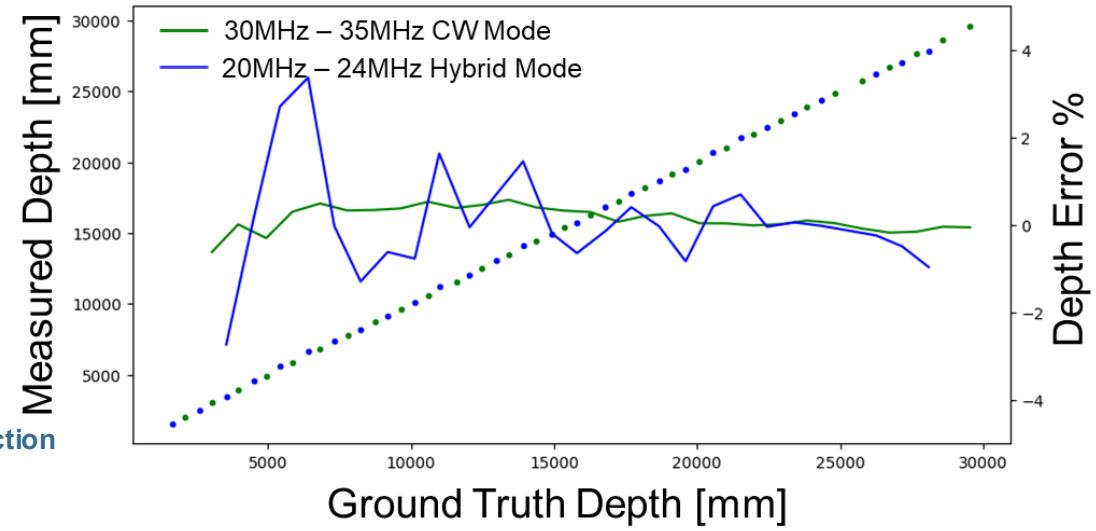
Hybrid iToF - Implementation

- The figures show picosecond laser scan of the response vs. time
- 2 frequencies (20MHz, 24MHz) are used to enable anti-aliasing

- Advantages of Hybrid mode are emphasized:
  - Reduced response from nearby targets → increased dynamic range
  - GS is blocking ambient light ~50% of integration time → x2 ambient rejection
- Disadvantage of Hybrid mode – lower depth accuracy
  - Might be improved with better LUT correction

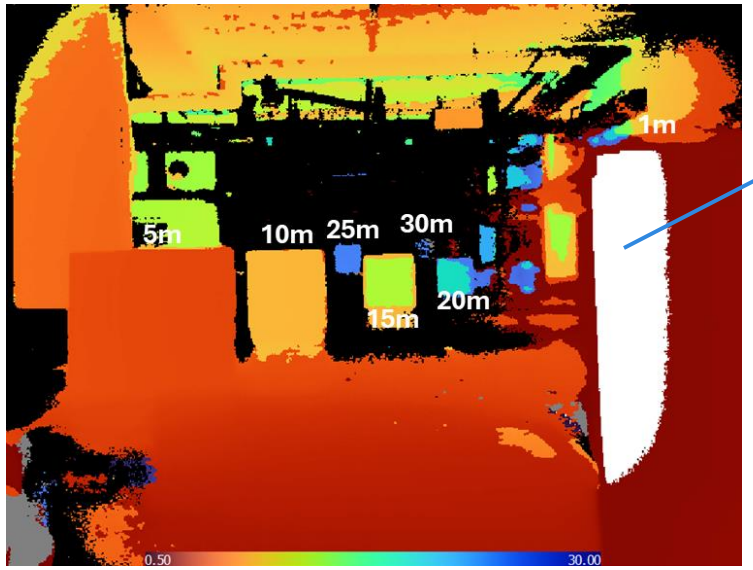
- Design/Optimization of the mode (slightly complex):
  - 20MHz & 24MHz give unambiguous range of 4MHz = **37.5m**
  - 5 Illumination cycles at 24MHz give range of 5x6.25 = **31.25m**
  - 4 Illumination cycles at 20MHz give range of 4x7.5 = **30.0m**
  - Patterns:
    - 24MHz: 1x ‘11111’, 1x ‘01111’, 1x ‘00111’, 2x ‘00011’, 3x ‘00001’ → **47.5% ambient rejection**
    - 20MHz: 1x ‘1111’, 1x ‘0111’, 2x ‘0011’, 4x ‘0001’ → **46.9% ambient rejection**

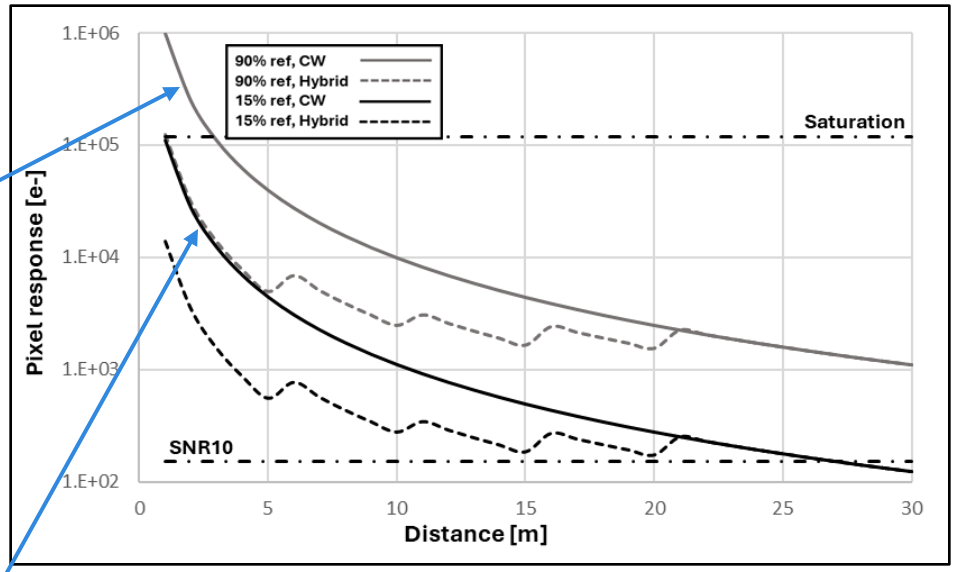




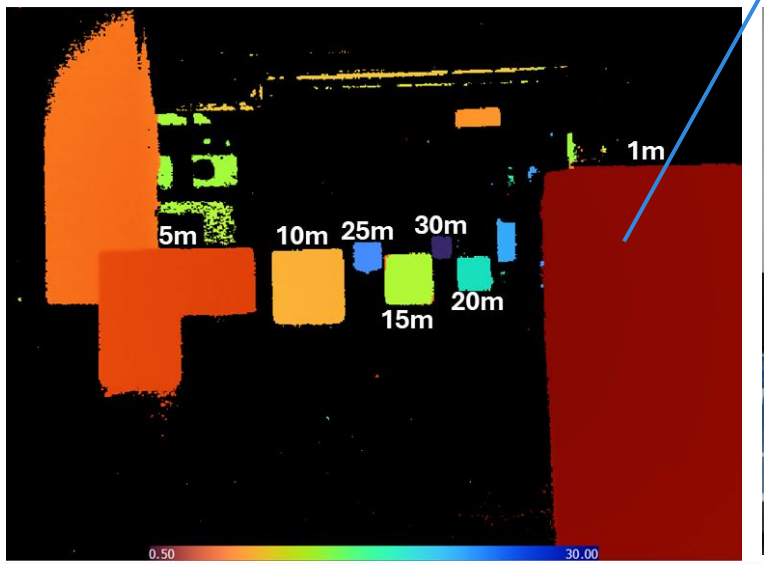
Hybrid iToF – Depth Dynamic Range Improvement

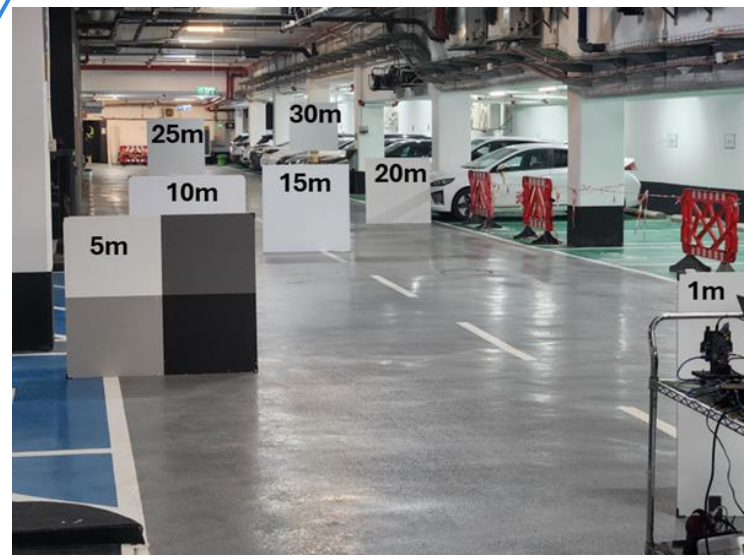
CW mode:





Hybrid mode:





Hybrid iToF – Ambient Light Rejection (114 KLux)

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