A monolithic BSI time-of-flight sensor supporting a resolution of up to 160x120 pixels with on-chip data processing enabling stand-alone or sensor fusion applications

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Agenda

Intro | Target applications in consumer 3D sensing

Image enhancement & AR / VR

- **Mobile device front facing**
  - Face ID
  - Gesture recognition
  - Proximity sensing / presents detection
  - Auto focus
- **Mobile device world facing**
  - Room mapping / scene reconstruction
  - Object scanning
  - Device tracking
  - Auto focus
  - Image enhancement
- **AR / VR glasses world facing**
  - Scene reconstruction
  - Head tracking
  - Hand / finger tracking
  - Auto focus








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Intro | Architecture of a Time-of-flight (ToF) system

Electrical and optical components

Time of flight sensors consist of multiple components that needs to be stacked to build an optical system.

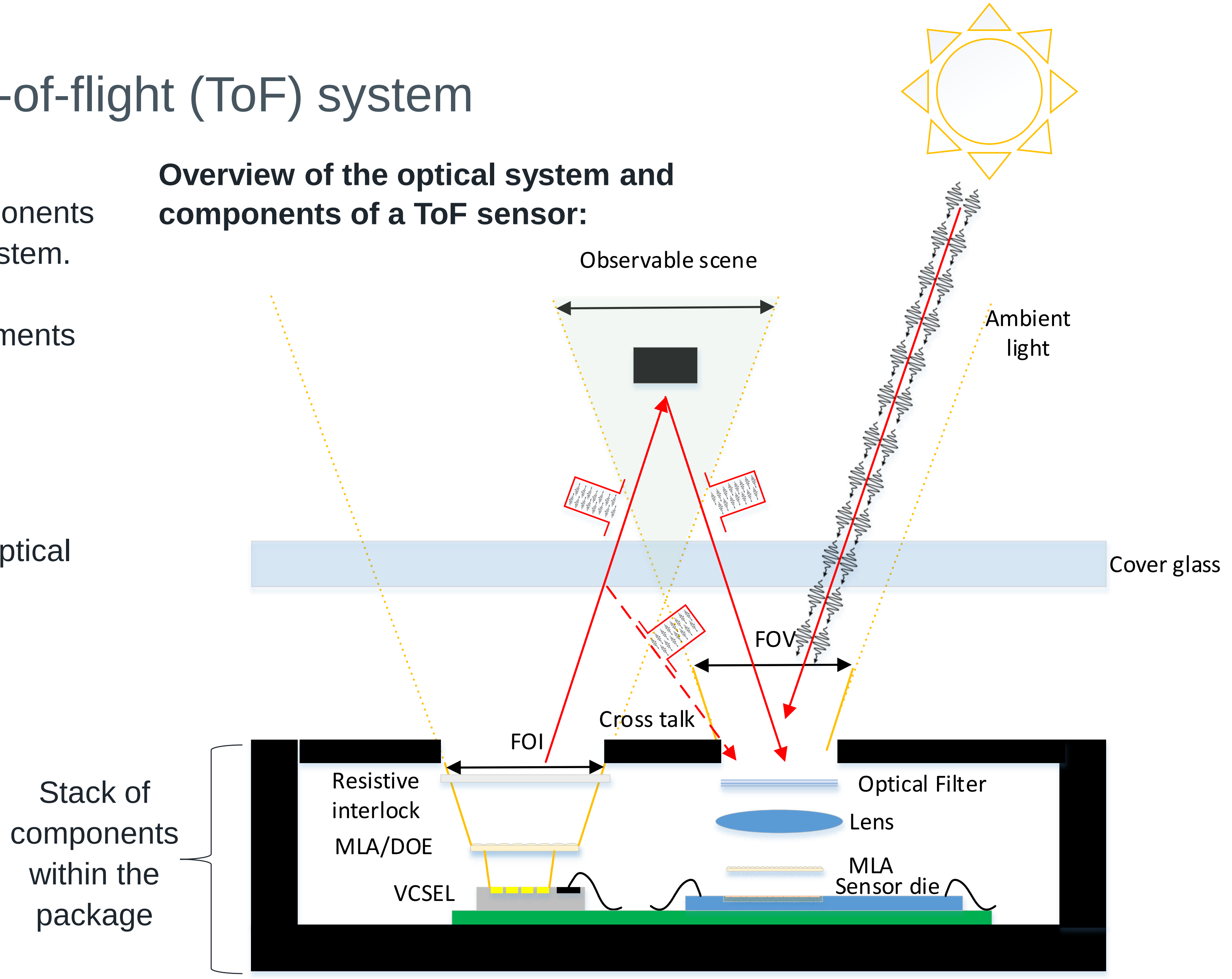
Wide spectrum of process technology requirements (high voltage and high density)

Stacked components of an 3D sensor

- IR Laser (VCSEL)
- MLA (Micro Lens Array)/ DOE (diffractive optical element) / resistive interlock
- Cover glass (parasitic)
- Optical filter
- (Imaging) lens
- Driver, sensor and processing dice

VCSEL…vertical cavity surface emitting laser
FOV…field of view (sensor)
FOI…field of illumination (emitter)

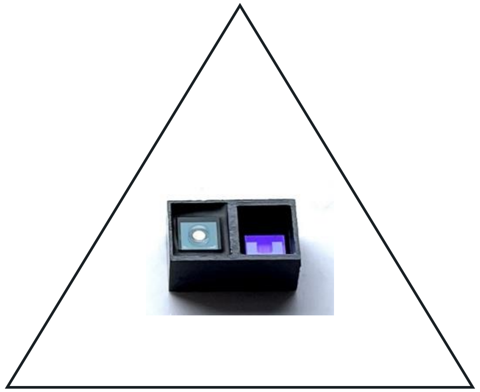
Overview of the optical system and components of a ToF sensor:



System | Design Target

Achieve good compromise on performance/size/cost trade-off

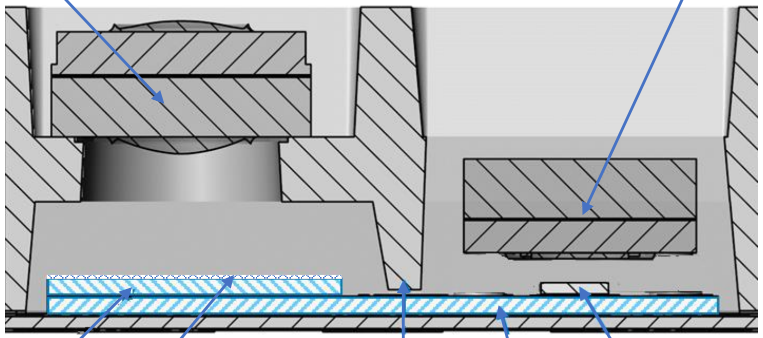
Minimize overall sensor size
- ❑ High fill factor $\left(\frac{A_{focal\ plane}}{A_{sensor}}\right)$
- ❑ Minimize no. IPs on 22nm
- ❑ Compromise on native resolution compensate by sensor fusion



Die-to-die stacking
- ❑ Sensor on PMU
- ❑ VCSEL on PMU

Dual surface lens and wafer level optics
- ❑ Reflowable

Monolithic module



High performance
- ❑ Hybrid-bonded BSI sensor
- ❑ Emitter MLA and receiver lens to adjust FOI/FOV
- ❑ Stacked high power multi-junction VCSEL

Windowing and on-chip data compression

High density vs. high voltage requirement
- ❑ Use of advanced process node and HV process

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System | D-ToF imaging Sensor

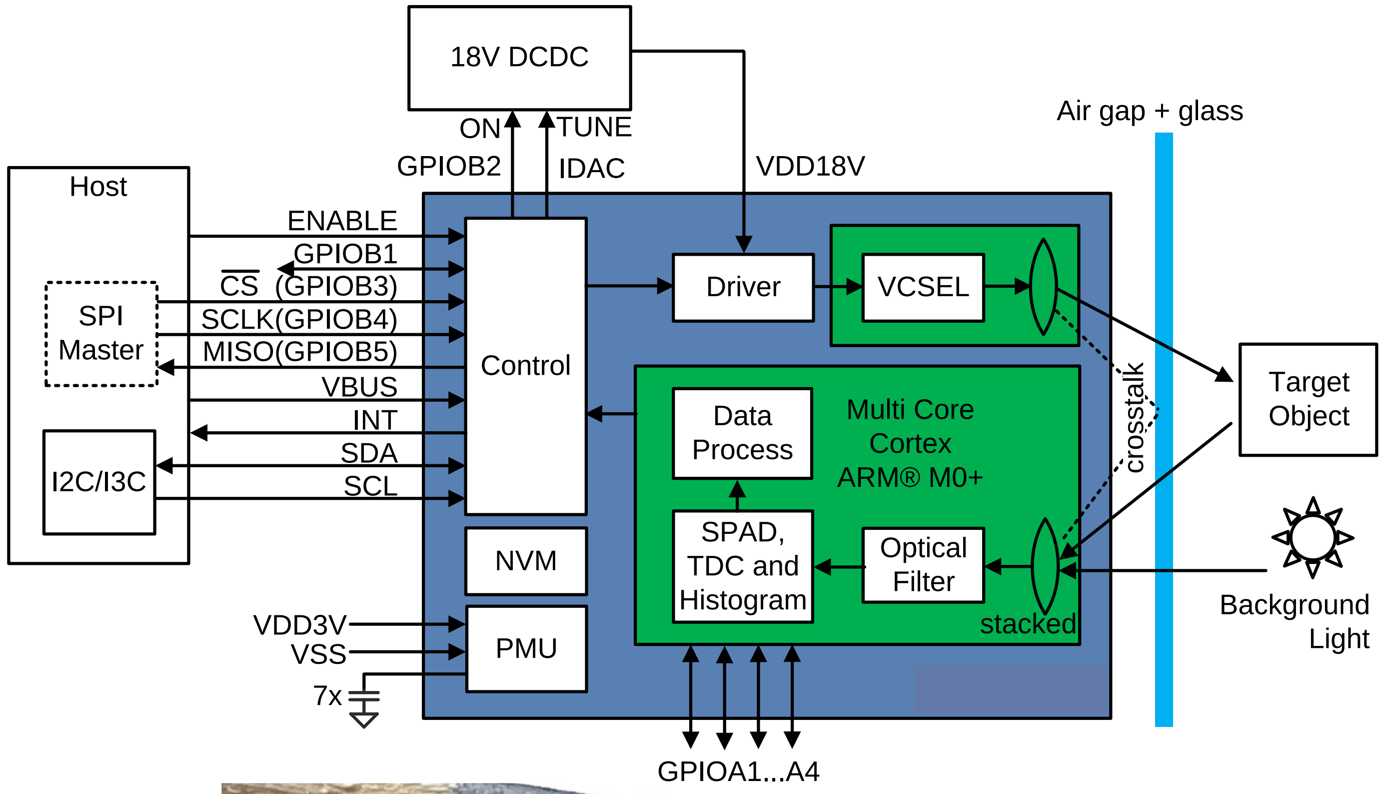
Overview

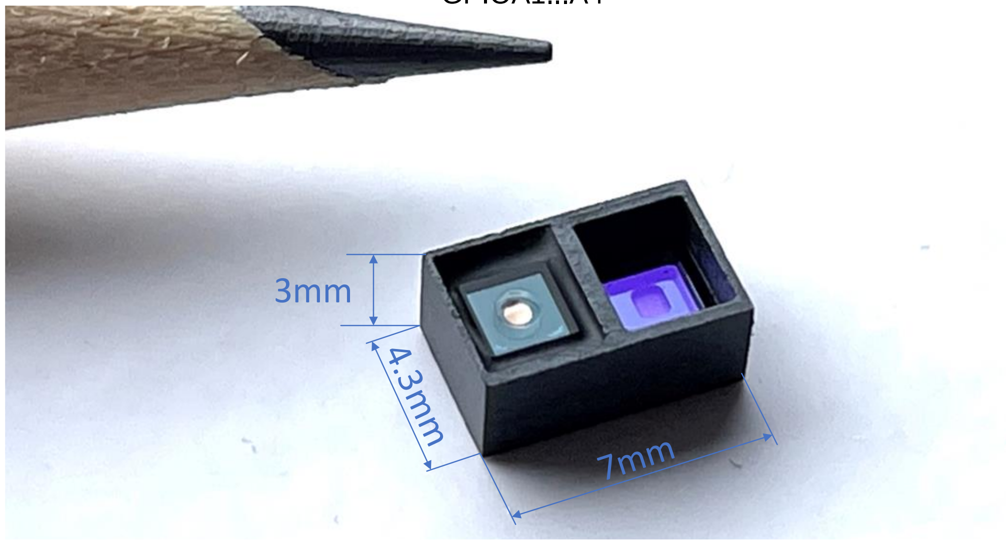
Key Features

- 22/45nm BSI process technology
- 160 x 120 SPAD resolution (19,200 SPADs)
- 20x15 macro-pixel resolution
- 40x30 to 160x120 time multiplexed
- 300 TDCs
- 70° field of view
- Full internal processing
- SPI option for streaming of data
- Integrated VCSEL driver, PMU and Flash memory

Modular package with integrated optics

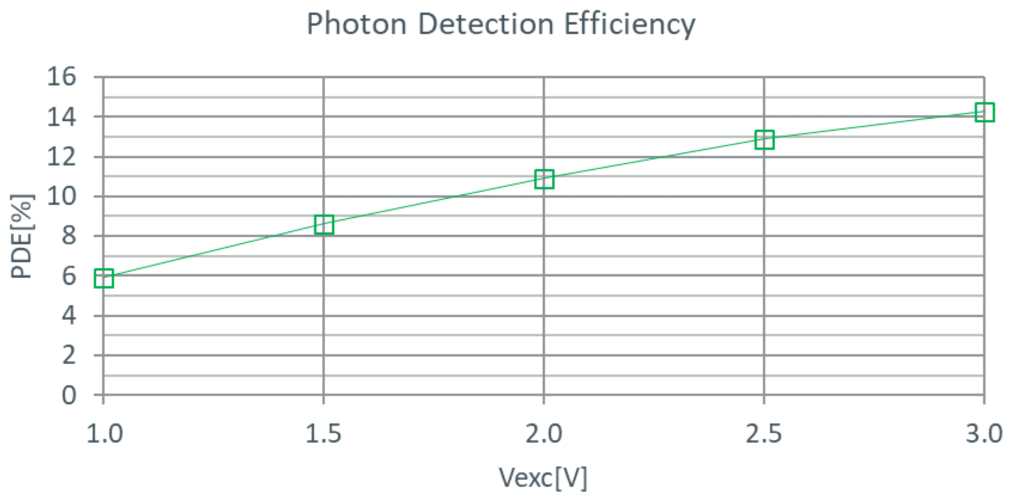
- 940nm VCSEL Class 1 Eye Safety
- Reflowable
- 7.0 x 4.3 x 3.0mm package size

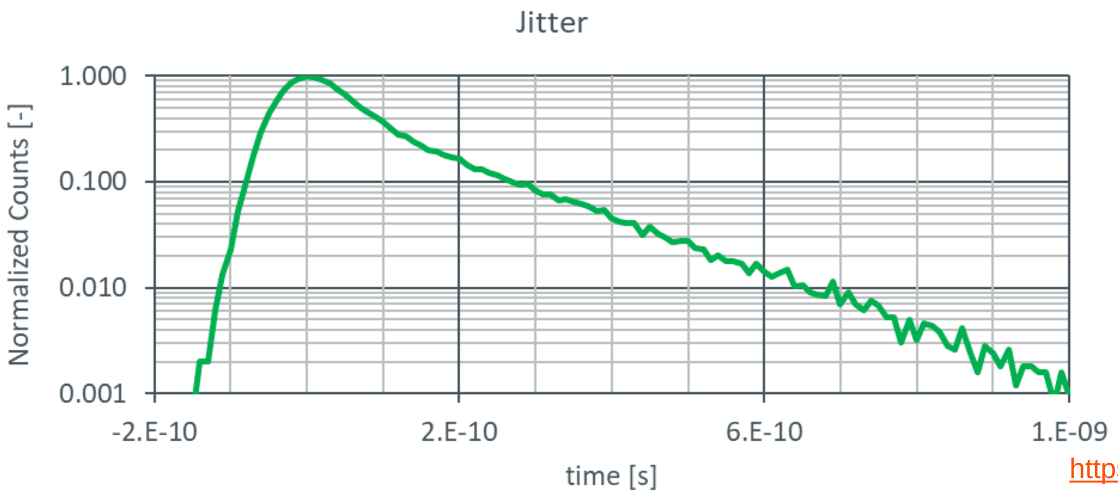




Sensor | SPAD performance

Characteristics (published at ISSW22)





Key Performance Indicator	Unit	Value
Pixel pitch	um	10.26
Breakdown voltage	V	17.6
DCR (25°C)	cps	<10
DCR (75°C)	cps	250
PDE at 940nm	%	10.9
PDE wafer variation (sigma PDE)/avg(PDE)	%	<5
Timing jitter FWHM at 940nm	ps	120
Timing jitter (FW10%M) at 940nm	ps	350
Timing jitter (FW1%M) at 940nm	ps	750
After pulsing probability at -40°C and 10ns dead time	%	<0.5

Data specified at 2V excess bias voltage and 25°C.

https://www.imagesensors.org/Past%20Workshops/2022%20ISSW/0900%20-%200930_Georg%20Roehrer.pdf

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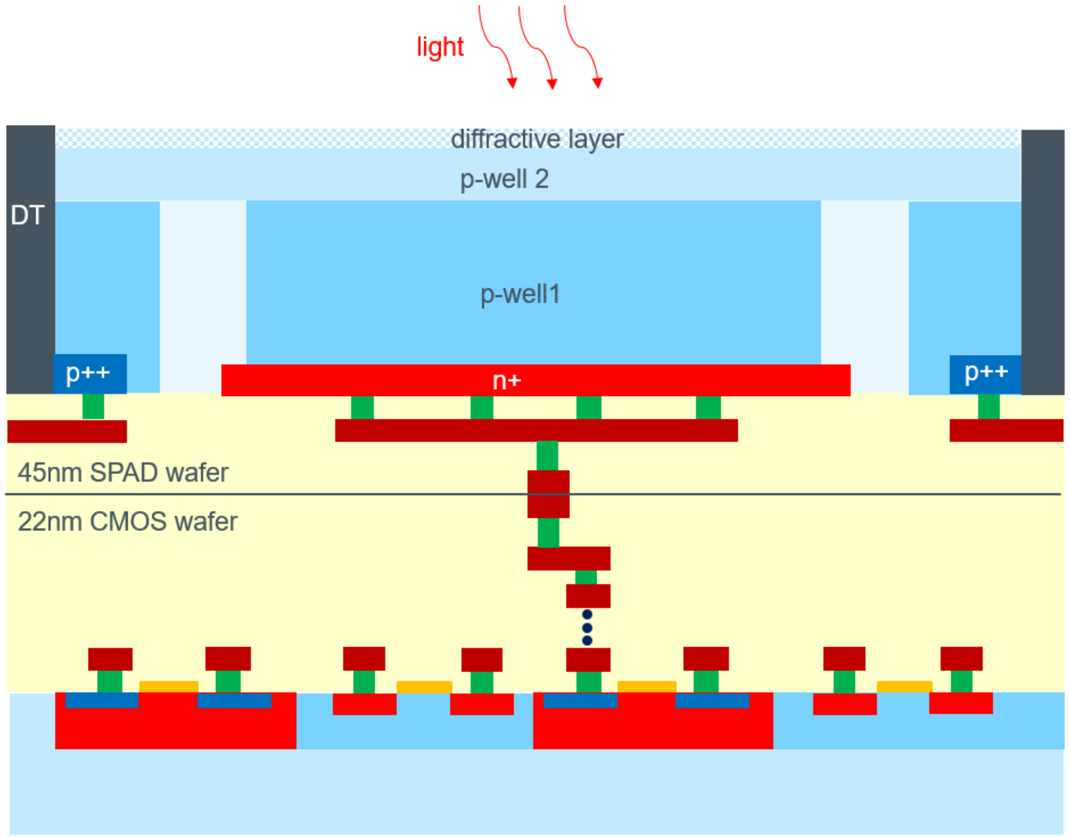
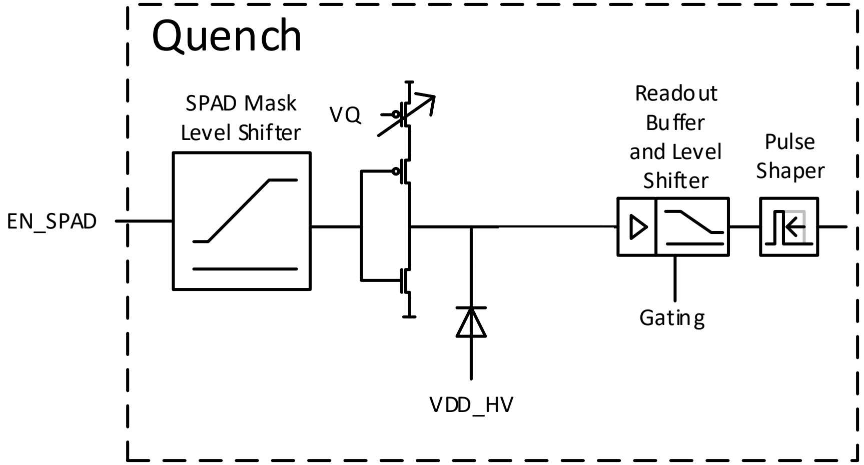
Sensor | 22nm / 45nm BSI SPAD front end

3D stacked frontend and quenching circuit

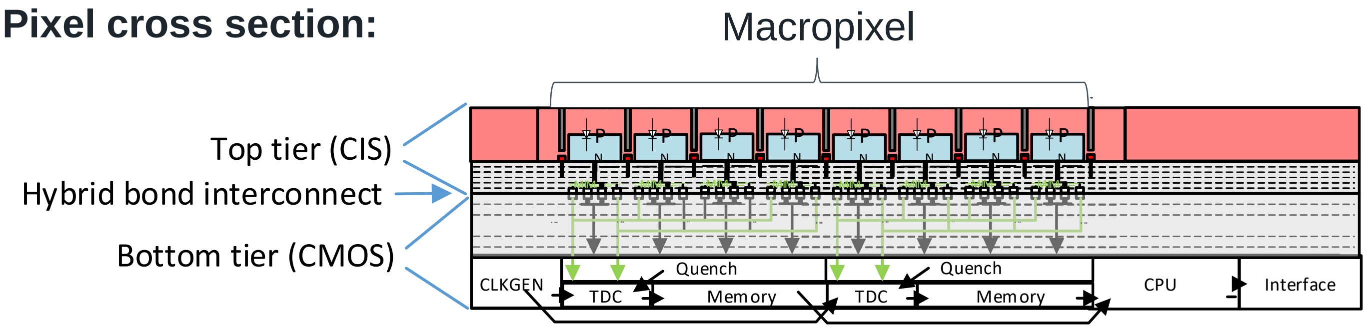
- Pixel pitch: 10.26µm
- Deep trench and diffractive layer
- Electrical test signal injection
- SPAD gating
- Pulse shaper and compression tree
- Adjustable deadtime setting



Quench circuitry:



Pixel cross section:



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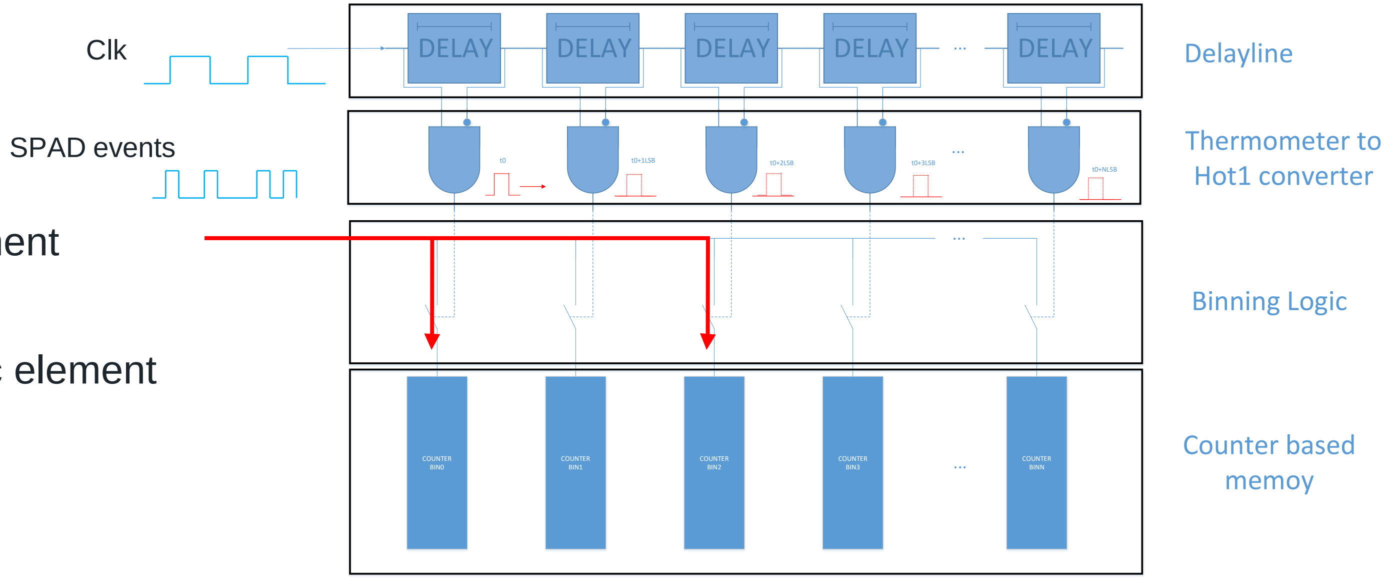
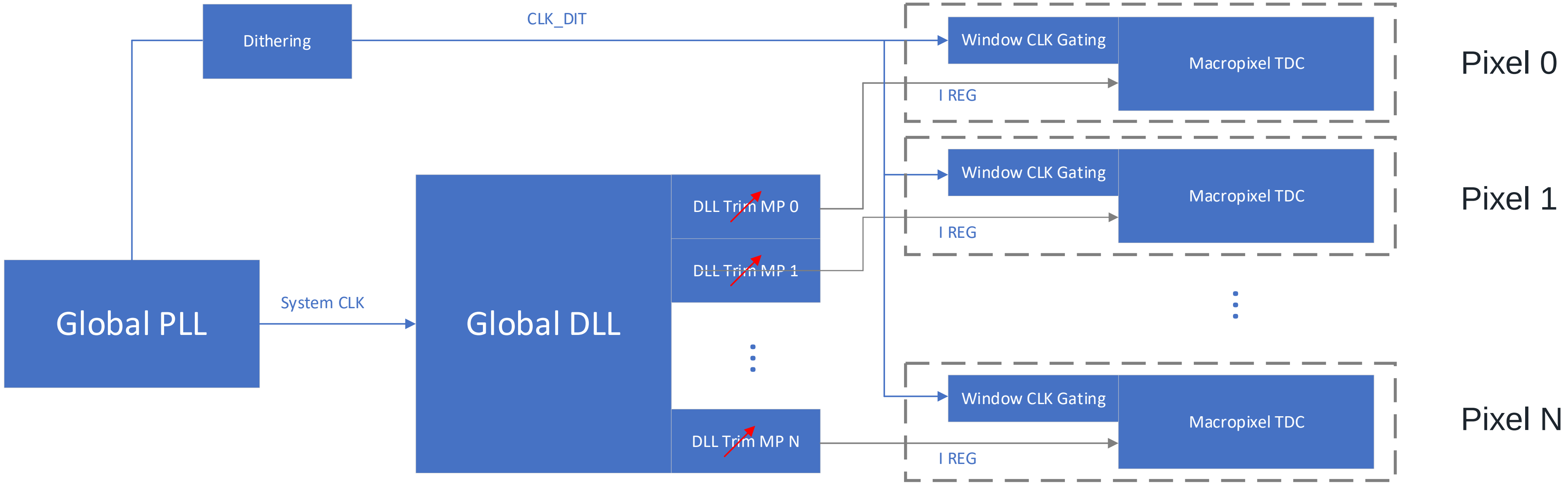
Sensor | TDC architecture

- DLL based delay generation
- Capable of processing multiple events per measurement
- High bandwidth: 1 event per 2 bins – 500 ps / event
- Mismatch of replica delay chains handled by dynamic element matching (DEM)

Basic TDC architecture:



TDC CLK distribution:



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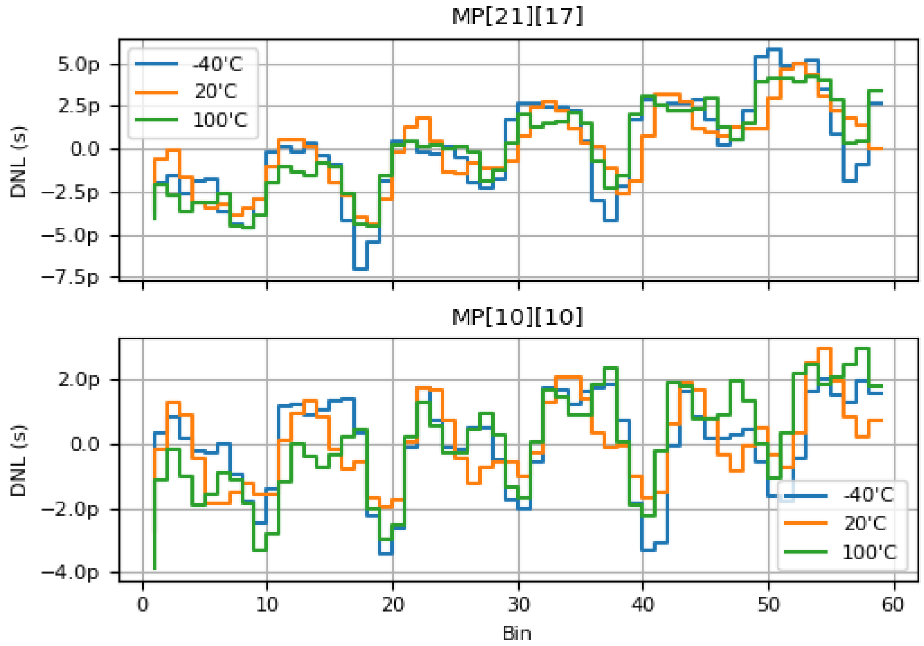
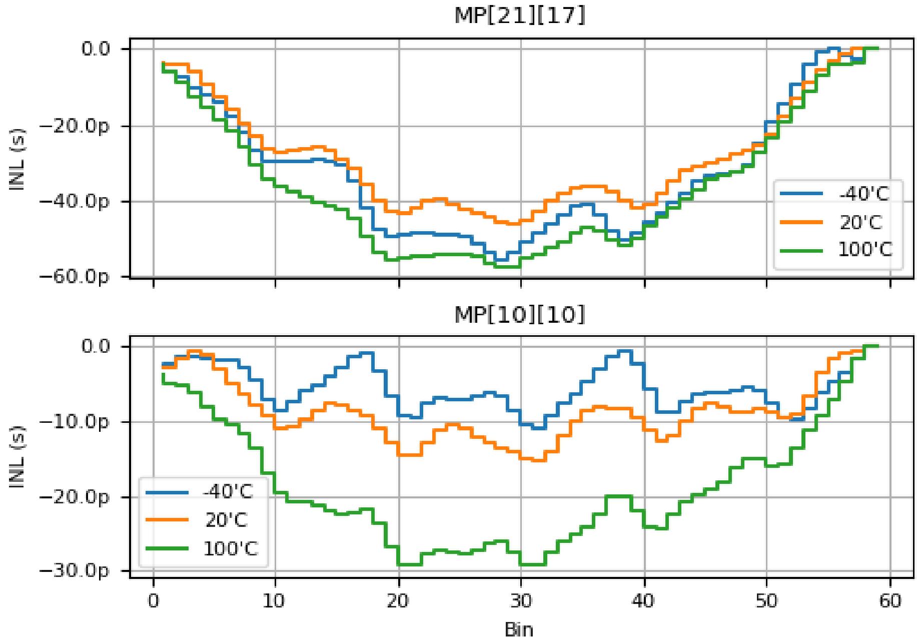
Sensor | TDC measurement

DNL/INL measurements over temperature of TDCs with enabled DEM

DNL | **INL**

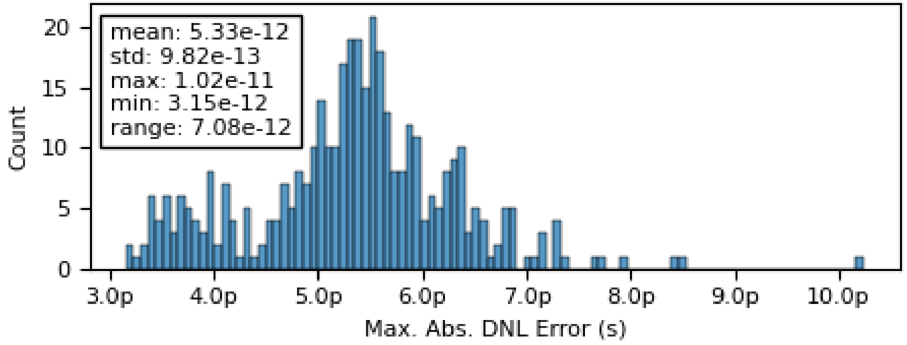


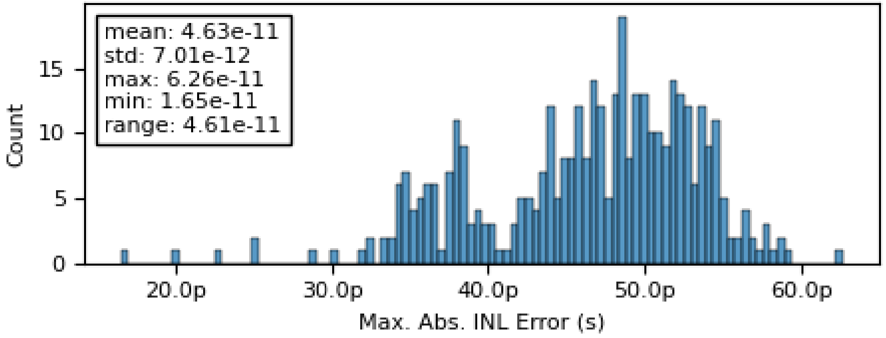


Single corner pixel

Single center pixel

All pixels





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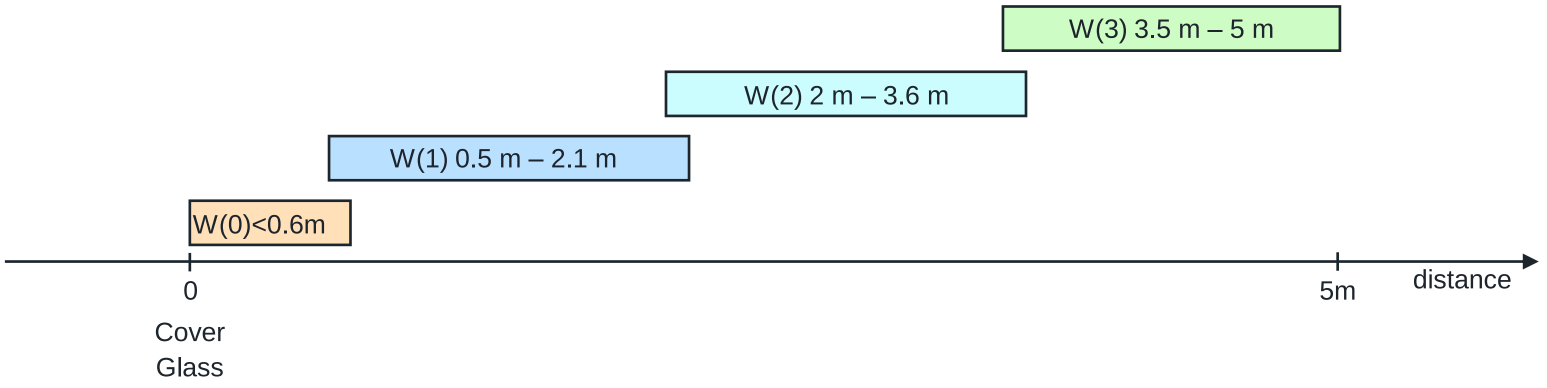
Sensor | Windowing

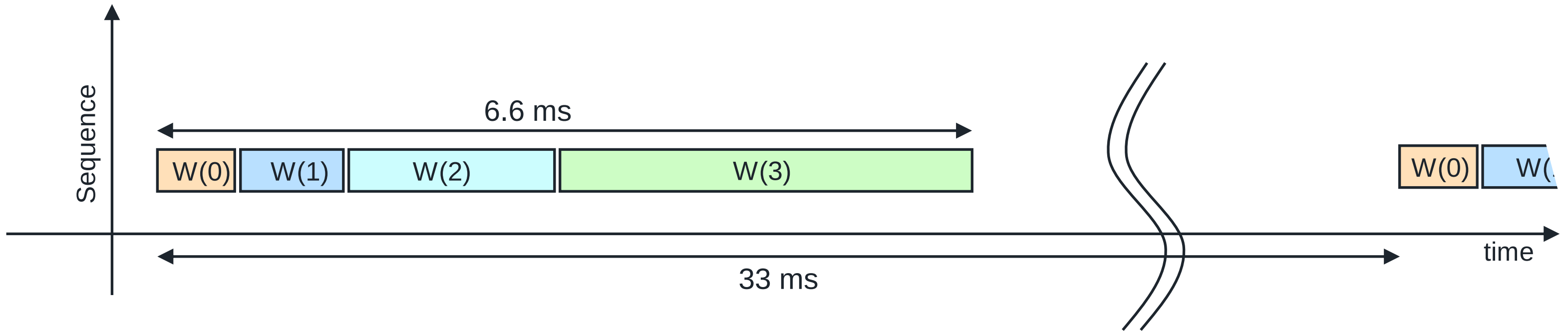
Data acquisition timing diagram

- Distance measurement partitioned in overlapping windows W(x)
- Windows are operated sequentially in bursts, enabling macro pixels (MP) to have individual settings
- Integration of macro pixels stopped by compute cluster interrupt when target SNR is reached

Distance partitioning:



Merged frame:



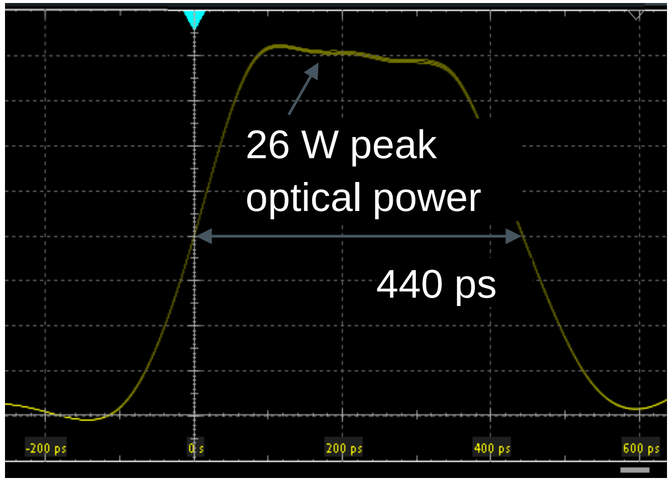
PMU/VCSEL DRV | VCSEL driver block diagram

Architecture and performance to achieve high SNR

Basic features:

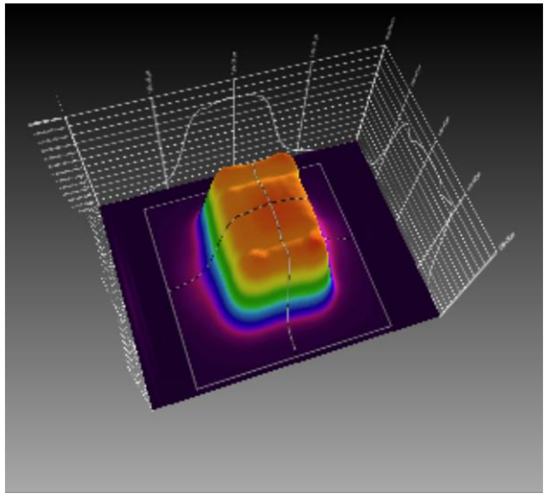
- Low side driver
- On chip capacitor to allow small inductive loop
- Configurable pulse width and pulse power
- Eye safety circuitry
- Resistive interlock in micro lens array

Optical peak power:

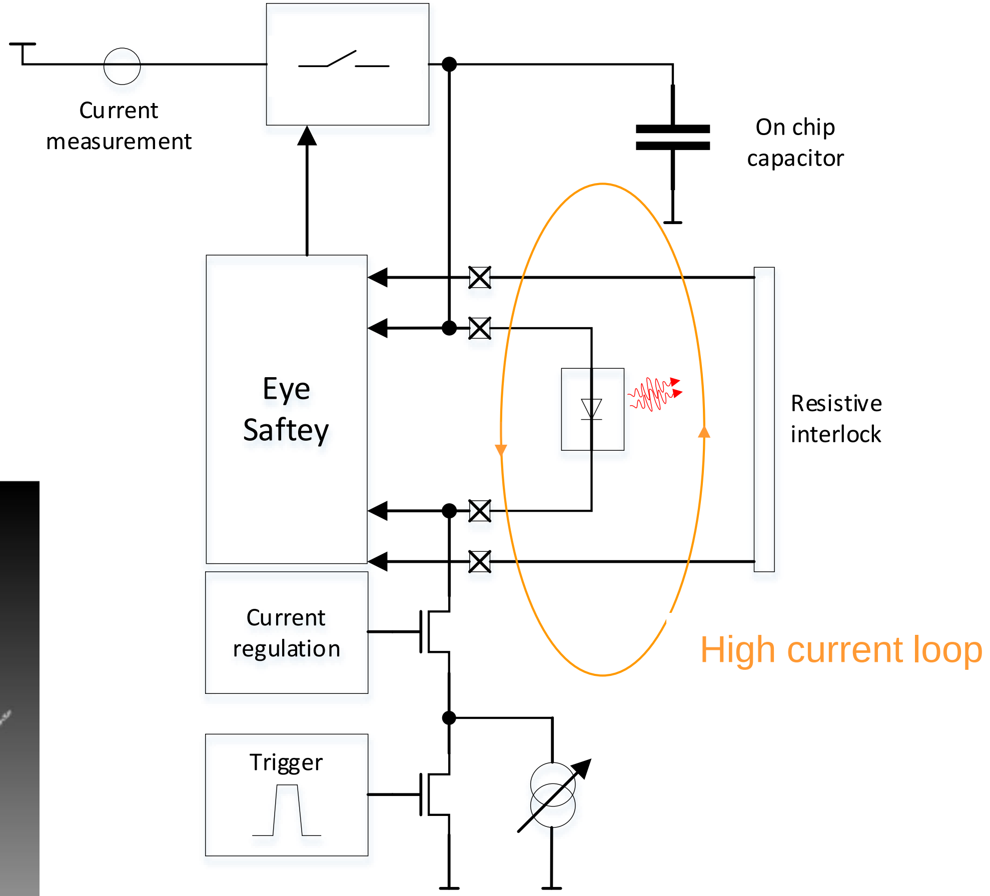


12.5 MHz repetition frequency

Beam profile:



Block diagram



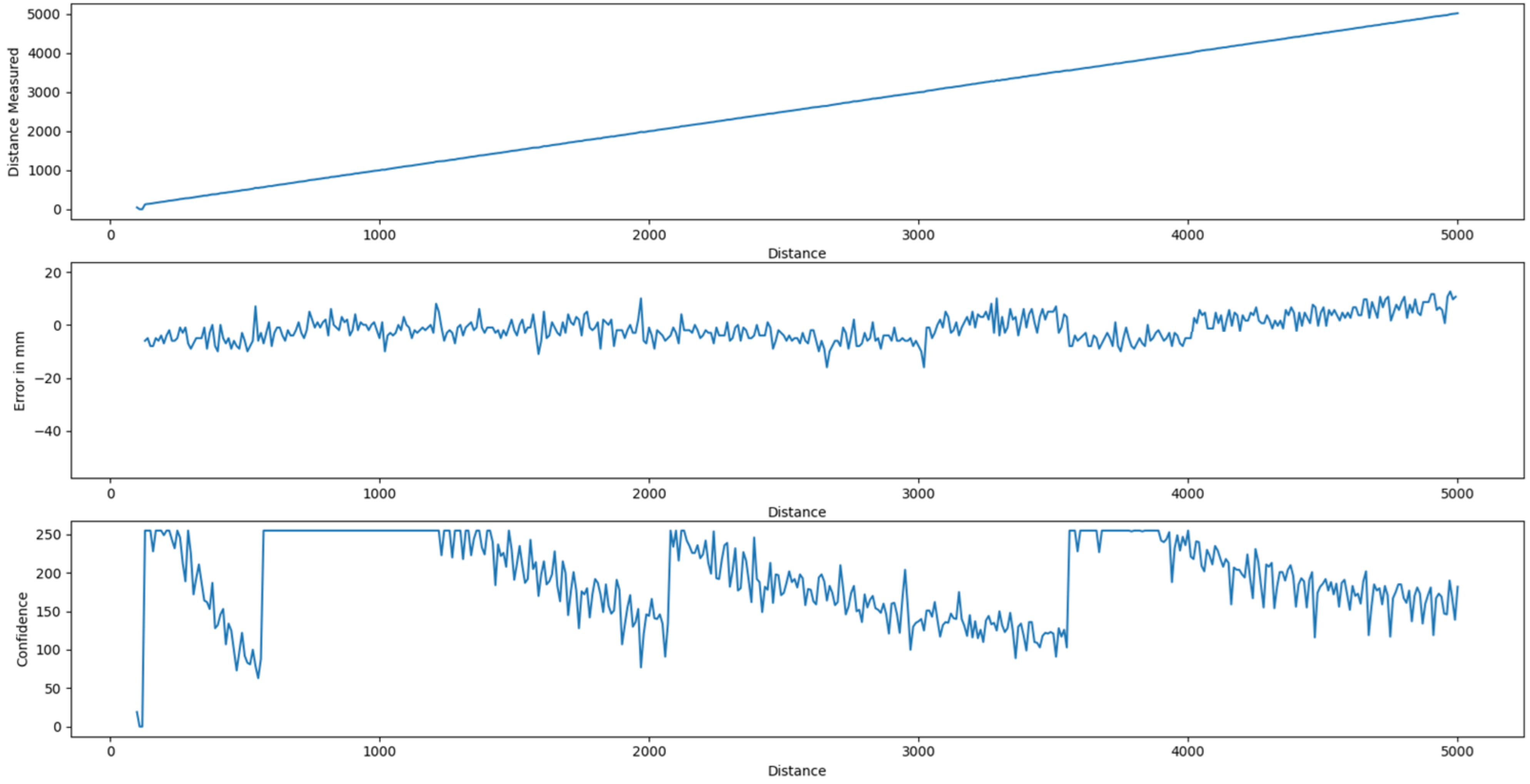
Distance measurement | Linear distance scan / center pixel

20x15, integration time 28 ms, 5.5 m maximum distance, grey target, office light

Distance

Error in mm

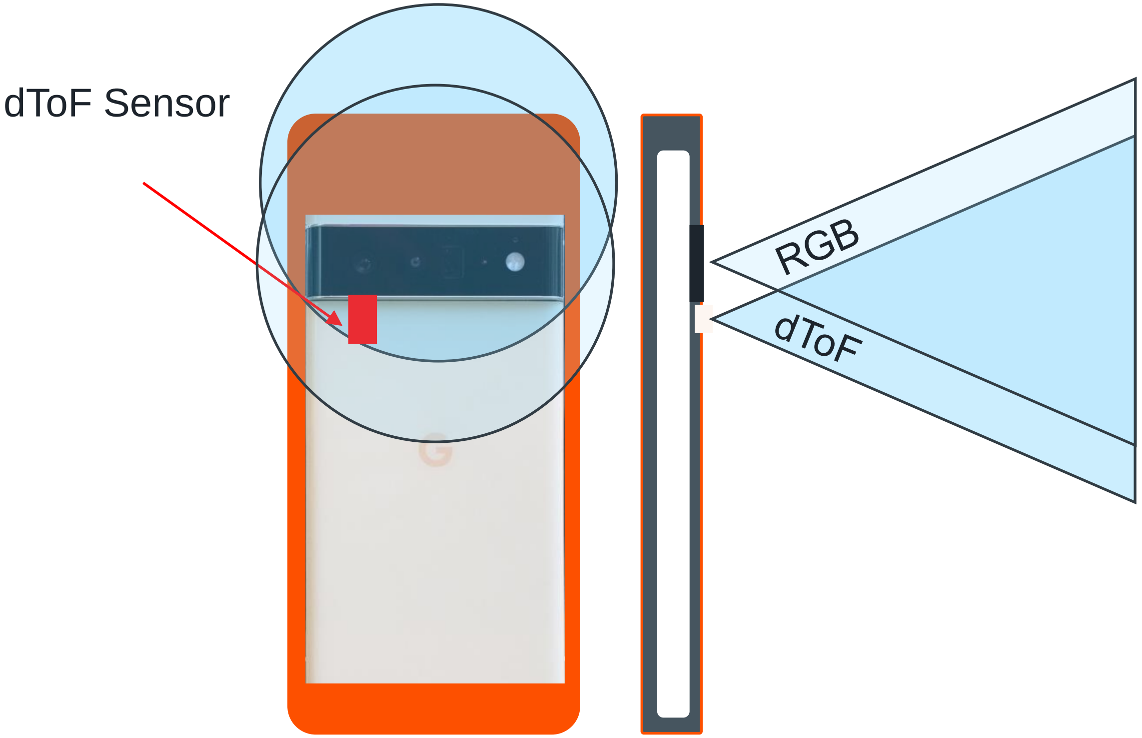
Confidence



Demonstration | RGB camera & dToF fusion demo

Sensor fusion principle:

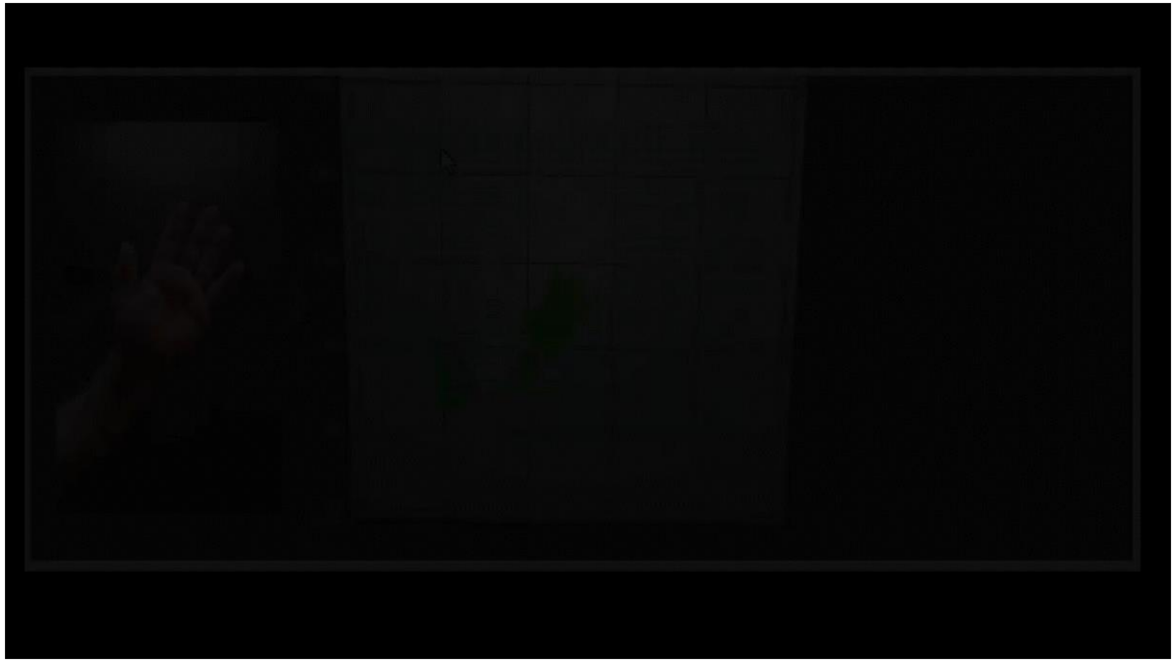
- High resolution RGB camera (-> resolution and color)
- Low resolution 3D-TOF (-> anchor points)



- Demonstrates RGBD fusion running on Android platform
- Google Pixel with 3D printed case to house sensor & interface
- Switchable configurations
  - 20x15 @ 30Hz
  - 40x30 @ 15Hz

Demonstration | Stand alone and sensor fusion

Stand-alone operation:
- 40 x 30 point cloud
- complex office environment with ambient light behind the target



Sensor fusion:
- 20 x 15
- RGB / raw depth / depth up-sampling (fusion)

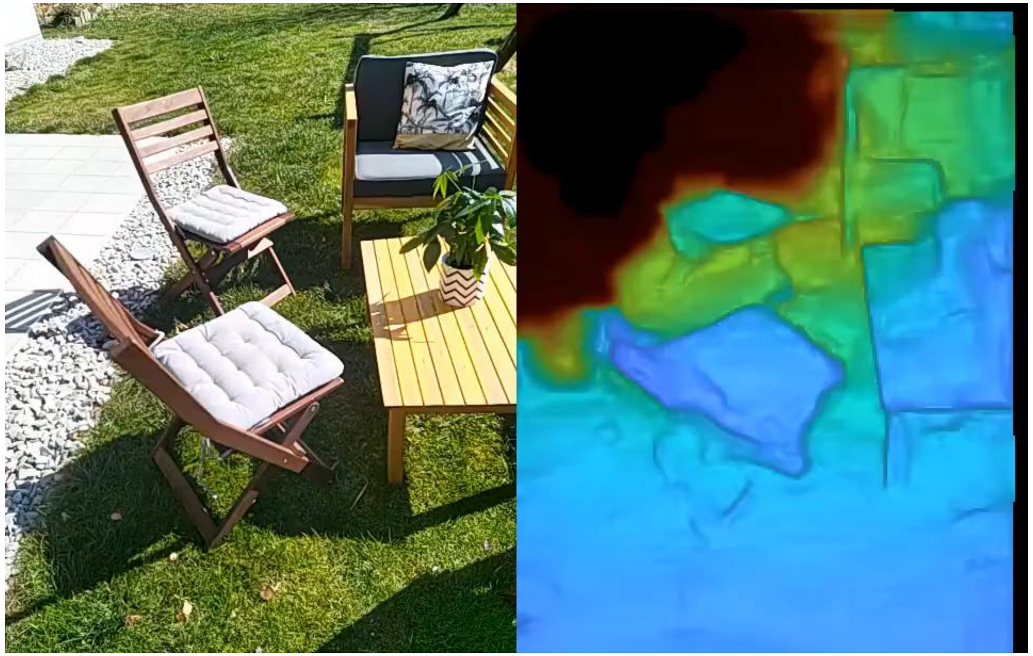
Demonstration | 3D dToF videos (Indoor/outdoor performance simulation*)

- Applying dToF + RGB fusion with machine learning algorithm

*RGBD fusion image based on real data down sampled from 22/45nm test device

Indoor 20x15

Outdoor 20x15



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Conclusion

Challenges of 3D cameras

- 3D-ToF imagers are systems of high complexity
- Monolithic modules allow good performance and reasonable size/costs
- Merging with RGB camera (sensor fusion) help to generate high resolution depth images

Next steps in the project:

- Continue development of firmware for long distance modes
- Further enhancement sensor fusion algorithm

Next step for all of us:

- The community needs to continue enhancing 3D camera performance in order to enable VR/AR application at reasonable costs for outdoor application in consumer

Sensing is life

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