A 1.2K dots dToF 3D Imaging System in 45/22nm 3D-stacked BSI SPAD CMOS

ISSW 2022 workshop

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20/05/2022

Agenda

1. ams OSRAM overview
2. 3D sensing use cases
3. System
4. Camera
5. Laser
6. Firmware
7. Application
8. Performance results
9. Power results
10. Conclusion and thanks

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ams OSRAM at a glance

5.04bn
EUR revenues 2021

5,500+
Engineers

20,000+
Customers

~24,000
Employees worldwide

~40/33/27%
Automotive/Industrial and Medical/Consumer revenue split FY 2021

40+
Major R&D locations

15,000+
Patents granted and applied for

110+
Years design + manufacturing

Vision and mission for ams OSRAM

To create the uncontested leader in optical solutions

Sensing

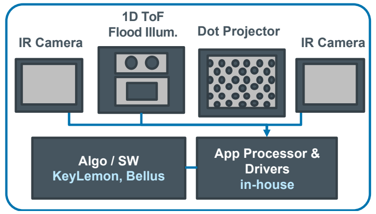
Illumination

Visualization

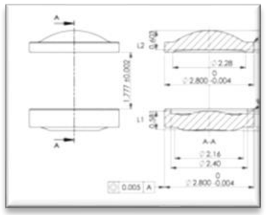
Become the uncontested leader in optical solutions through bold investments in disruptive innovation and continuous transformation delivering best in class profitability and growth

ams OSRAM | 3D Components, Sensing Modules & Solutions

ams technology portfolio allow unique differentiation in 3D sensing



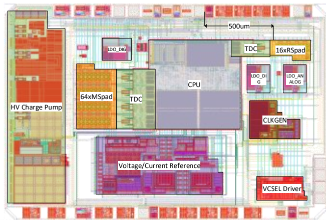
System Design
- in-house system design
- Qualcomm partnership for Android integration



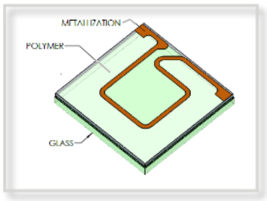
Optics
- extensive design know-how
- refractive & diffractive optics
- WLO manufacturing technology

Middleware & 3D algorithms
- depth maps, face recognition, machine learning
- feedback to component & system design

VCSELs
- in-house design & fabrication
- best in class efficiency



Deep sub-micron CMOS design
- in-house design capabilities
- pixel IPs (SPAD,TDC, global shutter)
- driver IPs (high power, short pulse)



Packaging & Eye Safety
- miniature, compact modules
- unique, integrated eye safety methods

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3D use cases | mobile phones

World-facing 3D use cases

Photo Enhancement

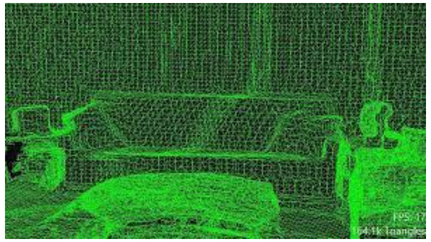
3D camera supporting corner cases

Low texture, low light

Faster/ better autofocus

Optimized Bokeh

Object Scanning



Enhancement of the digital world

Scanned objects

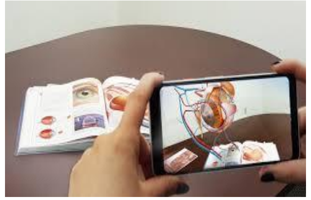
room scanning

Augmented reality – immersive experience

Gaming

Social media

Education



Navigation & virtual tour guide

Design & modelling

Measurement

Shopping

Remote assistance & virtual manuals

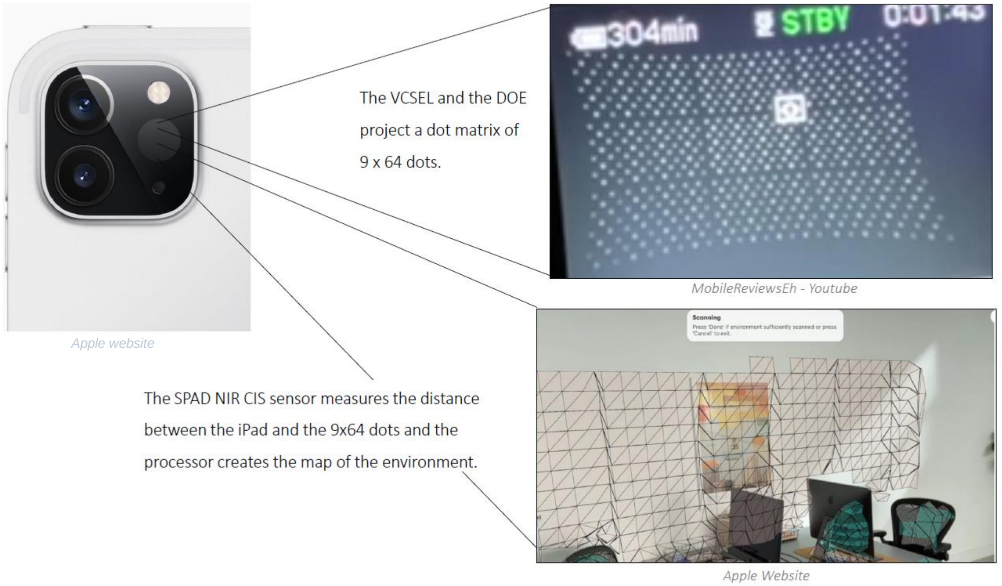
- Optimized end-user experience with growing number of AR applications
- AR with 3D dToF being exciting new part of social media apps
- People can navigate space and learn more about the world around them
- Create a 3D house plan by simply specifying the characteristics points on the camera view
- Have access to the expert directly and with 3D AR objects & pointers for step-by-step support
- Enabling correct placement of virtual objects in a room

AR/VR use cases | 3D sensing enabling AR technology

Requirements for AR 3D depth camera

1. **High quality depth map**
   - High accuracy + low noise + high confidence
   - Over a useful distance and ambient light range
2. **Low power operation**
   - Continuous streaming operation
   - Allowing useful battery run time
3. **Stable frame rate**
   - Allowing image fusion with other cameras
   - High frame rate decrease reconstruction time
4. **Relative high spatial resolution (independent of number of depth points)**
   - Better capturing edges and small objects
   - Accumulation of depth points by intrinsic scanning

Apple LiDAR technology



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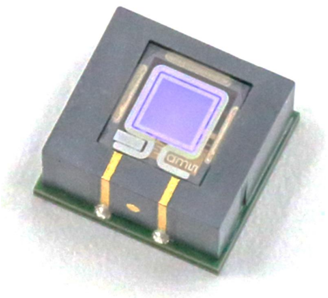
dToF system architecture overview | AR/VR markets and requirements

Full dTOF system enabling AR / VR experience

Continuation of the work presented in IISW21 by David Stoppa [1]



Parameter	Specification
XY-Resolution	Sparse QVGA (1200 depth points)
Z-precision / accuracy	< 0.5% / < 3% @ full range
Range	> 5m @ 60kLux, >8m @ 1kLux
Frame rate	Up to 60 fps
Total power	< 300mW @ 30fps
Data Interface	I2C, MIPI

Main features

- Modular dTOF architecture
- Sparse QVGA (1200 depth points)
- Long-distance and high accuracy range sensing
- Hardware enhanced configurable integration time control
- Dot illumination for superior ambient light rejection
- Flexible architecture with embedded processing
- Depth image output without external post-processing
- Data interfaces i2C, MIPI

Applications

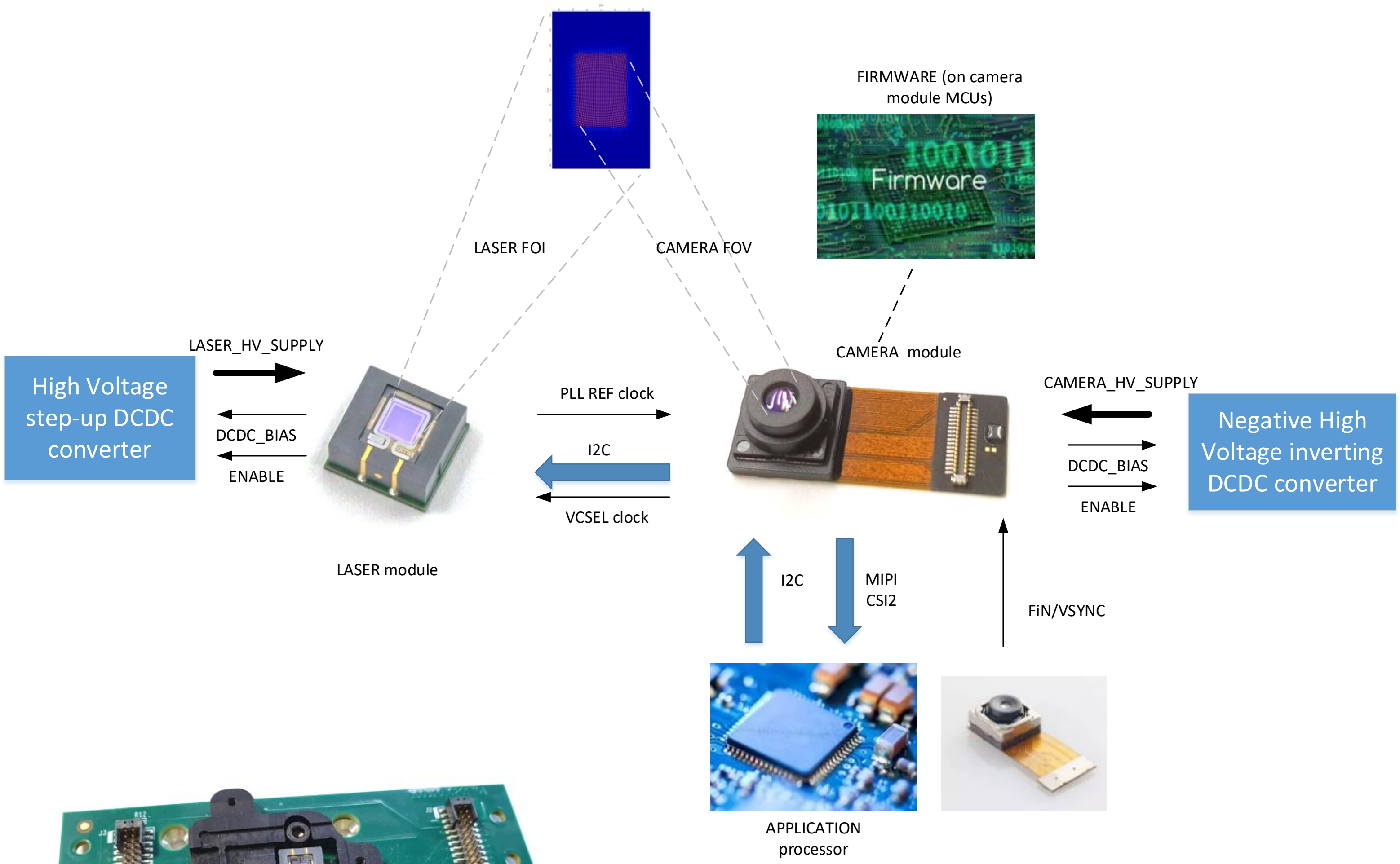
- Augmented Reality, Virtual Reality
- Photo enhancement (bokeh, autofocus)

dToF system architecture overview | system block diagram

Application block diagram

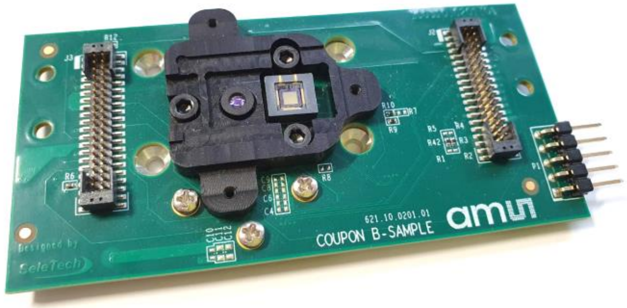
System

- **Camera module**
  - CMOS sensor
  - High brightness NIR optics
  - Flash memory
- **Laser module**
  - BCD laser driver
  - multiple junction VCSEL array stacked on laser driver
  - Micro lens array for dot illumination with resistive interlock for eye safety



Peripheral components

- Laser High voltage DCDC converter
- Spad High Voltage DCDC converter



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Camera | overview

Specifications

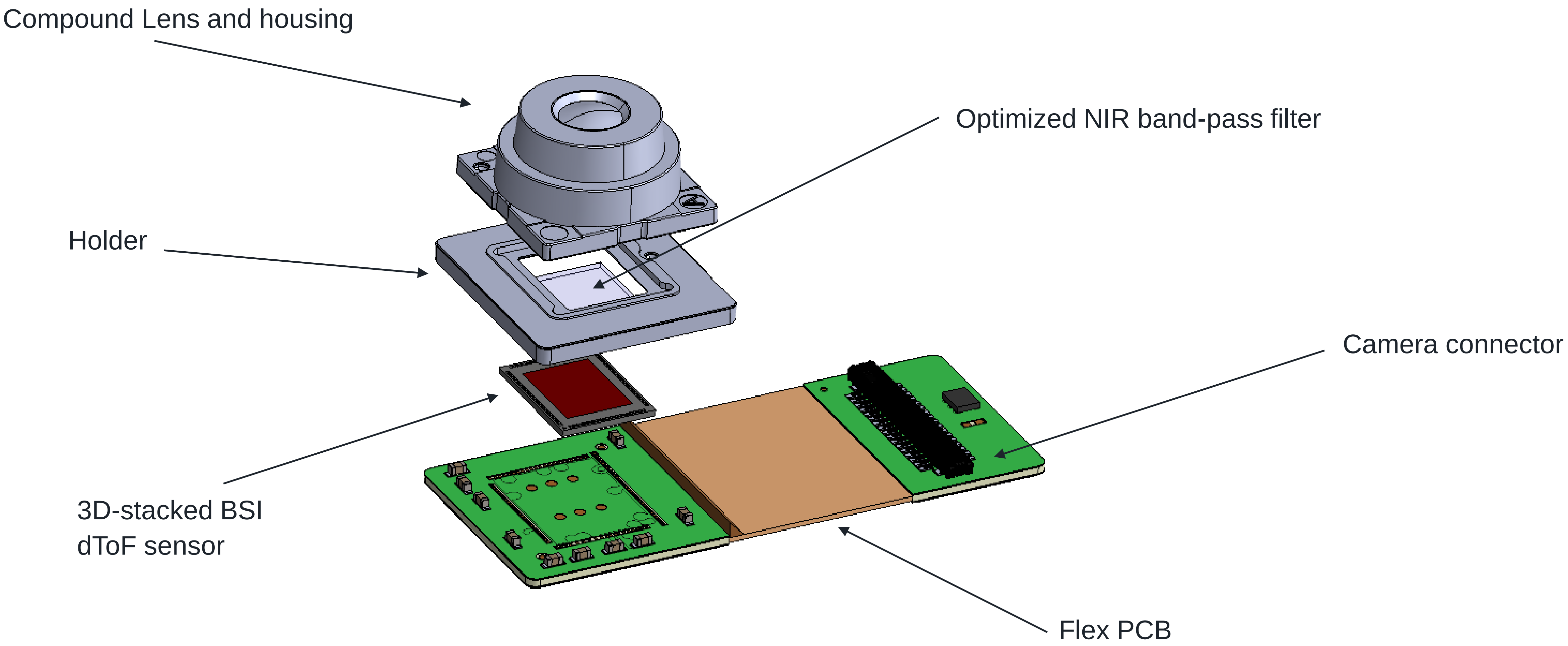
Sensor IC

- QVGA SPAD array
  - 10µm pitch
  - >12% PDE, 940nm, 2V excess bias, room temperature
  - Configurable dead time
- 30 x 40 parallel operating TDCs
  - 59 bins per TDC
  - ~250ps .. 350ps configurable bin size
- On-chip histogram memory with 12bit bin counter and overflow counter
- Peak finding and sub-bin interpolation on 6 compute cluster MCUs
- Depth image data reconstruction, streaming, and system monitoring on system MCU

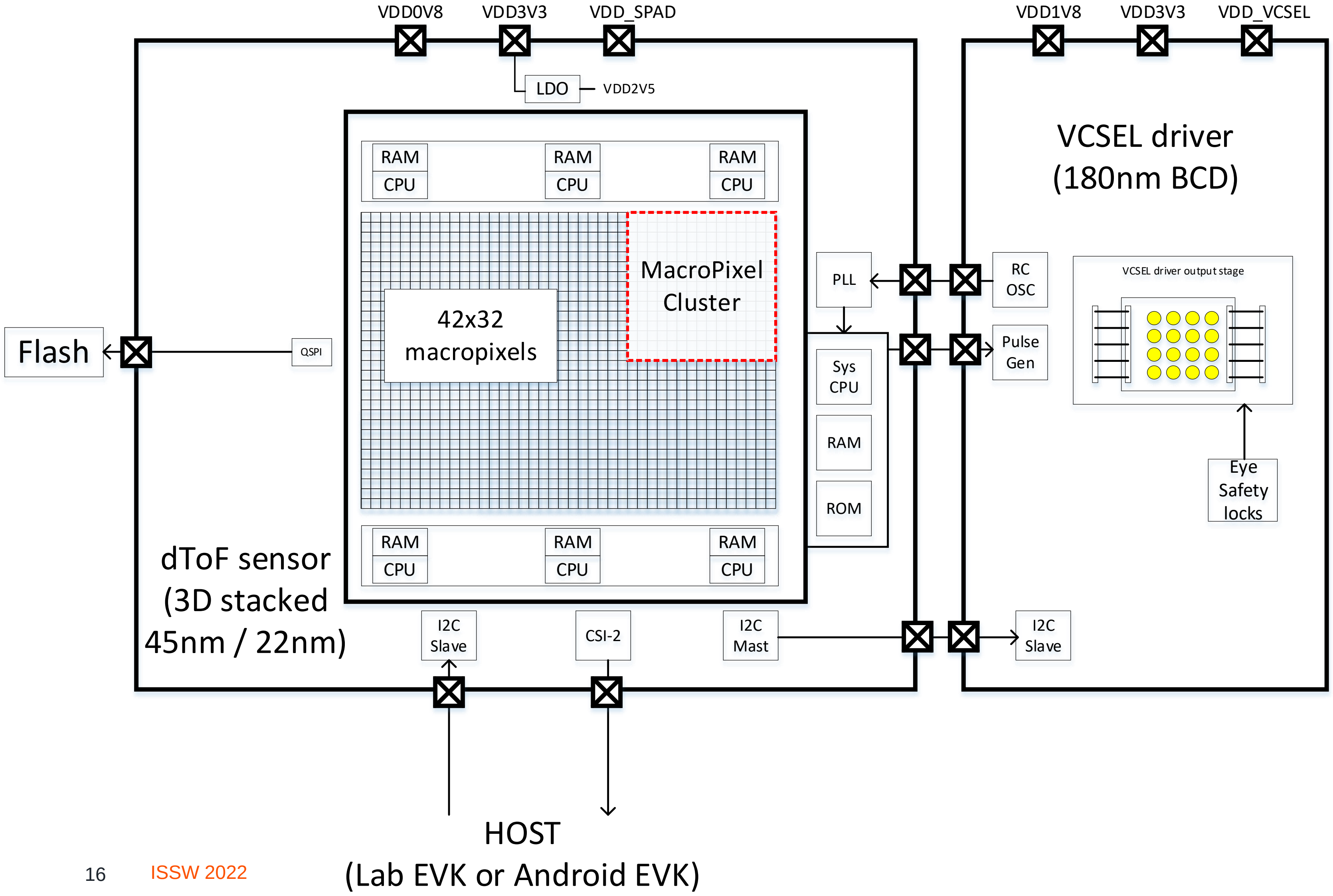
Imaging optics

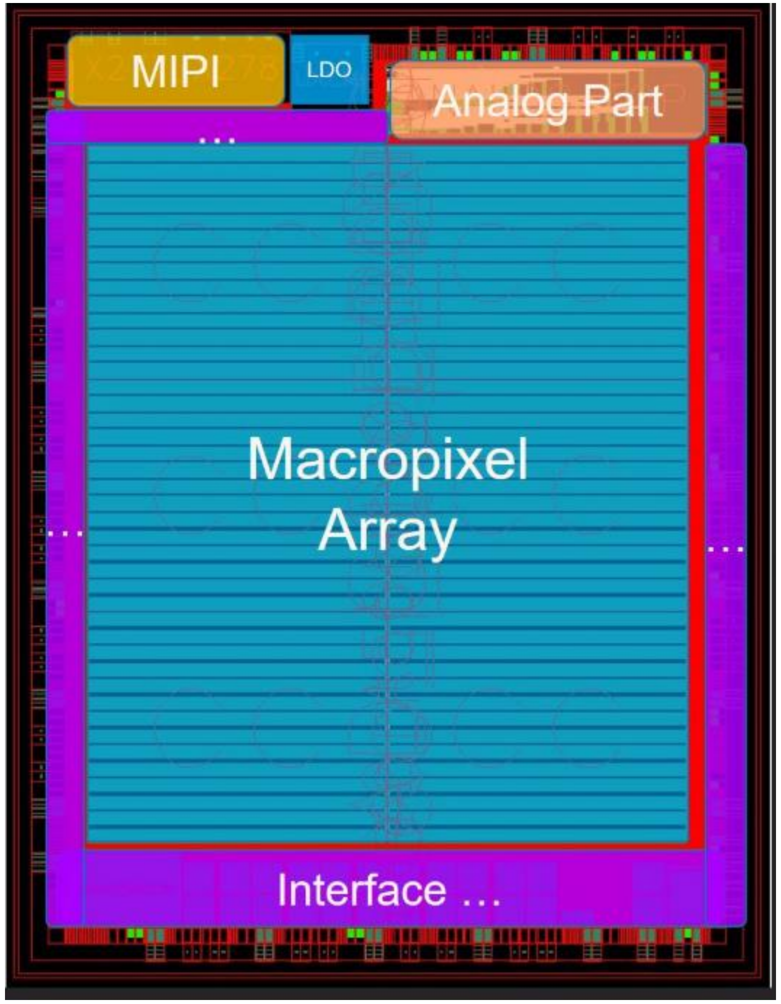
- 49° x 62° field-of-view
- F/1.2
- 940nm optical narrow-band filter, system-optimized bandwidth

Camera | components and assembly

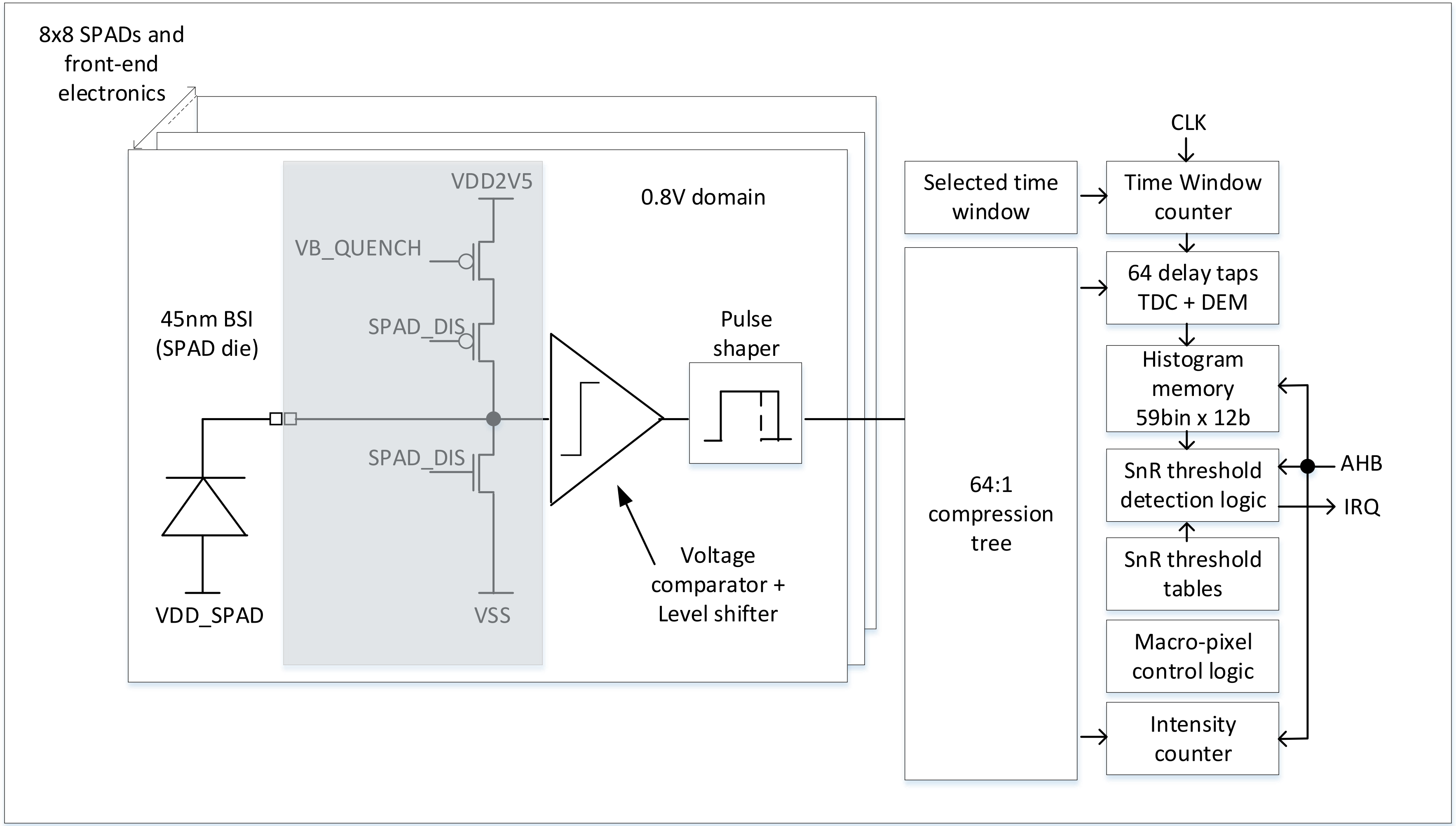


Camera | Sensor



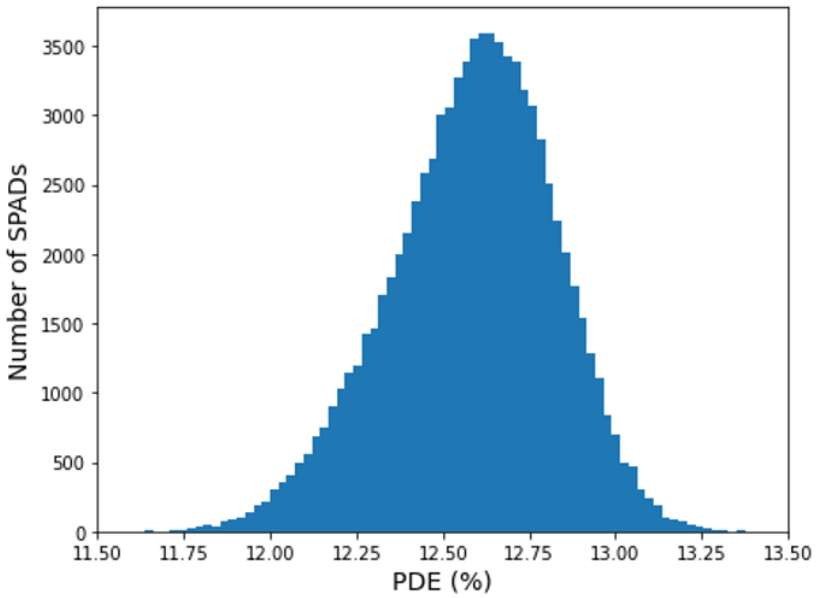


Camera | Macro-Pixel



Camera | Photon Detection Efficiency

- Count rates determined in intensity image mode
- Excess bias voltage 2V
- Room temperature
- 940nm



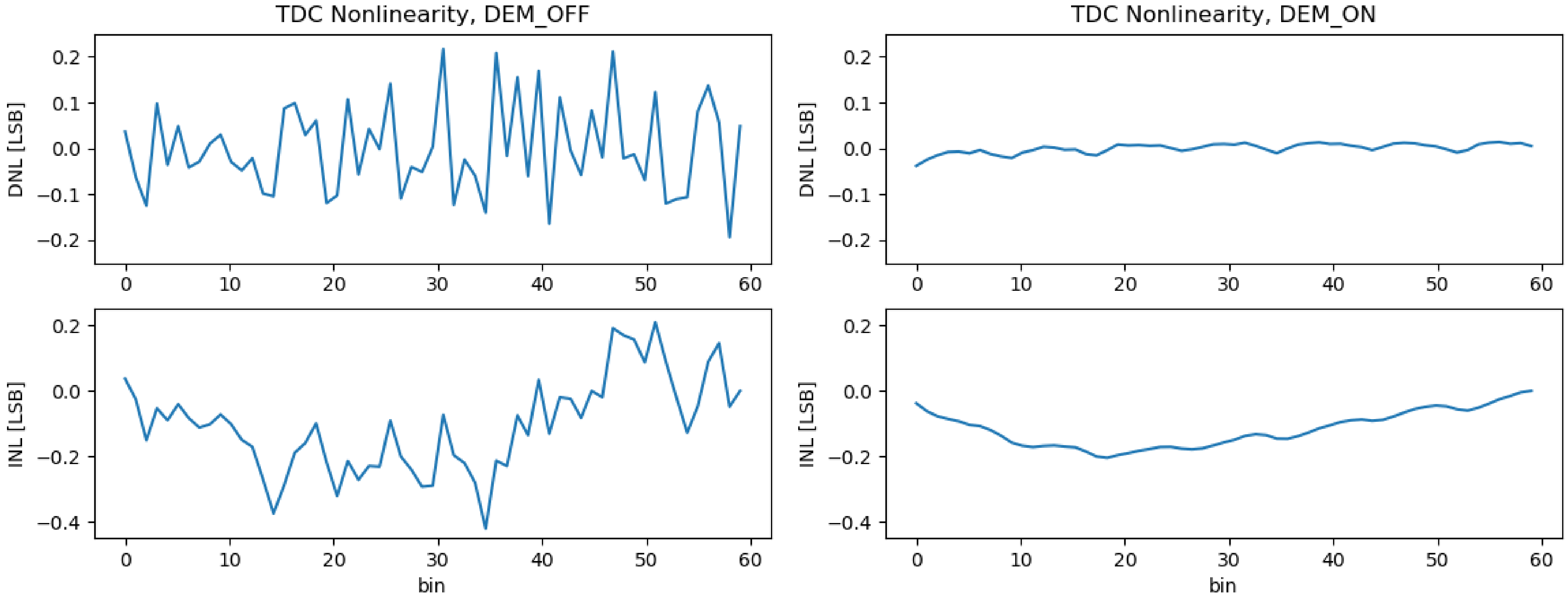
Key Performance Indicator	Unit	Measured on test chip (*)	Measured on dToF chip
Pixel pitch	um	10.00	10.26
Breakdown voltage (25°C)	V	17.5	17.4-17.6
DCR (25°C)	cps	0.8	<2
DCR (75°C)	cps	250 @75°C	480 @Tj~78°C
PDE at 940nm (25°C), 2Vex	%	11	>12

(*) Refer to presentation from Georg Roehrer in ISSW22, 'A Back Side Illuminated 3D-Stacked SPAD in 45nm Technology' [4]

Camera | TDC non-linearity

Differential and integral nonlinearity, DEM enhancement

- Measured through optical path in ambient light
- Dynamic element matching (DEM) significantly improving performance



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Laser | overview

Specifications

Module

- reflowable

VCSEL driver

- 390ps pulse width (90% energy method)

VCSEL array

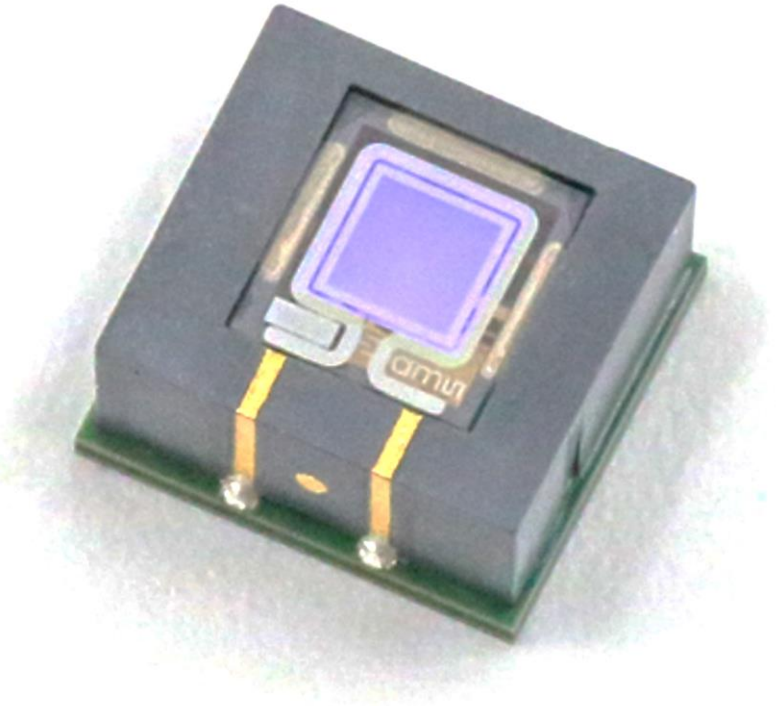
- >60W optical peak power

Micro lens array

- optimized for dot illumination (patented)

Eye safety features

- Resistive interlock in micro lens array
- Surveillance of average optical power by build-in photodiode
- Monitoring of module temperature
- Short circuit detection of output driver



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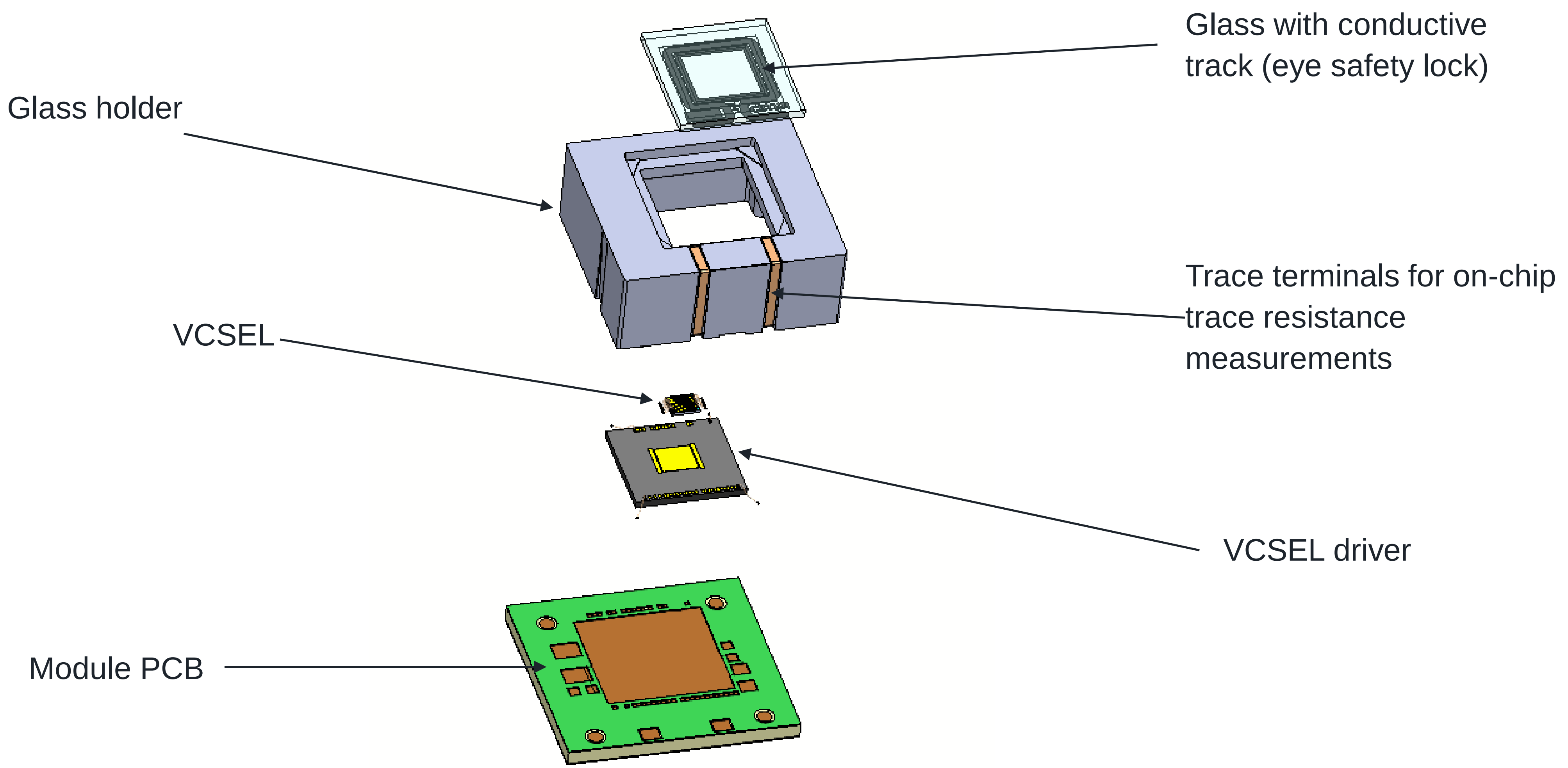
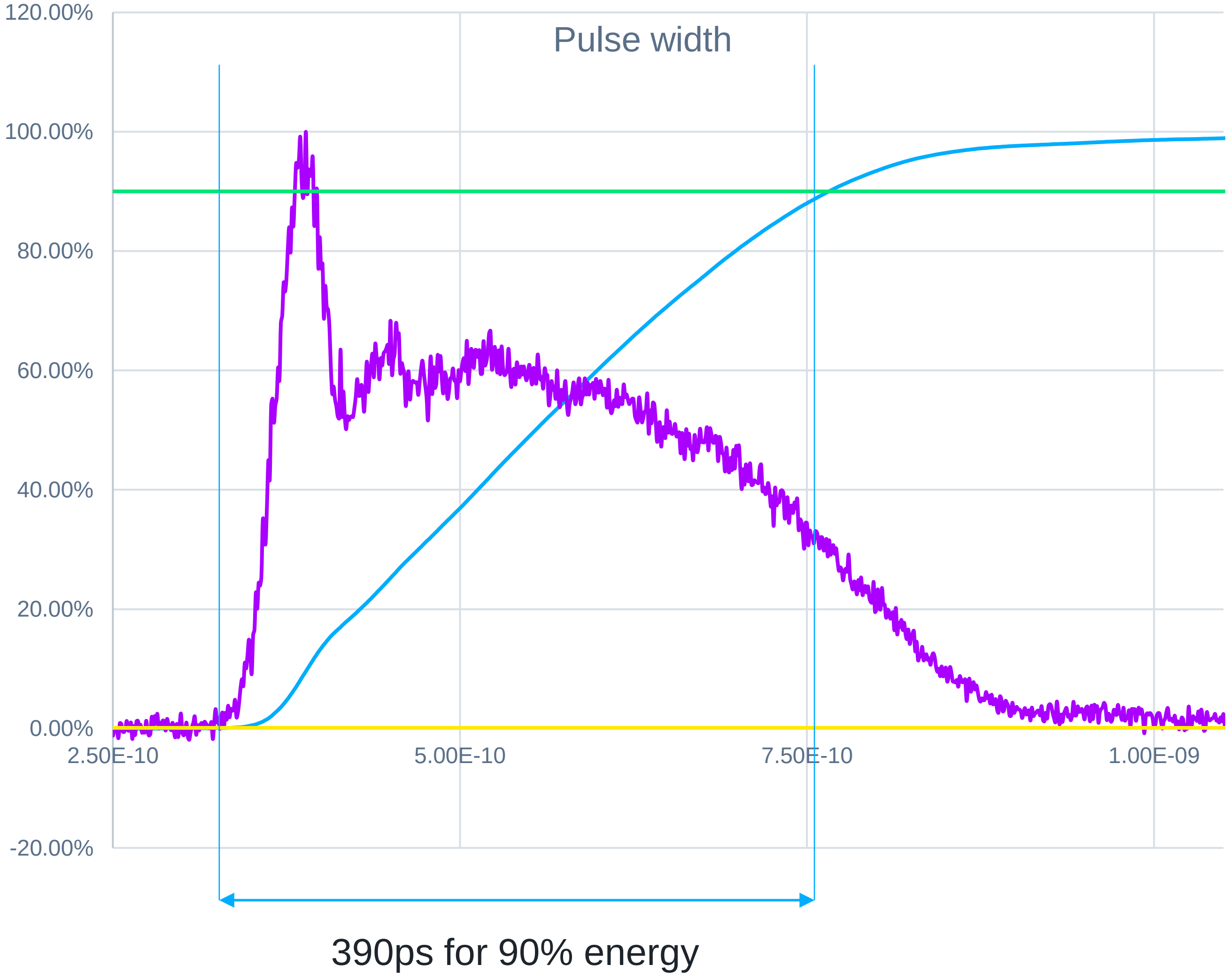
Laser | components and assembly



Laser | pulse

Sub-nanosecond pulse width

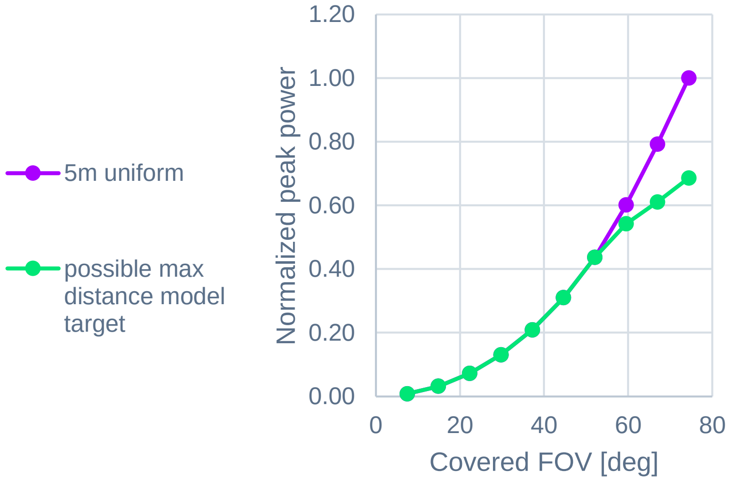


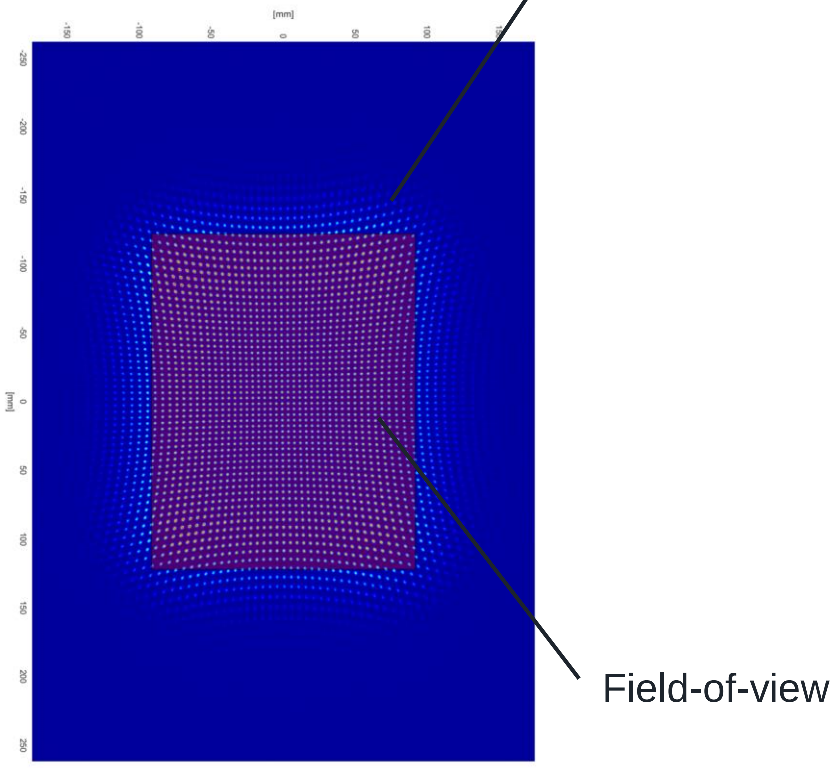
Laser | dot illumination

Power profile and optical alignment

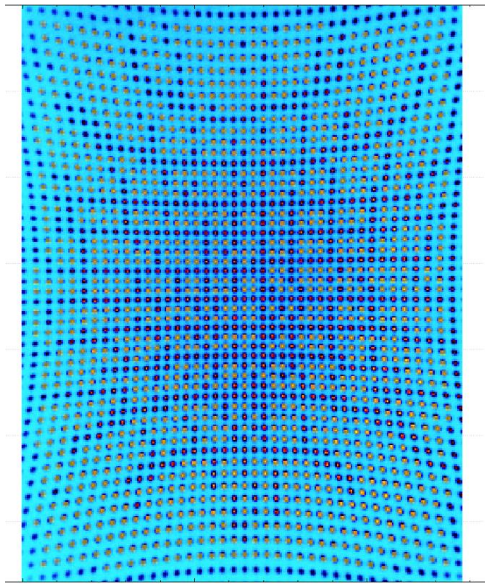
- 1900 dots projected into focal plane
- SPAD array multiplexed to 1344 TDCs
- SPAD mask and DOT position stored to in flash after calibration

Relative peak power vs covered FOV
(system design target)





SPAD mask (yellow) overlaid with dot intensity image (red / blue)



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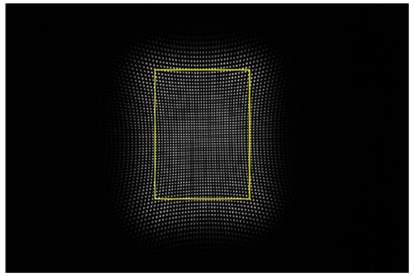
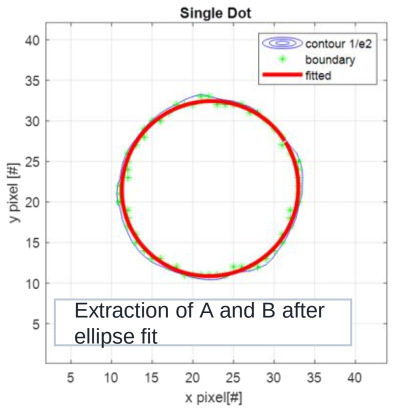
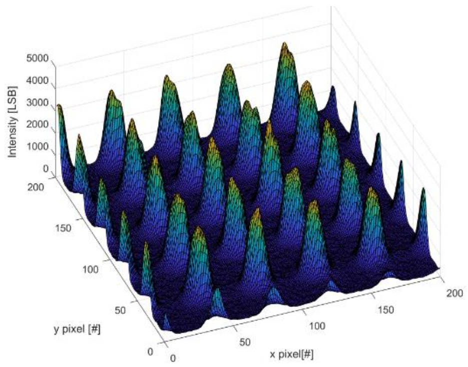
Laser | dot angular size and pitch

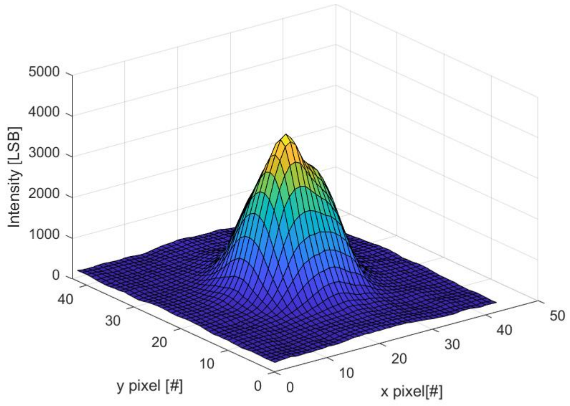
Dot angular size is critical to maximize peak optical power, increase signal-to-noise ratio and reduce number of activated spads

This has a triple effect in terms of power efficiency: increase the signal, reduce the ambient, and reduce the power consumption of the detector related to SPAD activity.



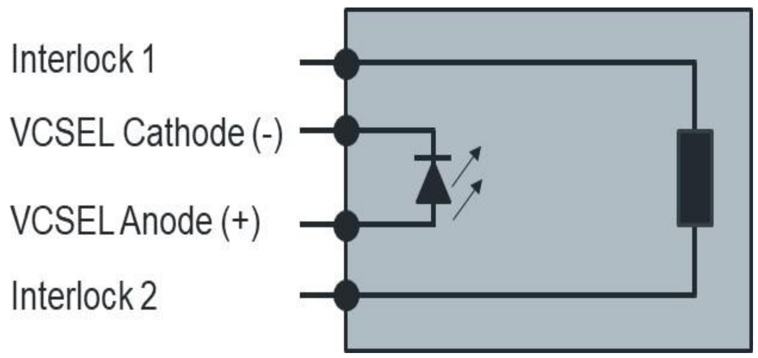


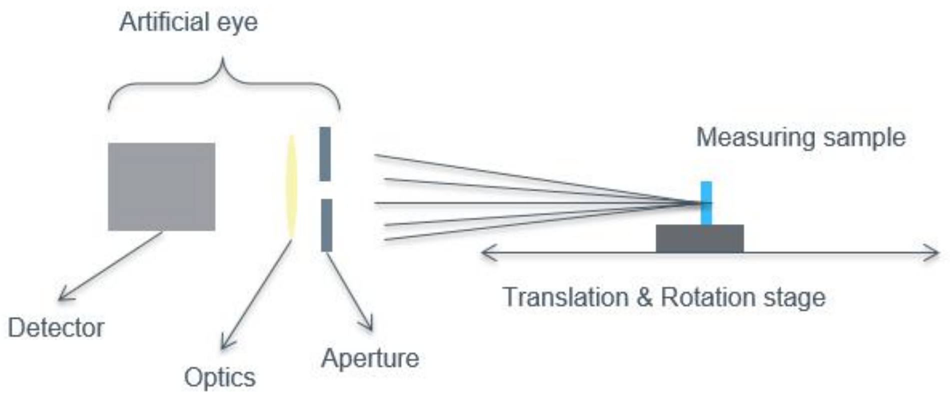




Laser | eye safety

Is covered by…		Safety mechanism			
		VCSEL clock frequency detection	Average optical power monitoring	Interlock / lens detached detection	VCSEL driver power stage short detection
Single fault	Too high VCSEL clock frequency	√			
	Too wide pulse		√		
	Too high average burst optical power		√		
	Lens detachment / severe damage			√	
	Power driver power stage shortage				√





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Firmware | overview

Specifications

Programming model

- dToF control/configuration and status interface management

Calibration toolbox

- spad mask, dot center and depth offset calibration

Dataflow management

- Control of hardware to sequence operations
- Peak detection, Sub-bin interpolation, range map assembly (from various clusters of macro-pixels)

Power management

- Power state machine
- Sequencing and synchronization of laser emission bursts and SPAD quenching

VCSEL driver control

- Abstracted high-level laser operating modes
- Pulse driving conditions run-time adaptation (to optimize in large temperature range)

Eye safety

- Temperature monitoring and adaptation for temperature dependent monitors
- Laser safety error monitoring and reporting to host

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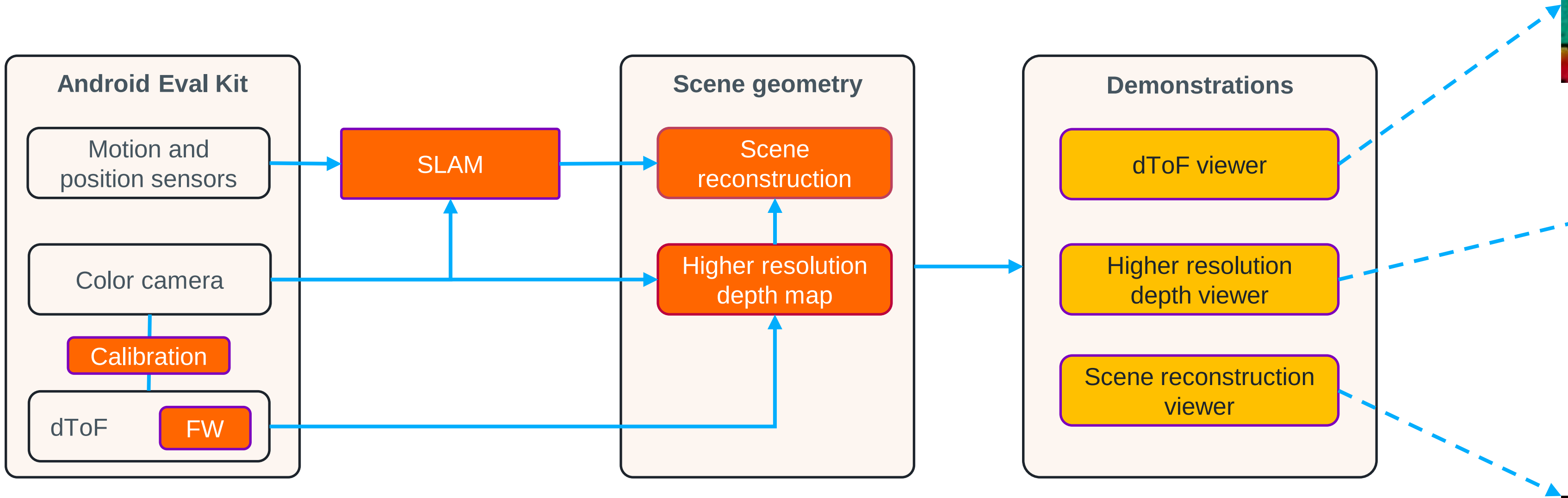
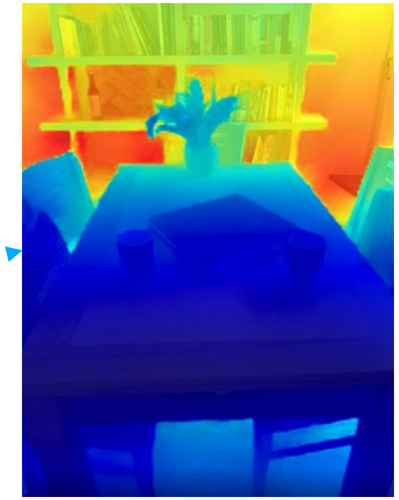
Application | 3d scene reconstruction

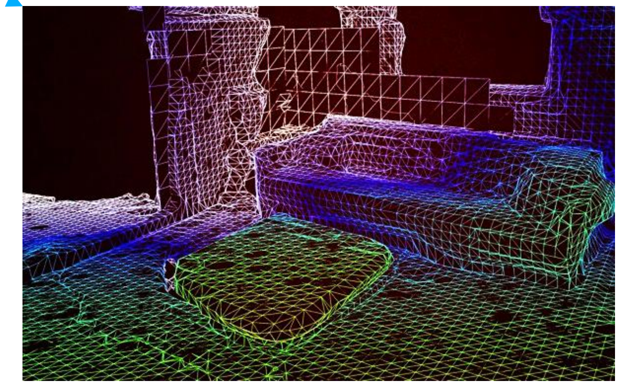
dTof sensor integrated in a RGBD system



raw output (40x30)



Higher res depth map



Scene geometry (3D mesh)

Ams OSRAM

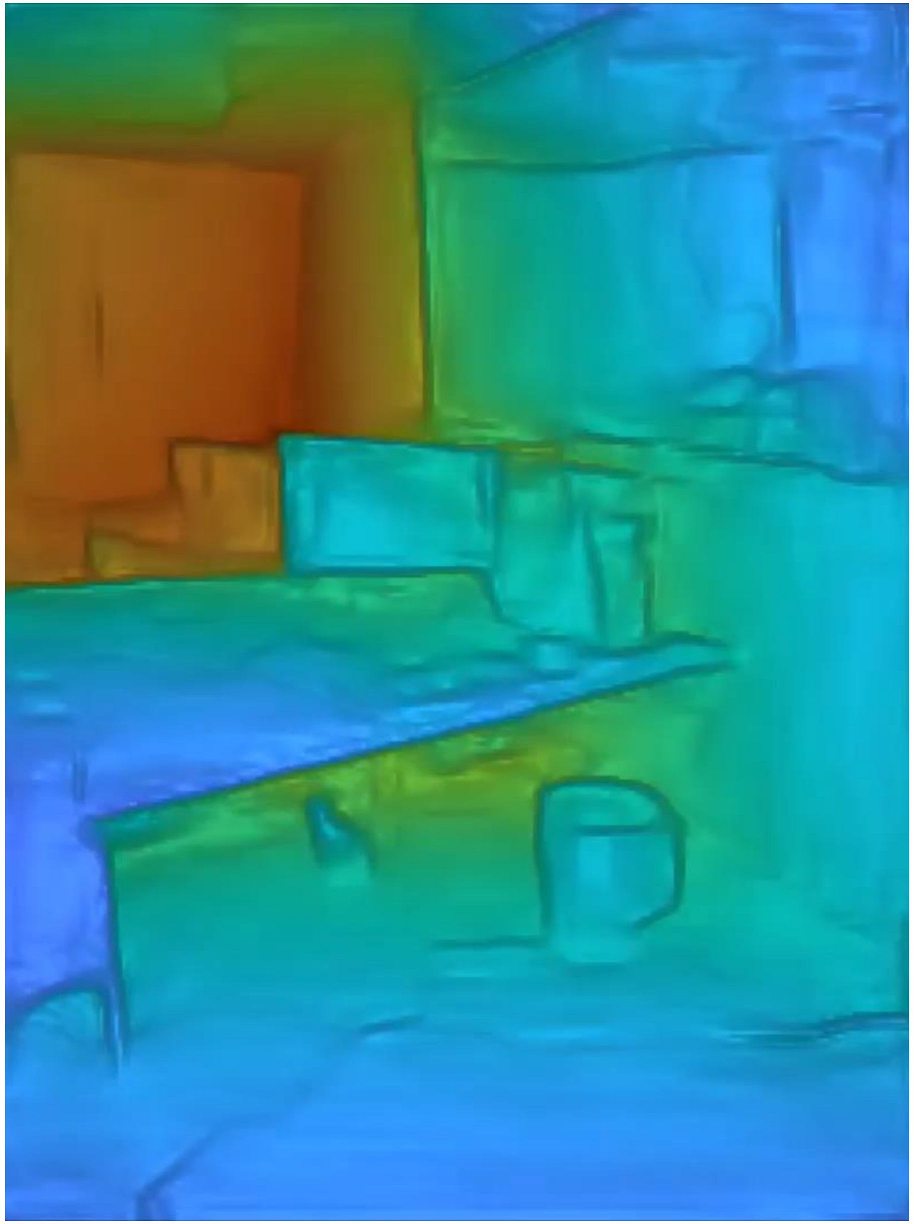
- Firmware (including on-chip depth map computation)
- Calibration and SLAM
- Partner management, algorithm integration
- Demonstrations

Partners

- Higher resolution depth map algorithm
- Scene reconstruction algorithm
- Demonstrations

Application | depth fusion

Android application in action



Application | 3d scene reconstruction

Android application in action

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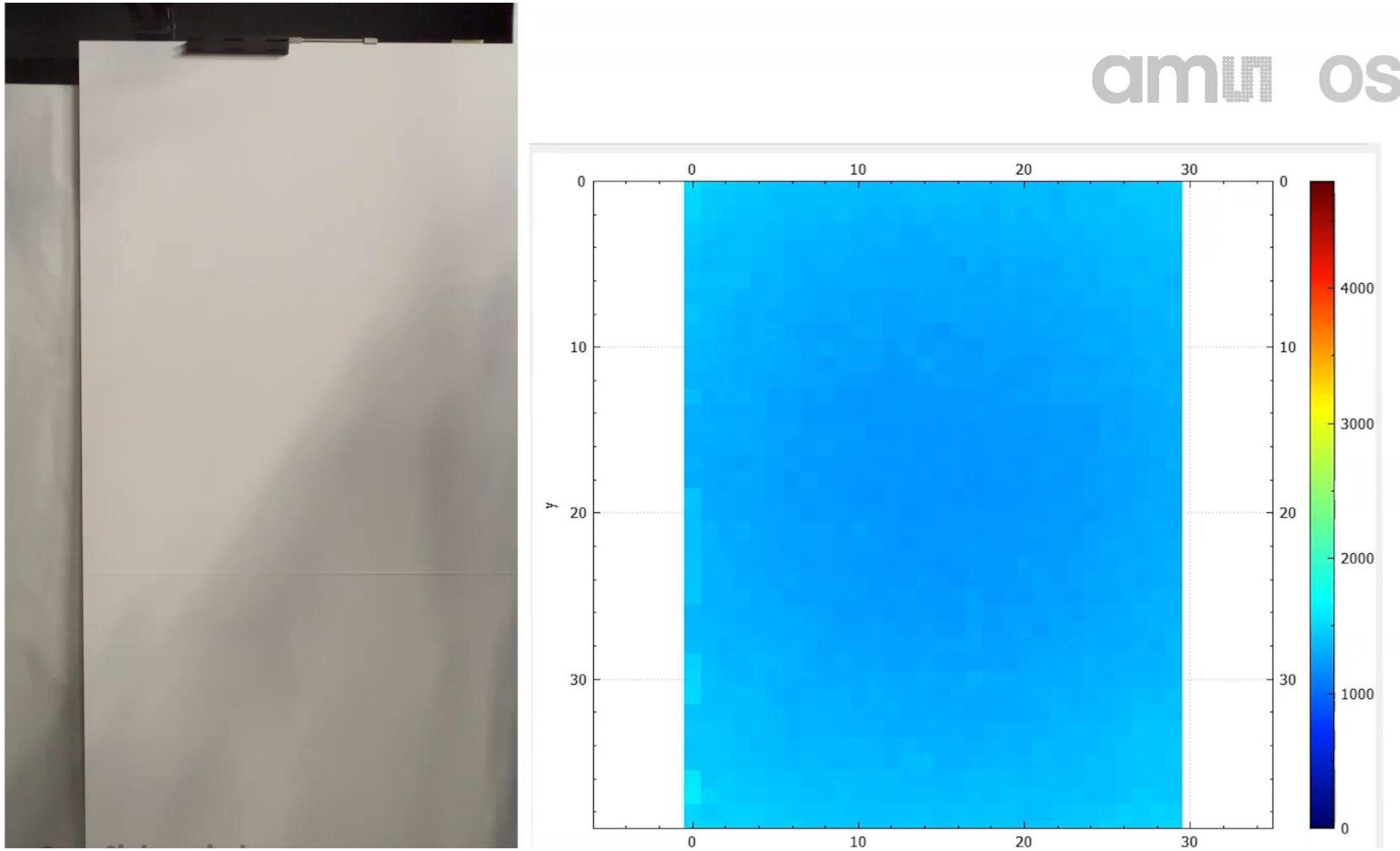
Performance | max distance, accuracy and precision

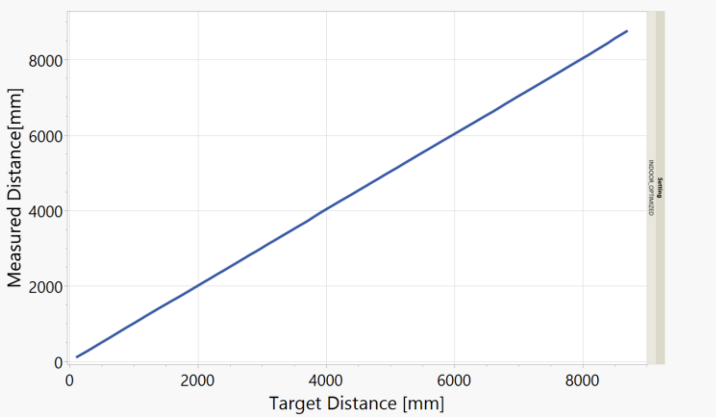
Test setup

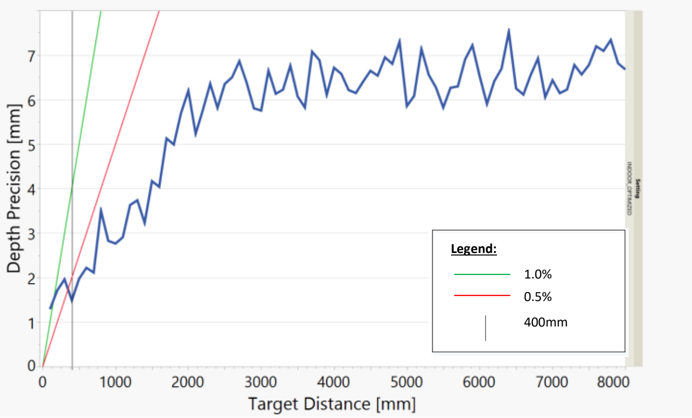


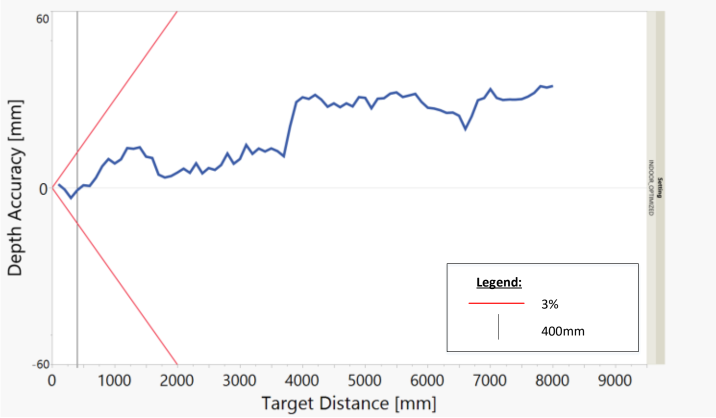
Performance | max distance, accuracy and precision

Precision and accuracy with white target

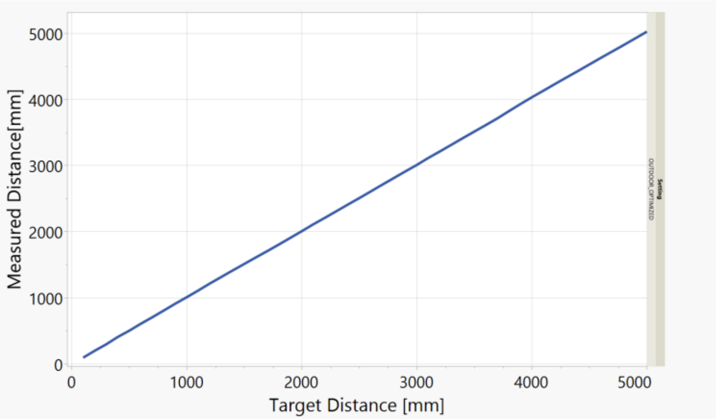
INDOOR
92% reflectance target
<1kLux

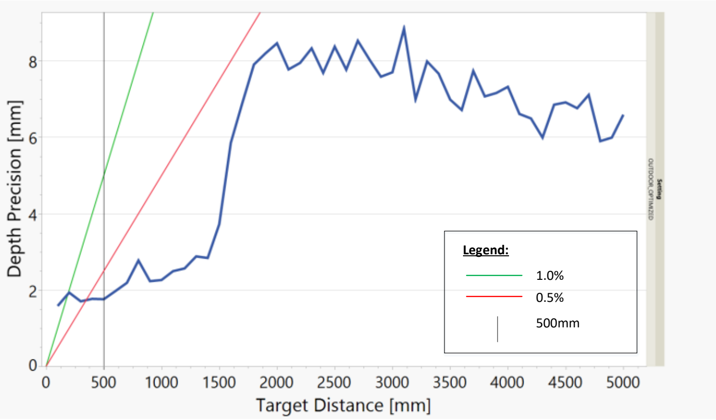


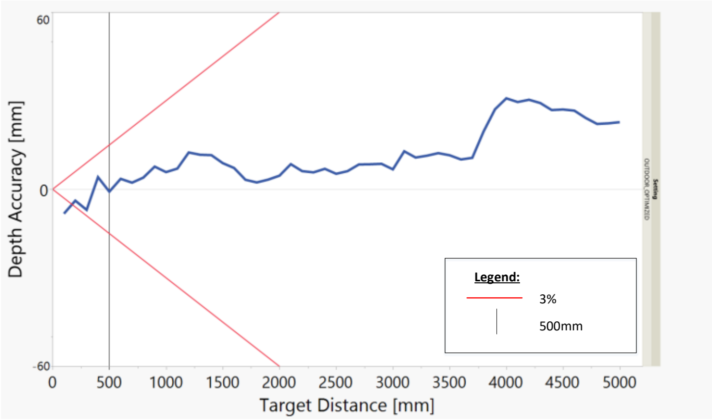




OUTDOOR
92% reflectance target
60kLux







Note: only points with 99% of detected points in 4x4 ROI over 100 repetitions are represented on the graph

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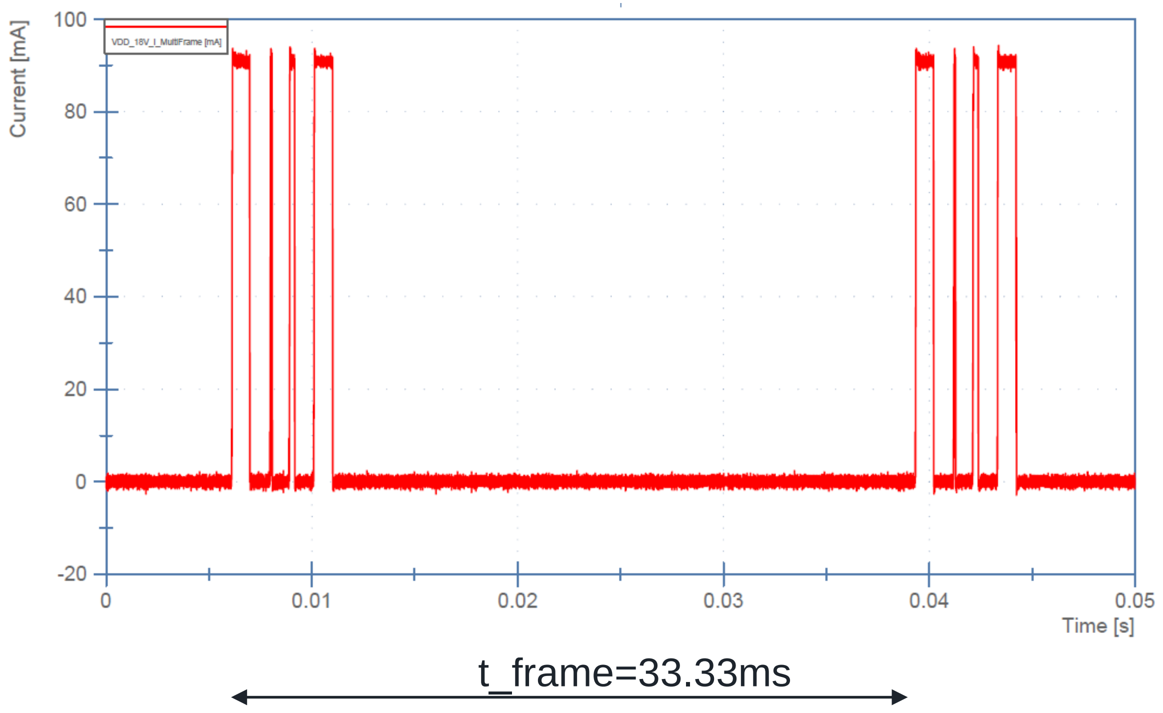
Power | conditions, settings and measures

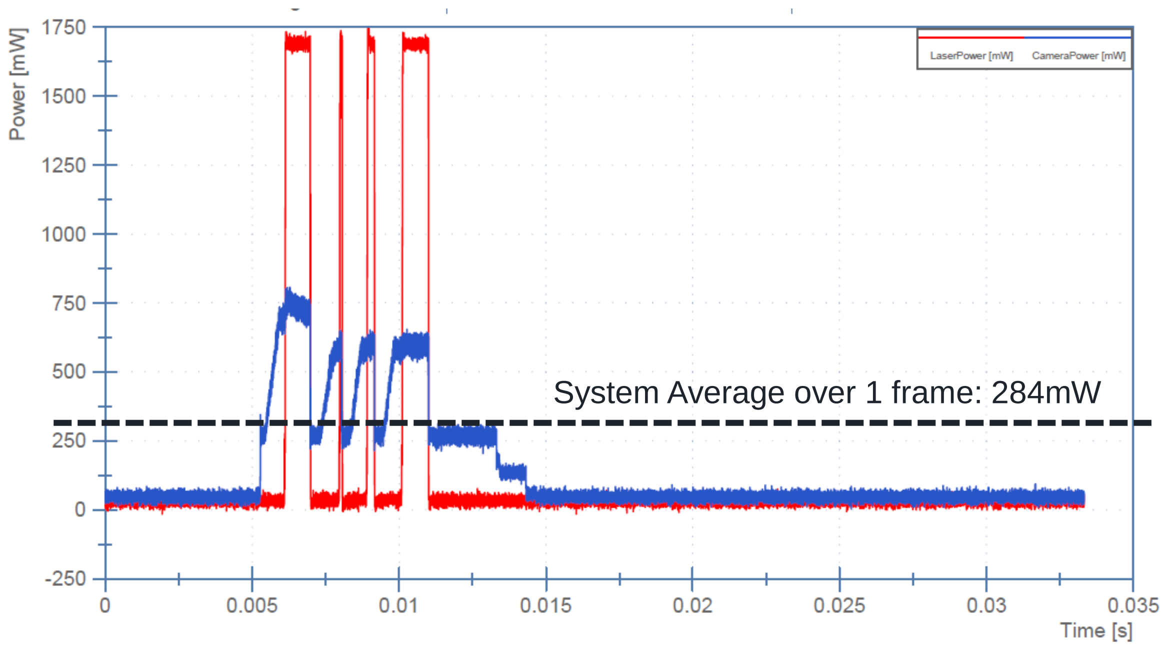
test mode	target reflectance	ambient light	max distance	frame rate	system power
OUTDOOR	92%	60kLux	5m	30fps	284mW
INDOOR	92%	<1kLux	8.2m	30fps	245mW
AF	18%	<1kLux	3.5m	10fps	109mW
AR_60FPS	18%	<1kLux	5m	60fps	342mW

Power | timing view

OUTDOOR

- 284mW power consumption @5m, 60kLux, 30fps
- Each peak is a burst of pulses with low-duty cycle (400ps/80ns)
- Possibility of reducing power in window W(0) with reduced precision requirement





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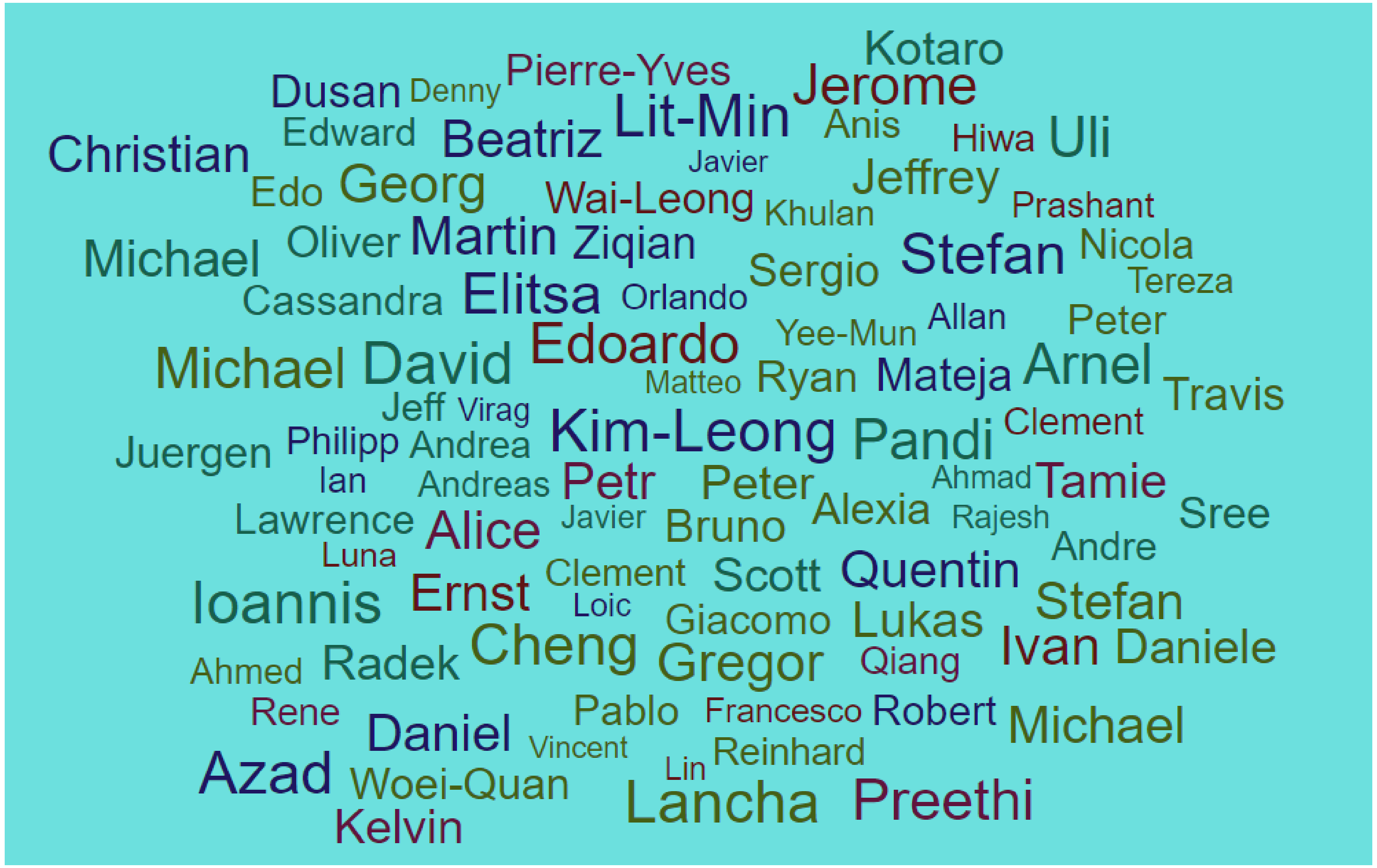
Conclusion | acknowledgments

We have presented a full dToF modular system with less than **300mW** system power consumption.

Thanks to all the team involved in the project.

Special thanks to **David Stoppa** for initiating and setting the direction of this fantastic journey

In memory of Uli, sponsor of the project, who has been an inspired and inspiring leader



Q & A

Sensing is life

appendix

Bibliography | references

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