DAY 2018 INNOVATION

SESSION 2

Umfeldsensorik mit LiDAR

Forschungsfabrik Mikroelektronik Deutschland

Eine Kooperation von Fraunhofer Mikroelektronik, FBH Leibniz Ferdinand Braun Institut, ihp

Gefördert vom Bundesministerium für Bildung und Forschung

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»Umfelderkennung in autonomen mobilen Systemen«

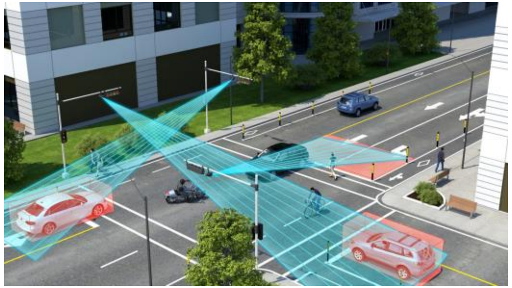
Werner Brockherde, Fraunhofer IMS

Outline

- LiDAR Technology
- Solid-State Photodetectors
- Design example
- Service of FMD

Lidar for automated driving

- LiDAR/LaDAR = Light/Laser Detection and Ranging
- Range determination by time-of-flight measurement
- To date mostly used in geoscience and military applications with use of active laser illumination in SWIR for eye-safety
- In automotive:
  - Use of active laser illumination, typically in NIR (905 nm)
  - Size, costs, and reliability become most important



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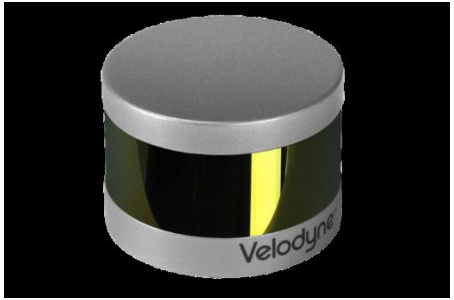
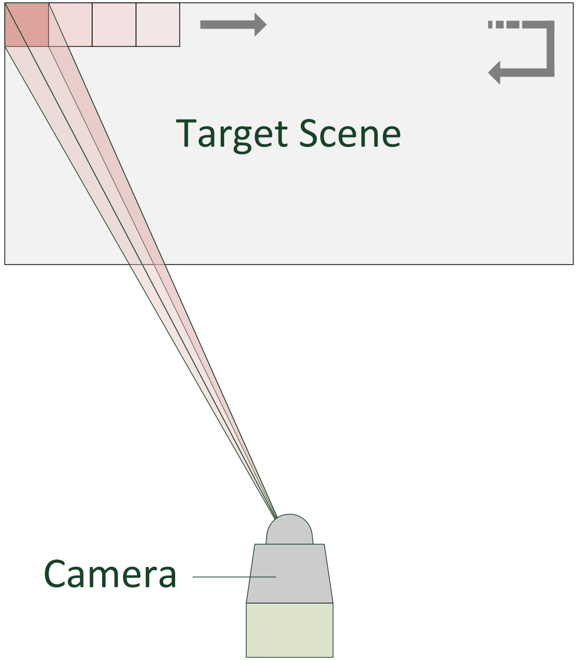
LIDAR-Methods: Scanning lidar



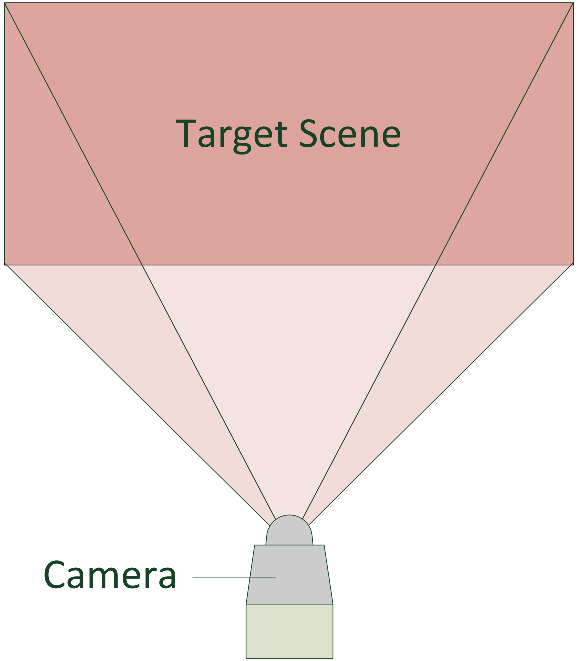
- Subsequent pointing to object area points
- Mechanical scan
- High optical power density
- High distance range
- Single detector element
- Only one object point at a time
- Low framerate
- Bulky and expensive

LIDAR-Methods: Beam stearing



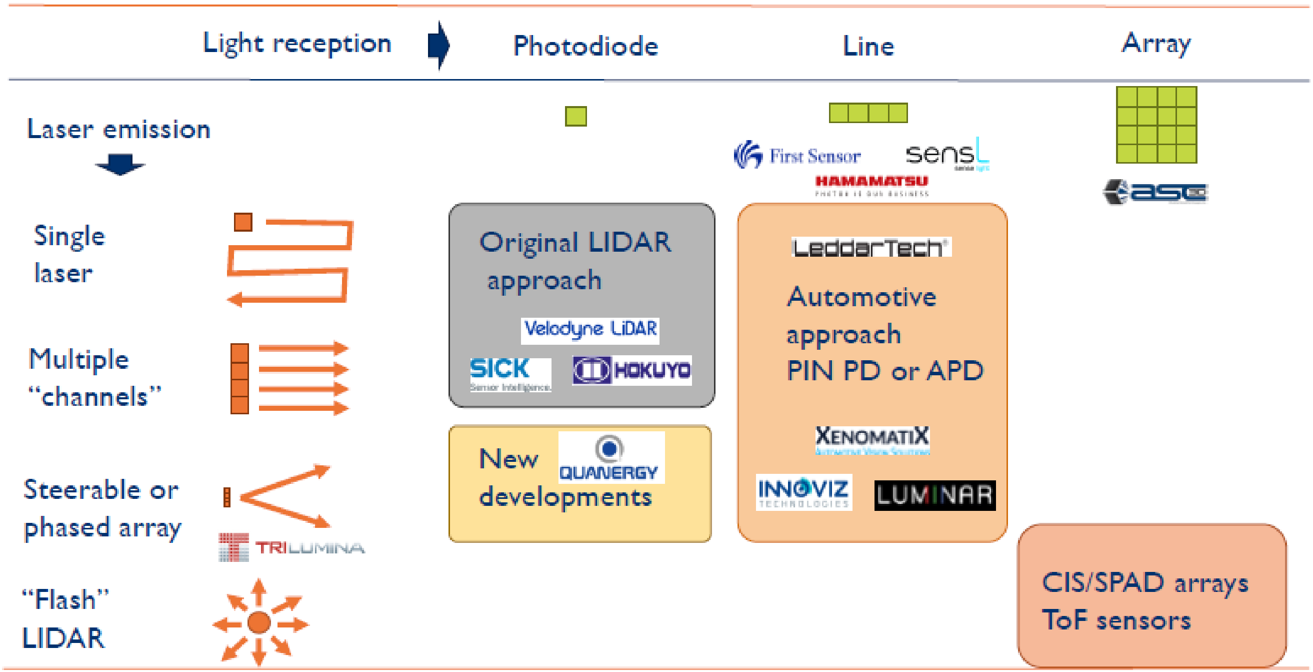
- Using **Micro Mirrors** or **Optical Phased Arrays**
- Subsequent pointing to object area points
- High optical power density
- Medium/High distance range
- **Detector array required**
- Only one object point at a time
- Low/moderate framerate
- Small size and low cost

LIDAR-Methods: Flash LiDAR



- Complete scene is taken in a flash
- **Solid state solution possible**
- No moving parts
- Low optical power density
- Low/Medium distance range
- Detector array required
- **High Framerate**
- **Small size and potentially low cost**

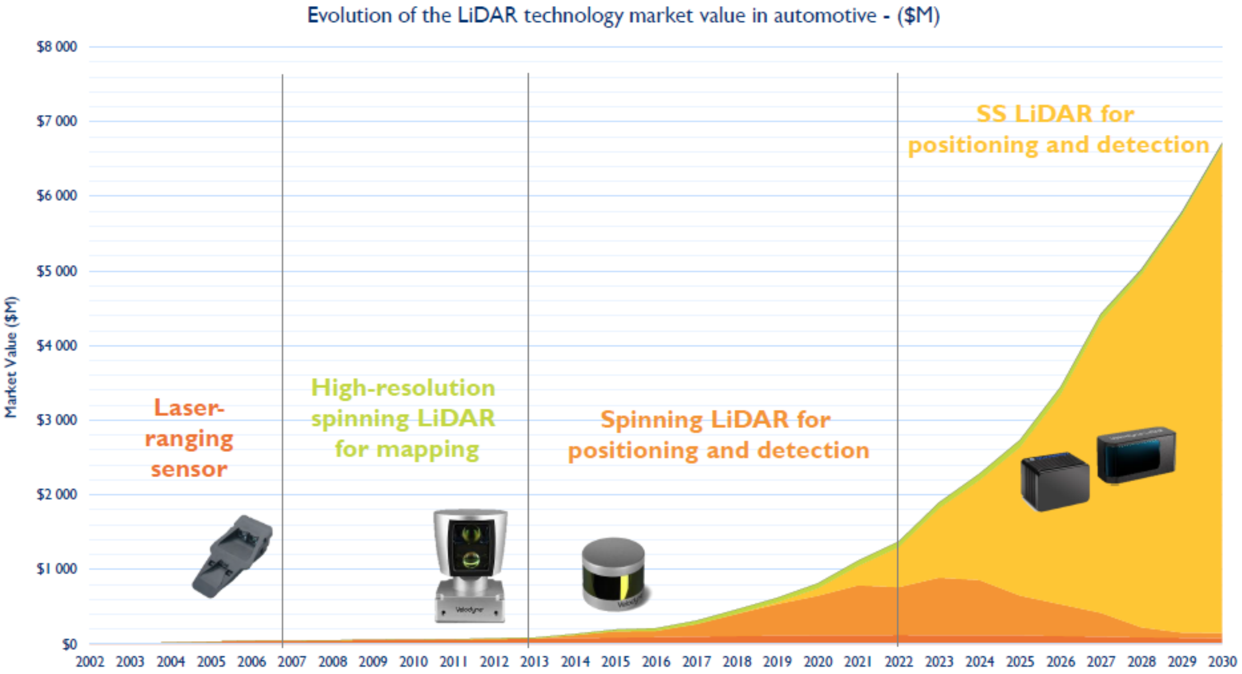
LIDAR-Methods



Source:

Yolé 2017

LIDAR-Methods – Market perspective



Source:

Yolé 2017

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Photodetectors for LiDAR

905 nm

- Silicon detectors
- Compatible to CMOS process technology
- High volume production possible
- Low cost

1500 nm

- III/V semiconductor detectors
- To be connected to Readout IC
- Performance is temp. dependent
- No high volume production yet

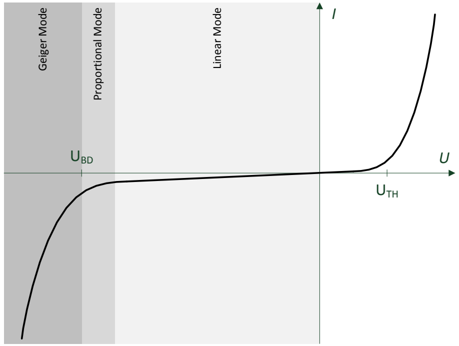
The 905 nm LiDAR is restricted to lower laser power and hence lower ranges compared to 1500 nm LiDAR

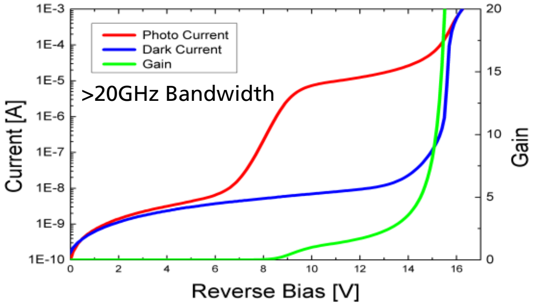
But it is best suited for low-cost systems

LiDAR @1500 nm allows much more laser power for eye-safe operation and hence is very useful in high-performance applications.

It is also less sensitive to background light

Solid-State Photodetectors

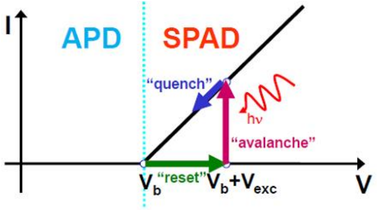


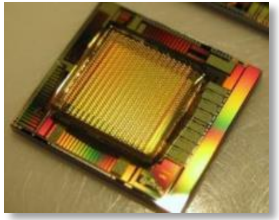


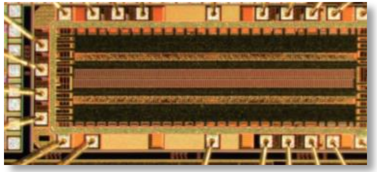
Avalanche photodiodes

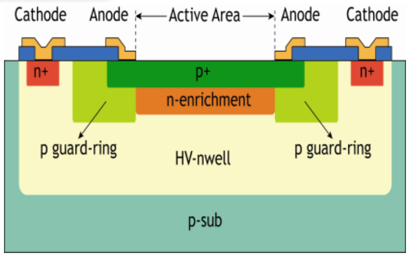
- Operation in proportional mode
- Gain is sensitive to bias and temperature variations
- Small arrays possible
- Available also for SWIR (~1500 nm)

Solid-State Photodetectors





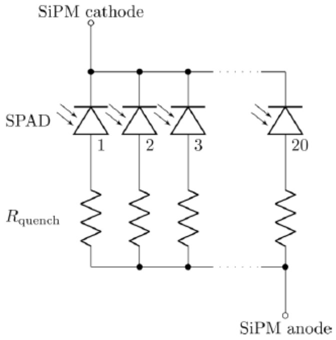


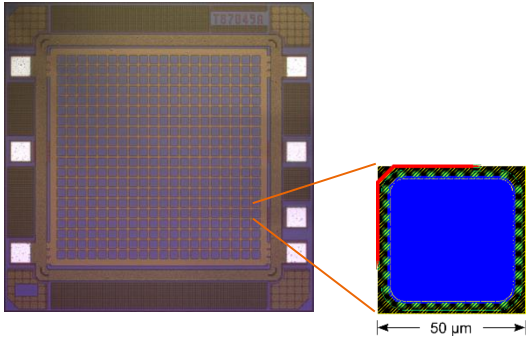


Single-Photon-Avalanche-Diode (SPAD)

- Avalanche photodiode operated above breakdown voltage (= Geiger-Mode)
- Very few photons can be detected
- CMOS integration allows for high spatial resolution and on-chip signal processing
- Fast operation with very good time resolution
- No analog signal processing needed

Solid-State Photodetectors

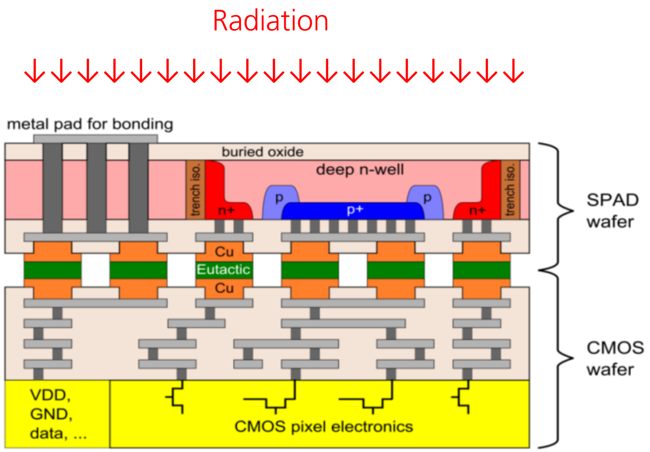




Silicon Photomultiplier SiPM

- Avalanche photodiodes in Geiger mode
- High gain and single-photon resolution
- CMOS integration allows on-chip pre-amplificaton and small arrays of SiPMs
- Example:
  - 20×20 SPAD-elements on 1×1 mm² active area
  - Geometric fillfactor: 68% @ 50µm pitch
- SiPMs are also used in high-energy physics or PET

Solid-State Photodetectors



Schematic cross section of backside illuminated SPAD sensor after integration

Backside Illuminated SPAD arrays

- High density CMOS readout circuit
- Optimized Si-wafers for best SPAD performance
- Wafer to wafer bonding process allows for higher production volumes
- Process more complex, but chip size can be drastically smaller

Silicon Photodetectors

	PIN-PD	APD	SiPM	SPAD
Gain	1	10^3	10^6	10^6
Single photon detection	No	No	Yes	Yes
Operational Bias	Low	Medium	Medium	Medium
Temperature Sensitivity	Low	High	Low	Low
Array possible	Limited	Limited	Limited	Yes
Readout / Electronics	Complex	Complex	Medium	Simple (digital)
Rise time	Medium	Slow	Fast	Fast

Outline

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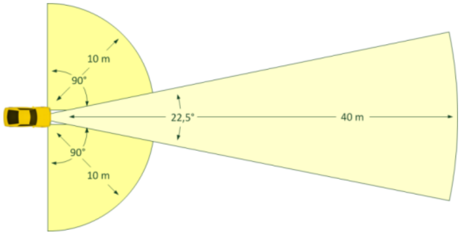
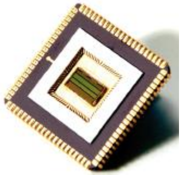
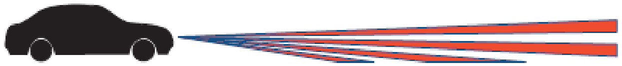
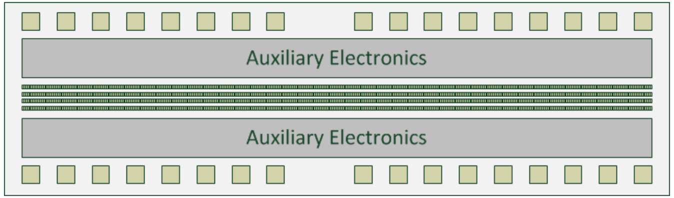
Design proposal for flash LiDAR



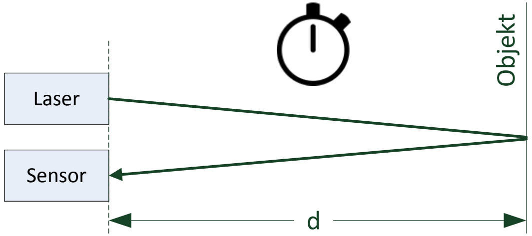


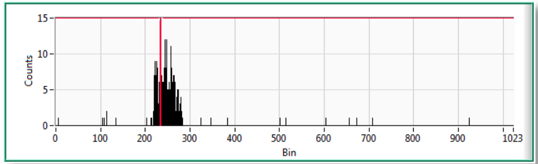


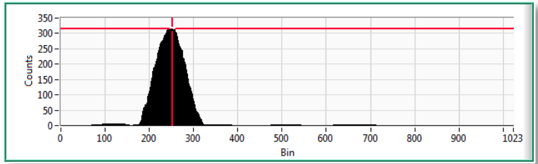


- Detection of target area by 4 lines
- Different FoVs and ranges
- Medium ranges < 100 m
- Detector allows high fillfactor
- Low vertical resolution may be overcome by push-broom effect
- Applications:
  - VRU detection
  - Side traffic
  - Parking assistance

Test vehicle: *OWL* camera with192 x 2 line sensor Distance measurement

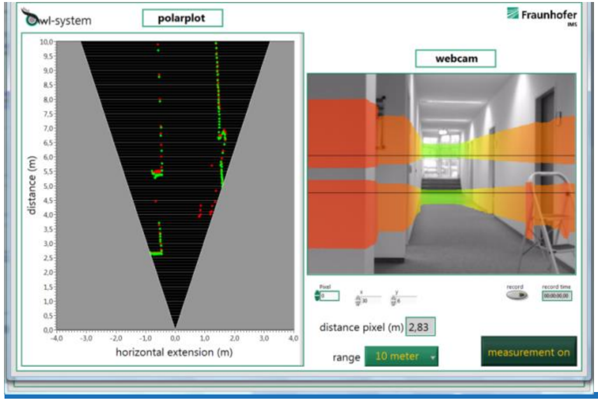






- Laser pulse width: 20ns
- Repetition rate:10kHz
- 400 pulses per frame
- Evaluation of timing histogram with filters and dedicated algorithms
- TDC resolution ca. 5cm
- Range: > 40 m @ 25fps

Test vehicle: *OWL* camera with192 x 2 line sensor



- 192 x 2 pixel SPAD LiDAR detector
- In-pixel TDCs
- Dynamic Range extension
- Circuitry for background light suppression
- Test with 905nm 75W laser
- FOV (laser): 2x (40,0° x 2,0°)
- Range: > 40 m @ 25fps

Test vehicle: *OWL* camera with192 x 2 line sensor
Background light suppression

Video

- Outdoor scene with ca. 90 klx sunlight
- Distance ca. 15 m; 25 fps
- BG light is suppressed

Outline

- LiDAR Technology
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Service of FMD

- Concept and feasibility studies
  - Based on existing technologies
  - New approaches, e.g. FMCW-LiDAR
- Modeling of LiDAR Systems in applications including
  - Laser, optics, MEMS, detectors and signal processing
  - Environmental conditions (e.g. sunlight)
- Development of custom photodetectors and photodetector arrays
  - APDs (Si and III/V); SPAD arrays; BSI SPAD arrays; SiPM (-arrays)
- Qualification for series production
- Pilot production

Thank You !

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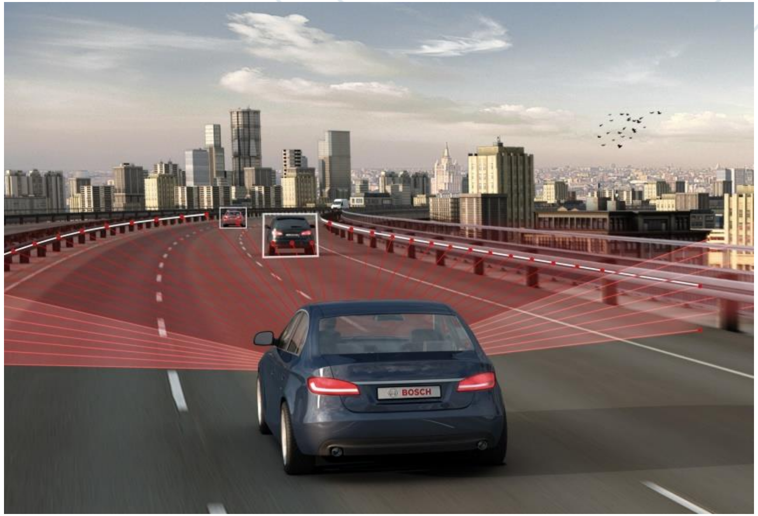
»Laserquellen für LiDAR-Systeme«

Dr. Andrea Knigge, Dr. Hans Wenzel

Ferdinand-Braun-Institut
Leibniz-Institut für Höchstfrequenztechnik

Outline

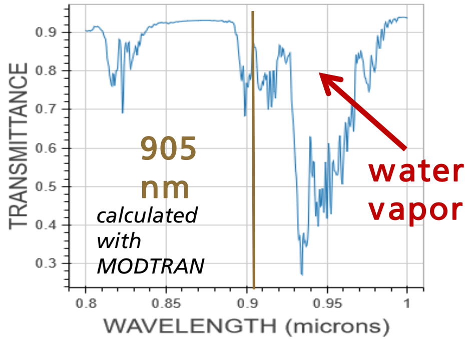
- Diode lasers for automotive LiDAR systems with 905 nm wavelength (FBH)
  - Motivation, Requirements
  - Layer structure, Bragg grating, electronic driver
  - Diode lasers with one and three emitters
- Diode lasers with longer wavelengths (1.5 µm HHI and > 2 µm IAF)
- Summary



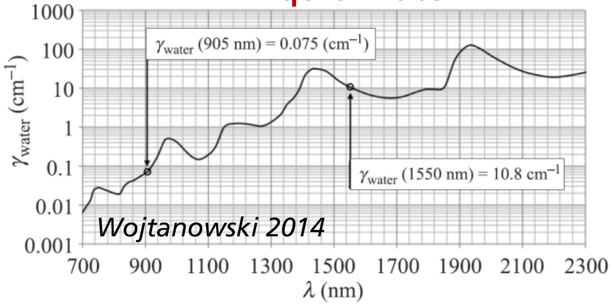
https://www.bosch-presse.de/pressportal/de/de/neue-sensorik-fuer-intelligente-automatisierung-78080.html

Requirements for lasers to be used for automotive point-scanning time of flight (TOF) LiDAR

- Application under real atmospheric conditions
  - ⇨ emission wavelength within transparency window ⇨ λ = 905 nm
  - ⇨ wide working temperature range (-40°C … +85°C) to enable non-temperature stabilized operation
  - ⇨ suppression of sun light to improve SNR ⇨ emission within a small spectral window < 10 nm over whole temperature range
    - ⇨ wavelength stabilization by monolithic integrated Bragg grating
    - ⇨ adapted layer structure
- High temporal resolution and eye safety
  - ⇨ short pulses < 10 ns ⇨ layer structure optimized for high current densities
- Large scanning range
  - ⇨ pulse power of 100 Watt ⇨ broad-area edge-emitting laser diode
- High spatial resolution
  - ⇨ sufficiently good beam quality ⇨optimized emission aperture

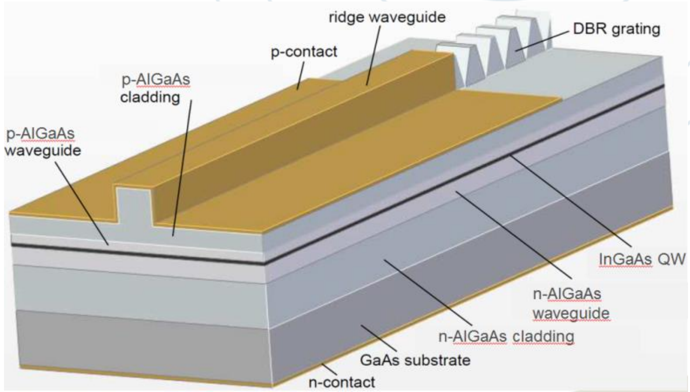


liquid water



FBH device:
Distributed Bragg reflector (DBR) broad area (BA) laser

- GaAs-based
- single-step MOVPE
- emission wavelength near 905 nm at RT
- lateral optical and electrical confinement by dry-etched trenches
- contact widths: W = 30, 50, or 100 µm
- total cavity length L = 6 mm
- higher-order surface Bragg grating integrated in the rear part of the cavity, L(DBR) = 1 mm
- suitable for p-up or p-down mounting



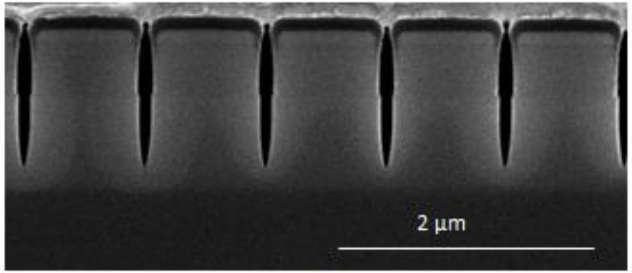
Structure for pulsed automotive LiDAR application controlled by simulation using drift-diffusion based model (WIAS-TeSCA):

- only small carrier accumulation at high current densities (strongly reduced leakage currents and additional free carrier absorption)

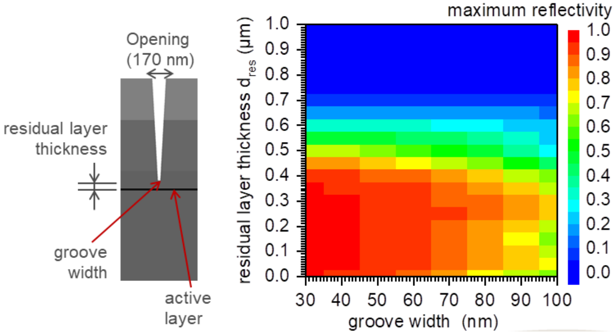
Design of surface Bragg grating

- Processing
  - E-beam lithography (i-line wafer stepper alternative)
  - dry-etching
  - no regrowth (single step MOVPE)
- Parameters
  - 7th order, period 960 nm
  - length of grating LDBR = 1 mm
  - opening of V-shaped slits 170 nm
  - width at bottom (groove width) and residual layer thickness
- Simulation of grating reflectivity with mode matching tool
  - peak reflectivity > 90% for residual layer thickness up to 0.3 µm and groove widths < 50 nm
  - absorption losses neglected

Fricke 2012

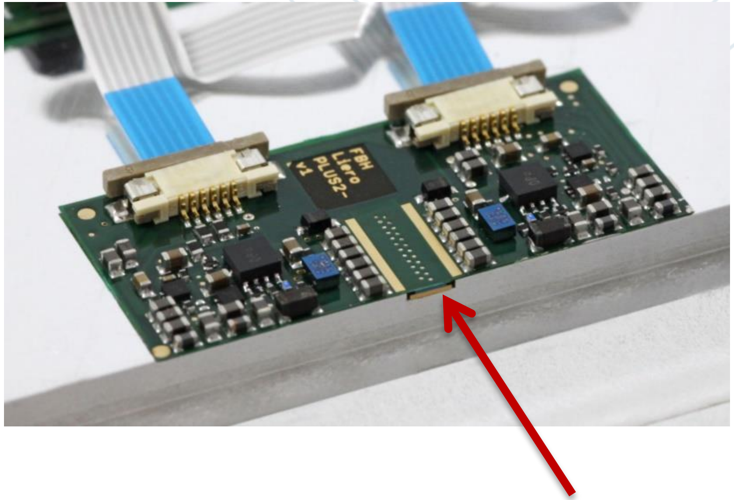


SEM picture of cleaved DBR section



GaN Pulse Laser Drivers for LiDAR

- Specs
  - Lasers with > 100 W peak power
  - Pulse widths 3 … 10 ns
  - Switching currents > 100 A_{pp}
- Challenges
  - Transistors with high-speed high-current capabilities
  - Low-inductive assembly
- Solution
  - GaN offers best performance
  - Hybrid circuit with CMOS & GaN
  - TTL input
  - Dedicated mounting scheme



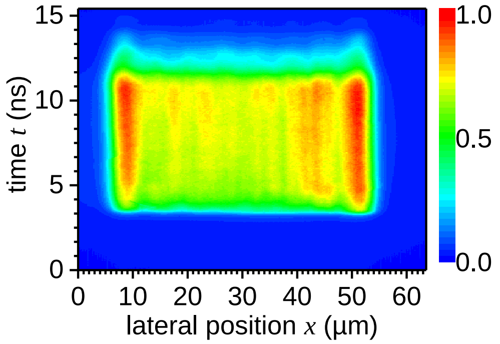
laser

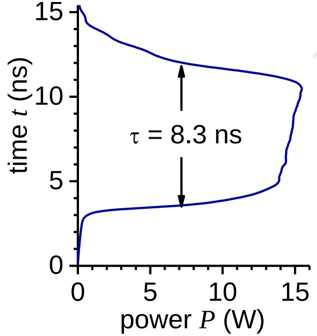
Single emitter diode laser: Pulse characteristics

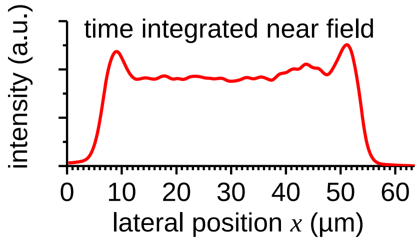
- Known or measured quantities
  - repetition frequency f
  - average current I_{av} and power P_{av}
  - lateral near field intensity NF(x,t) versus time
- Derived quantities

pulse energy	E	$= \dfrac{P_{\text{av}}}{f}$		$= 130$ nJ
pulse shape	$p(t)$	$= \int \text{NF}(x,t)\,dx$		
power vs. time	$P(t)$	$= \dfrac{p(t)E}{\int p\,dt}$		
pulse width	τ	$=$ FWHM of $P(t)$		$= 8.3$ ns
pulse power	P_{pulse}	$= \dfrac{E}{\tau}$		$= 15.7$ W
current	I	$= \dfrac{I_{\text{av}}}{\tau f}$		$= 20.5$ A

time resolved lateral near field intensity NF(x,t)
streak camera (100 pulses averaged)







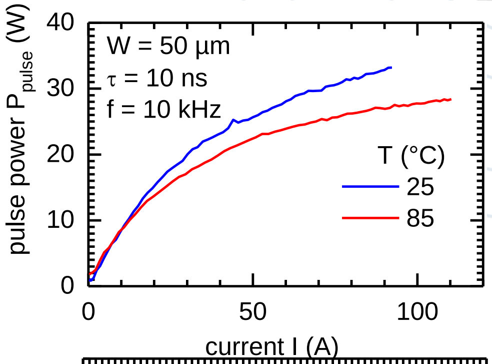
τ_{Gen} = 10 ns
f = 10 kHz
I_{av} = 1.7 mA
P_{av} = 1.3 mW

Klehr 2018

Single emitter diode laser: Power and optical spectra in dependence on temperature

- Pulse power P
  - up to 33 W @ T = 25°C
  - up to 28 W @ T = 85°C

  starting saturation for P > 15 W or I > 20 A

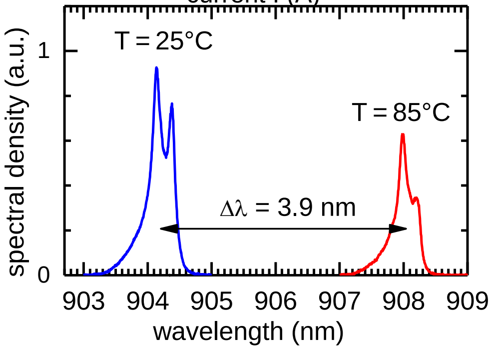


- Time-averaged optical spectra
  - spectral shift Δλ = 3.9 nm for ΔT = 60 K

    ➪ Δλ / ΔT = 65 pm/K

    ➪ Δλ ~ 8 nm for T = [-40°C, +85°C]

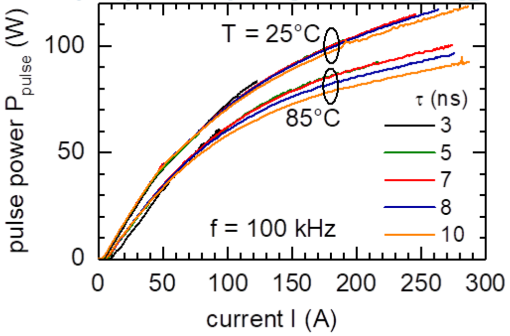
    (would be Δλ ~ 40 nm without Bragg grating)
  - spectral width: < 0.5 nm



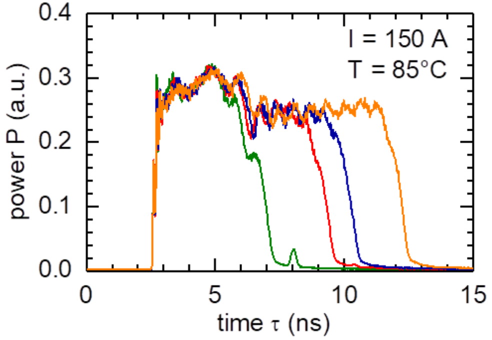
A. Knigge 2018

3-emitter diode laser: Power and optical spectra in dependence on temperature

- 3-emiter chip:
  - adjustable optical pulse length: 3 ns … 10 ns
  - maximum optical pulse power:
  - P_{pulse} = 120 W @ T = 25°C
  - P_{pulse} = 100 W @ T = 85°C

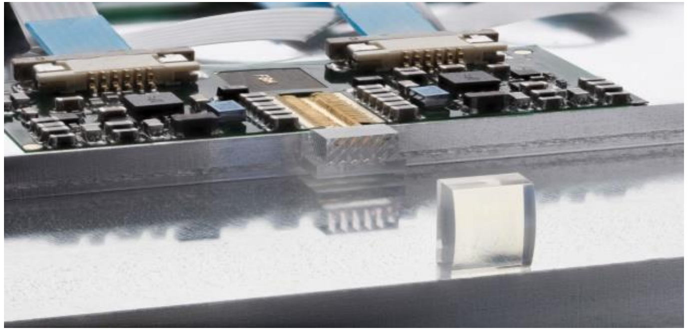


- Pulse shape
  - steep pulse edges
  - ⇨ good matching of electrical driver and laser chip with minimized distances for low inductive losses

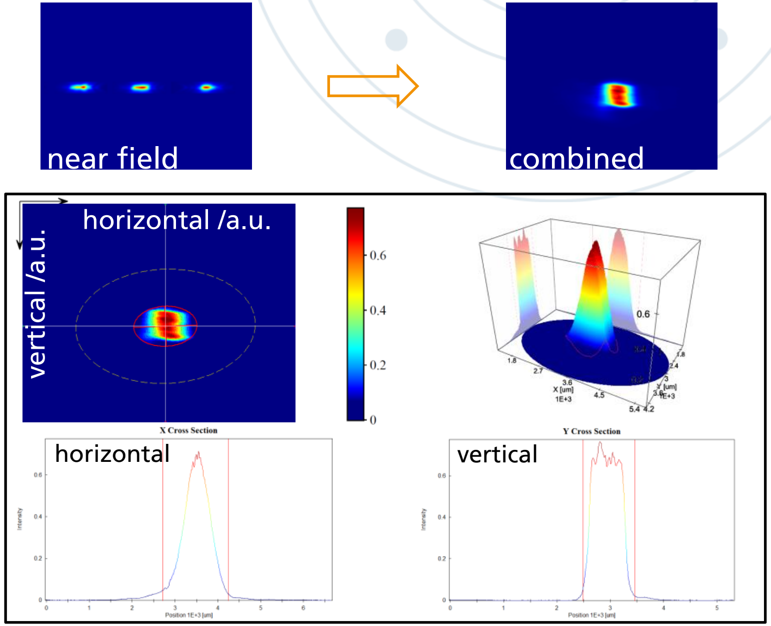


Beam collimation of 3-emitter chip

- 3 emitters combined with fast and slow axis collimation and BeamTwister™ by FISBA Photonics GmbH, Berlin
  - Remaining divergence: 5 mrad (H) / 3 mrad (V)
  - 90 cm x 56 cm spot after 180 m (calculated)



FISBA



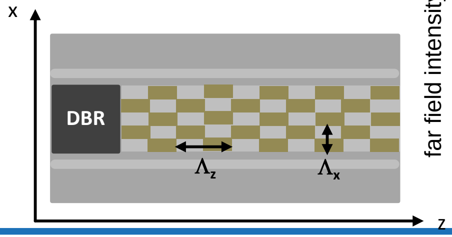
Beam propagation behind SAC-lense (@P_{Puls} ~70 W;120 A;10 ns;100 kHz)

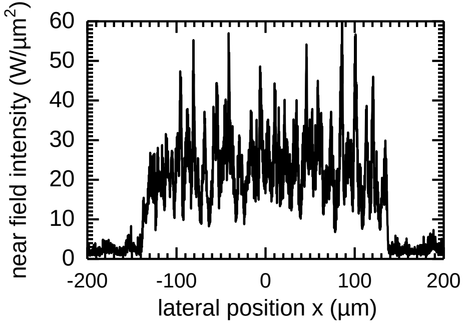
Flexible technology kit for a broad range of LiDAR applications

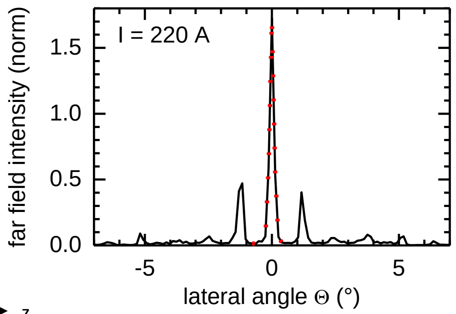
- In a single housing:
  - laser chip directly integrated with driver unit
  - electrical and programming control unit
- At present on hand:
  - wavelength: 905 nm, wavelength-stabilized
  - optical pulses: 0,4 – 20 ns
  - optical pulse power up to 100 W
  - switching currents up to 250 A
  - internal or external trigger
  - repetition frequency 10 kHz – 1 MHz
- Other configurations on request

Next steps of development of 905 nm diode laser

- Further power increase:
  - Increase of emitter width ⇨ decrease of beam quality
  - Bars with up to 48 DBR emitters
- Improvement of lateral beam quality (smaller spot size)
  - periodic lateral (x) and longitudinal (z) gain and index variations
  - results of a simulation with WIAS-BALaser:
    - total power P = 80 W
    - central lobe:
      - P_{cl} = 32 W
      - $Q_{95\%,cl}$ = 0.65°, $W_{95\%}$ = 272 µm
      - $BPP_{95\%,cl}$= 0.77 mm mrad, $B_{95\%,cl}$ = 41 W/(mm mrad)

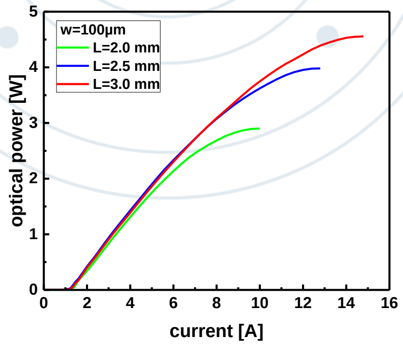


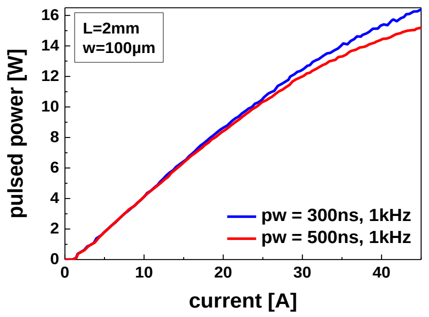




Fraunhofer-Institut für Nachrichtentechnik, Heinrich-Hertz-Institut, HHI: InP diode lasers for ~ 1.5 µm

- Advantages compared to 905 nm:
  - lower solar radiation background
  - better performance under hazy conditions (lesser scattering loss)
  - much higher eye safety power limit
- Available InP diode lasers at 1.5 µm from HHI:
  - BA-lasers: cw operation: 5 W; pulsed operation: 16 W (300 ns), thermally limited → much higher output power possible at 5 ns for pulsed LiDAR
  - coherent light source; tunable lasers for beam steering for FMCW LiDAR
- Special adaption for LiDAR systems possible also with detector integration

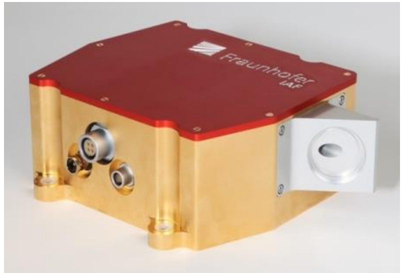




Fraunhofer-Institut für Angewandte Festkörperphysik, IAF: Semiconductor lasers for 2 – 11 µm wavelength range

- In comparison to 905 nm:
  - Higher visibility range due to lower scattering losses
  - Eye safety: lower Nominal Ocular Hazard Distance, i.e. higher power permitted
- Applications:
  - Military: Long-range surveillance and reconnaissance
  - Security: Support of task forces and rescue teams under degraded visual environments
  - Space: Atmospheric research and earth observation

Semiconductor Disk Lasers (SDLs)
for 2 – 3 µm:
- Output power > 1 W at 25°C
- Spectral line width > 20 kHz (stabilized)
- Pulse length > 32 ns
- Pulse energy < 3.3 mJ



Quantum Cascade Lasers (QCLs)
for 4 – 11 µm:
- Output power > 0.5 W
- Spectral tuning range < 300 cm^{-1}

Summary

- Distributed-Bragg-reflector broad-area laser integrated in a nanosecond electronic driver suitable of automotive LiDAR
  - optical pulse lengths 3 … 10 ns
  - emission wavelength 904 nm @ T = 25°C
  - wavelength shift < 10 nm between temperatures of -40°C and +85°C
  - pulse power 100 W @ 85°C (3-emitter chip)
  - spot of combined beam 90 cm x 56 cm at distance of 180 m
  - ease of manufacture due to higher-order surface grating
  - flexible technology kit available: single housing for diode laser, electrical and programming control unit
- 1.5 µm wavelegth: BA diode lasers available, adaption for LiDAR application possible
- 2 – 11 µm wavelength range: Semiconductor Disk Lasers and Quantum Cascade Lasers available

With thanks to:

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  - Ralf Ostendorf
  - EU project »MIRPHAB« – Mid-infrared photonics devices fabrication for chemical sensing and spectroscopy applications
  - Research contracts with German MoD (BMVg, WTD91)

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SESSION 2

Umfeldsensorik mit LiDAR

Forschungsfabrik Mikroelektronik Deutschland

Eine Kooperation von

Fraunhofer MIKROELEKTRONIK

FBH Leibniz Ferdinand Braun Institut

ihp

GEFÖRDERT VOM

Bundesministerium für Bildung und Forschung

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»Mikrospiegel für die Laserstrahlführung«

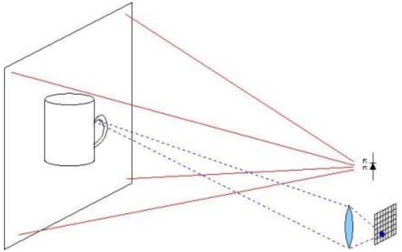
Jörg Amelung, FMD

Time of Flight (ToF) 3D-Distance Measurement

Parallel Data Capture ⟷ **Serial Data Capture**

3D-Cameras

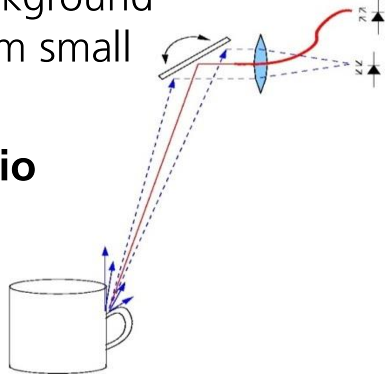
- Signal light is distributed over entire FOV of 3D measurment (small intensity per Pixel
- collects Signal- und background light over long integration times



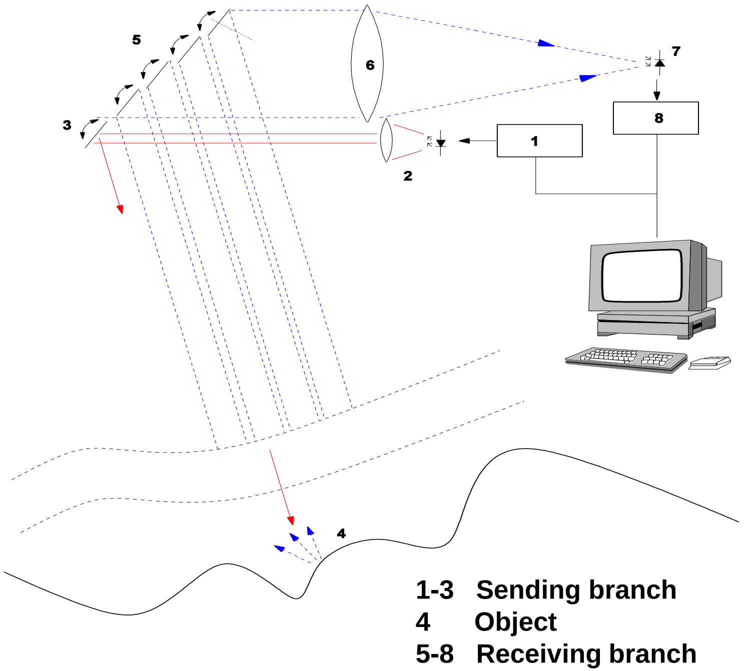
Laser Scanners

- Single measuring points are illuminated sequencially within FOV
- collects light of signal- & background (noise) in short time only from small measured area

⇒ **Enhanced signal/noise ratio**



MEMS based LIDAR Scanner Concept



Distance Laser Scanner using MEMS

Advantages

+ **fast scanning** (no air bearings)
+ **low weight, very robust**
+ (potentially) low cost

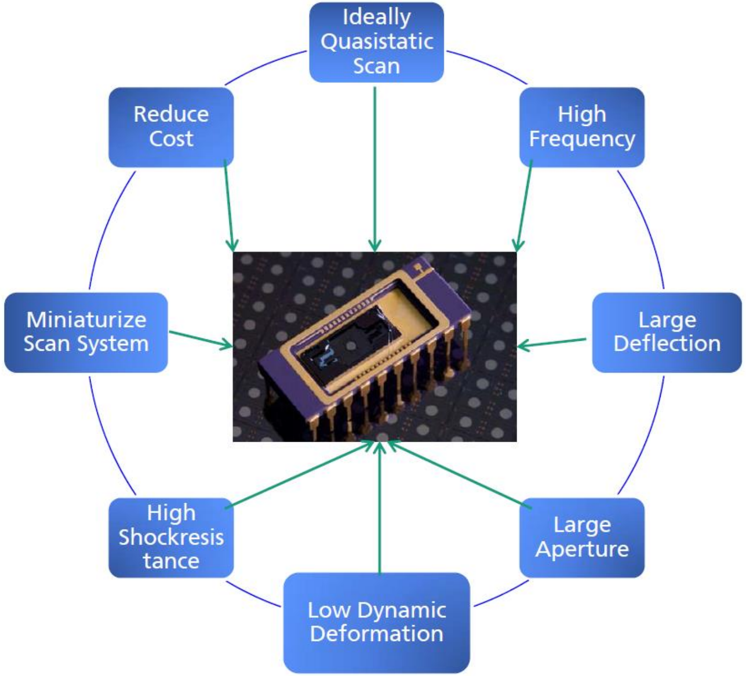
Challenges

- **large receiving aperture indispensable**

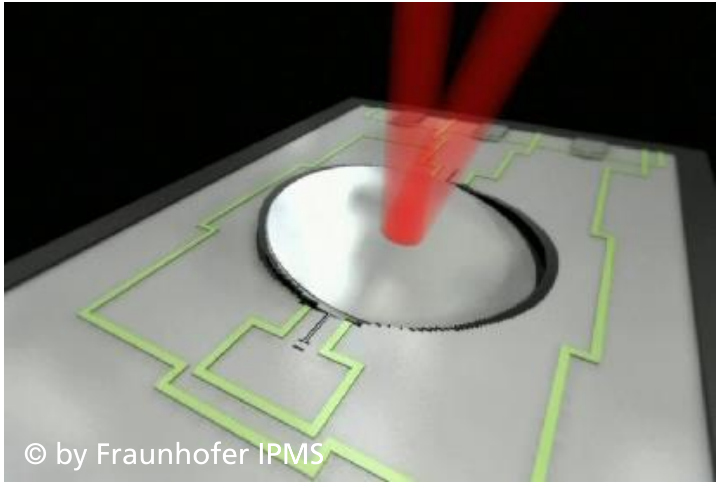
⇒ **several mirrors required** in reception branch to enable **large amplitude**

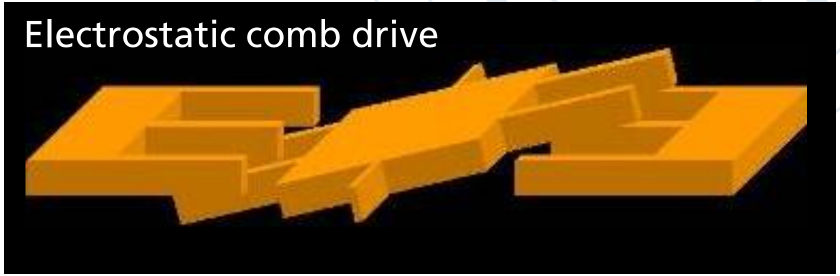
⇒ **synchronized movement of all mirrors**

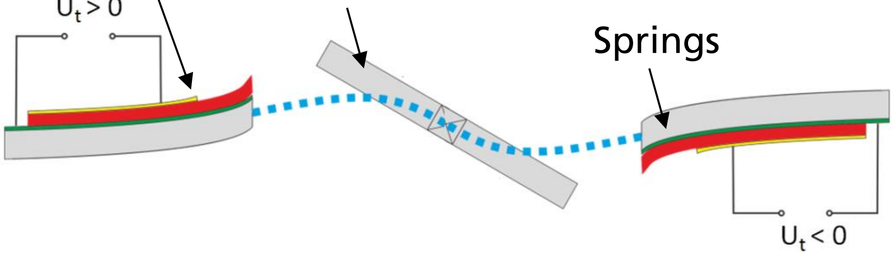
MEMS Mirror requirements for LIDAR applications



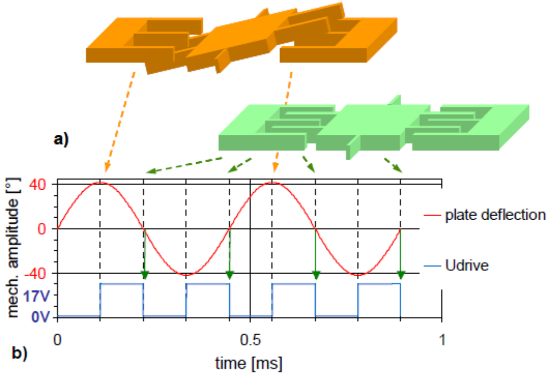
MEMS Mirror Principles

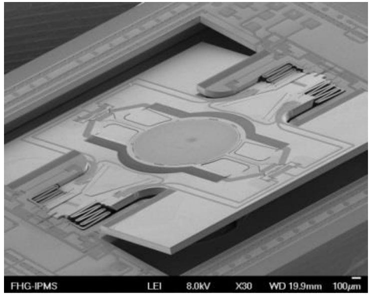


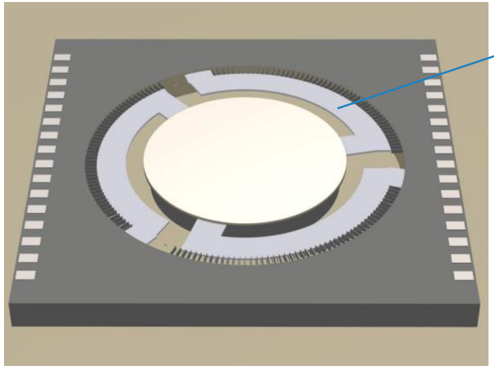




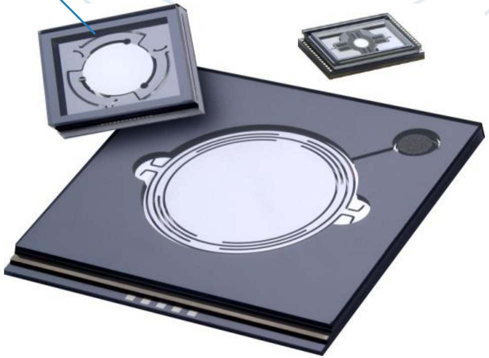
Resonant principle for combdrive





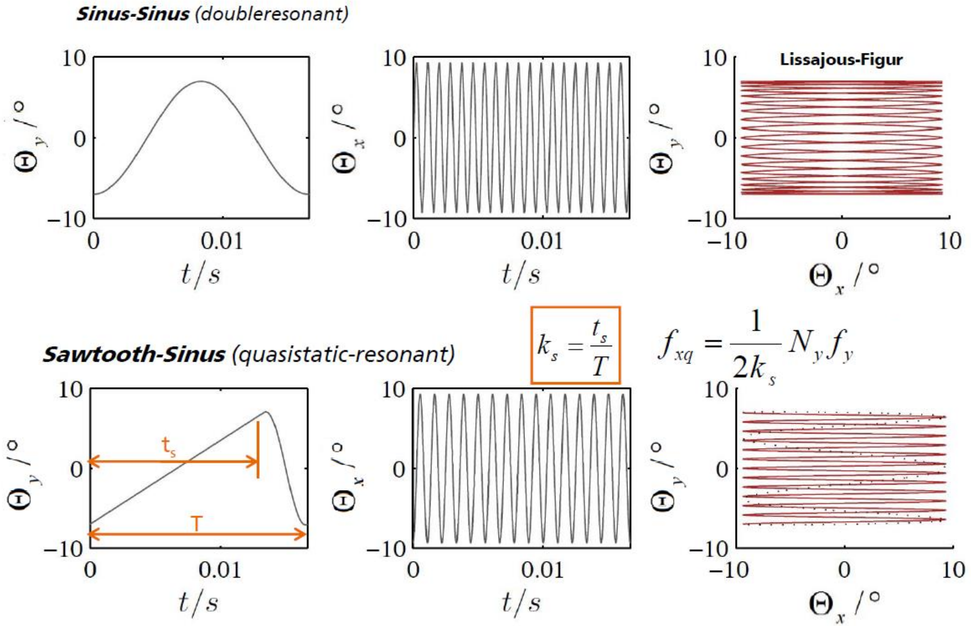


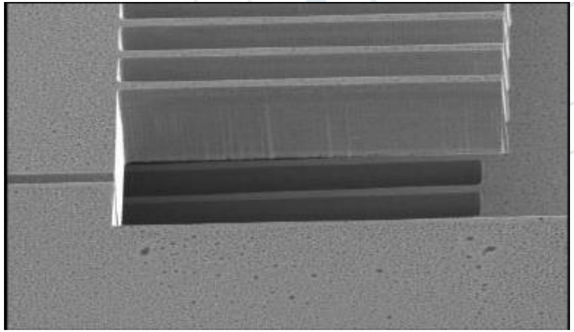
circular bending springs

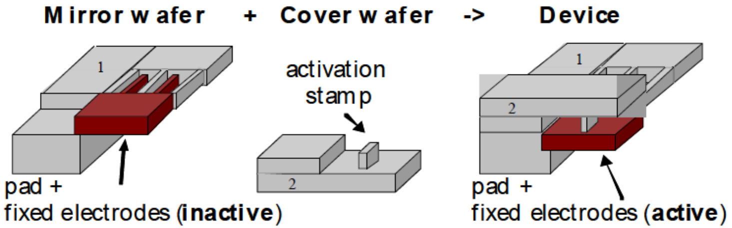


- Identical resonant frequencies in xy
- Minimum chip-size
- Circular springs enable large tilt angle
- Advantageous eigenmode spectrum

Resonant and quasistatic-resonant principle for combdrive

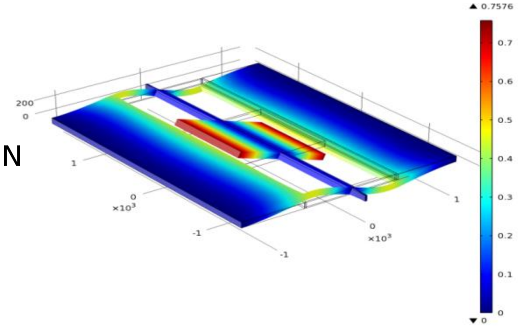


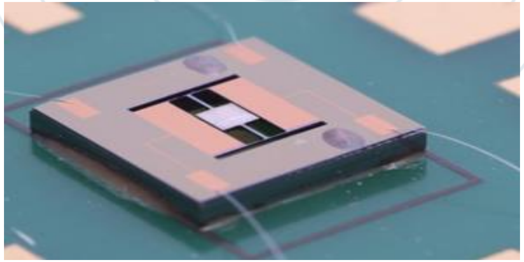




Piezoelectric actor principle

- **Unimorph MEMS structures**
  active layer: AlN, PZT, AlScN
  typical electrodes: Pt, Mo, Ti, Cr/Au
  typical passive layer: mono-Si, poly-Si, SiO_2, AlN
- **AlN**
  non-ferroelectric, IC-compatible
  low loss dielectrics, bipolar
  $e_{31,f} \approx 1.08$ C/m² → sensor material
- **$Al_{0.57}Sc_{0.43}N$**
  non-ferroelectric, IC-compatible
  low loss dielectrics, bipolar
  $e_{31,f} \approx 3.16$ C/m² → sensor/actuator material
- **PZT**
  ferroelectric, non IC-compatible
  lead zirconate titanate, $Pb(Zr_x,Ti_{1-x})O_3$, $x \approx 52\%$
  $e_{31,f} \approx 21$ C/m² → actuator material





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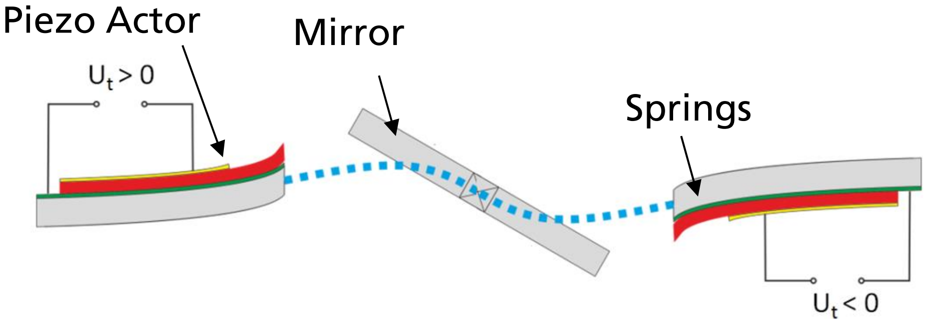
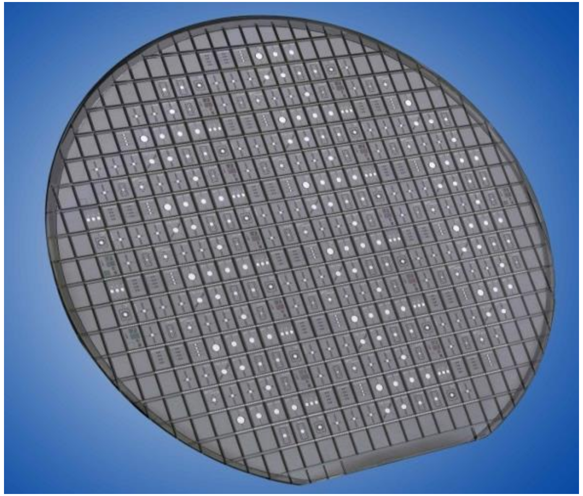
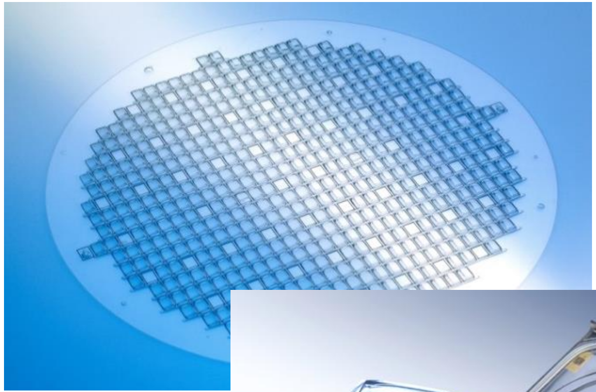
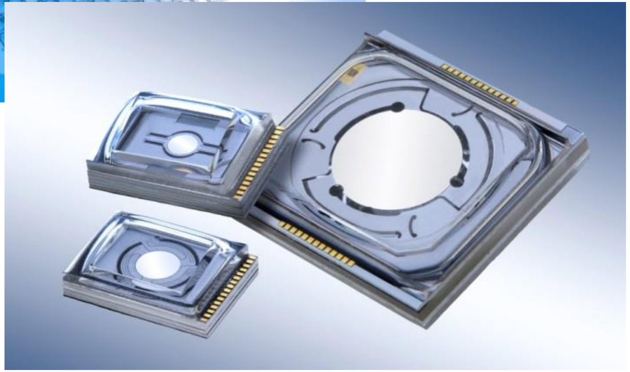
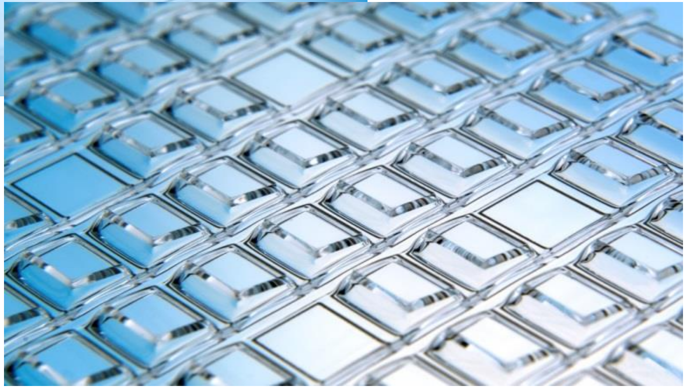


Integration Issue
Hermetic Wafer Level Vacuum Packaged MEMS Mirrors



Unique Glass Forming Technology for WL-Opto-Packages



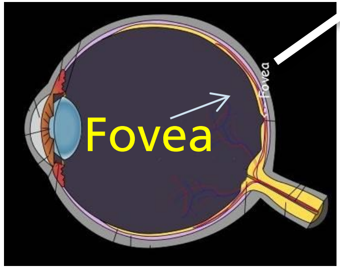
3D-Camera with Object Detection and Foveation

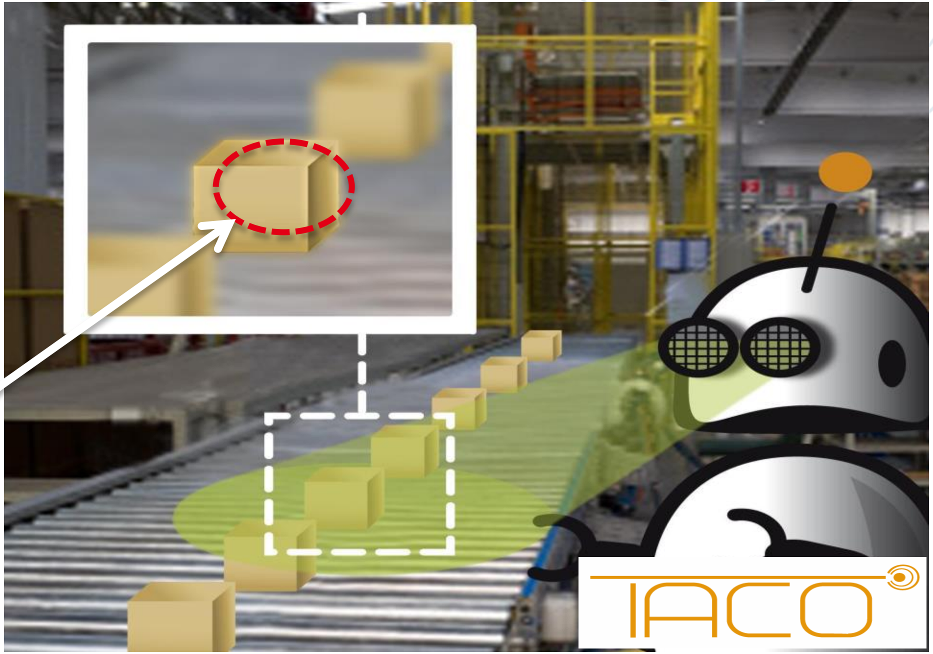
Problem:

- 3D-TOF Sensors are bandwidth limited (max. 1M Voxel/s).

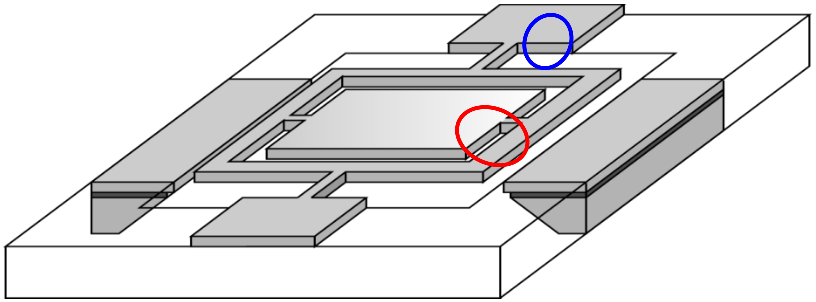
Concept:

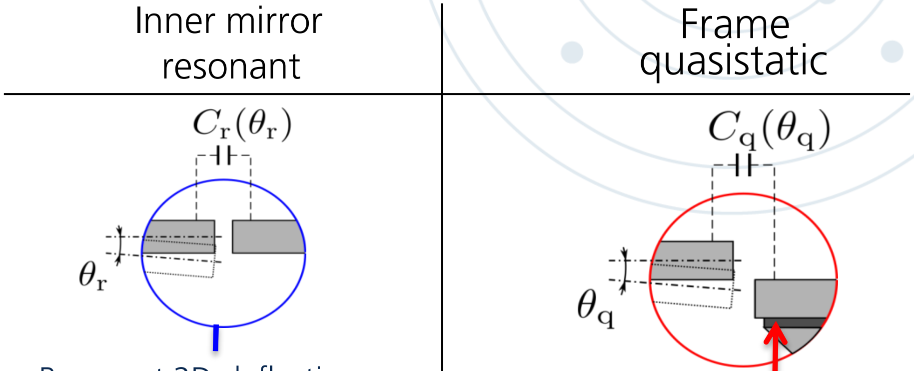
- Adaptive 3D-TOF camera with Foveation in analogy to eye
- 2D-MEMS-scanner for fast adaptive scanning required





Adaptive 2D Microscanner

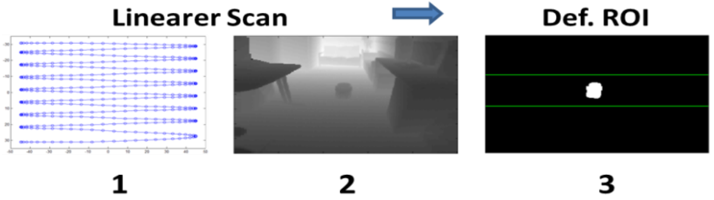


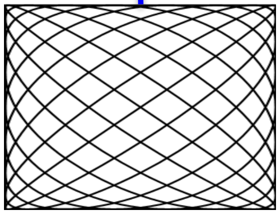


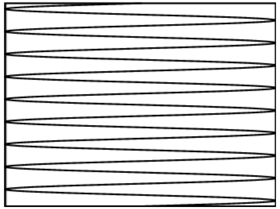
Resonant 2D-deflection

vertical comb drive electrodes

3D data rate is limited to 1 MVoxel / s







Foveation: resolution locally enhanced within ROI

Lissajous-Scan

Raster-Scan

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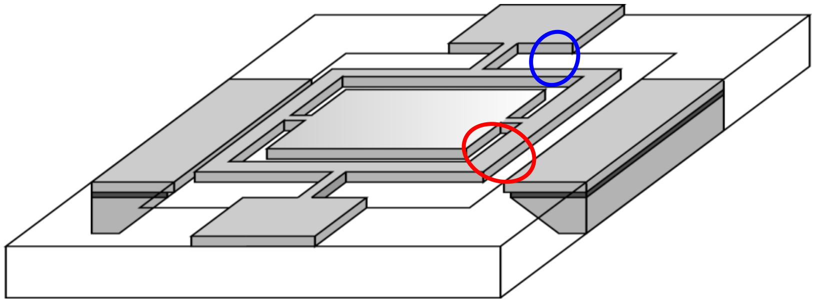
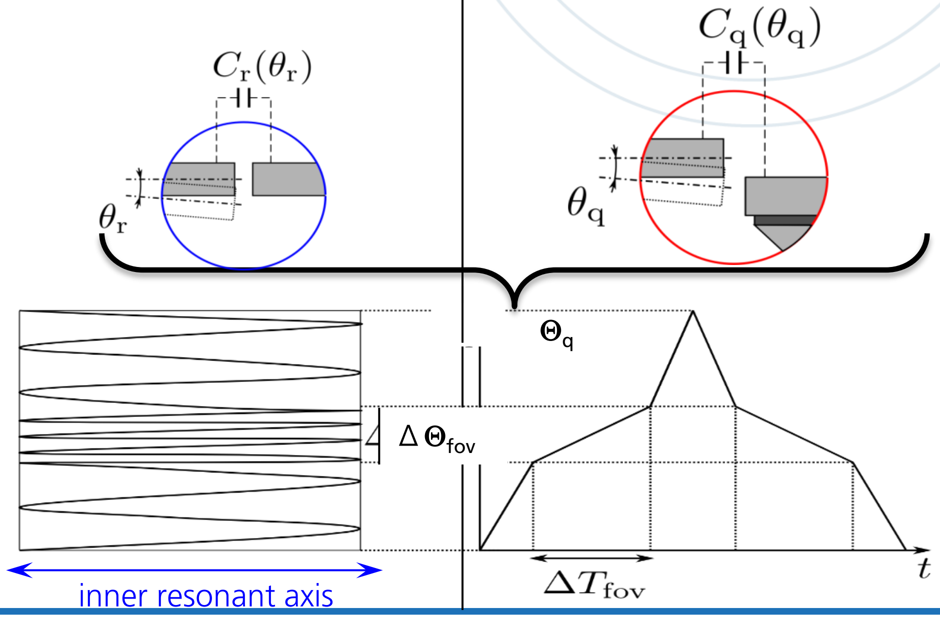
Adaptive 2D Microscanner



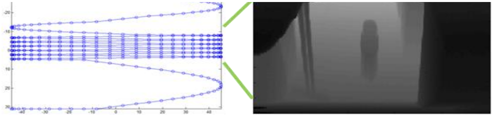
Inner mirror resonant

Frame quasistatic



Adaptive vertical scan by quasistatic frame

3D-mapping zoomed within ROI



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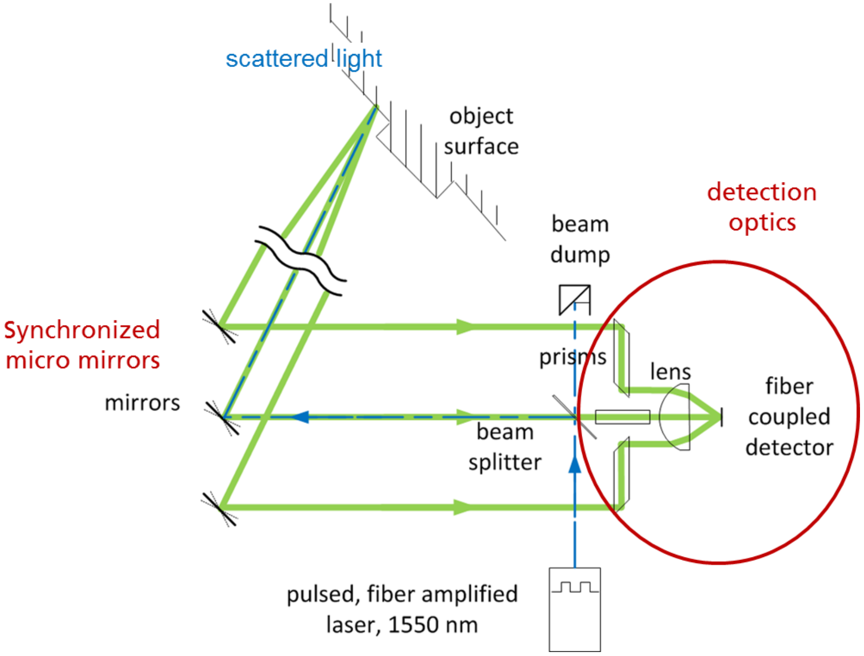
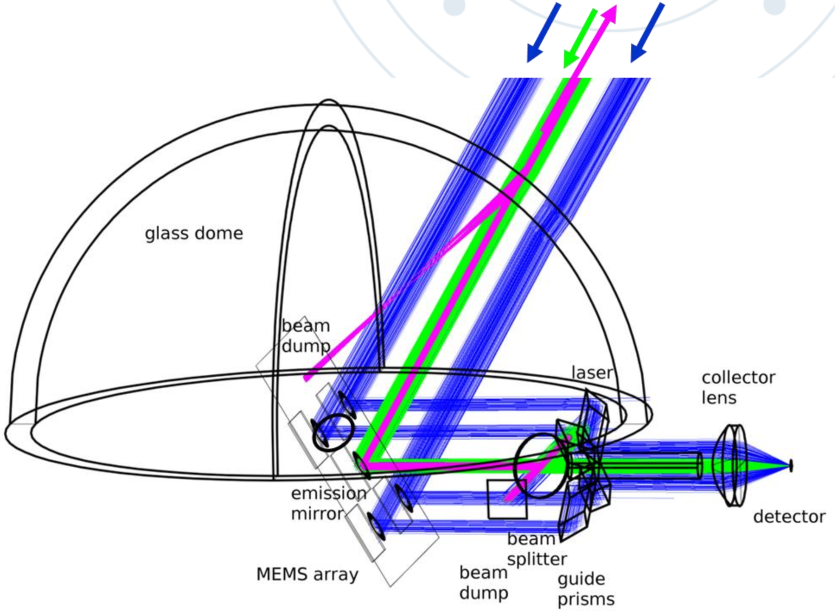
Foveation: continous intuitive optimised trade-off of resolution and frame rate

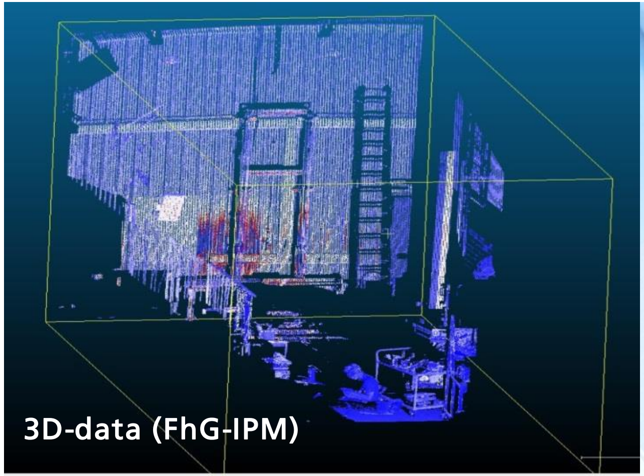
Optical Concept of 3D Camera





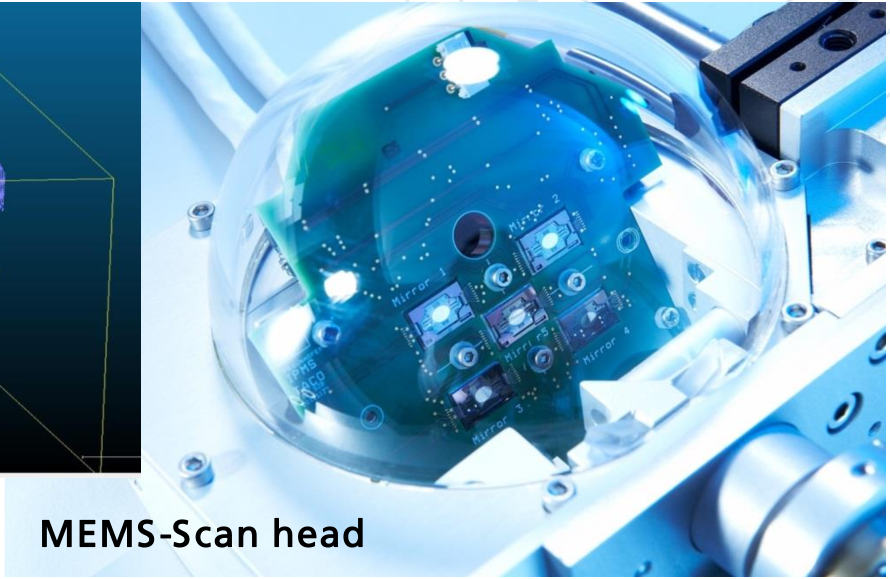
Adaptive 3D-Laser Camera TACO

Capability	
Measurement principle	Single-pixel TOF
Field-of-view (max)	80x60 ➔ 60x40
Resolution (max)	250x20 => 1600x1100
Frame rate (max)	240 => 0.5


3D-data (FhG-IPM)

TACO

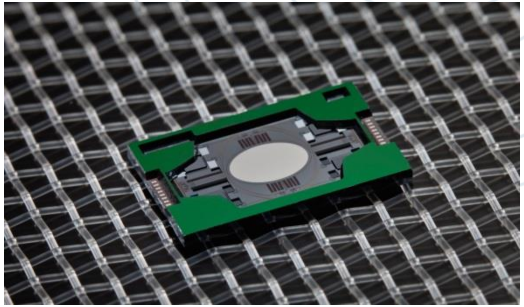
SEVENTH FRAMEWORK PROGRAMME

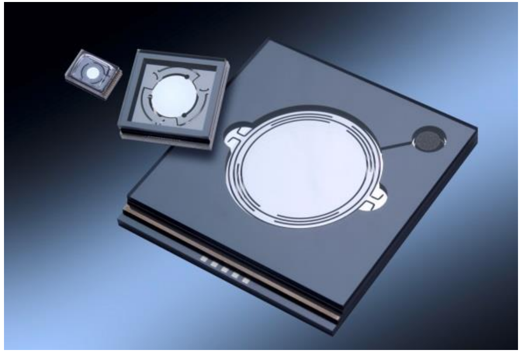


MEMS-Scan head

Zusammenfassung

- Mikroscannerspiegel, realisiert in Bulk-Mikromechanik, ermöglichen die resonante und quasiresonante Ablenkung von Licht für LiDAR Anwendungen
- Durch die Verwendung von optimierten Scanner-spiegeln und Scannerspiegelarrays lassen sich effektive und hochauflösende LiDAR Systeme realisieren
- Die Institute der FMD haben langjährige Erfahrung in der Realisierung und Herstellung von Scanner-spiegel und LiDAR Konzepten





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