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9th esa round table on micro and nano technologies

Lausanne, Switzerland, 10 - 13 June 2014

European Space Agency

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CMOS-INTEGRATED MEMS AND PHOTONIC SENSORS FOR APPLICATION IN PICO-SATELLITES

X. ROTTENBERG, V. ROCHUS, R. JANSEN, A. RAY CHAUDHURI, P. HELIN, S. SEVERI, B. DUBOIS, G. BRONDANI TORRI, T. CLAES, P. NEUTENS, P. VAN DORPE, A. LAMBRECHTS, P. SOUSSAN, P. DESHPANDE, S. DONNAY, P. DE MOOR, H.A.C. TILMANS

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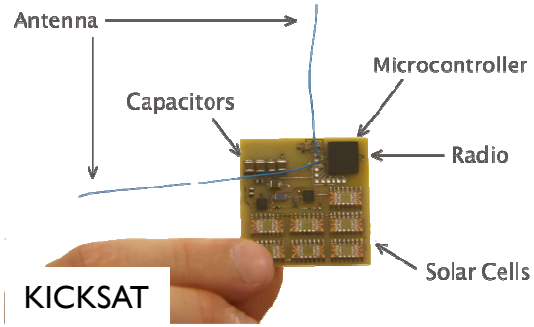
OUTLINE

- Context
- Monolithic CMOS-MEMS platform
  - Integrated measurement unit
- SiN Photonic platform
  - On-chip light manipulation
- Imager platform
  - Hyperspectral data aquisition
- Conclusions

SCALING FUELS THE NEED FOR SENSING TECHNOLOGY INTEGRATION

MOORE'S LAW FOR SPACE?

- Size, weight and costs are under pressure.
- Typically, compactness and performance are in trade-off.



- Enabling technologies for a scaling roadmap
  - MEMS
  - Integrated photonics
  - Imager technologies

OUTLINE

- Context
- Monolithic CMOS-MEMS platform
  - Integrated measurement unit
- SiN Photonic platform
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- Conclusions

IMEC developed various MEMS sensors and actuators in a multi-puspose high-end above-CMOS SiGeMEMS platform

Generic poly-SiGe technology for MEMS:

"stand-alone" MEMS, or, "MEMS above IC" (CMOS-MEMS)

Two structural SiGe layers:

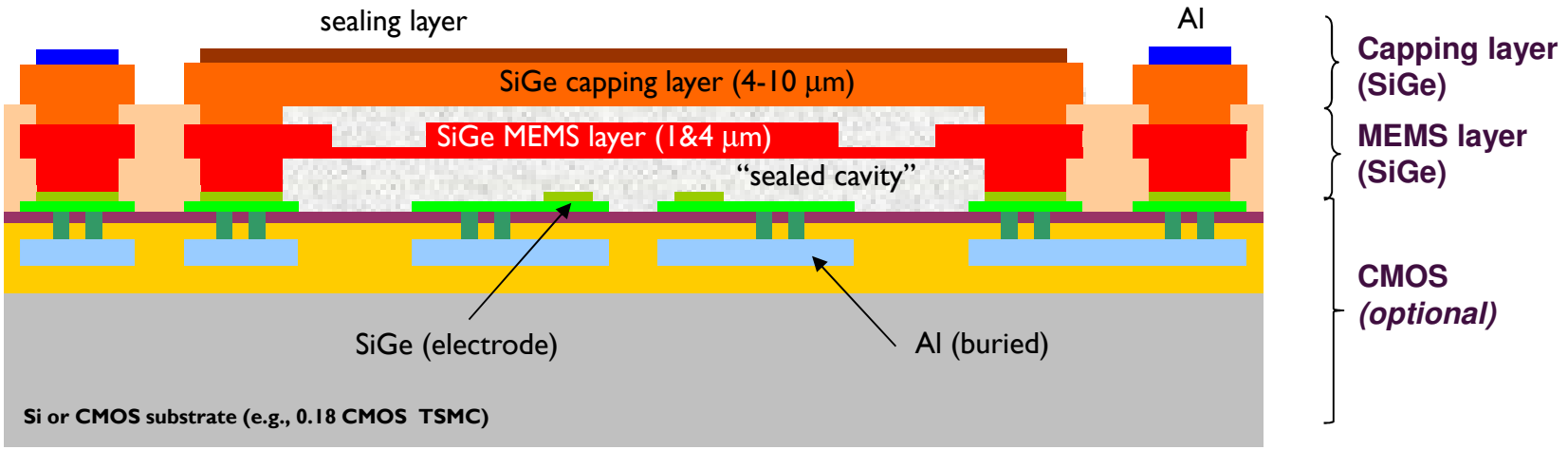
- **MEMS** structural layer (4µm standard)
- Thin film **capping/packaging** layer (4µm up to 10µm thick)

Gap SiGe structural layer of 0.5µm (optional: 0.2µm)

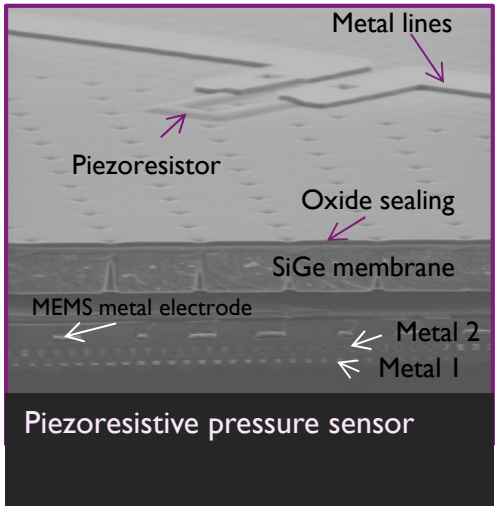
Low-T processing (< 460°C)

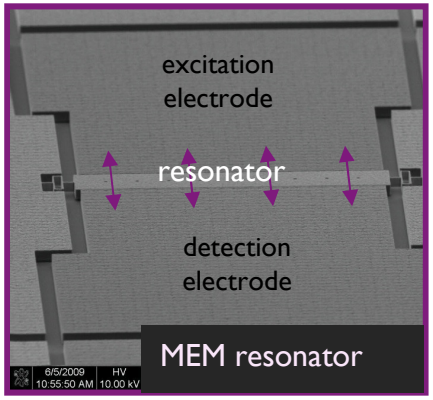
Hermetic package seal (1-100 Pa)

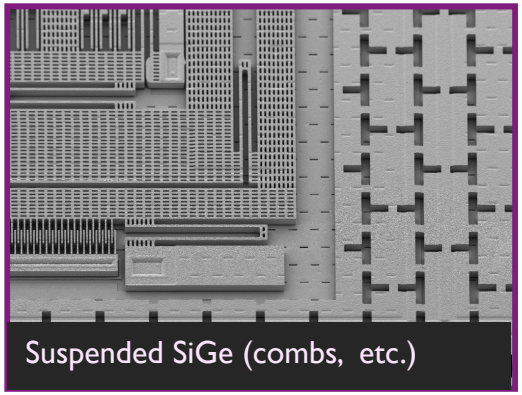
Optional modules:
- Optical (reflective)
- Electrical (metal trace)
- Piezo-resistive layer

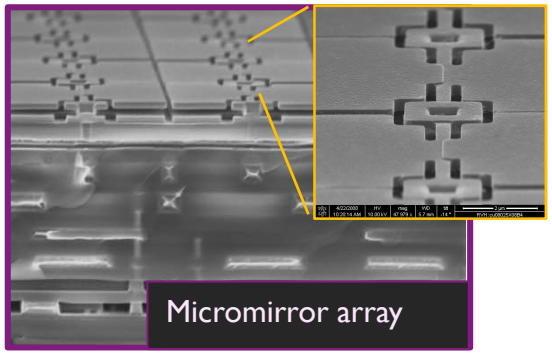


IMEC developed various MEMS sensors and actuators in a multi-purpose high-end above-CMOS SiGeMEMS platform

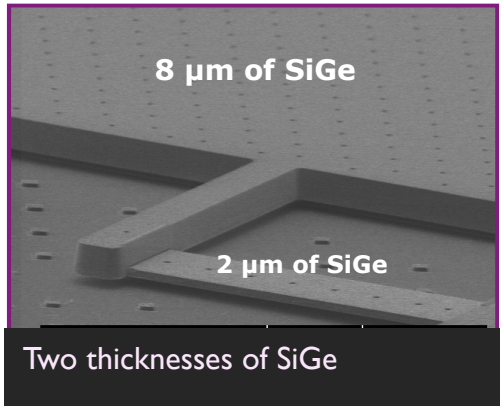


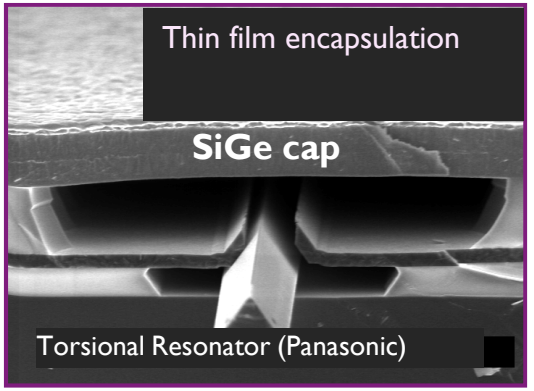






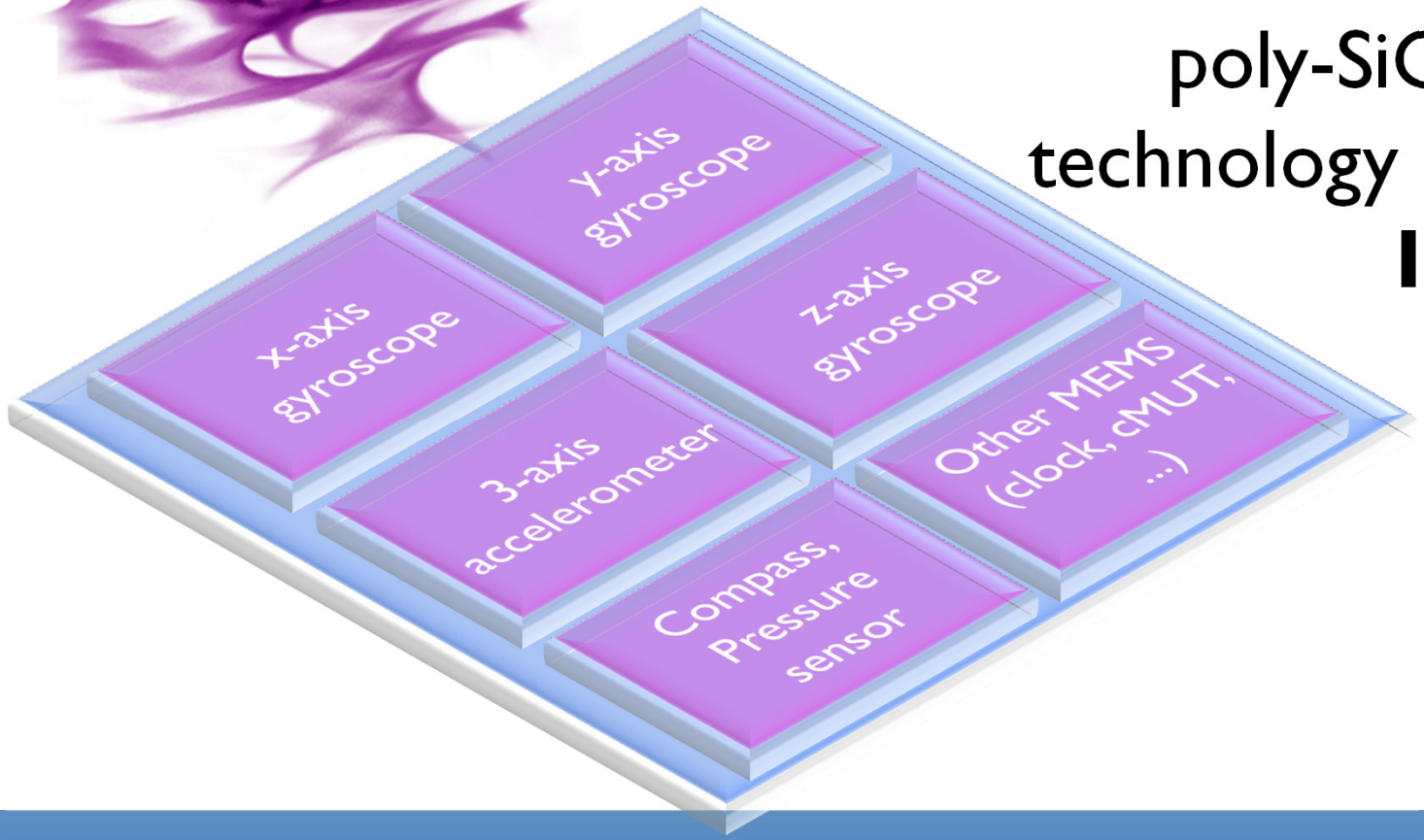
with ASML





with Panasonic

Opportunity in Imec's above-CMOS poly-SiGe MEMS technology platform: **IMU+(+)**



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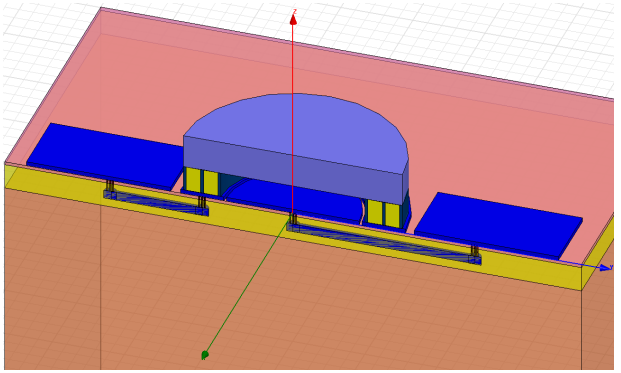
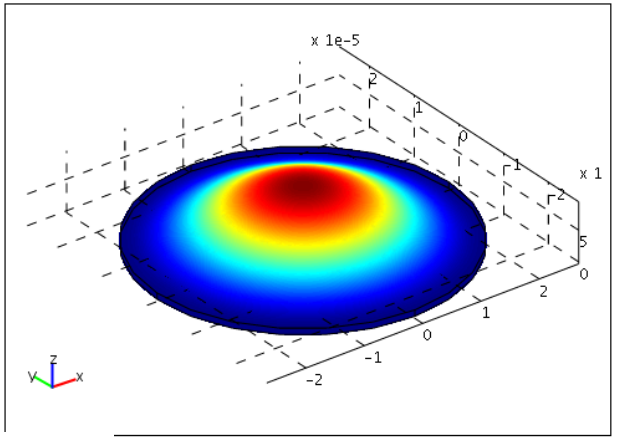
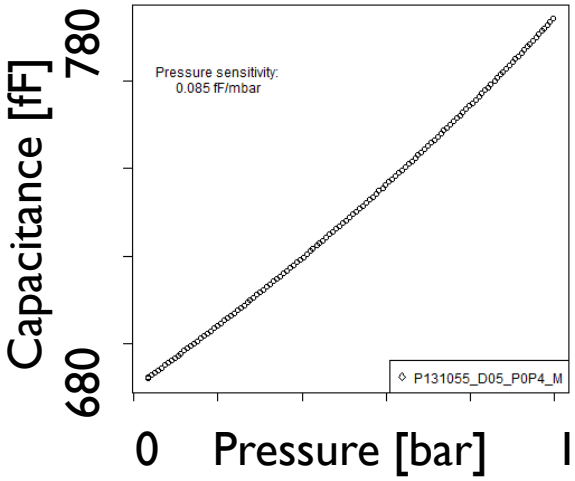
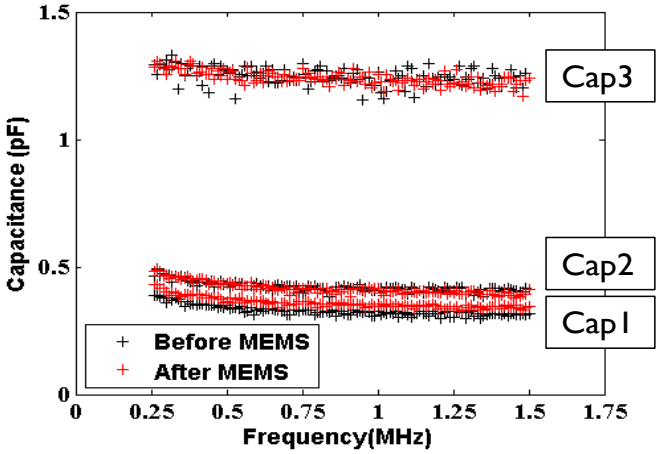
STANDARD DESIGNS: CAPACITIVE P-SENSOR

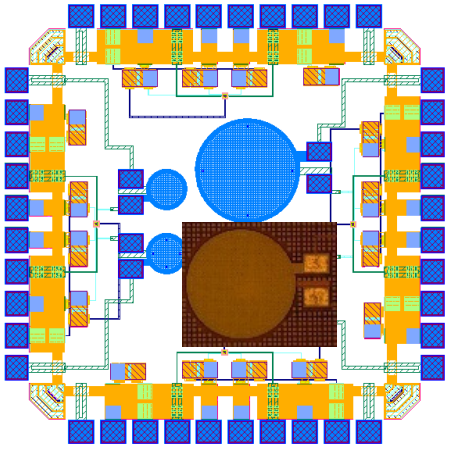
- Sealed cavity with fixed electrode and conductive deformable membrane
- Integration with simple capacitive readout
- Integration with unsealed reference cap.
- Dual set for dual range





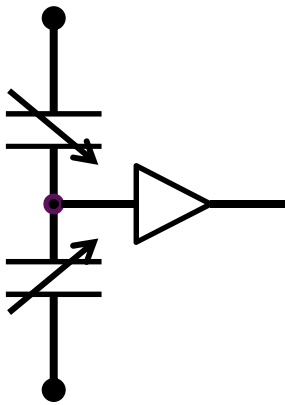


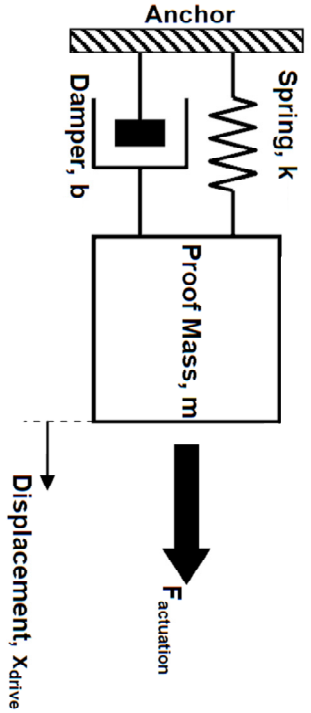


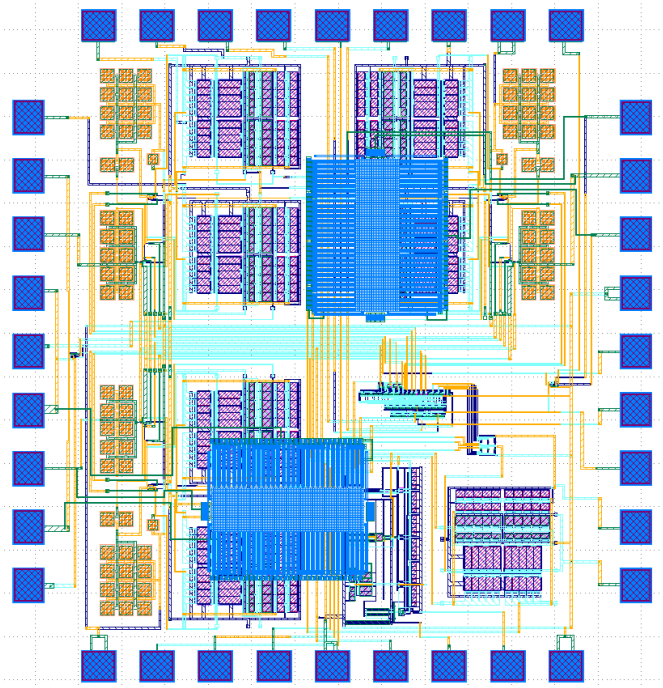


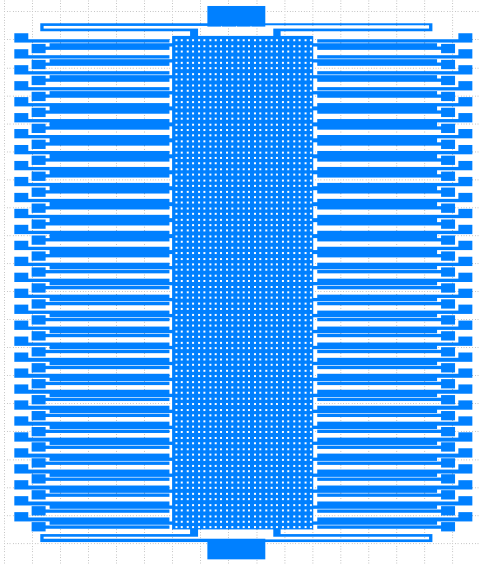
STANDARD DESIGNS: CAPACITIVE ACCELEROMETERS

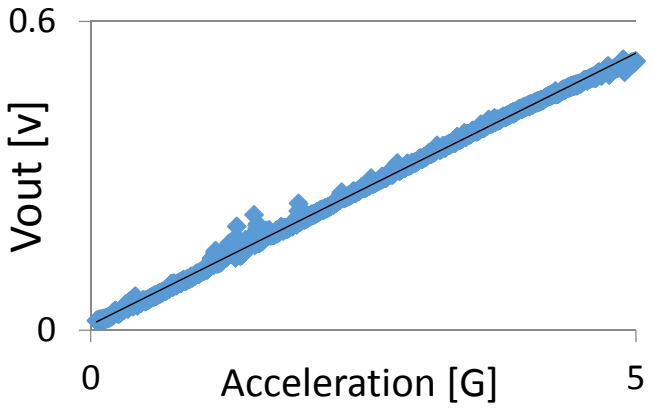
- 1-axis spring-mass-damper
- Capacitive interdigitated sensor
- x- and y- integrated with dual channel differential readout











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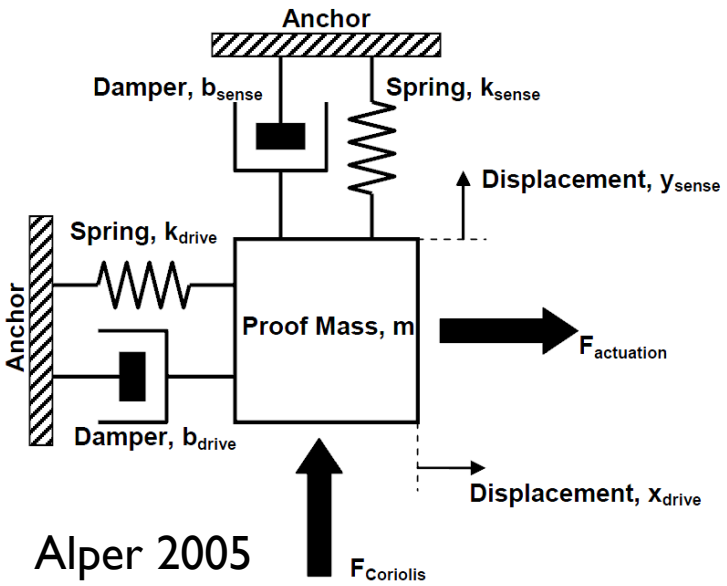
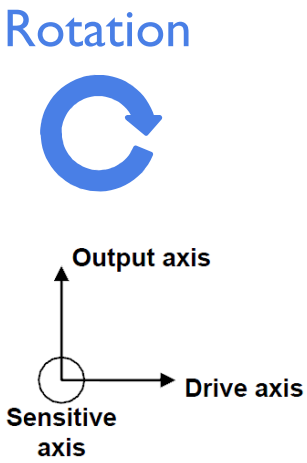
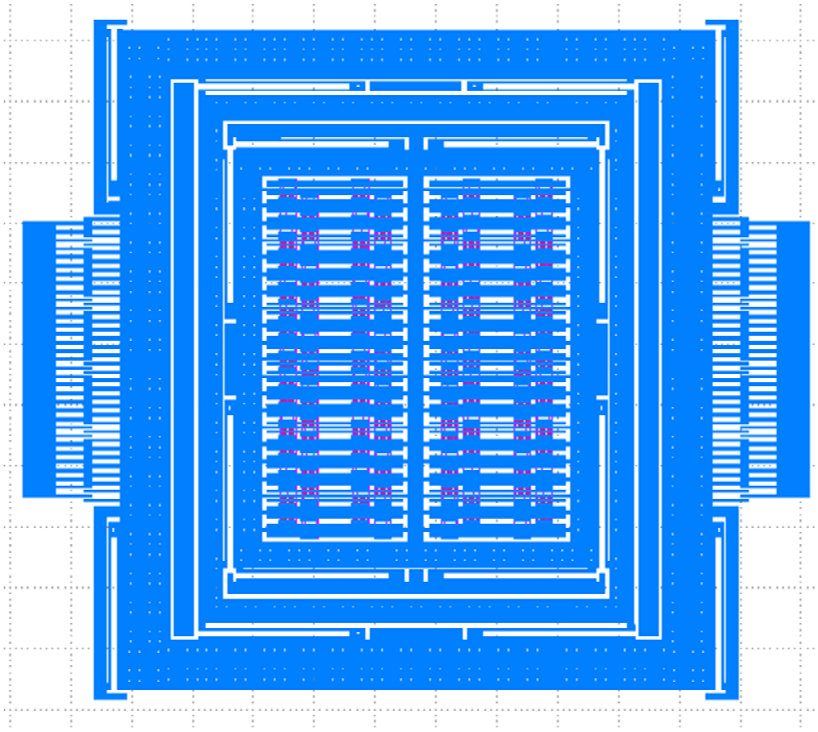
STANDARD DESIGNS: ELECTROSTATIC GYROSCOPES

- 1-axis dual spring-mass-damper
- Electrostatic comb-drive ~4kHz
- Capacitive interdigitated sense ~5kHz
- No ASIC implemented (only readout)



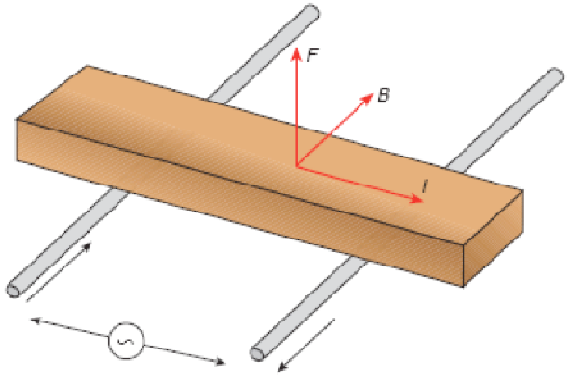
Alper 2005

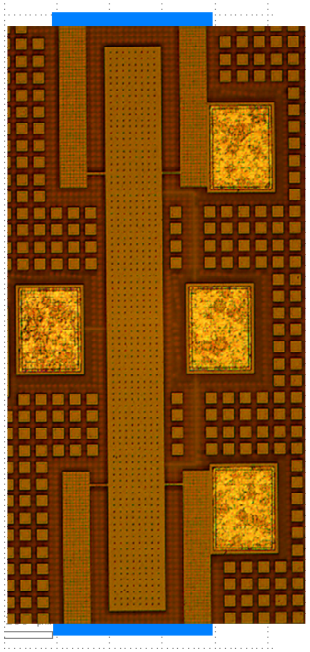


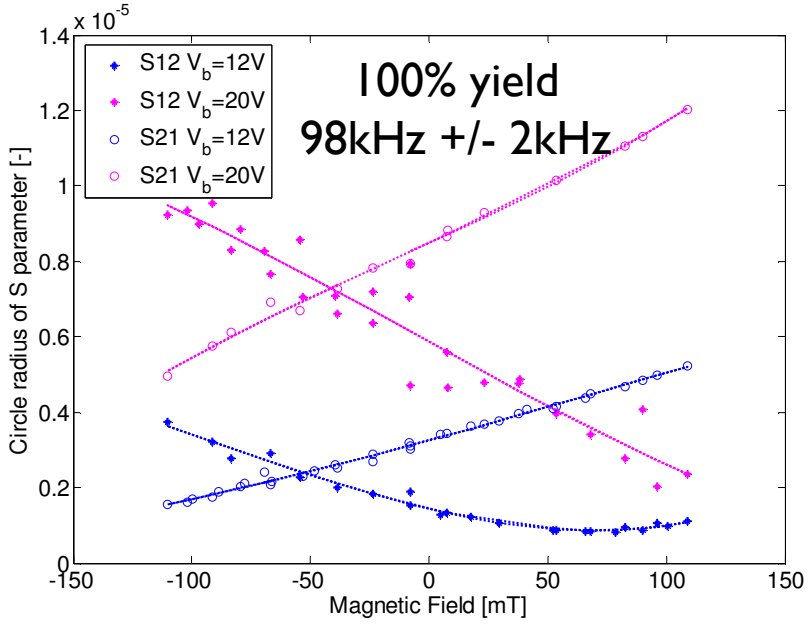


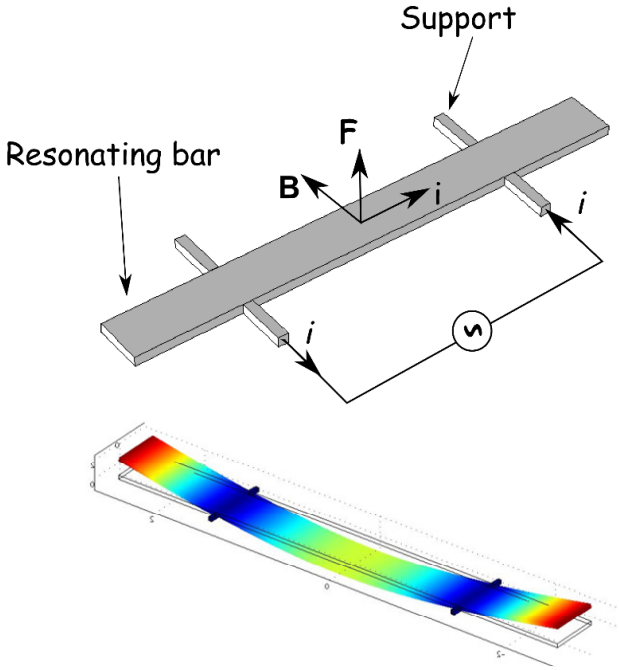
STANDARD DESIGNS: XYLOPHONE BAR MAGNETOMETER (XBM)

- 1-axis free-free beam
- Lorentz-force / electrostatic drive
- Electrostatic / magnetoinductive sense
- No ASIC implemented





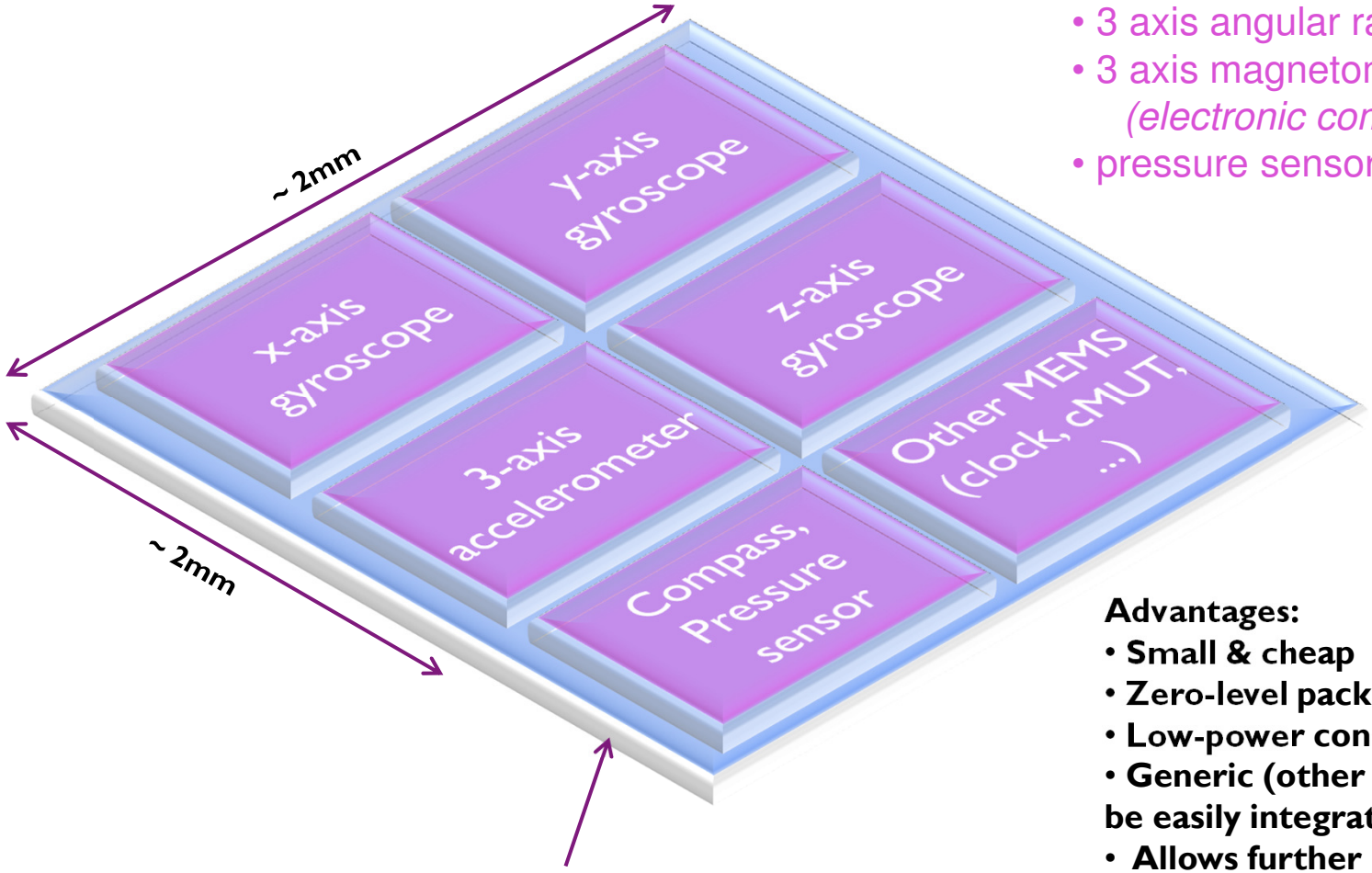




Opportunity in Imec's Poly SiGe Platform Technology: IMU++ (+)

10 DOF motion tracking:

- 3 axis acceleration sensor
- 3 axis angular rate sensor
- 3 axis magnetometer *(electronic compass)*
- pressure sensor

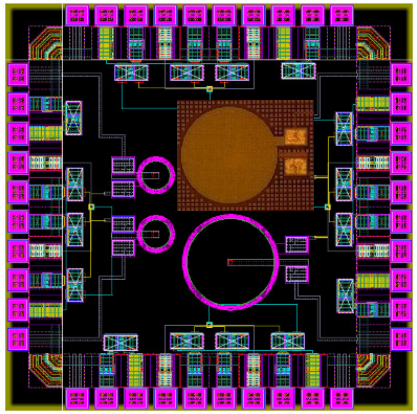


Advantages:

- **Small & cheap**
- **Zero-level packaged**
- **Low-power consumption**
- **Generic (other transducers can be easily integrated)**
- **Allows further integration (thinning, stacking, ...)**

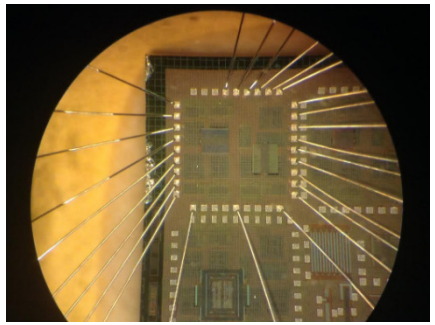
MONOLITHIC CMOS-MEMS MULTI DOF IMU

Multiple P-sensors

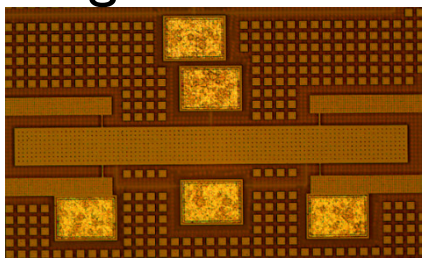


5x5mm²

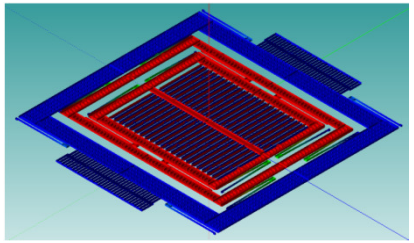
Multiple accelerometers



Multiple magnetometers



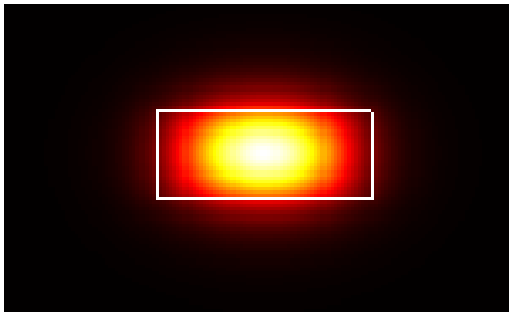
Multiple gyroscopes



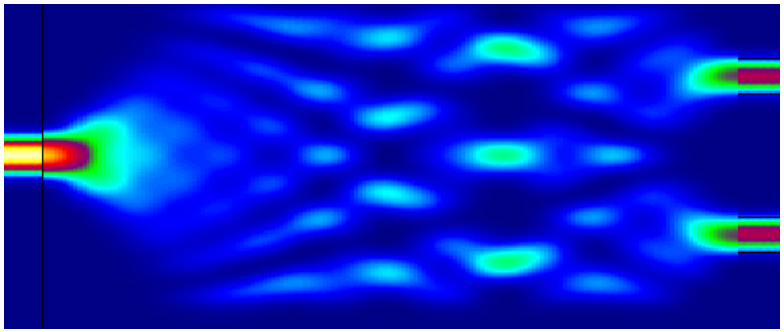
OUTLINE

- Context
- Monolithic CMOS-MEMS platform
  - Integrated measurement unit
- SiN Photonic platform
  - On-chip light manipulation
- Imager platform
  - Hyperspectral data aquisition
- Conclusions

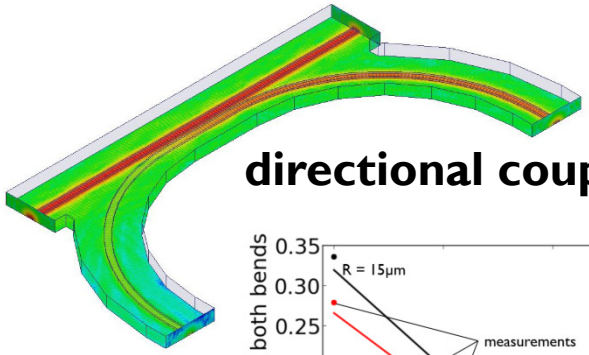
single-mode waveguides
1 dB/cm propagation loss
0.036 dB/90° bend loss for 20µm radius



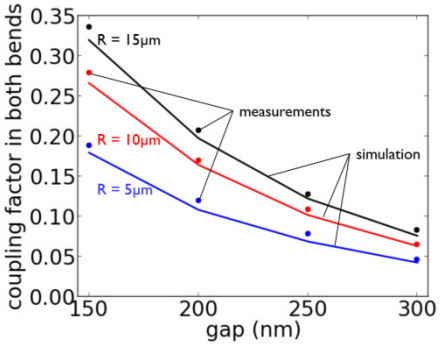
3dB-splitters
only 0.04dB total insertion loss



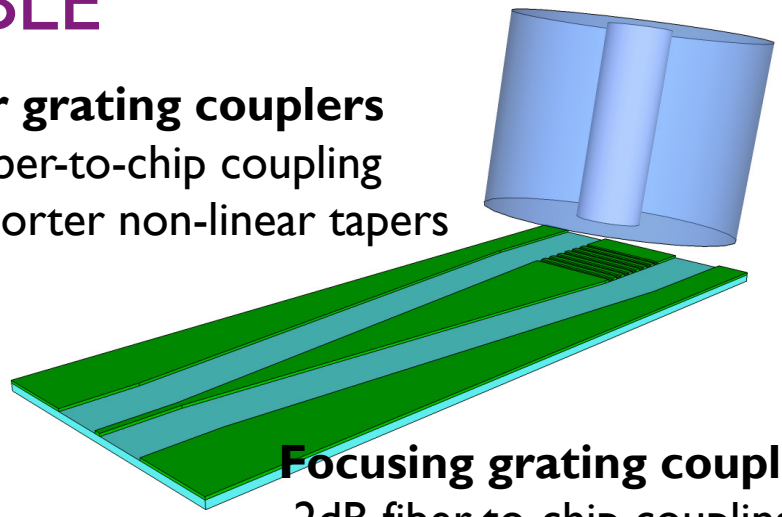
HIGH QUALITY *SIN PHOTONICS* COMPONENTS FOR APPLICATION IN THE VISIBLE



directional couplers



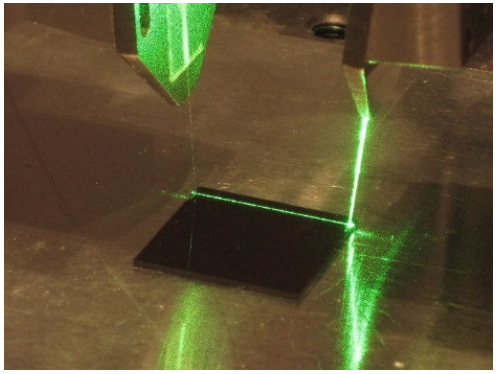
Linear grating couplers
-4dB fiber-to-chip coupling
60% shorter non-linear tapers

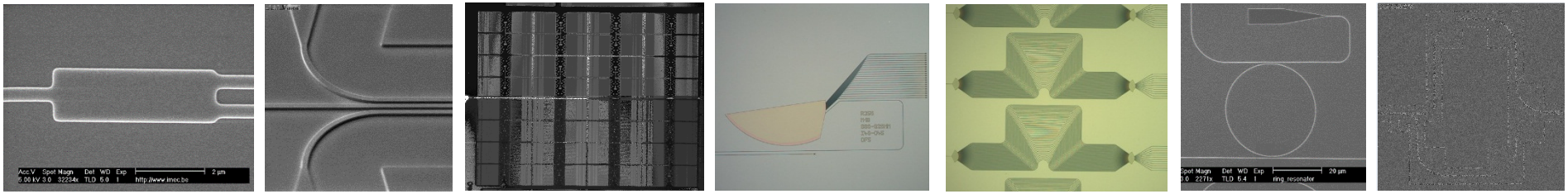


Focusing grating couplers
-2dB fiber-to-chip coupling

IMEC ports its developments of Si-photonics platform for telecom applications (1300nm&1550nm) to a SiN-photonics platform targeting applications in the visible and NIR

- Light coupling to a chip and manipulation on this chip
- Light output to a sensor set (photodiodes) or to underlying CMOS sensor
- Very good overall system compactness
- Applications: Spectroscopy, NDT, bio-sensing, telecom, ...





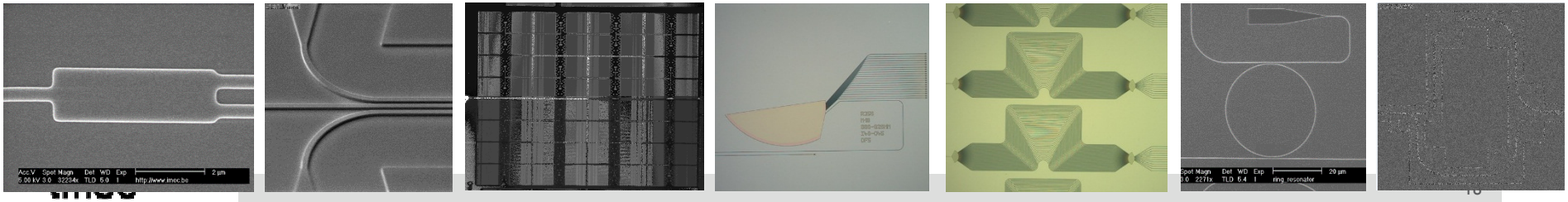
INTRODUCTION TO SIN PHOTONICS

- Silicon photonic components are the standard at 1300nm and 1550nm wavelength

→ **Why PECVD SiN?**

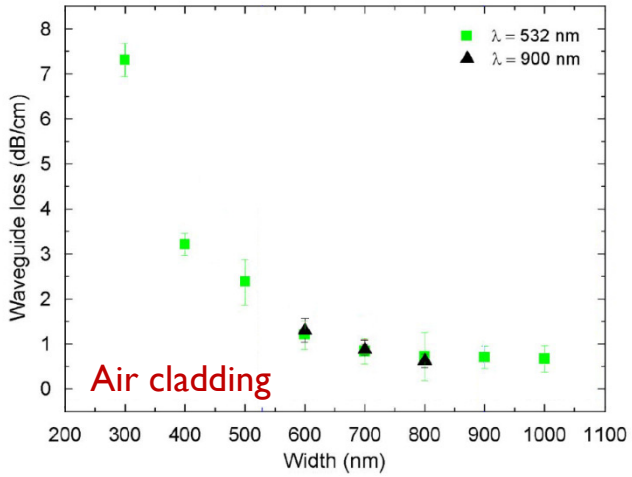
- Low loss in visible to IR wavelength
  - Use in studying biological samples (fluorescence)
  - Applications in Raman spectroscopy (visible and NIR)
- Compatible with CMOS BEOL (low temperature process)
- Moderately high refractive index (1.8-2.1)
- No 2-φ absorption
- Lower temperature-sensitivity than silicon

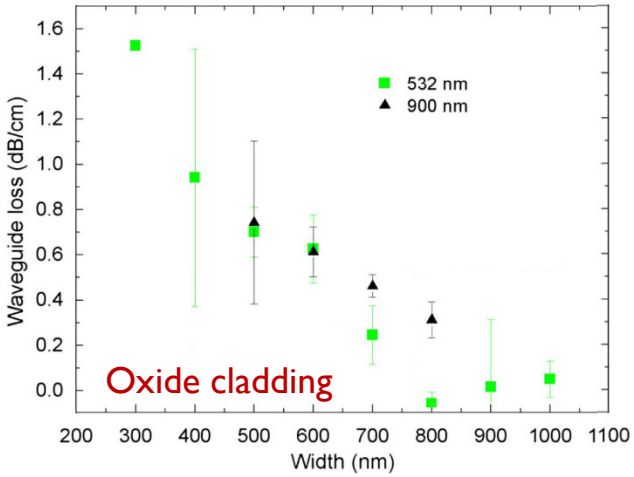
→ **Goal:** Compose a library of PECVD SiN photonic elements to be used as building blocks for complex circuits in bio, industrial, mobile, space ... applications

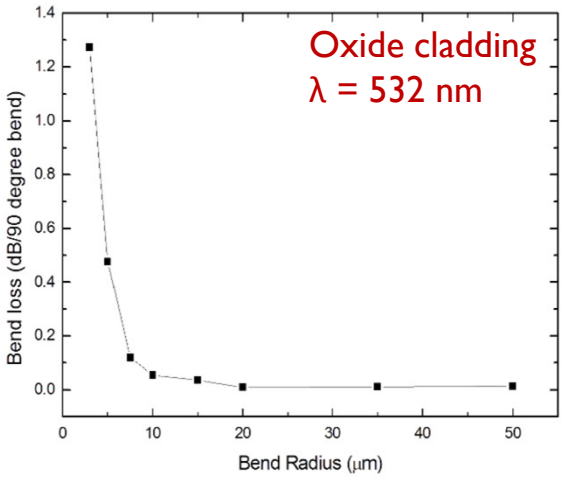


Low loss strip waveguides and bends

- Propagation losses measured via cutback method.
- Bend losses measured via meandering waveguides with 120 bends of 90 degrees for different bend radii.



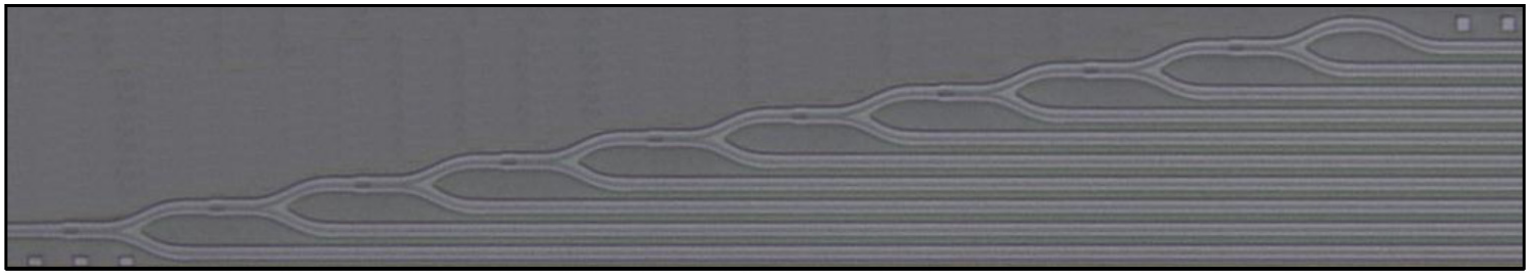


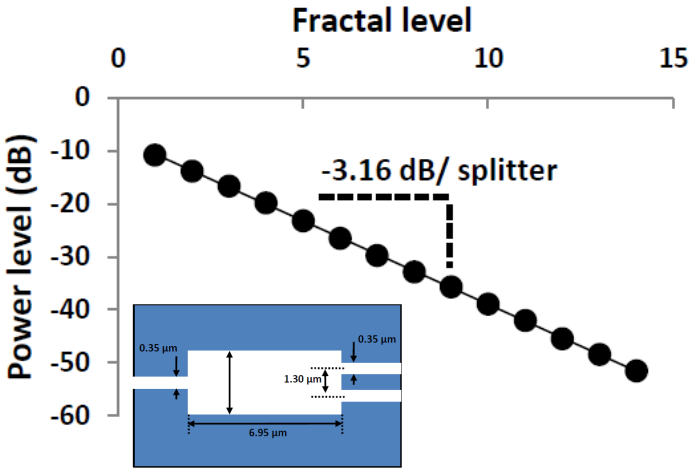


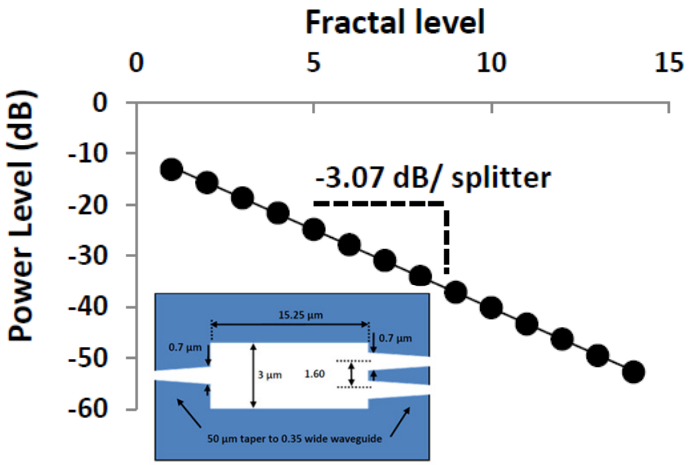
→ With oxide cladding: < 1dB/cm propagation loss for both wavelengths for SM operation.
→ With air cladding: < 1dB/cm for 900 nm, > 2 dB/cm for 532 nm.
→ Bend loss at 532nm: 0.055 dB/ 90 degree bend with radius of 10 μm.

Excellent loss performance for MMI splitters

→ Use of cascaded test structures to accurately measure the excess splitter loss.







* Today, we have designs with a loss of 0.018 dB/splitter level.

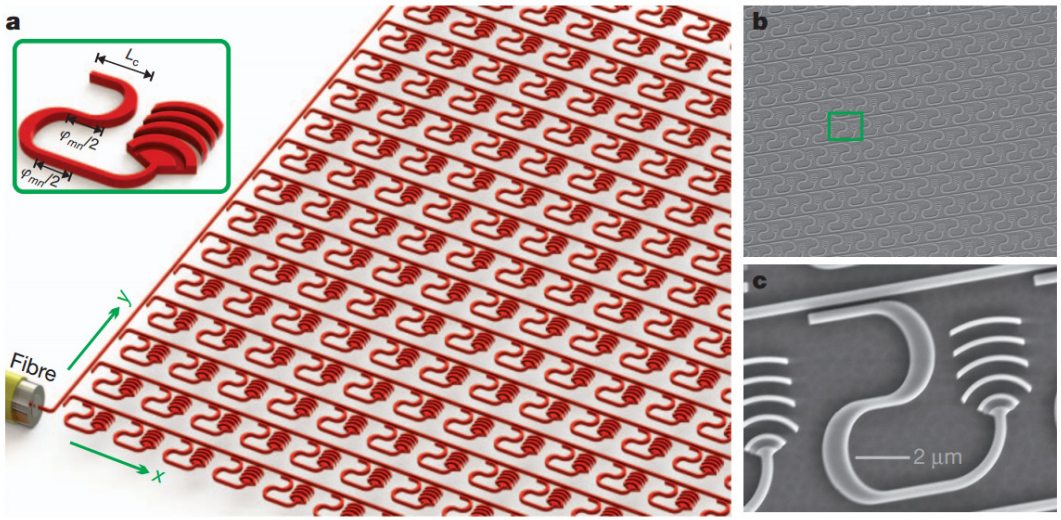
Case study:
Optical power distribution for nano phased arrays

Distribution of optical power from a single input port among many photonic components.

→ Fluorescence sensor arrays.

→ Integrated Raman detection array.

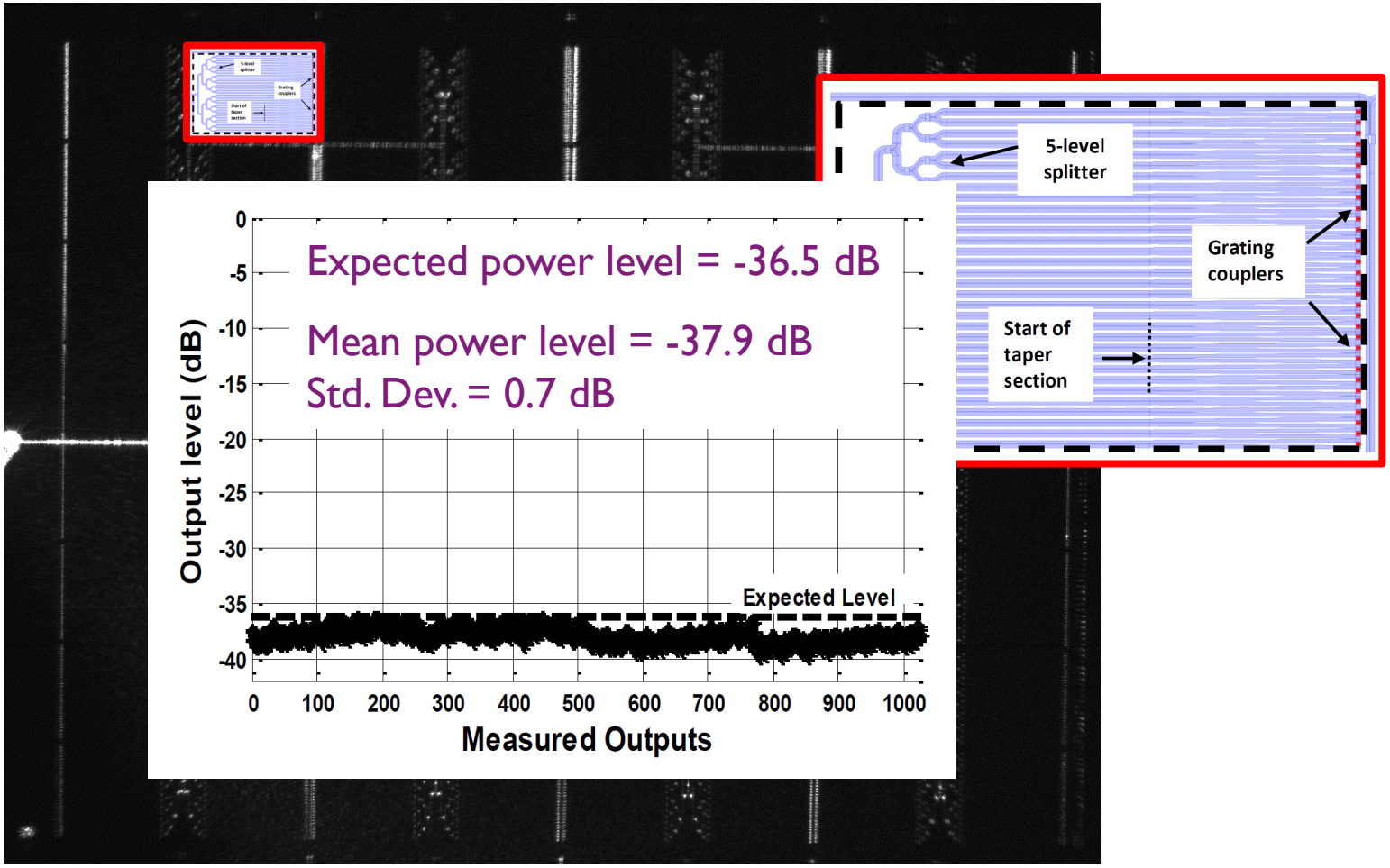
→ **LIDAR phased arrays.**



J. Sun et al, Nature 493, 195-199 (2013)

Case study:
Optical power distribution for nano phased arrays

Fractal feeding



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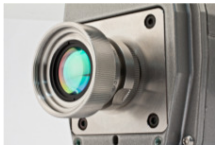
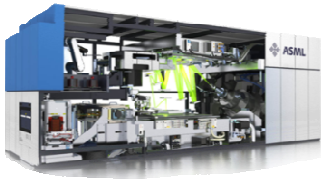
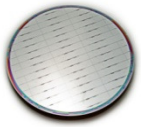
HIGH-END IMAGERS: APPLICATIONS & FEATURES



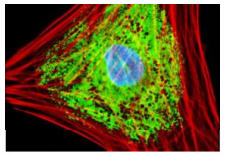
Industrial sorting & Machine Vision

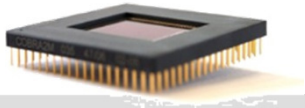
Industrial Instrumentation





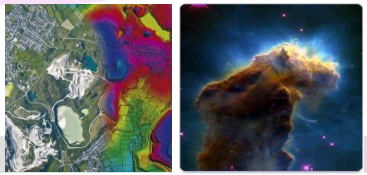
Life-Science & Medical Imaging





High-end **transports, security & surveillance**

Space, Physics & Scientific

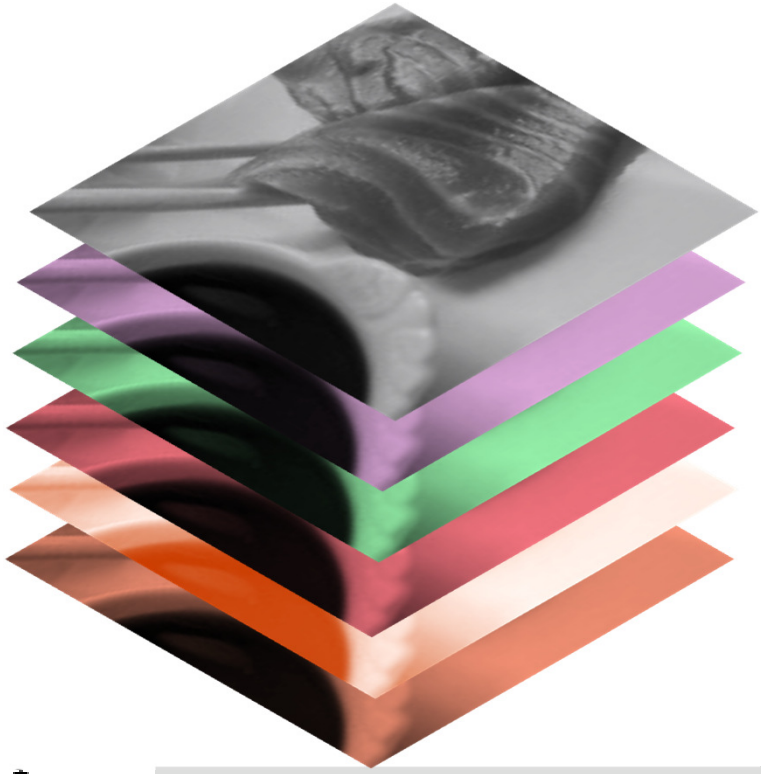


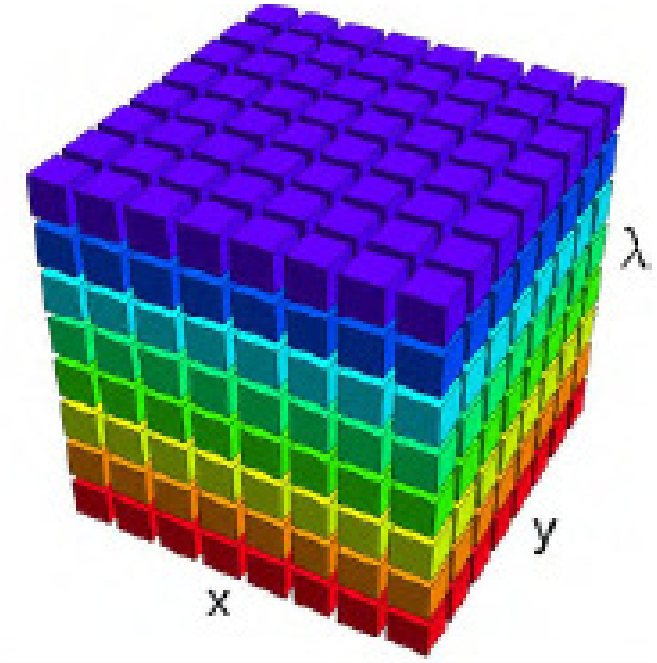
Key features

- Low noise
- High QE
- Low power
- High speed
- Radiation Hard
- Non-Visible sensing
- Spectral Filters/ARC

IMAGINE A HYPER-COLOR IMAGER

- spatial domain:
  - a full image
  - in many wavelengths

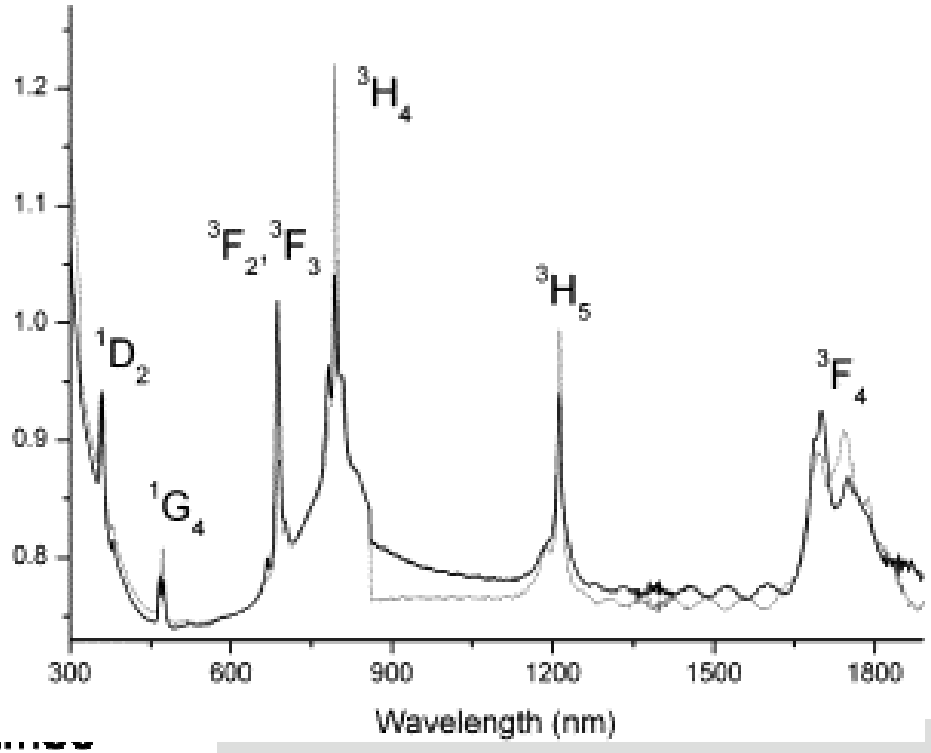


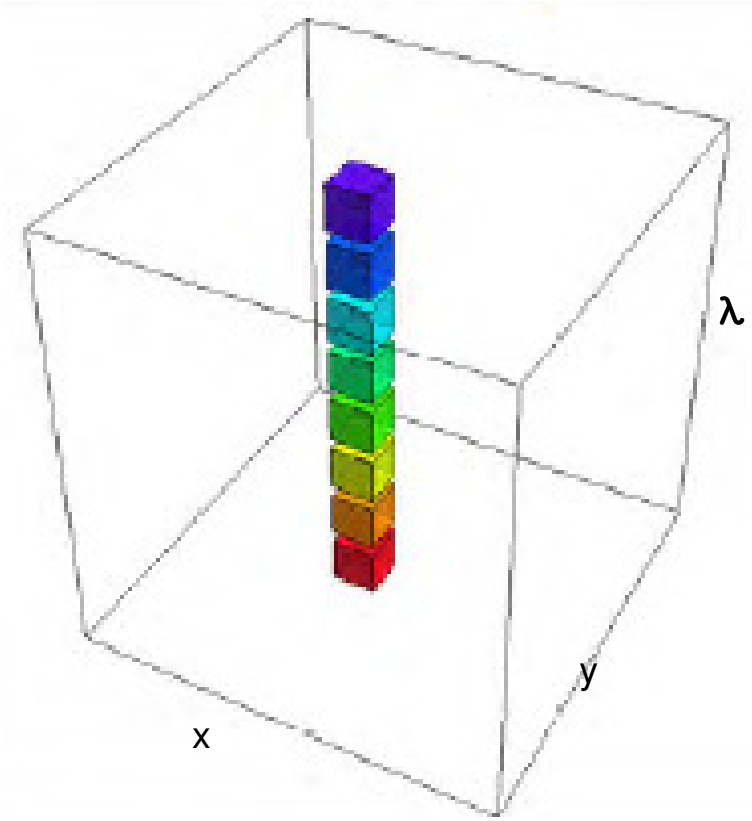


- 'image cube'

IMAGINE A HYPER-COLOR IMAGER

- spectral domain:
  - a full spectrum

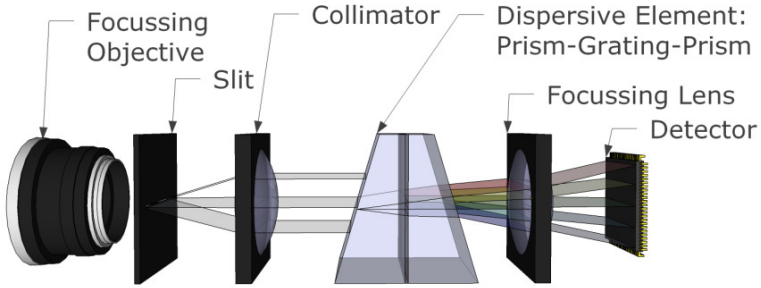


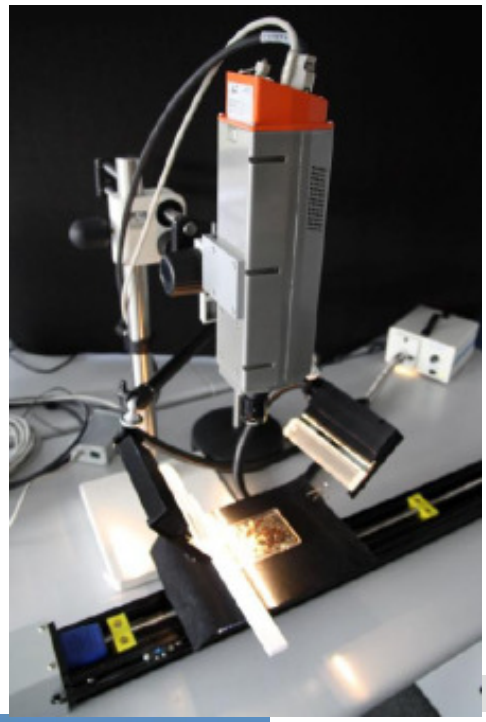


- in each pixel

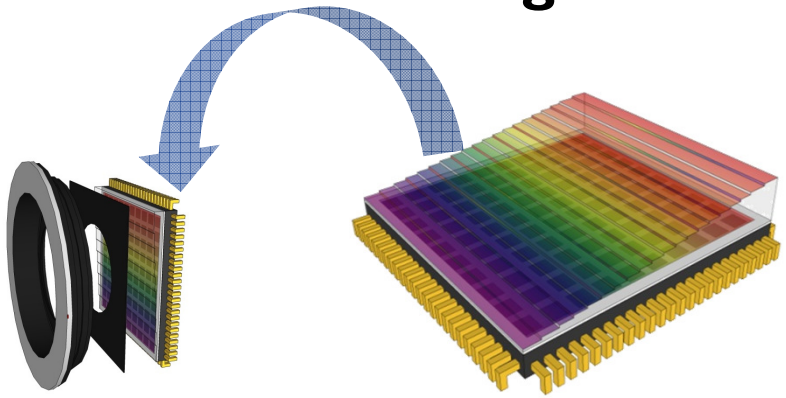
HYPERSPECTRAL IMAGERS: PRINCIPLE

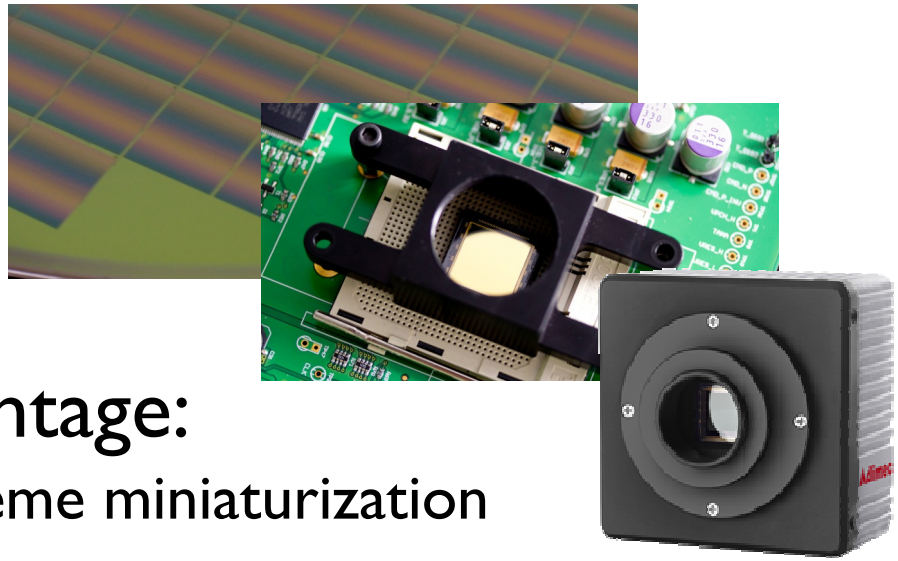
- State-of-the-art:
  - Imager + grating/prism





- Imec solution:
  - **Wafer level filter integration**





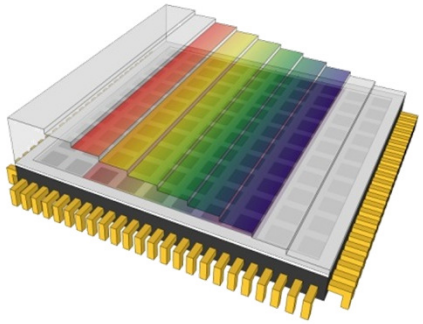
Advantage:

- Extreme miniaturization

HYPERSPECTRAL IMAGERS: DESIGN FREEDOM

Linescan

'wedge' design

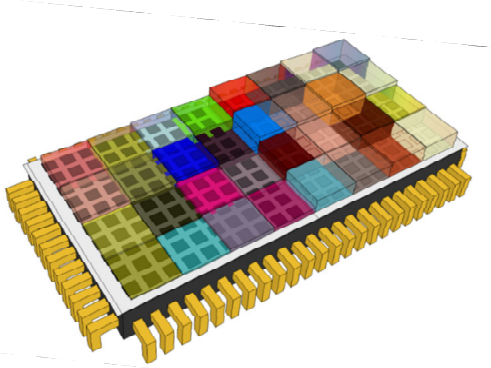


- Requires scanning
- Highest spatial & spectral resolution

Or

Snapshot tiled

'area' design

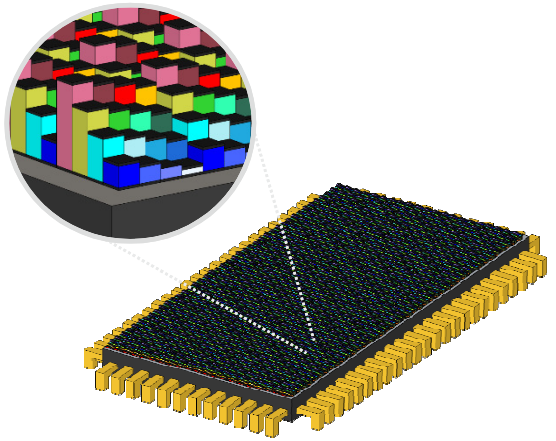


- No scanning allows video applications
- Optical duplicator required

Or

Snapshot mosaic

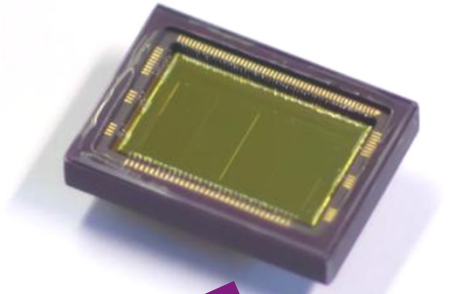
'per-pixel' design

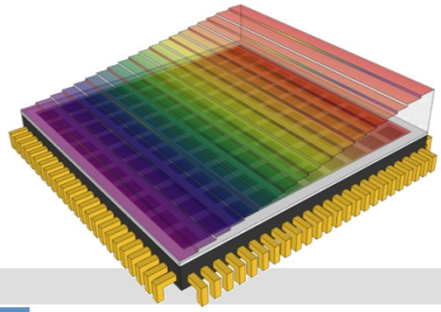


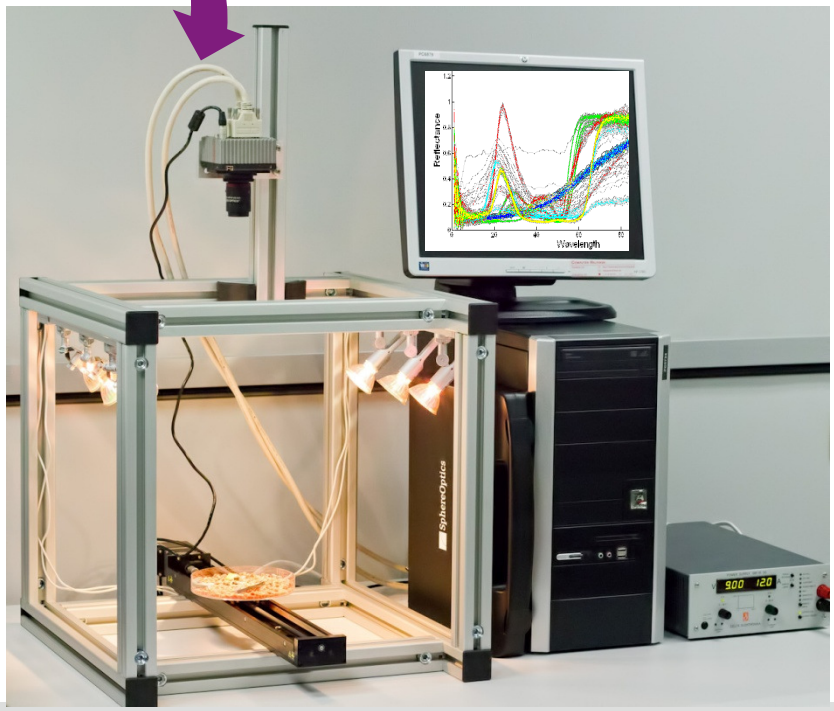
- No scanning allows video applications

HYPERSPECTRAL IMAGING: LINESCAN HSI CAMERA SYSTEM

- HSI linescan evaluation system:
  - Camera with HSI imager, translation stage, lighting, software

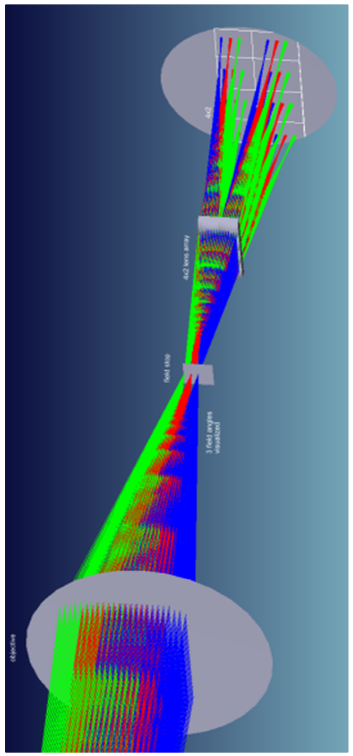


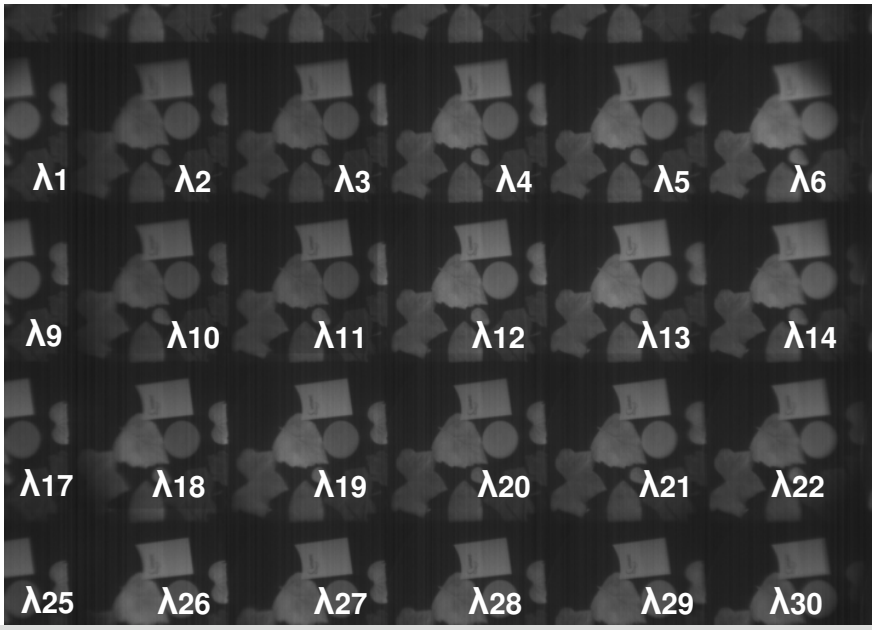




HYPERSPECTRAL IMAGING:
HSI VIDEO CAPTURE USING SNAPSHOT TILED

duplicator lens

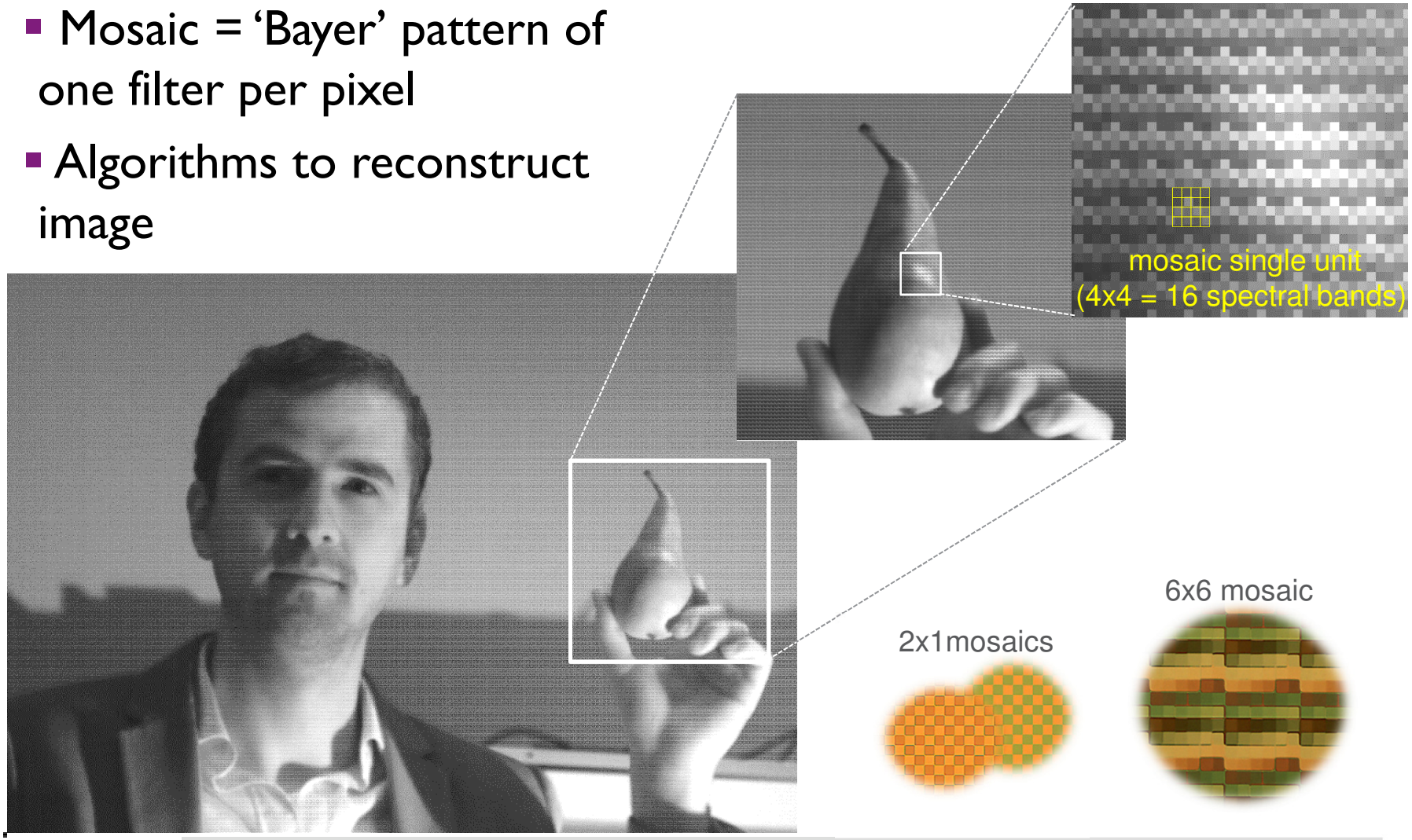




tiled sensor
with 32 bands

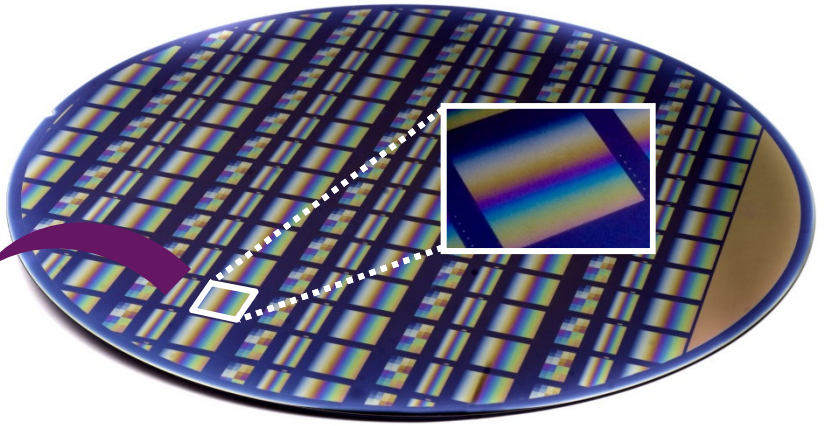
HYPERSPECTRAL IMAGING:
HSI VIDEO CAPTURE USING SNAPSHOT TILED

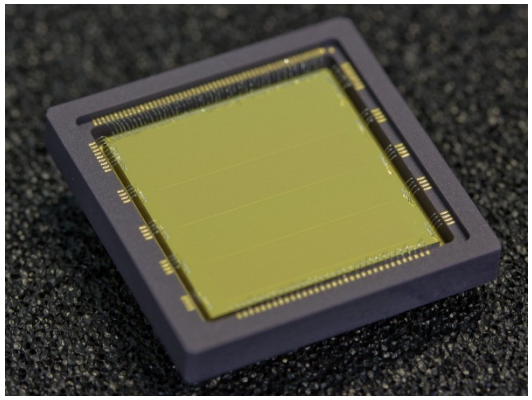
- Mosaic = 'Bayer' pattern of one filter per pixel
- Algorithms to reconstruct image



HYPERSPECTRAL IMAGERS: STATUS

- technology established for 600 -900 nm
- technology development ongoing:
  - 470 – 900 nm
  - combination with panchromatic
- post-processed on top of CMOSIS's CMV2000 & CMV4000 sensors
- 4 different camera implementations
- evaluation kits available





3D-ONE

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esa 9th esa round table on micro and nano technologies

APPLICATIONS OF HYPERSPECTRAL IMAGING

Medical

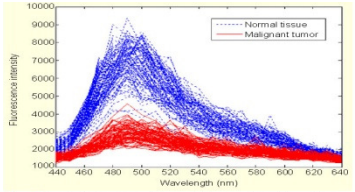
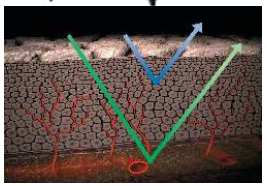
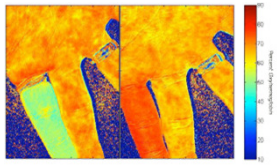
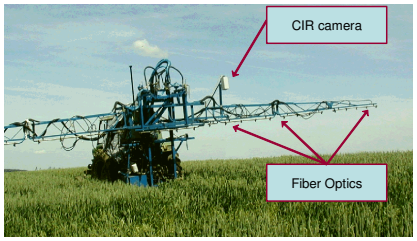


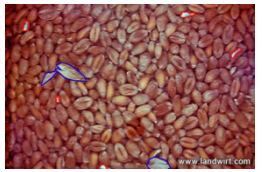
Fig. 6. Spectral signature of normal tissue and malignant tumor. The fluorescence intensity is measured with a laser excitation at wavelength 337 nm.



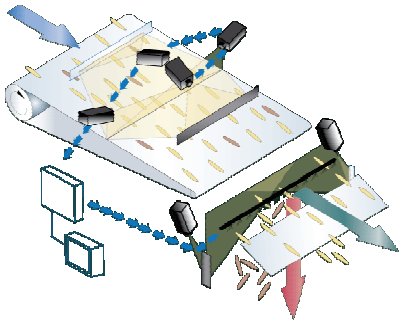


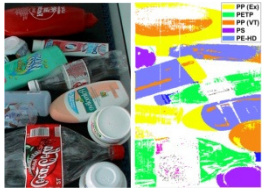
Precision agriculture

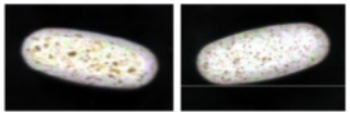




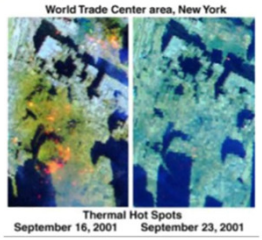
Optical sorting

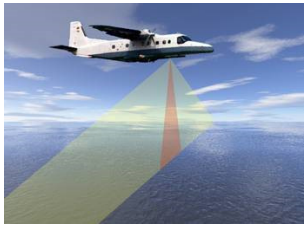


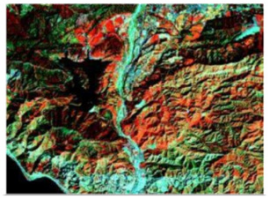




Remote sensing







OUTLINE

- Context
- Monolithic CMOS-MEMS platform
  - Integrated measurement unit
- SiN Photonic platform
  - On-chip light manipulation
- Imager platform
  - Hyperspectral data aquisition
- Conclusions

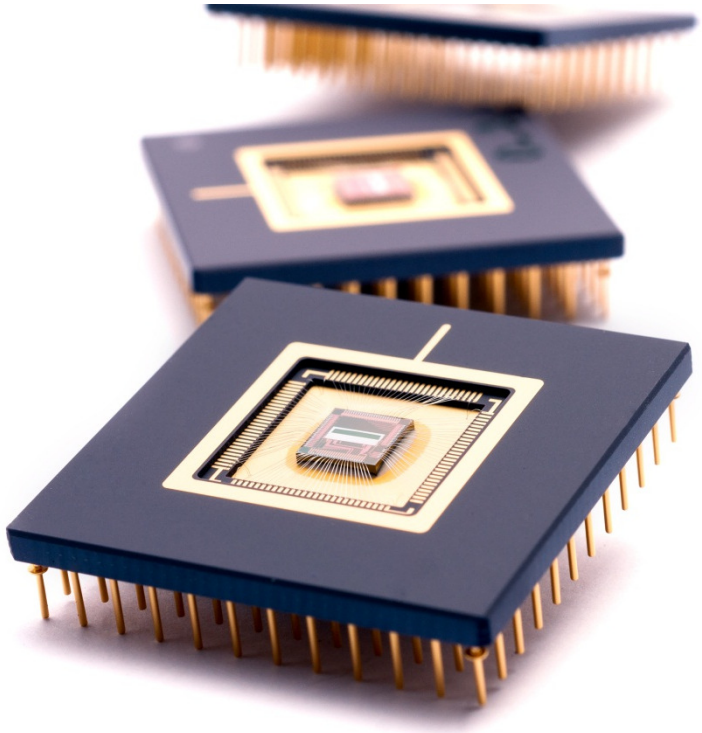
CONCLUSIONS

- Convergence of integration capabilities towards compact sensing systems wih higher functionality.

- Demonstration of monolithically integrated CMOS-MEM multi DOF IMUs, i.e., accelerometer, gyroscope, magnetometer,P-sensor

- Presentation of a technology development for on-chip integrated photonics in the visible and NIR

- Demonstration of an imager platform with hyperspectral capabilities



ASPIRE
INVENT
ACHIEVE

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9th esa round table on micro and nano technologies

Lausanne, Switzerland, 10 - 13 June 2014

European Space Agency

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