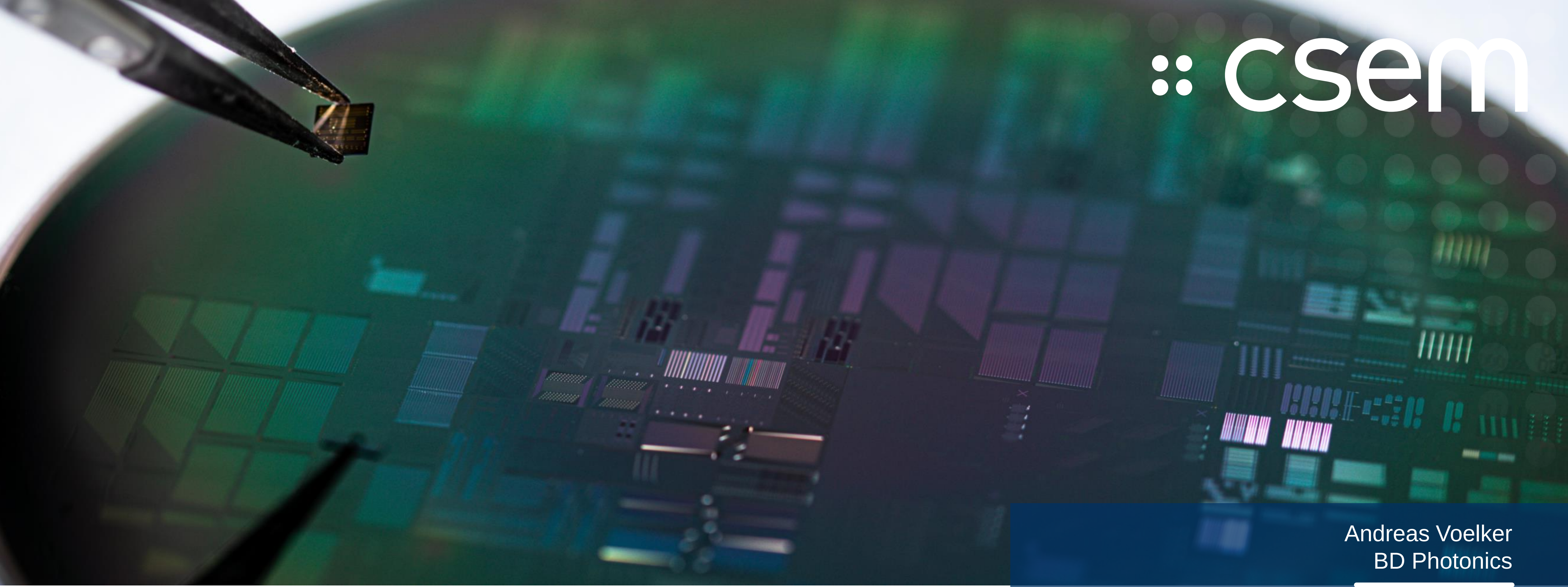


Andreas Voelker
BD Photonics

11.10.2023

PHOTONIC SOLUTIONS FOR QUANTUM TECHNOLOGIES

Tissot T-touch Connect with ultra-low power OS and black photovoltaic dial developed and manufactured at CSEM

CSEM is a public-private, non-profit Swiss technology innovation center, focusing on micro- and nanotechnologies.

CSEM enables competitiveness through innovation by developing and transferring world-class technologies for the industrial sector.

Our technologies fuel the innovation of more than 200 industrial partners every year.

OUR USP #1: CUSTOMER CENTRICITY

Staff with industry experience

Long-term support

(80% of staff on permanent contract)

Processes with built-in confidentiality

Industrial equipment

(clean rooms, characterization labs)

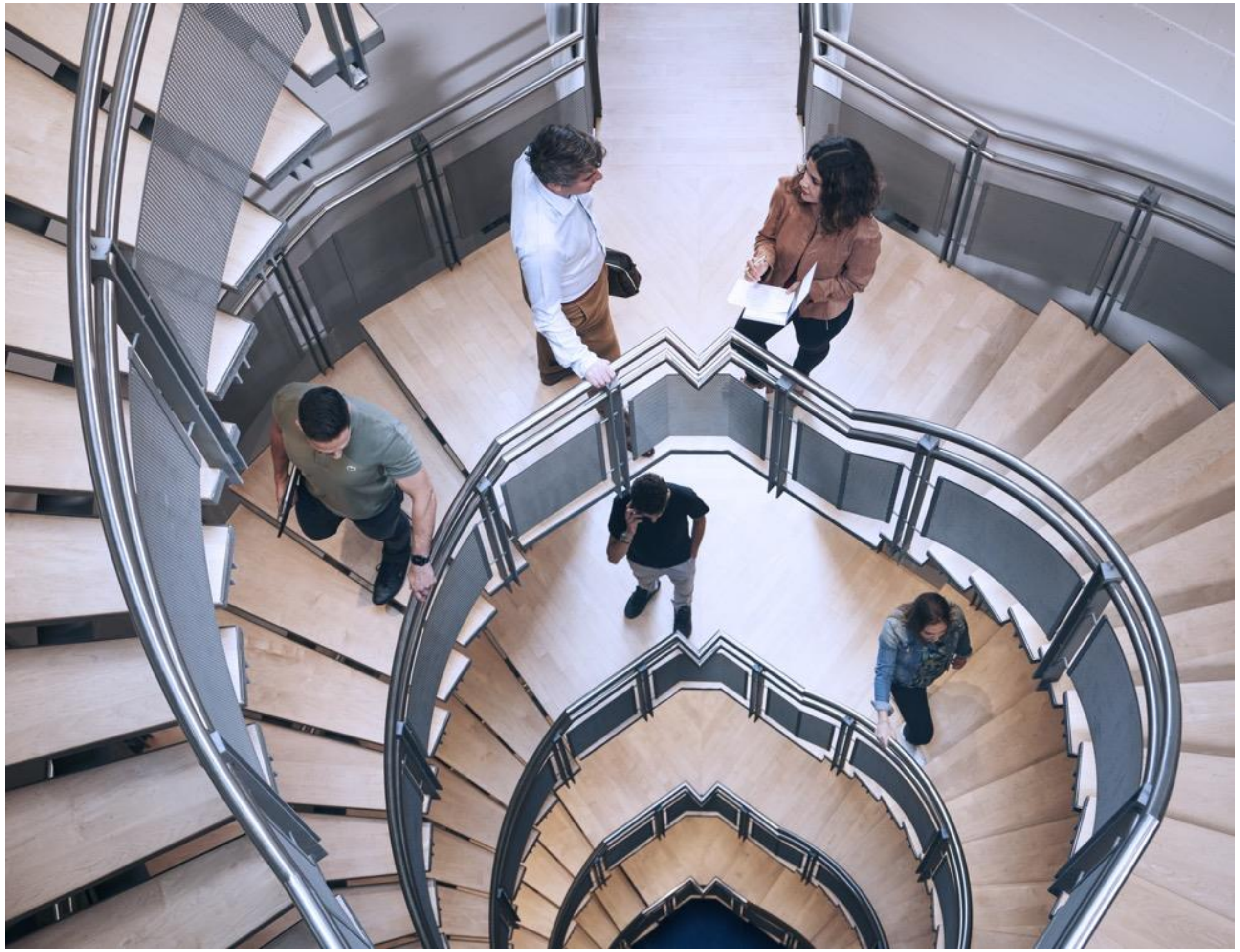
Proven project management methodology

(300 projects/year)

QMS & certifications

(ISO 9001 QM, 14001 Environment and 13485 Medical devices)

COMBINING EXPERTISE, PASSION, AND DIVERSITY FOR SUCCESS



566
EMPLOYEES

46
NATIONALITIES

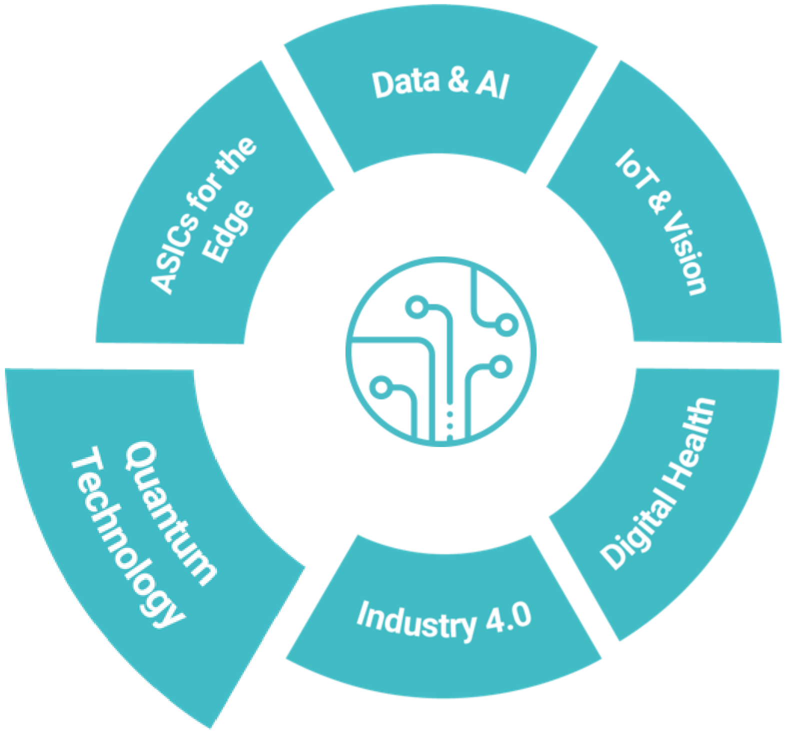
35%
PHD

28%
WOMEN

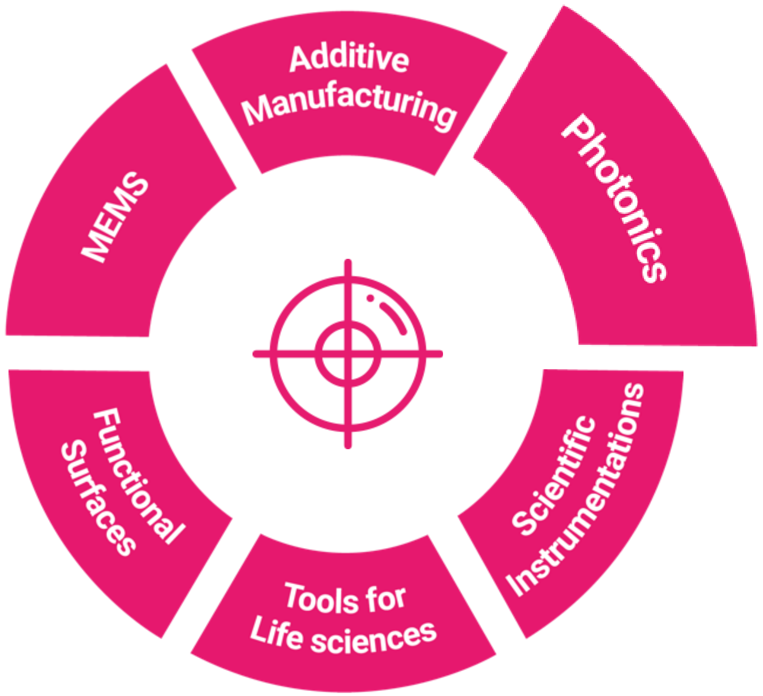
csem

TECHNOLOGIES IN FOCUS TO FOSTER INNOVATION

Digital Technologies



Precision Manufacturing



Sustainable Energy

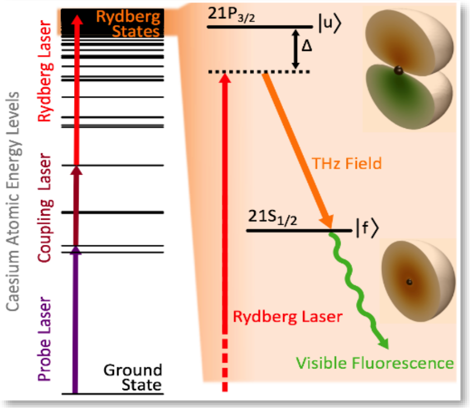
csem

QUANTUM ACTIVITIES AT CSEM

- **Quantum sensing with hot vapors**
  - MEMS atomic vapor cells
  - Miniature atomic clocks
  - Optically pumped magnetometers
  - Miniature gyroscopes

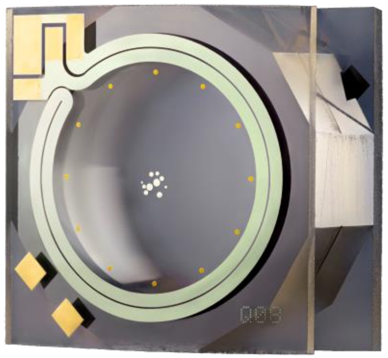
- **Beyond the state-of-the-art**
  - PIC for miniaturization
  - PIC for quantum computation
  - Non-classical light states

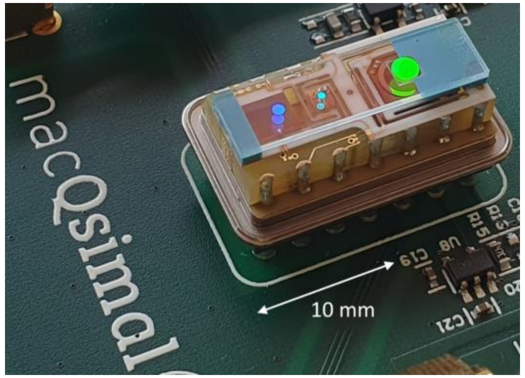
MEMS atomic vapor cells: a platform for different applications



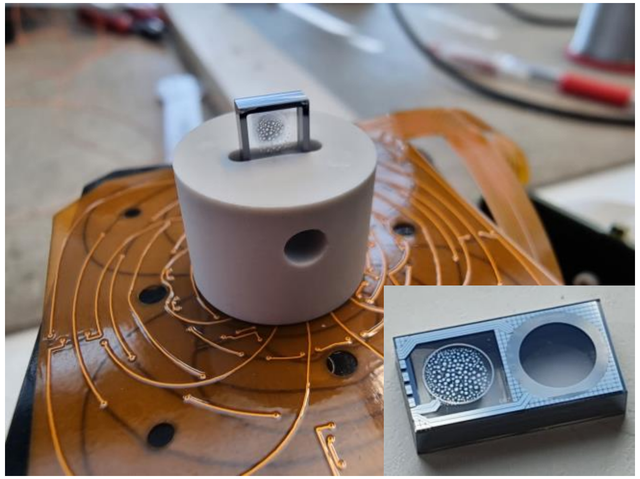
GHz sensor and imager

THz sensor and imager

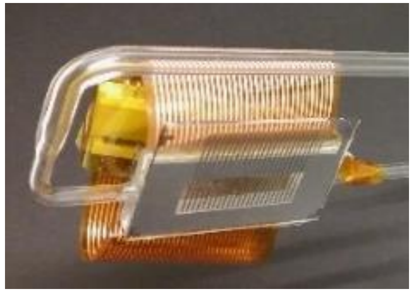




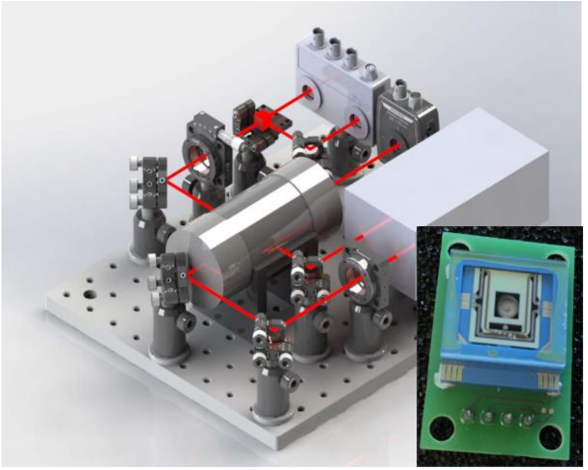
Miniature atomic clocks



Magnetometers



Rydberg gas sensor

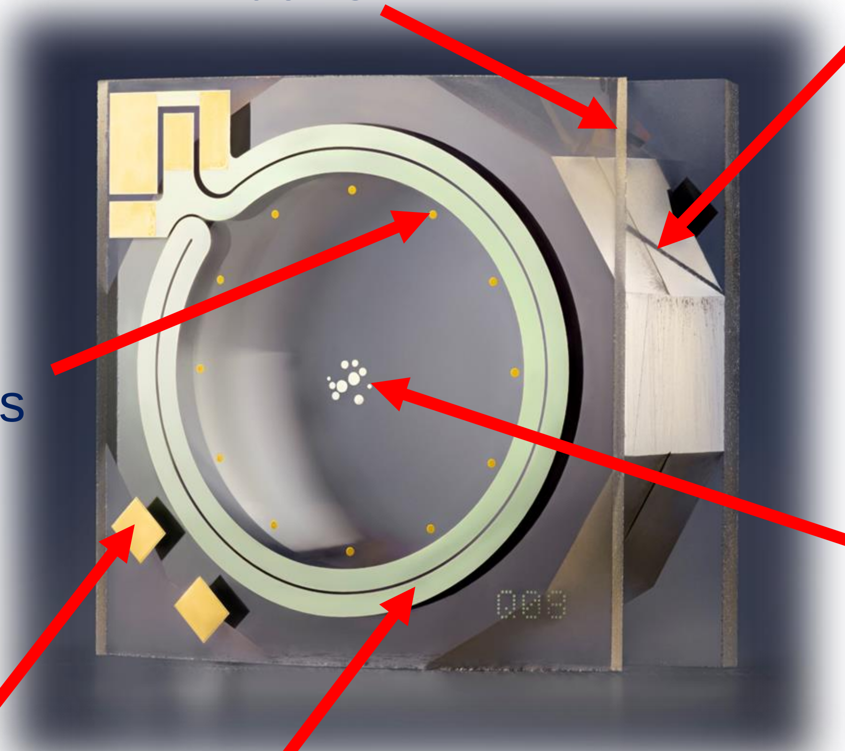


Gyroscopes

macQsimal

csem

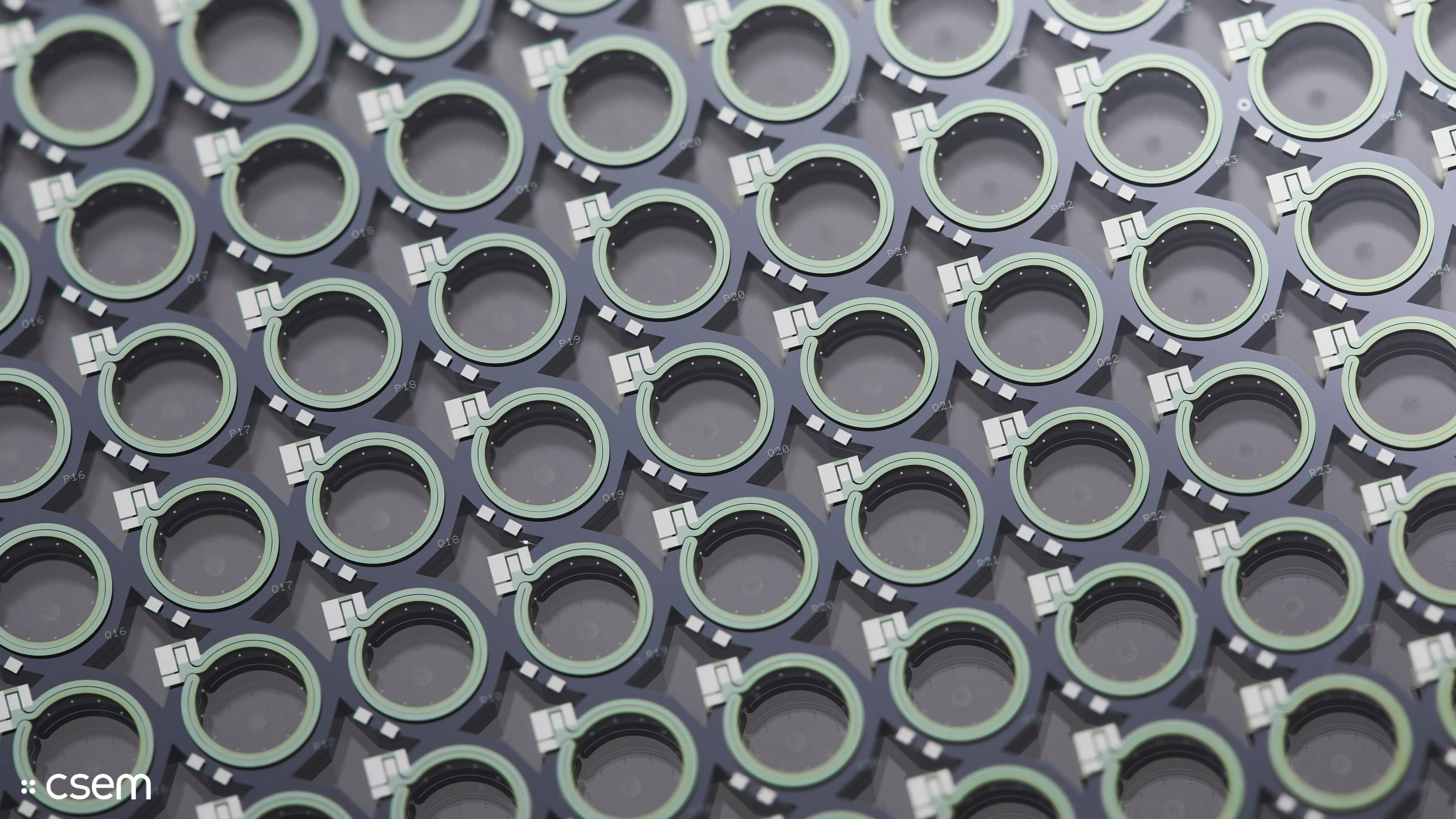
MEMS ATOMIC VAPOR CELLS



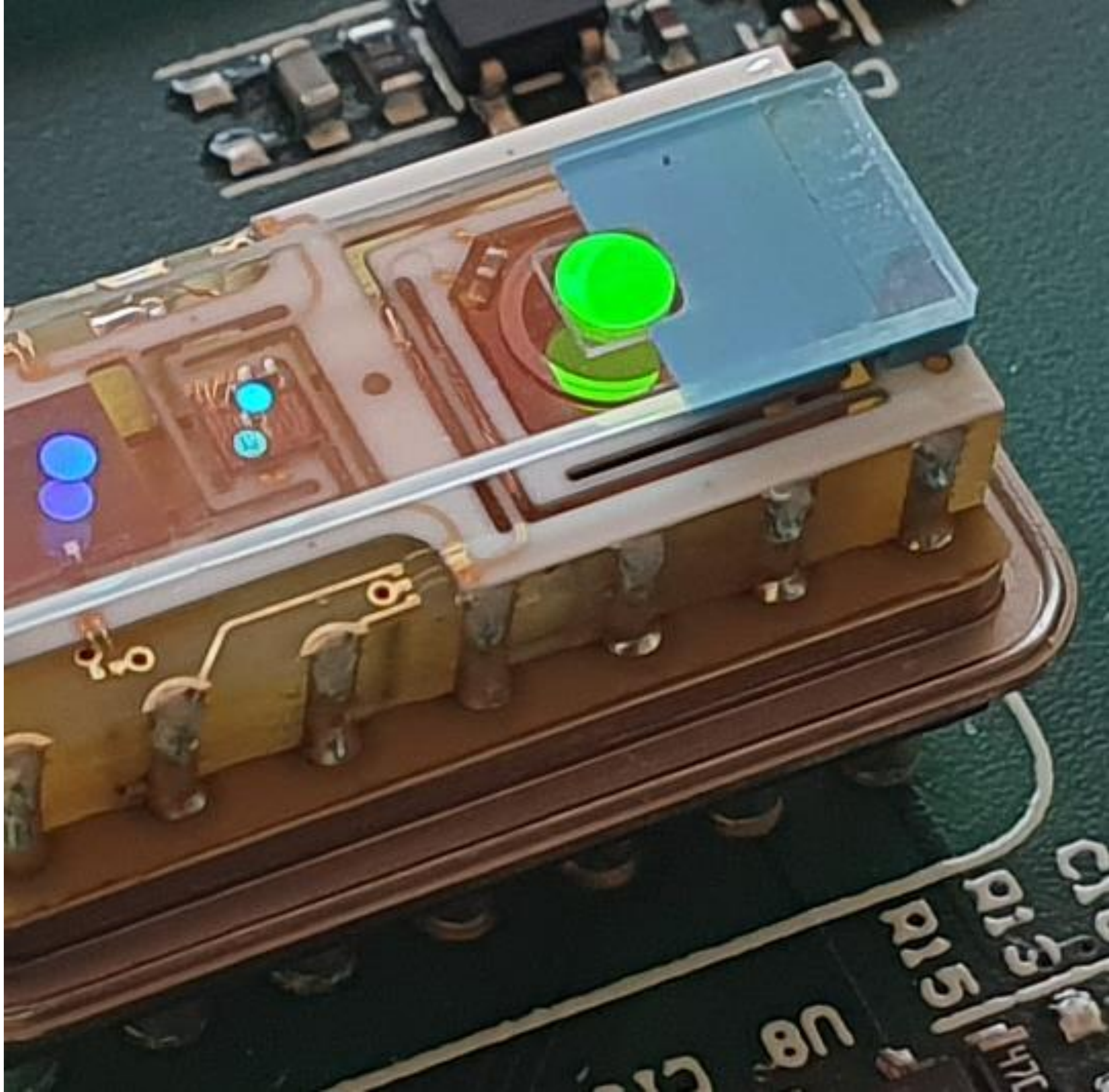
$4 \times 4 \times 1.9\ mm^3$

CSEM cells specific features:

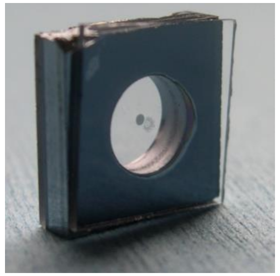
- RbN_3 **wafer-level** filling
- Al_2O_3 coating for lifetime enhancement
- **Au microdiscs** for clock frequency stability improvement


csem

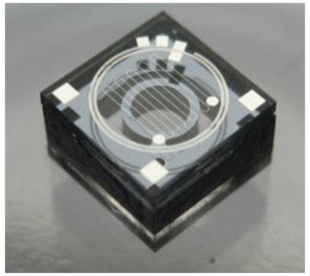
CHIP-SCALE ATOMIC CLOCK



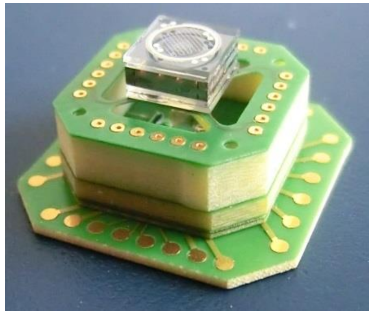
Chip-scale atomic clock development at CSEM



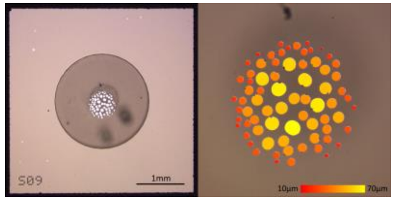
First MEMS atomic vapor cell



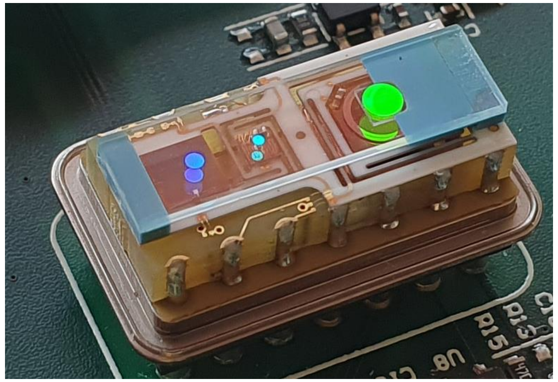
First functionalized cells filled with RbN_3



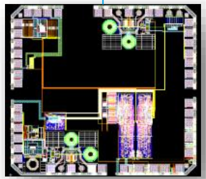
First integrated package



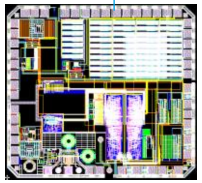
Lifetime improvement of RbN_3-filled atomic vapor cells



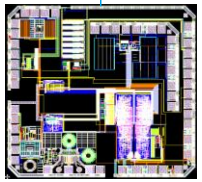
Industrial DIL-14 package



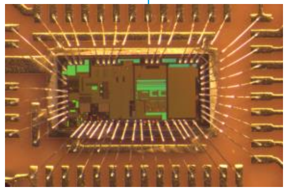
ASIC v. 1



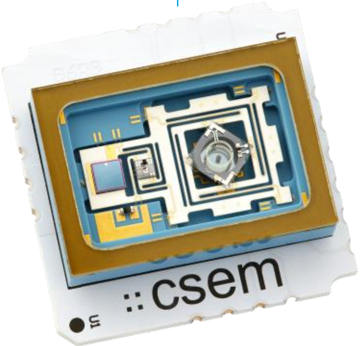
ASIC v. 3



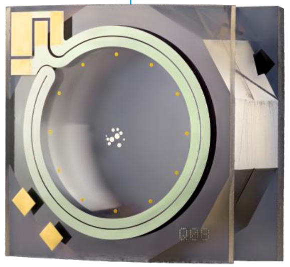
ASIC v. 2



ASIC v. 4



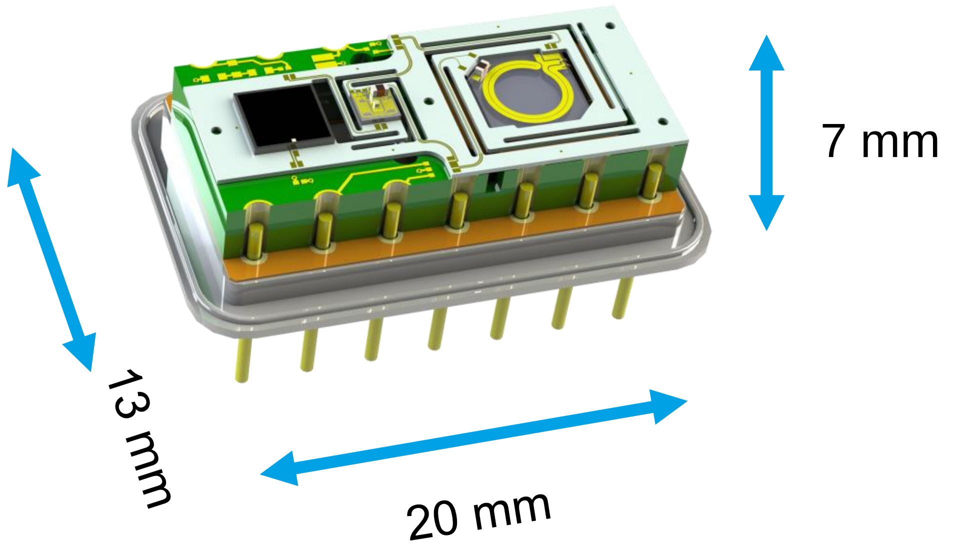
Flat-form factor package

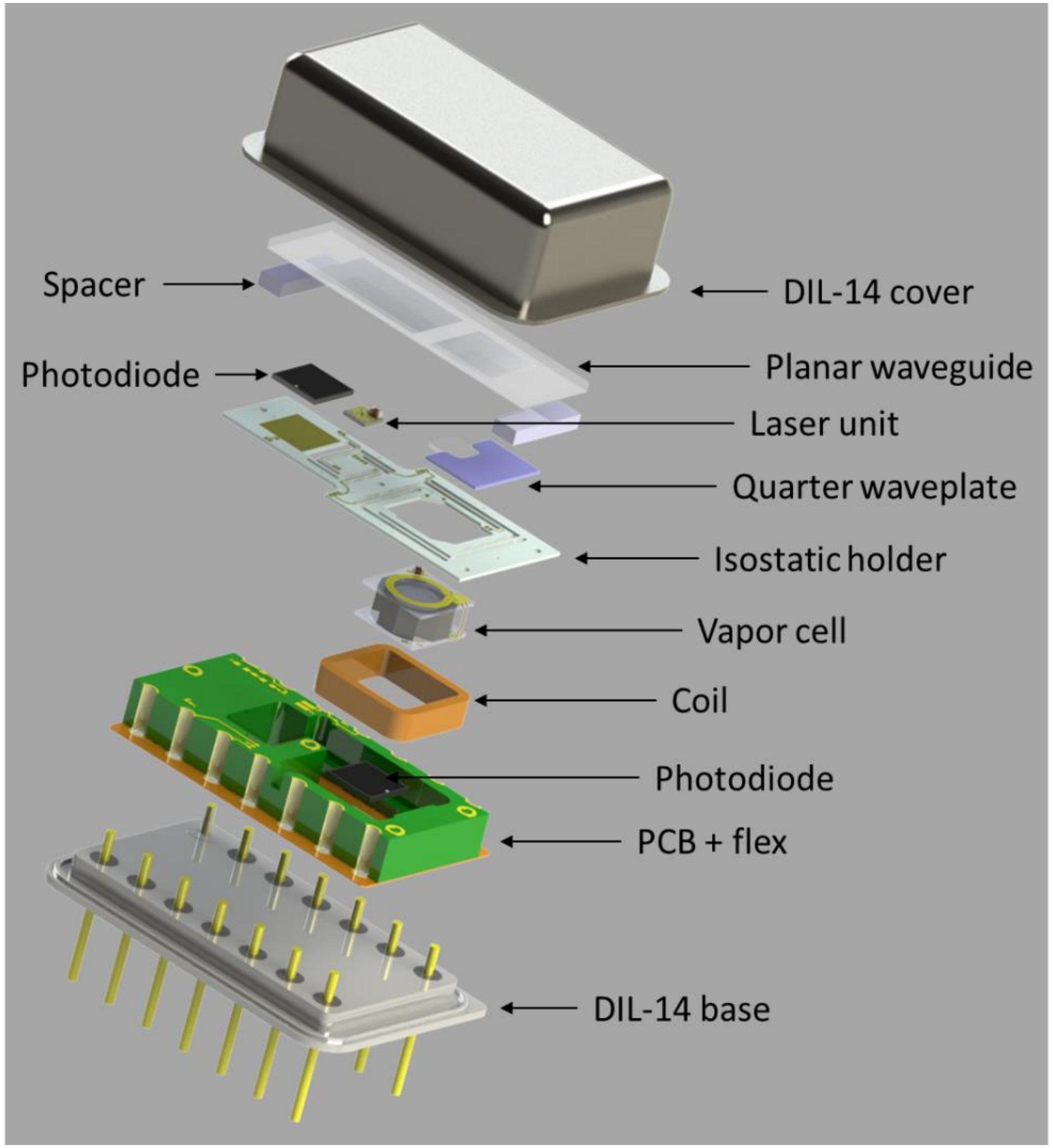


MEMS cell with Au discs

PHYSICS PACKAGE DESIGN

- CSEM flat formfactor design
- 3 patents
- Adapted for industrial needs





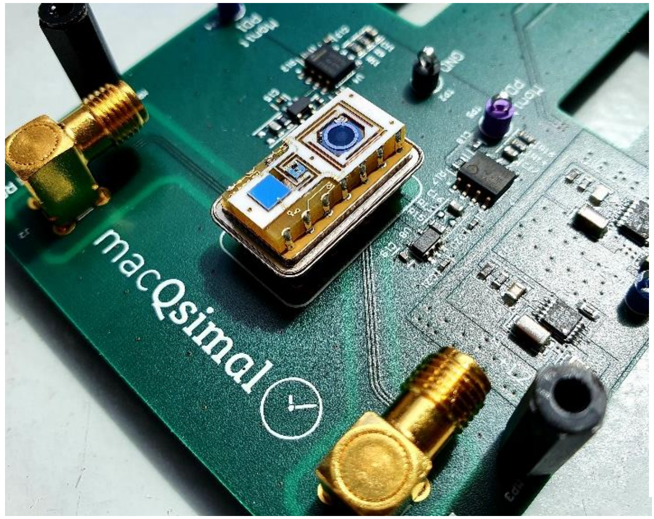
CSEM CHIP-SCALE ATOMIC CLOCK

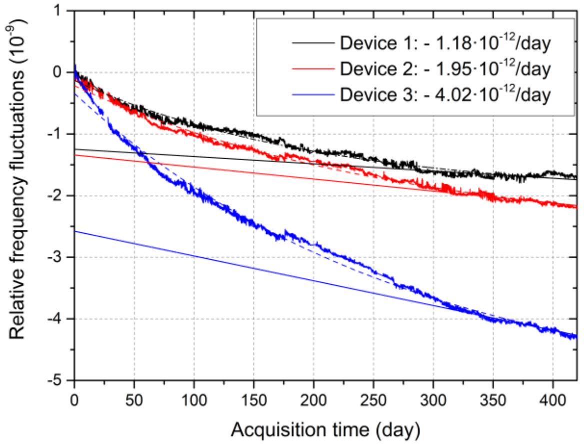
< $5 \cdot 10^{-11}$ stability @ 1s

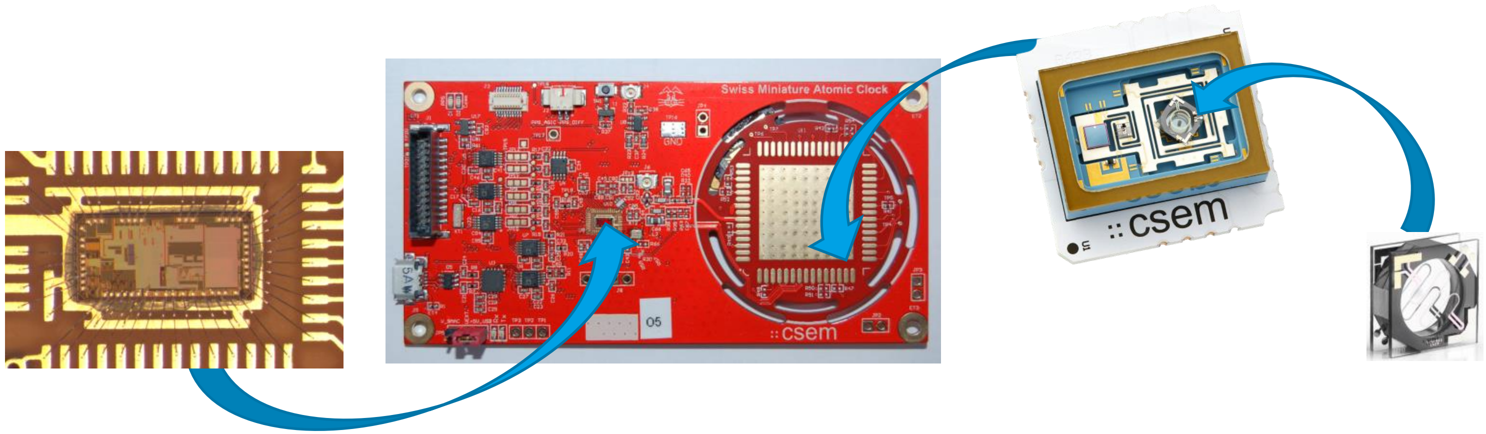
< $5 \cdot 10^{-12}$ / day frequency drift

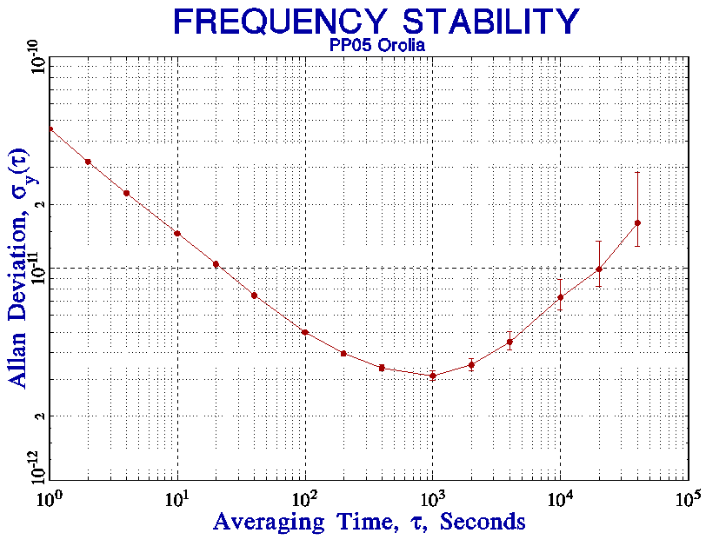
< 50 mW power consumption (PP + ASIC)

Volume: 1.8 cm^3 (PP)

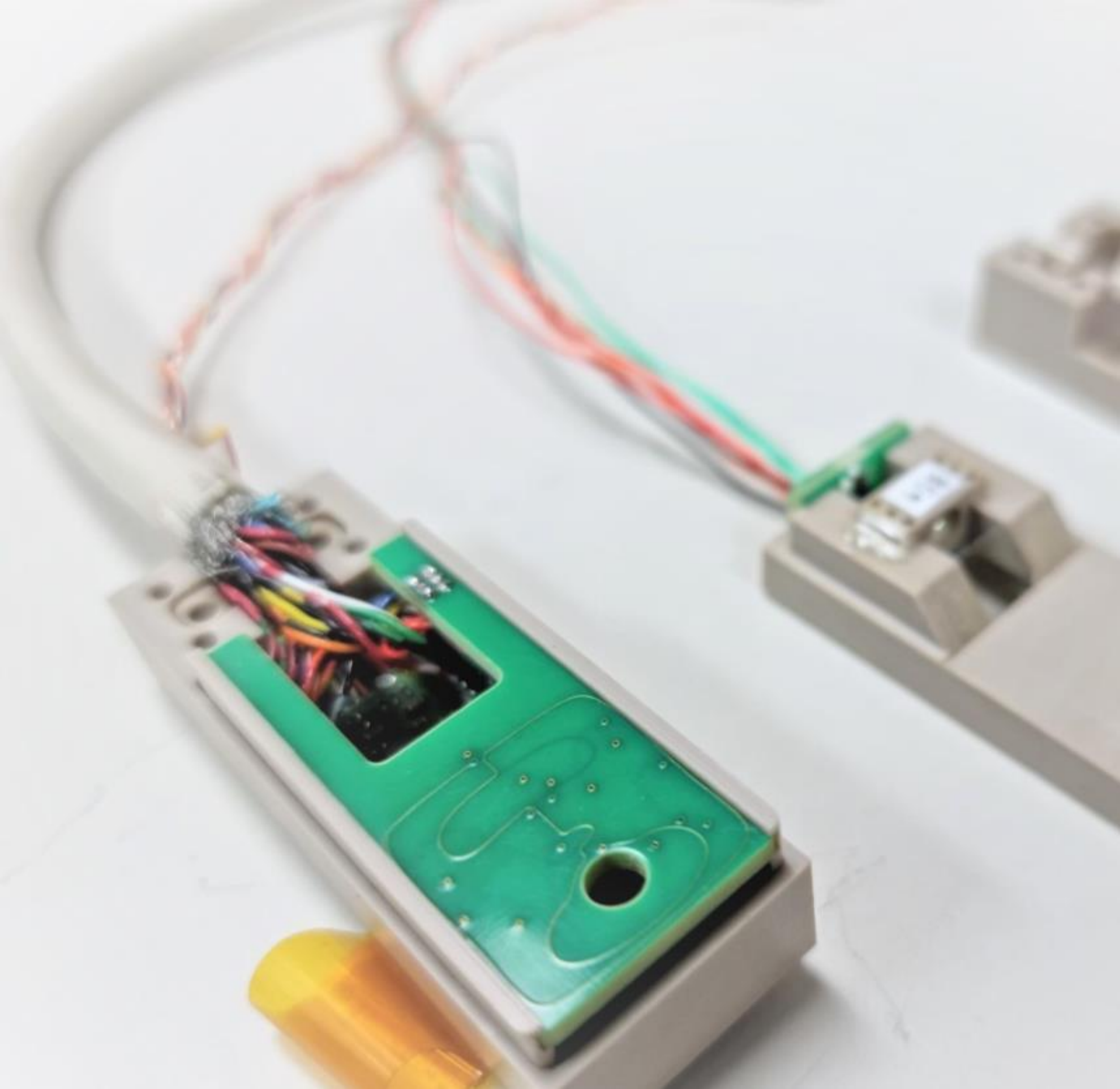




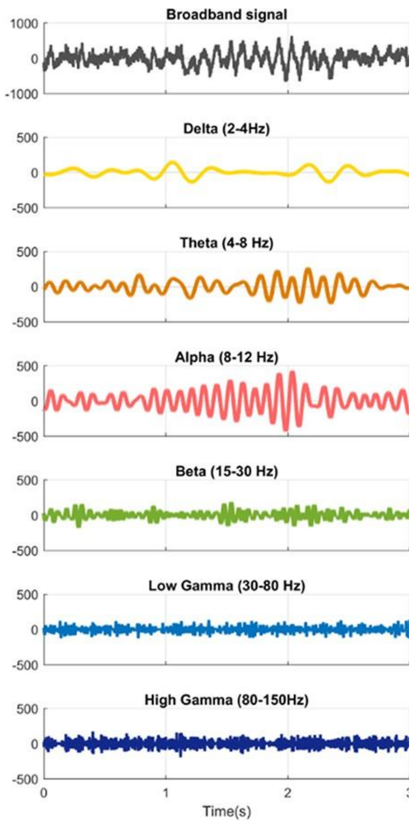


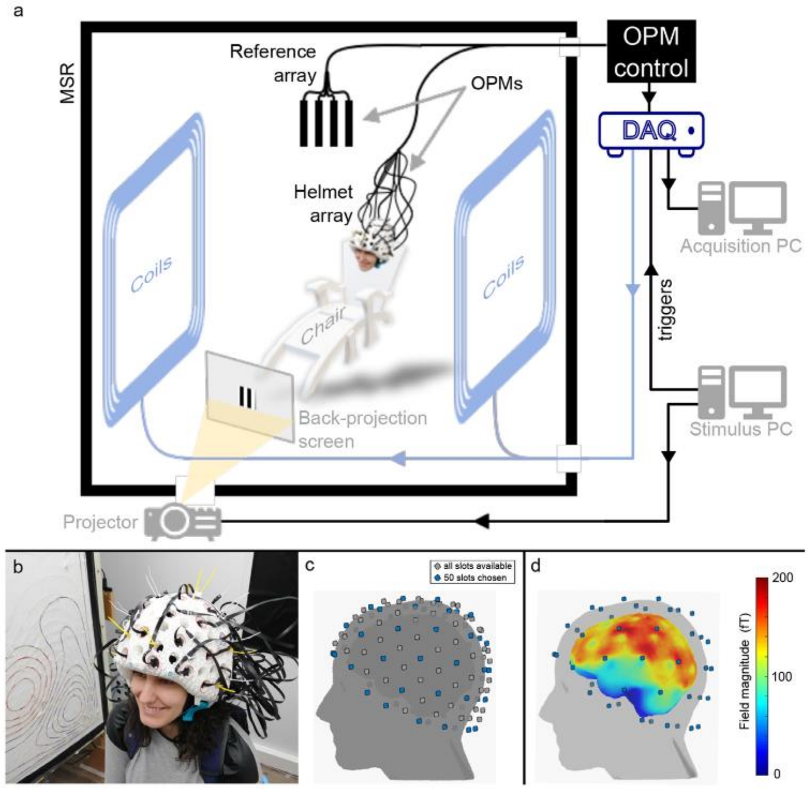


OPTICALLY PUMPED MAGNETOMETER

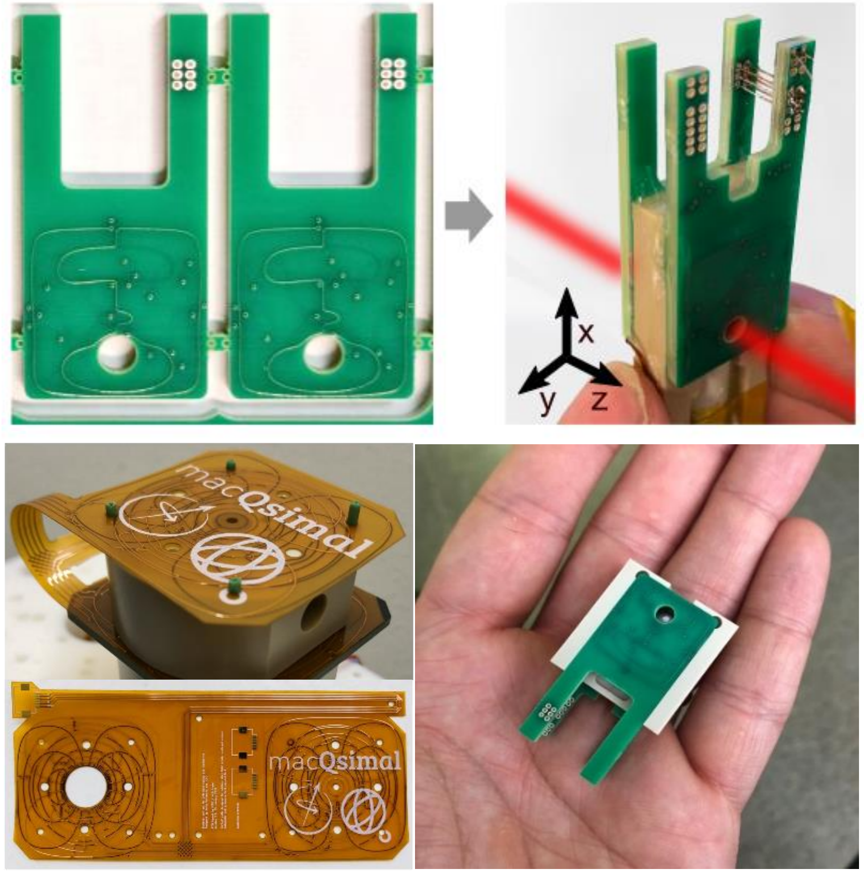


MOTIVATION: MAGNETOENCEPHALOGRAPHY (MEG)





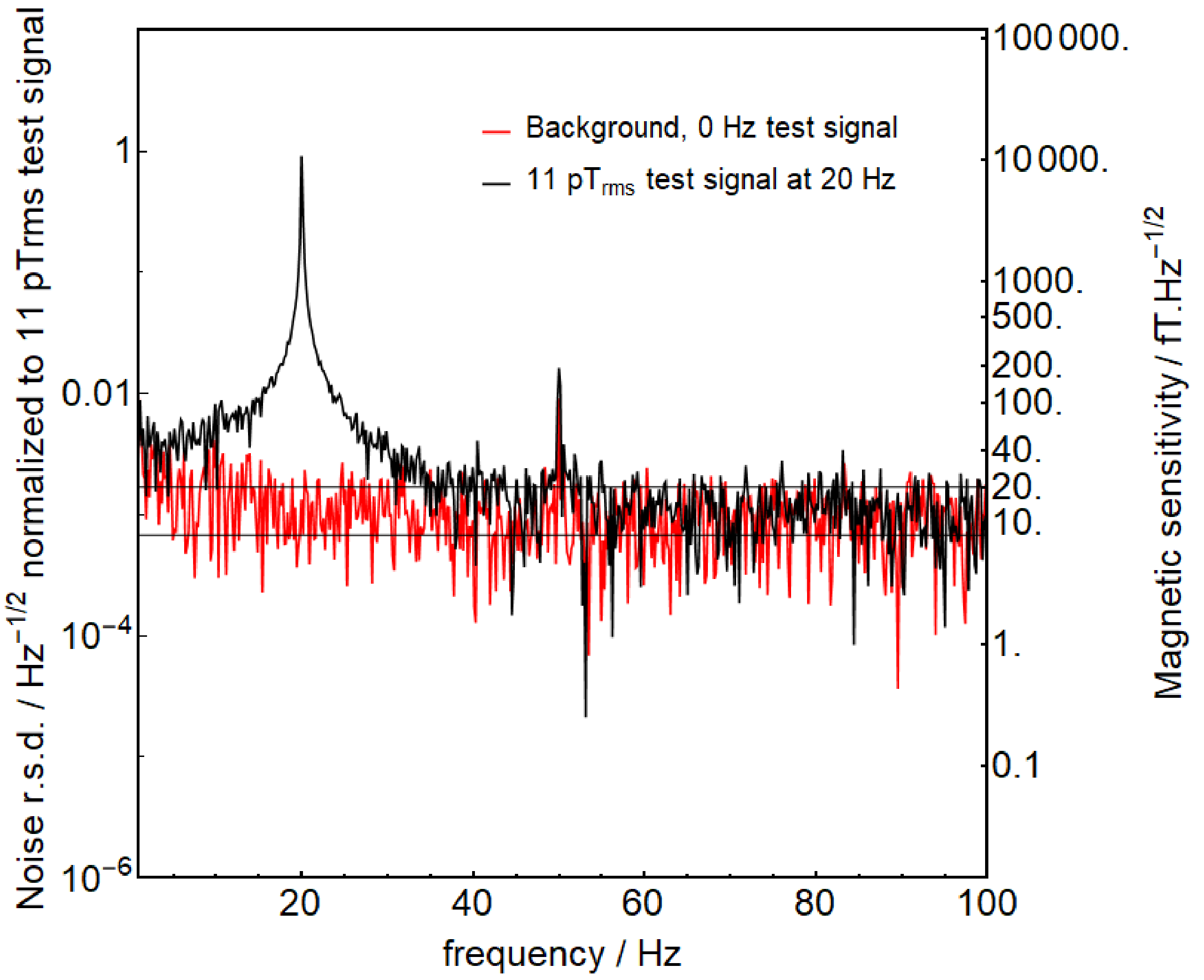
NeuroImage 230 (2021) 117815



macQsimal ICFO

RESULTS AND NEXT STEPS

15 fT/Hz$^{1/2}$ sensitivity in the 20 Hz – 100 Hz range



Journal of Applied Physics ***128****, 063906 (2020)*

macQsimal ICFO

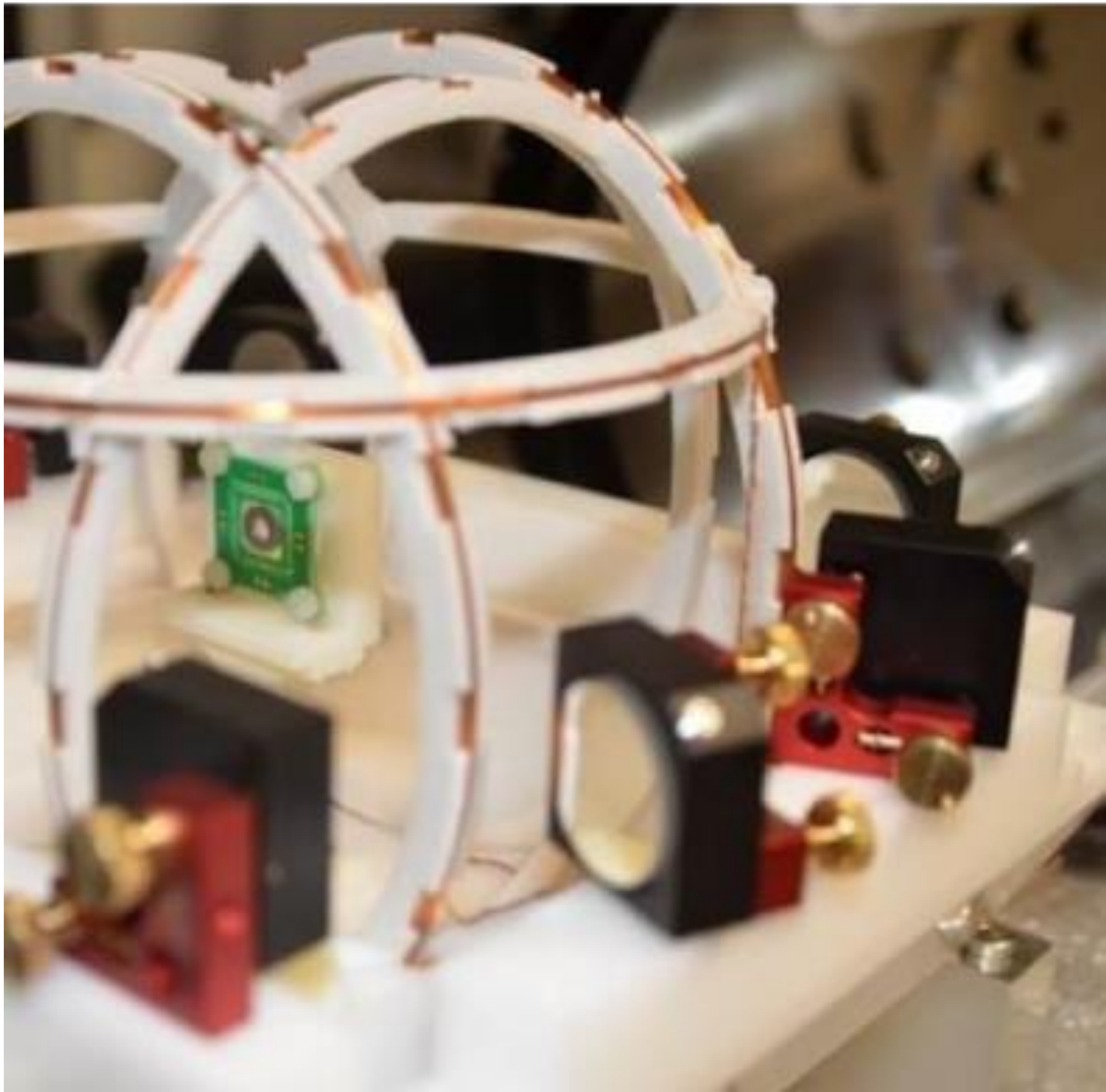
MINIATURE GYROSCOPES

macQsimal

csem

VTT

BOSCH



ATOMIC GYROSCOPE: SPIN PRECESSION

Larmor precession

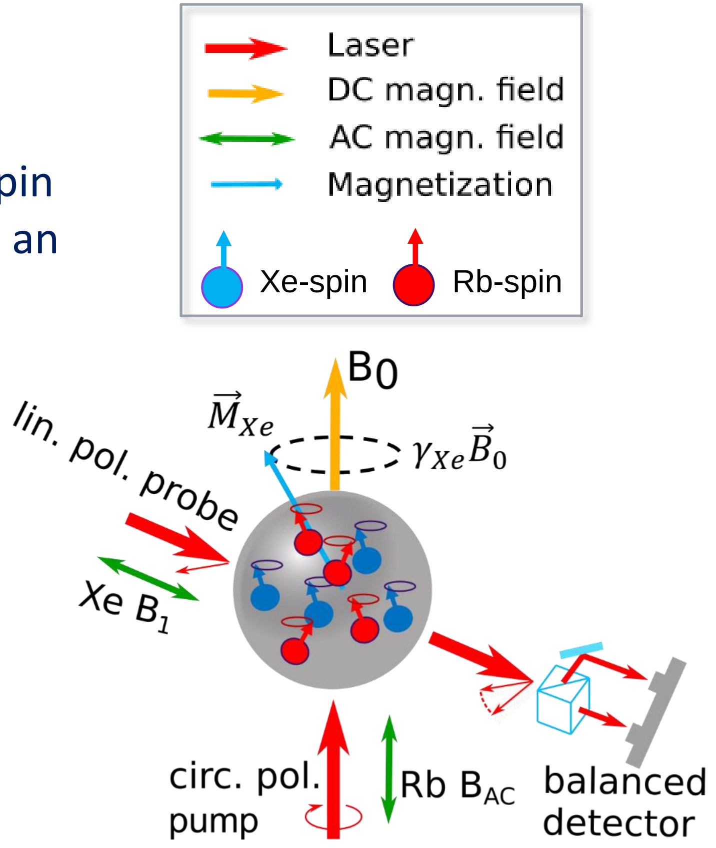
- Spin precession: Magnetic moment $\vec{\mu}$ of the atomic spin exhibits a torque $d\vec{\mu}/dt$ in an external magnetic field $\vec{B}$:

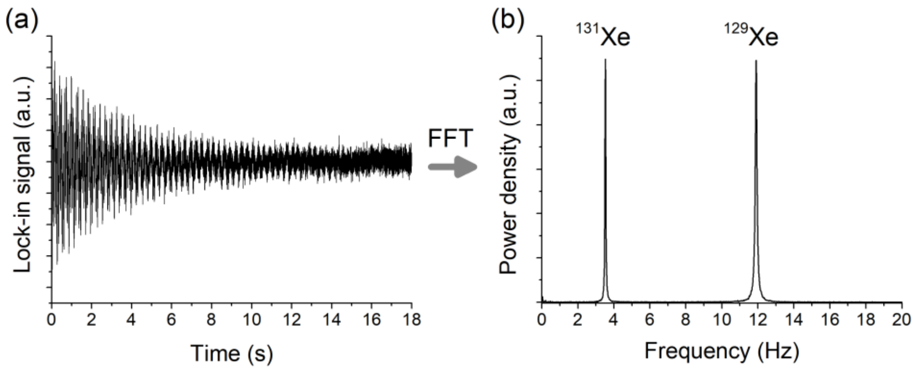
$$\frac{d\vec{\mu}}{dt} = \vec{\mu} \times \gamma \vec{B}$$

- Larmor frequency w/ external rotation ω_r

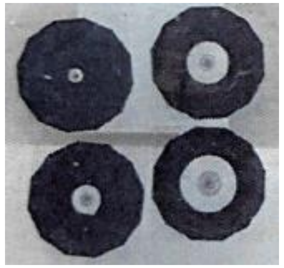
$$\vec{\omega}_L = \gamma \vec{B} + \vec{\boldsymbol{\omega}}_{\boldsymbol{r}}$$

γ: gyromagnetic ratio

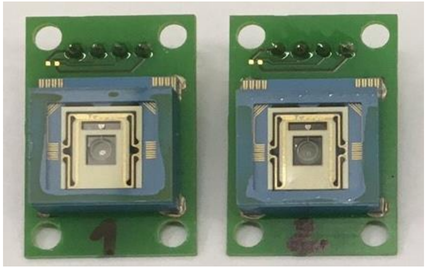




Xe free-induced decay signal



MEMS cells by CSEM



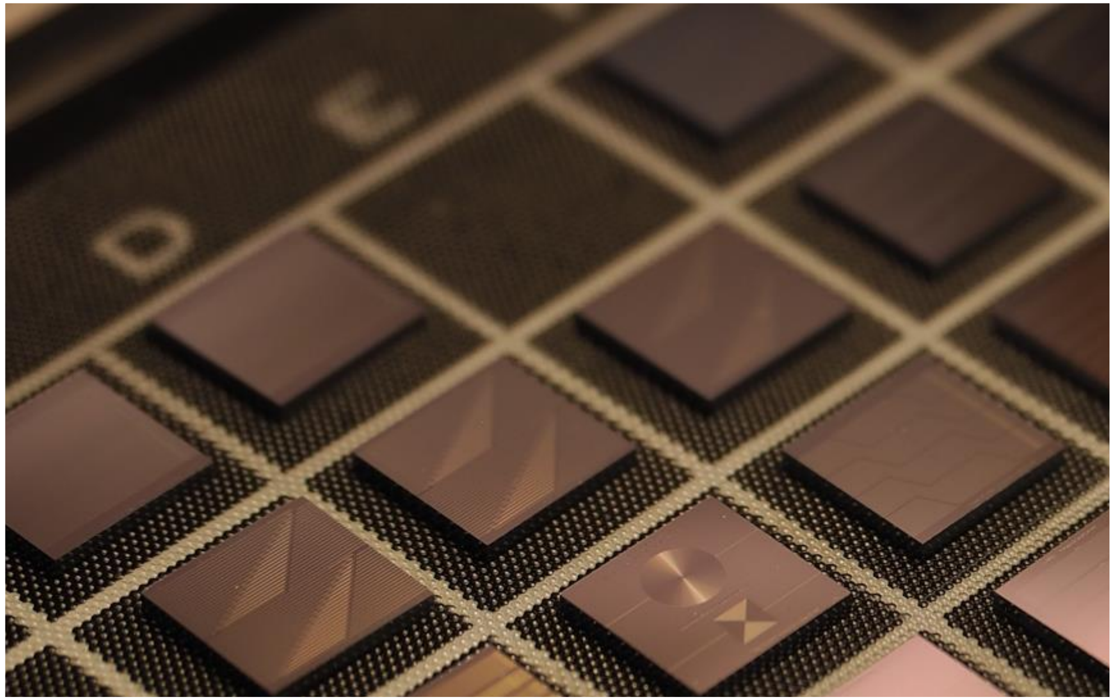
Ceramic cell package

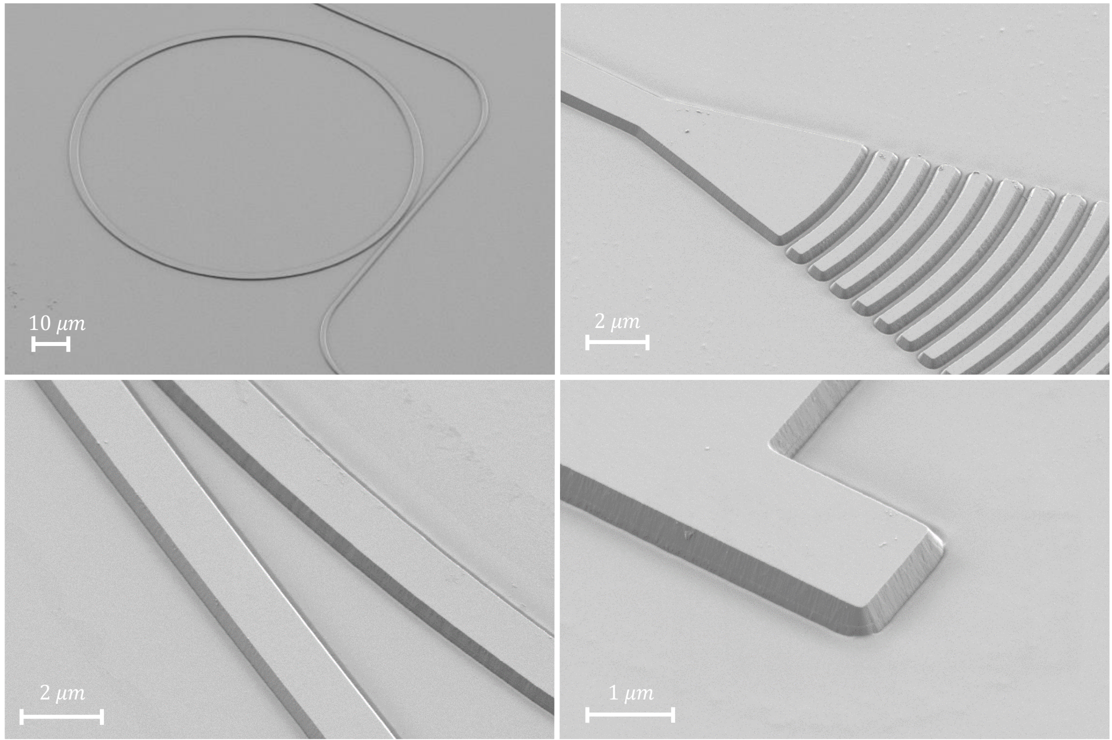
VTT BOSCH macQsimal csem

PHOTONIC INTEGRATED CIRCUITS FOR QUANTUM APPLICATIONS

- PIC for quantum computing

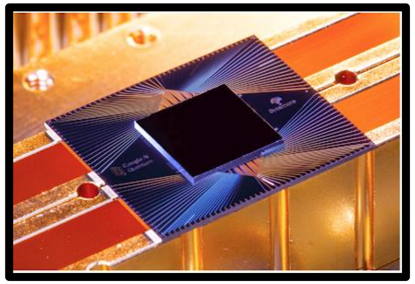
- PIC for quantum sensing



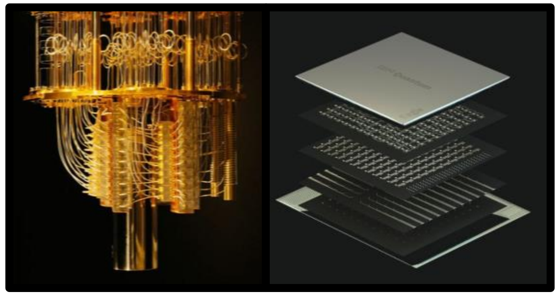


QUANTUM COMPUTER RACE: PHOTONS VS. SUPERCONDUCTING CIRCUITS

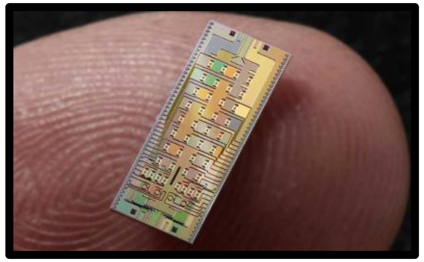
2019: Google's Sycamore solved a computational problem in just 200 seconds with 54 qubits—compared to a supercomputer's 10,000 years



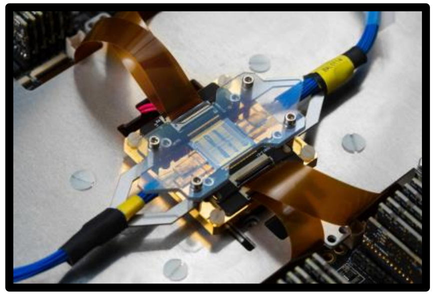
2021: IBM presents 127-qubit Eagle processor



2021: Xanadu presents 8-qubit photonic quantum chip

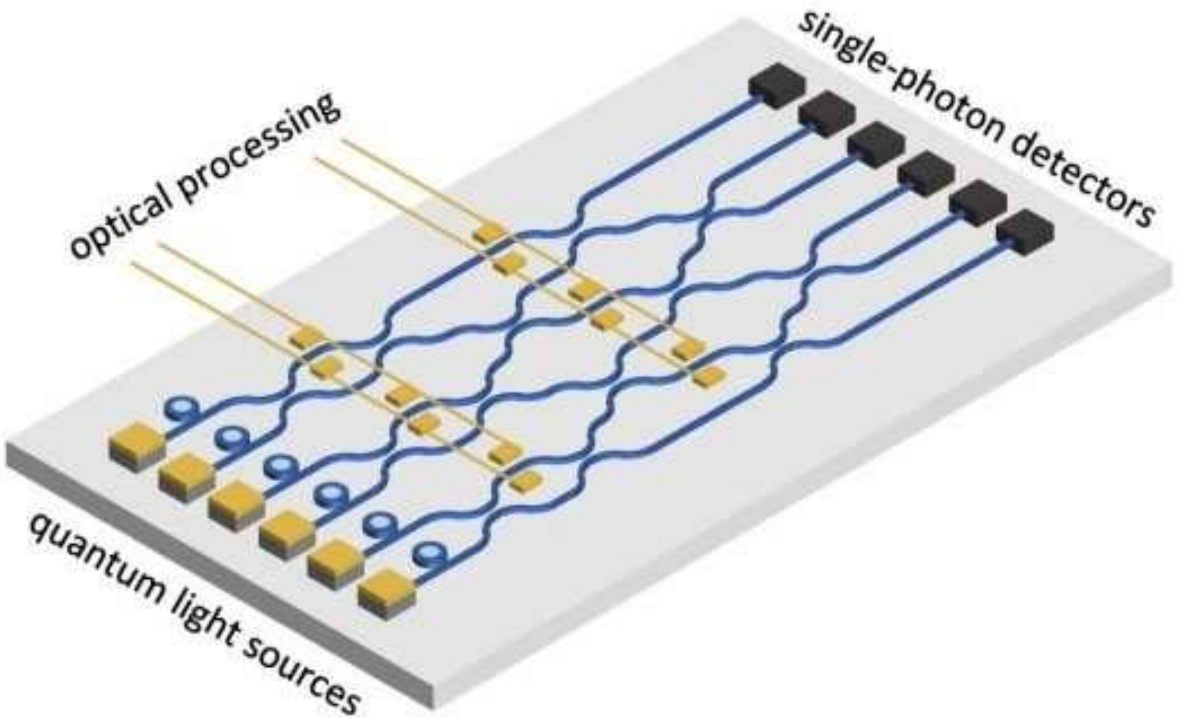


2022: QuiX releases 20 mode photonic quantum processor



2023: IBM announced 1121-qubit Condor processor announced
QuiX announced 32 mode photonic quantum processor

PHOTONIC QUANTUM COMPUTER: BUILDING BLOCKS



https://phys.org/: Andrew Masuda, University of California - Santa Barbara

MOTIVATION: LNOI PLATFORM FOR PICS

More bandwidth

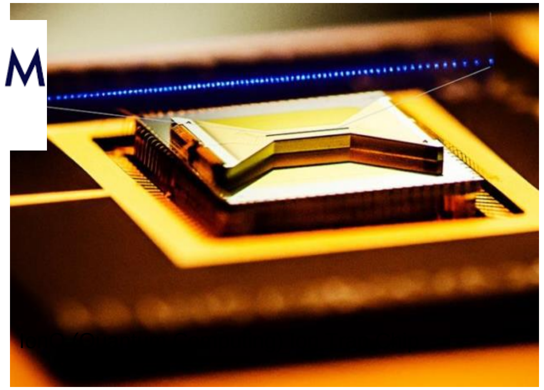
(internet bandwidth grows by100x in the next decade)

Facebook connectivity map - 2018

More Compact and Faster EO Modulators!

EO Light control below $1\mu m$ wavelength

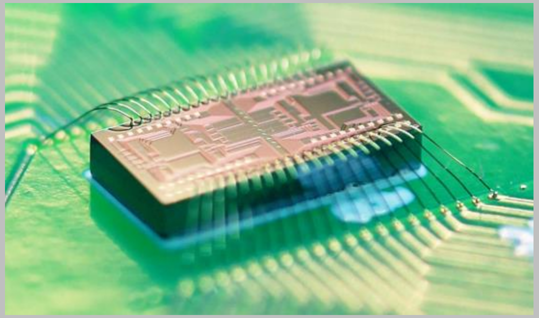
(In wavelength range that Si or InP are not transparent)



Wide-Transparency Window

Integration and scalability

The magic of PICs in miniaturization of optics



Small bending radii

Issue of power consumption

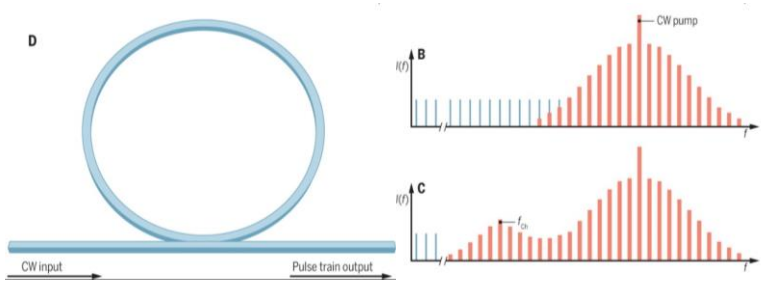
(ICT today consume ~10% of total electrical energy in the world)

Efficient and Low-loss EO Modulators!

Europe chip act

Non-Linear Photonics and Metrology

(Wavelength conversion, 2nd harmonic generation, optical frequency combs)



Large $\chi^{(2)}$ and $\chi^{(3)}$ optical nonlinearity

N. Jones, Nature 2018 -------- N. Akhmediev et al., Science 2016
https://blog.telegeography.com/466-tbps-the-global-internet-continues-to-expand

LNOI PROPERTIES

Property	Value
Wafer cut	x
Refractive index (ordinary)	2.21 (@ 1550 nm)
Refrafctive index (ex-ordinary)	2.13 (@ 1550 nm)
Bandgap	4.9eV
Transparency window	350nm – 5.5 μm
EO coefficient	r_{33}= 31 pm/V
$\chi^{(2)}$ nonlinearity	3×10^{-11} m/V
$\chi^{(2)}$ nonlinearity	$1.6 \times 10^{-21}\ m^2\ V^{-2}$
Piezoelectric coefficient	d_{33}= 6.0×10^{-12} C/N

Piezoelectric effect

- Acousto-optical modulators (AOM)
- Optical MEMS integration
- Gyros and pressure sensors

Intrinsic EO coefficient

- Fast (> 100 GHz) and low $V\pi$ (< 1 V) modulators
- Addressing the need for a wider bandwidth
- CMOS-level voltage operation
- Ultra-low insertion loss modulators

Wide bandgap

- LiNbO3 bandgap = 4.9 eV
- High optical power handling
- Low optical loss
- No parasitic two-photon absorption

Integration and scalability

- Low-loss waveguides (< 0.1 dB/cm)
- Small bending radii (~ 30 µm)
- Compact circuit footprint
- low-power building blocks
- Programmable photonics
- High-port-count switches

NO PHOTONICS PLATFORM IS IDEAL → FUTURE IS HYBRID!

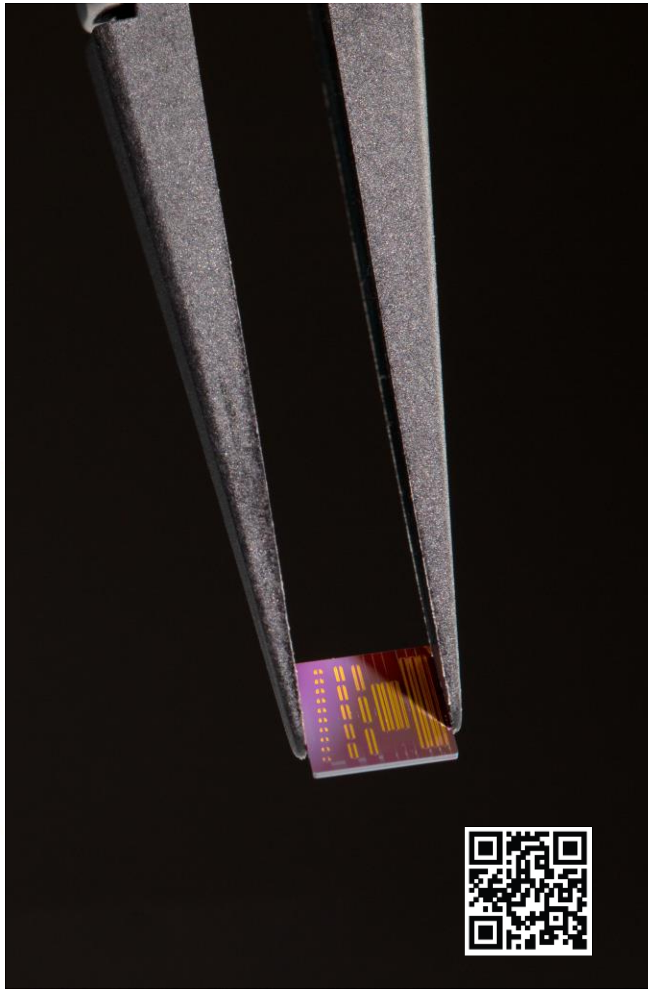
Need for Components to Generate, Transport, Process, and Detect light

No single material can do everything!

Famous PIC platforms / Property	InP	Si	SiN	LNOI	Polymers
Transparency window	0.9 – 2 µm	1.1 – 8 µm	0.25 – 8 µm	0.3 – 5.5 µm	0.5 – 2 µm
Propagation losses	1.5 to 3 dB/cm	0.1 to 3 dB/cm	0.01 to 0.1 dB/cm	<0.1 dB/cm	<0.5 dB/cm
Two-photon absoprtion	high	high	Very low	Very low	low
Electro-optic coefficient (Modulators)	not intrinsic	not intrinsic	-	High (31pm/v)	Some polymers
Optical gain (lasers, amplifiers)	Yes	-	-	-	-
Detectors	Yes	Yes (<1µm)	-	-	-
Industry Status	Ramping up	High Volume	Low Volume	First R&D foundry at CSEM	R&D Qualification

CSEM PIC PROJECTS PORTFOLIO

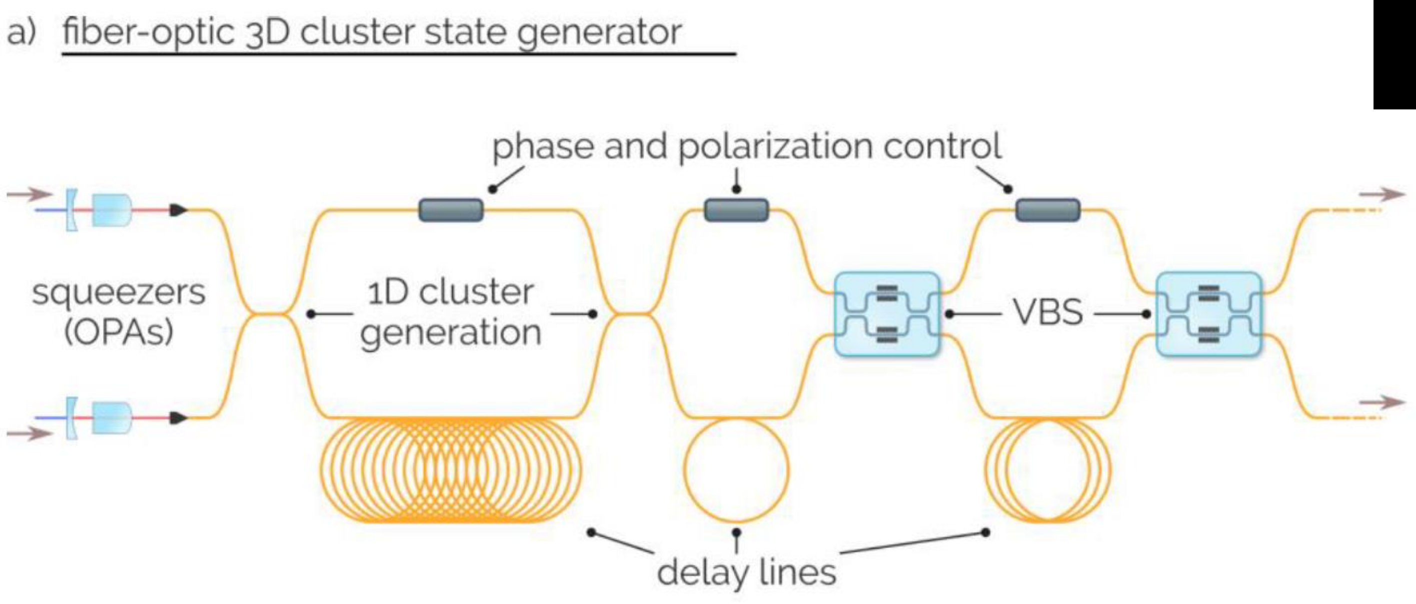
LNOI Foundry	ELENA	https://www.project-elena.eu/	CSEM, Soitec, VPIphotonics, ETH zürich, Vanguard Automation, Thales, III-V lab, Rosenberger, UP, Leti
LNOI Foundry	PATTERN	https://pattern-project.eu/	CSEM, LUCEDA, phix, Fraunhofer HHI, imec / Ghent University, Thales, CNRS, Microwave Photonics, UP, UCL
Telecom	sprinter	https://horizon-de-sprinter.eu/	ICCS, LioniX International, imec, uc3m Universidad Carlos III de Madrid, Fraunhofer HHI, phix, CSEM, Ericsson, Fill, Cumucore, Intracom Telecom, NVIDIA
LiDAR	LOLIPOP	https://horizon-de-lolipop.eu/	ICCS, LioniX International, CSEM, phix, imec, UCC, Superlum, University of Twente, Polytec, QuiX Quantum, Irida Labs, Optagon Photonics
Quantum	QUANTERA	https://www.quantera-utp4q.eu/	Ghent University, CSEM, Sparrow Quantum, University of Ljubljana, Universität Heidelberg
Quantum	CLUSTEC	http://clustec.eu/	DTU Technical University of Denmark, CSEM, Palacký University Olomouc, Universität Heidelberg, Q.ANT, Johannes Gutenberg Universität Mainz, SDU University of Southern Denmark, Sorbonne Université

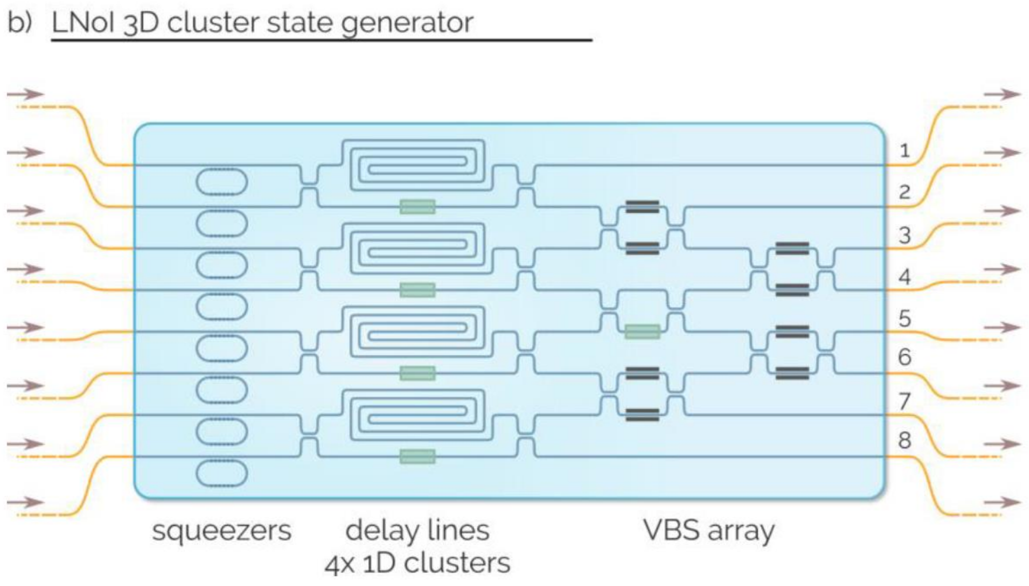


CLUSTEC

Project scope:
Develop a scalable quantum computer (technology and protocols) based on large-scale continuous variable (CV) cluster states

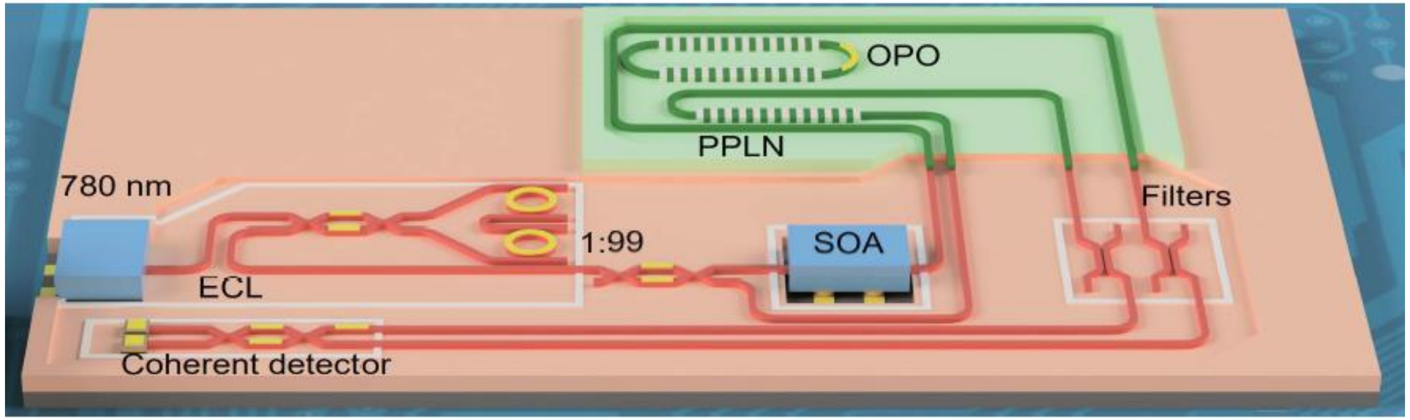
- Develop squeezed state generators based on PPLN and circuitry





Project scope:
Heterogeneous integration
of LNOI and GaAs on SiN

- QKD system on chip
  (squeezed state generation and OPO)
- Frequency converter
  1560/780 nm and 1000/500 nm
- PIC-based FMCW LIDAR module

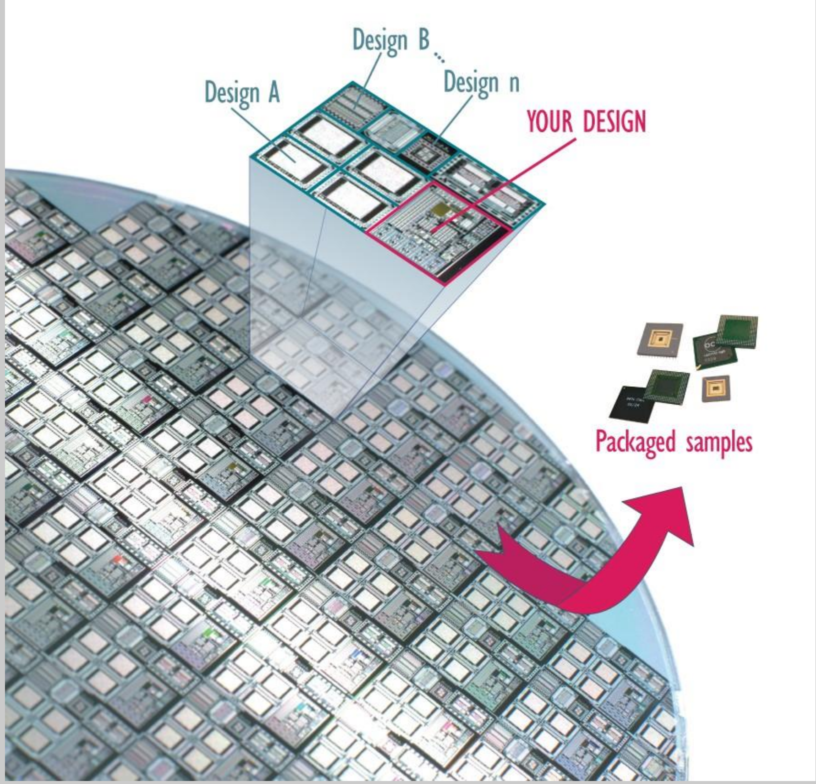


https://horizon-de-lolipop.eu/

QKD transmitter

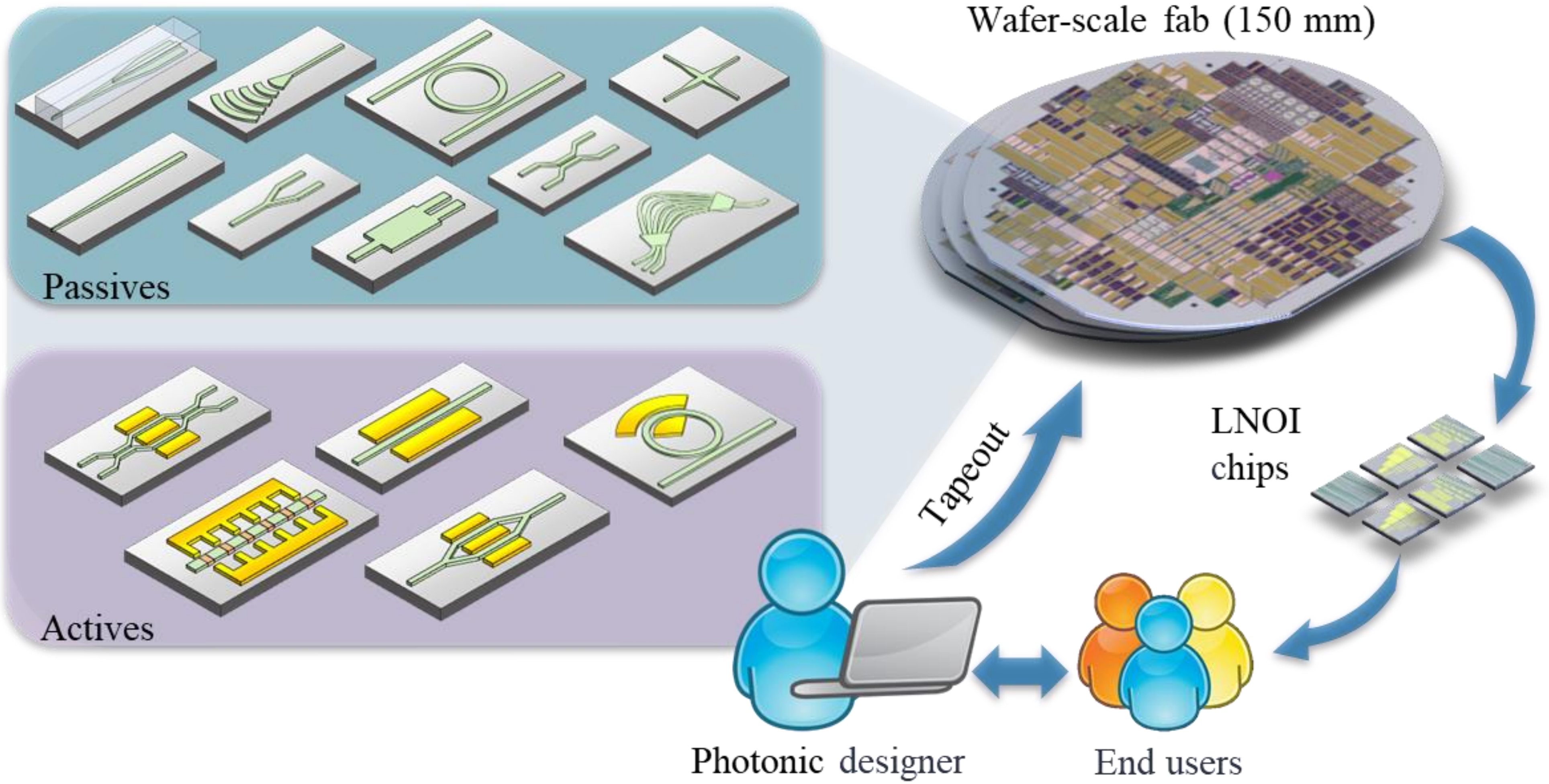
LITHIUM NIOBATE ON INSULATOR (LNOI) PIC PLATFORM AT CSEM

Commercially available MPW service



STANDARDIZATION AND ACCESS

- Process Design Kit (PDK)

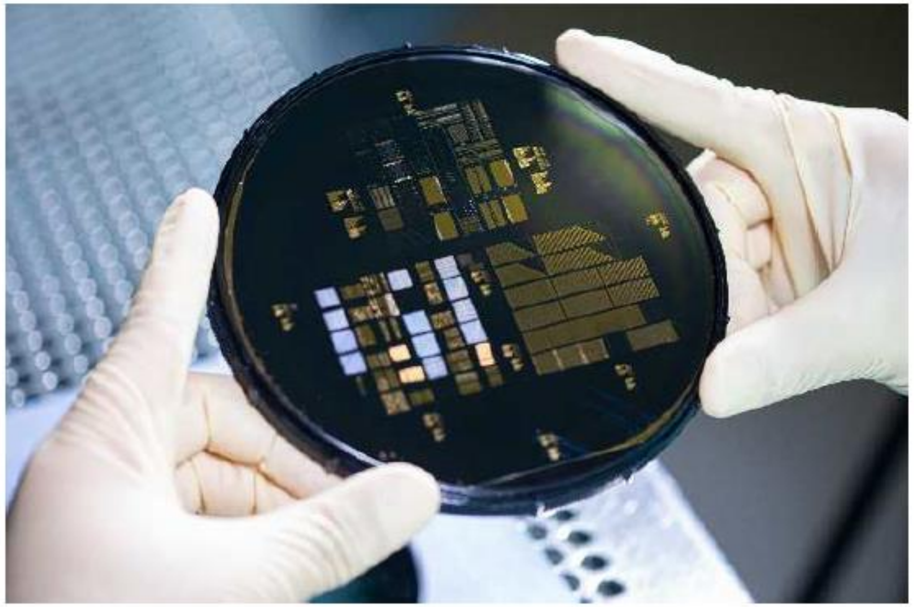


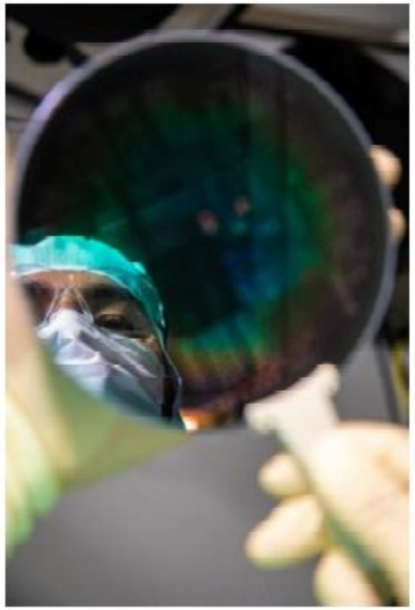
csem

LNOI MPW CURRENT OFFERING

MPW RUNS	Multiple RUNs/year	Customers would receive > 8 copies/design	Custom chip size from 5x5 mm2 up to 10x30 mm2 *
Custom RUNs	Flexible starting date(per customer's request)	Customers would receive > 500 chips/wafer	Complete freedom in customizing chip size and shape

* envisioning to reduce chip size down to 2.5 x 2.5 mm^2

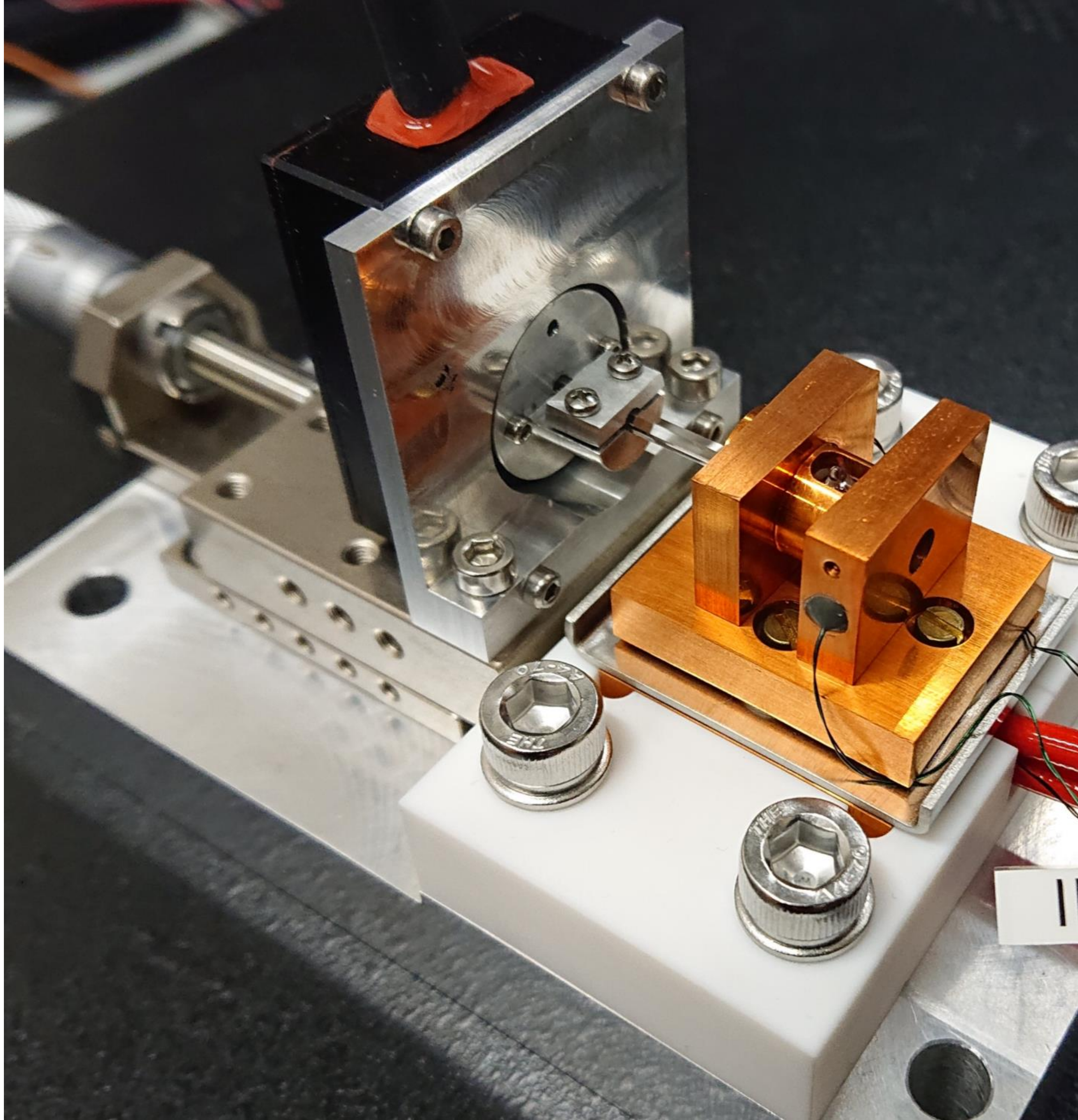




Minimum order:
100 mm^2 design area / mask

PIC IN QUANTUM:

Miniature two-photon atomic clocks



ESA NAVISP A-CSAC project

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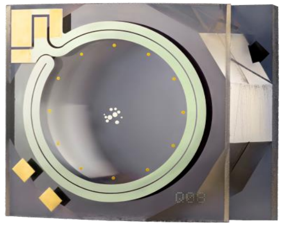
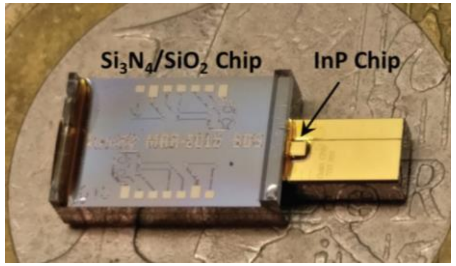
PIC IN THE TWO-PHOTON CLOCK



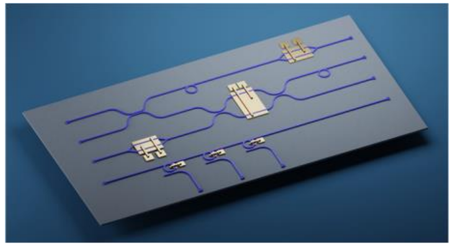
MEMS cell

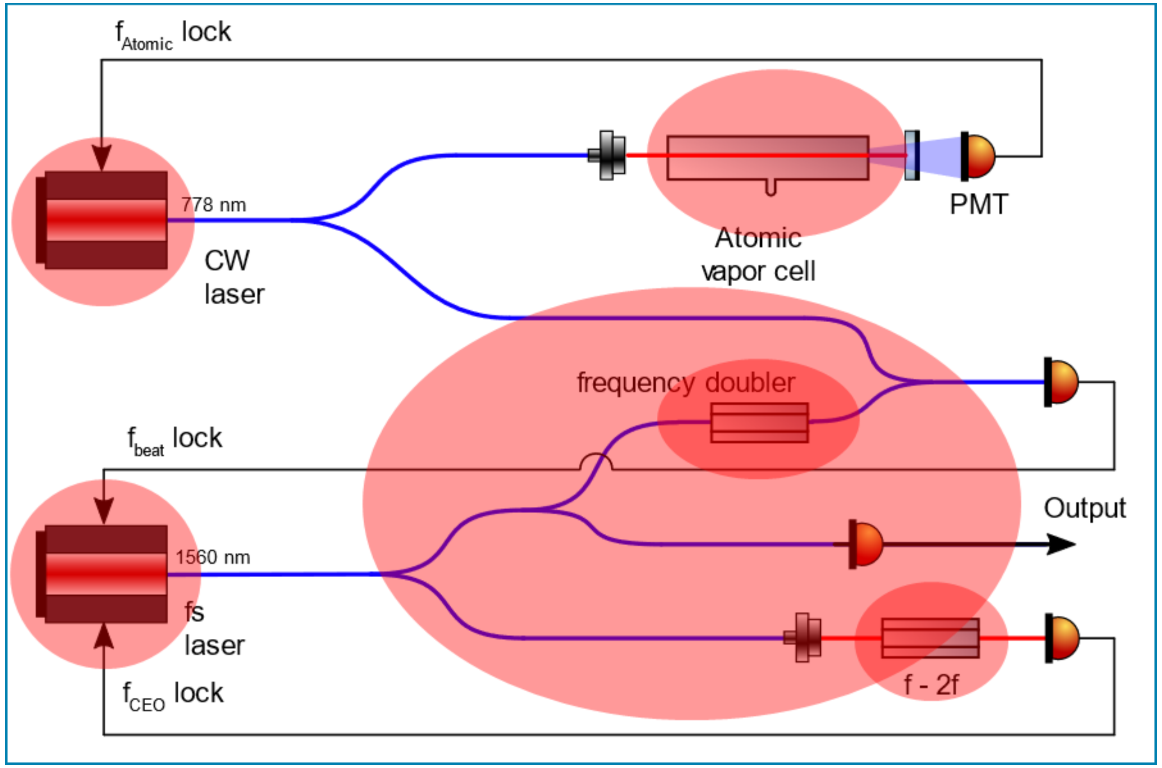
Narrow CW source



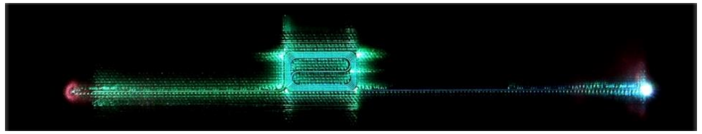
Boller et al., Photonics, 2020

Signal mixing / filtering, …



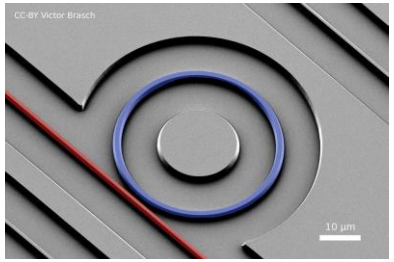


Wavelength conversion



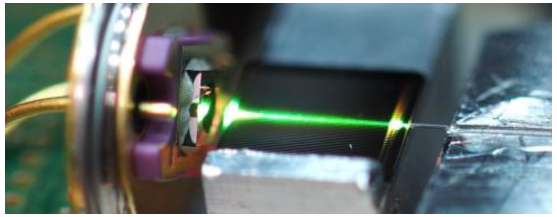
Obrzud et al., OL 2019

Kerr FC



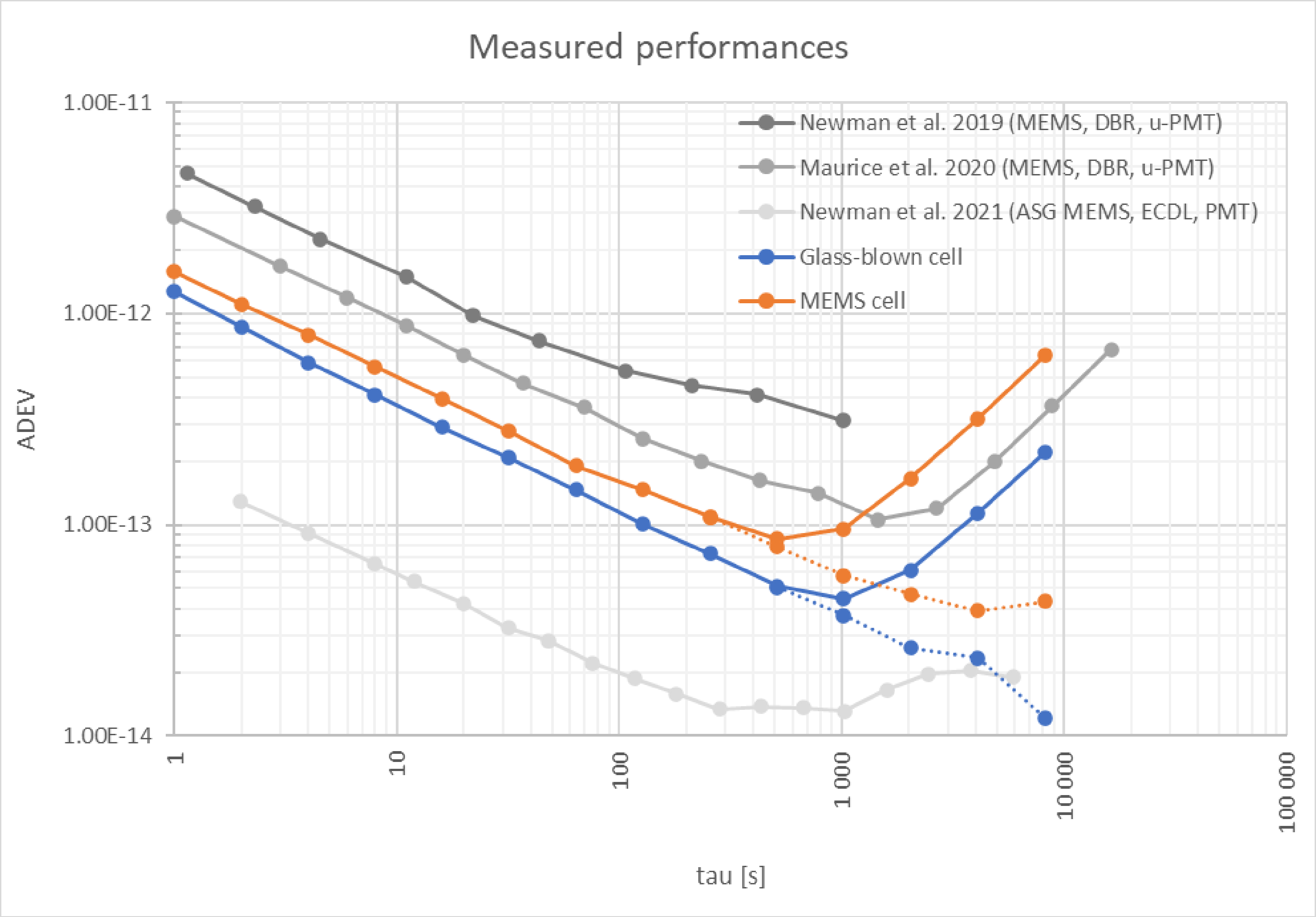
Wildi et al., OL 2019

CEO frequency detection

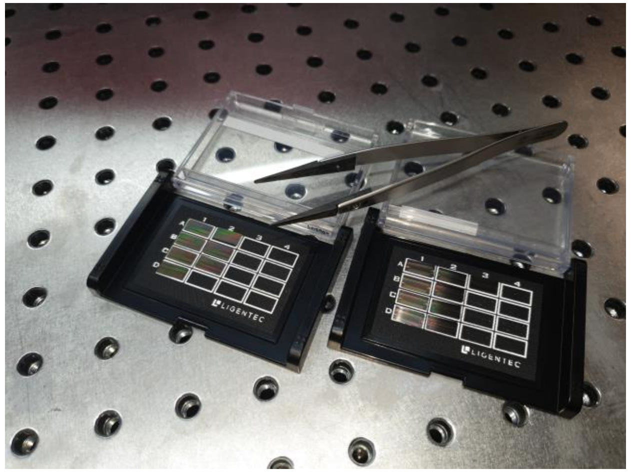


Obrzud et al., APL Photonics 2021

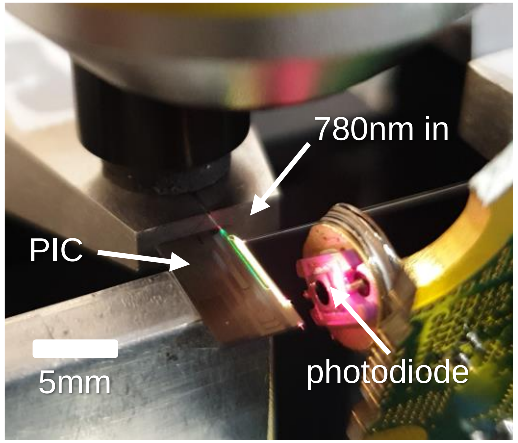
CLOCK STABILITY AND PIC TESTING



Optical atomic clock test results with chip-scale compatible elements



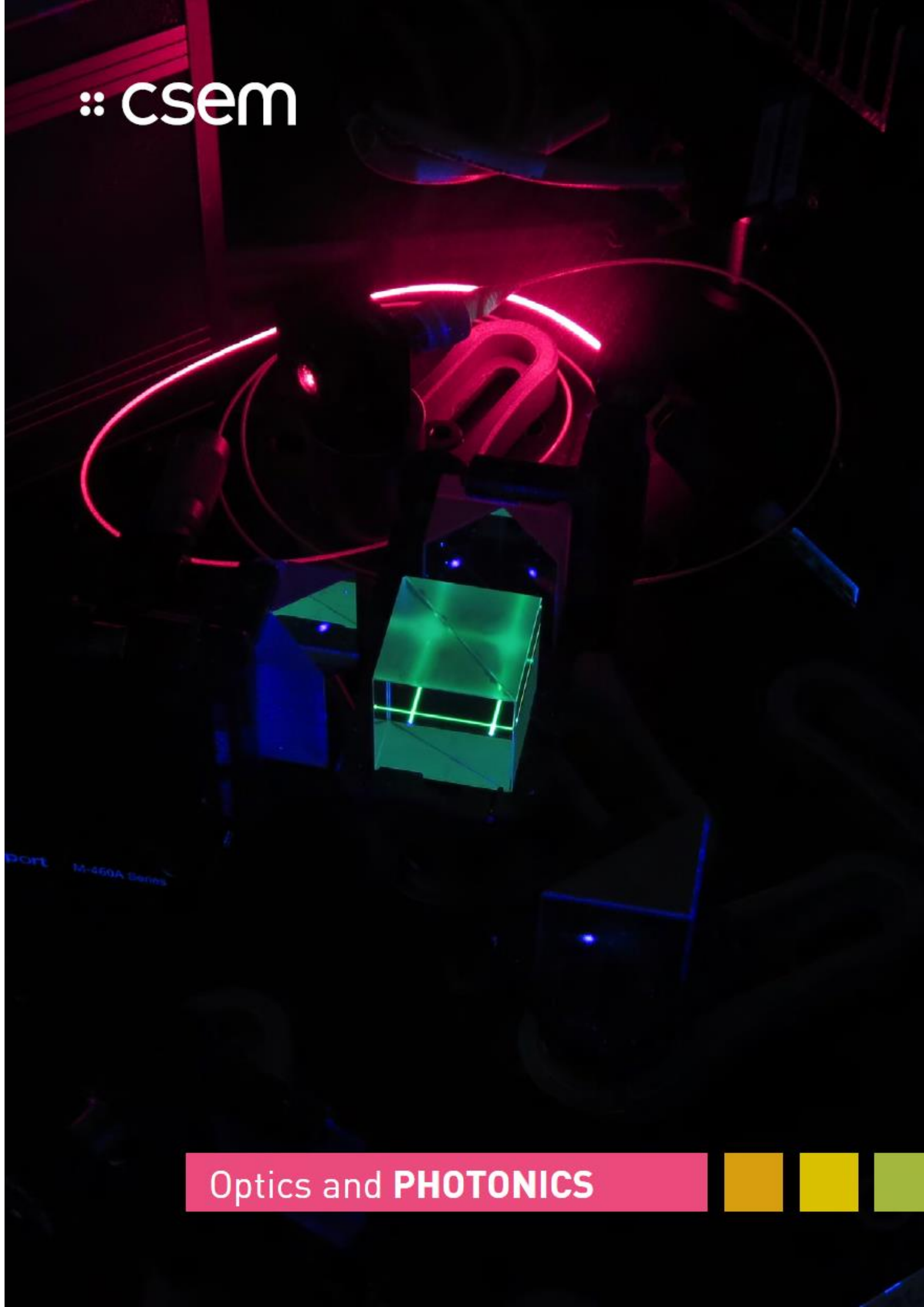
SiN PIC with functionalities for a 2-ph clock



PIC testing

SUMMARY

- Photonics is a key enabling technology for many quantum applications
- Rubidium cell technology is a qantum platform
- LNOI PICs are core building block for photonic quantum computation
- LNOI MPW allows you to get involved: make your own quantum PICs!




DON’T FACE CHALLENGES
ALONE - PARTNER WITH US.
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