Micro-fabrication of field deployable quantum sensors

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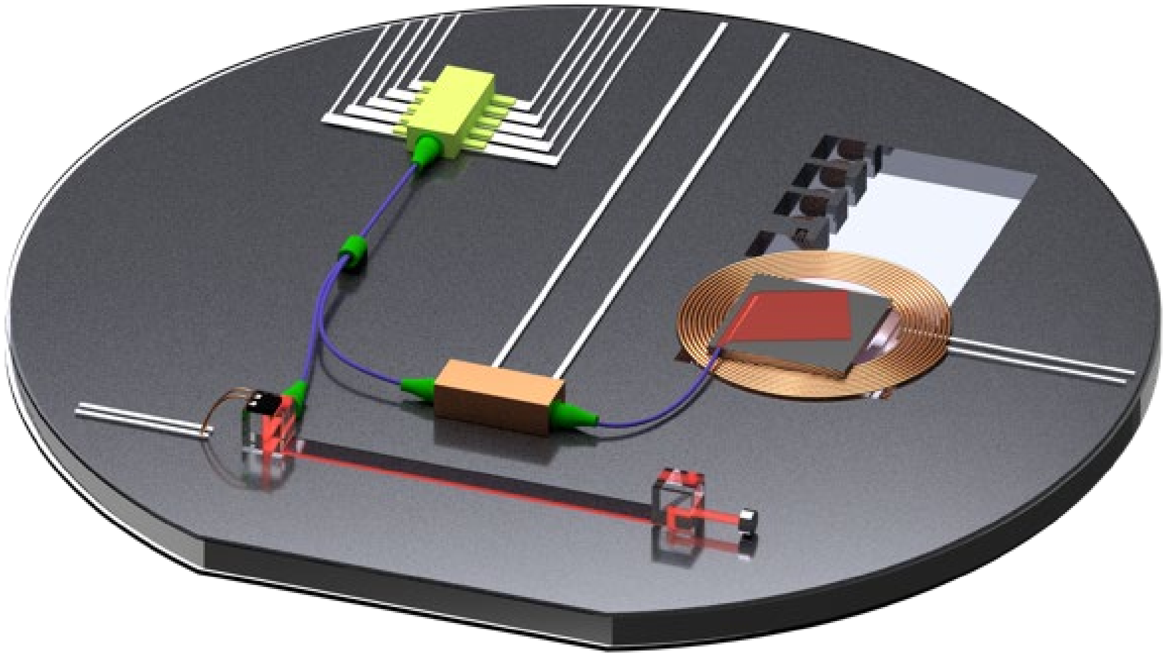

Importance of Quantum Technology

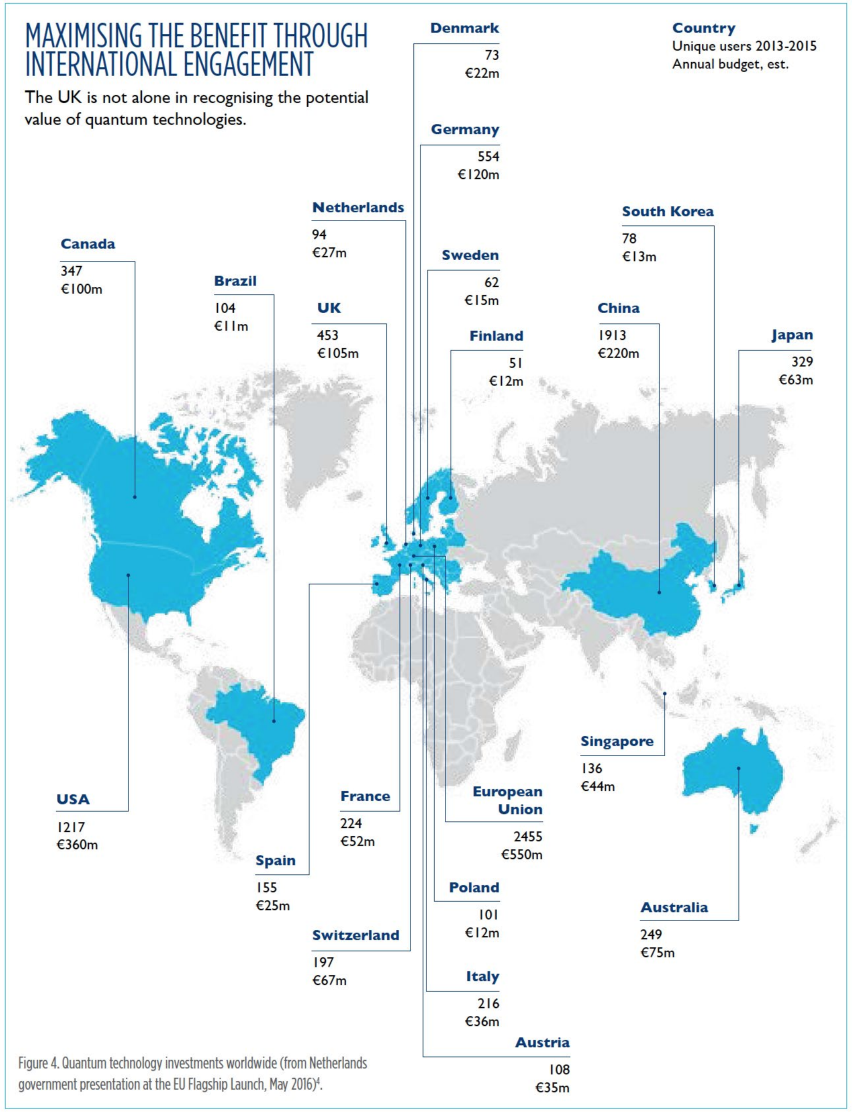

Figure 4. Quantum technology investments worldwide (from Netherlands government presentation at the EU Flagship Launch, May 2016)[4].

UK Blackett Review, "The quantum age: technology opportunities" (2016)

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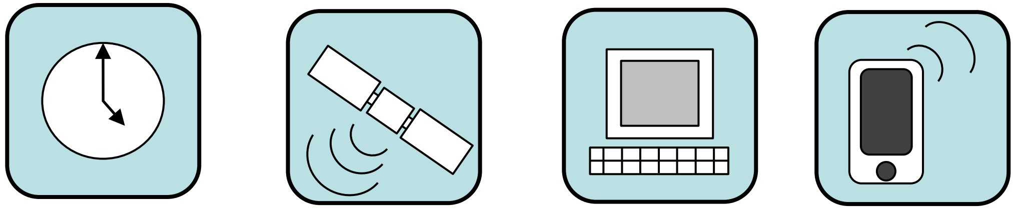
Examples of quantum technology

- Atomic clocks
- Atomic interferometers
- Quantum computing
- Quantum communication
- …



Application for miniature atomic clocks

- Global Navigation Satellite Systems
- Gravimetry
- Telecommunications
- Time stamping
- …

} ○ Physical height reference system
  - Early warning systems
  - Civil engineering
  - Earth observation

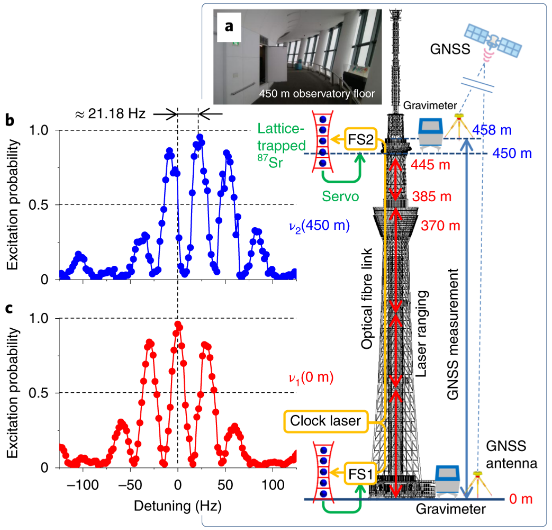
Importance of Quantum Technology

State of the art atomic clocks, now measuring uncertainty to 1 part in 10^{-20}

0.00000000000000000001

At this level clocks are open to measurement of gravitational redshift

Sensitivity of atomic sensors can be utilised for gravimetery



Article

Resolving the gravitational redshift across a millimetre-scale atomic sample

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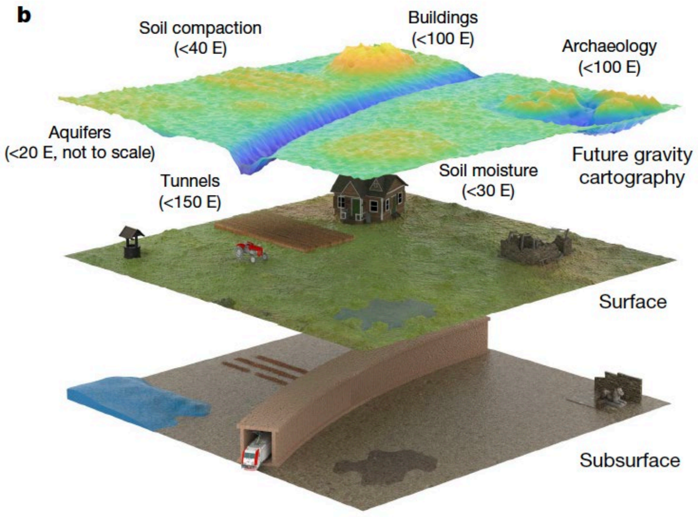
Tobias Bothwell[1✉], Colin J. Kennedy[1,2], Alexander Aeppli[1], Dhruv Kedar[1], John M. Robinson[1], Eric Oelker[1,3], Alexander Staron[1] & Jun Ye[1✉]



Takamoto, M., Ushijima, I., Ohmae, N. *et al.* Test of general relativity by a pair of transportable optical lattice clocks. *Nat. Photonics* **14,** 411–415 (2020).

Stray, B., Lamb, A., Kaushik, A. *et al.* Quantum sensing for gravity cartography. *Nature* **602,** 590–594 (2022).

The accuracy and precision of these measurements comes from using cold-atoms at their core

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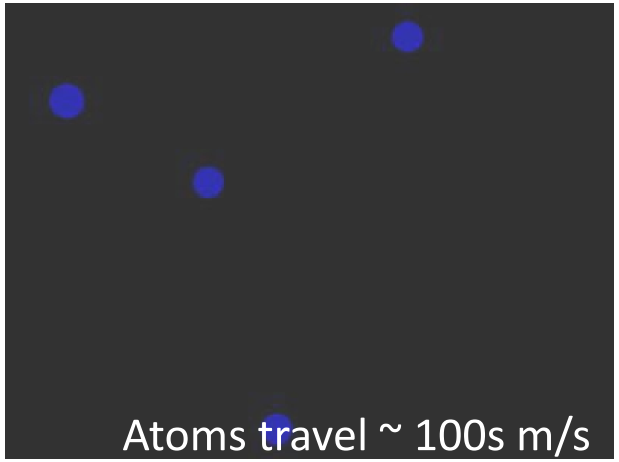
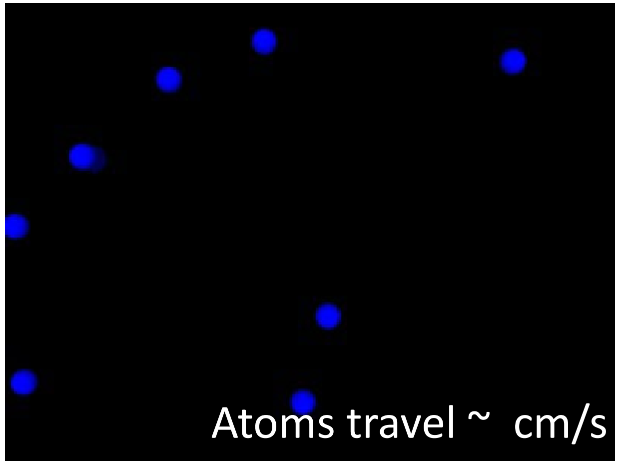
Cold Atom Quantum Technology

Thermal atoms

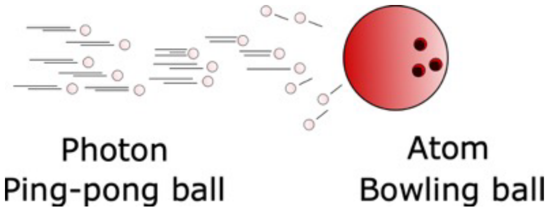


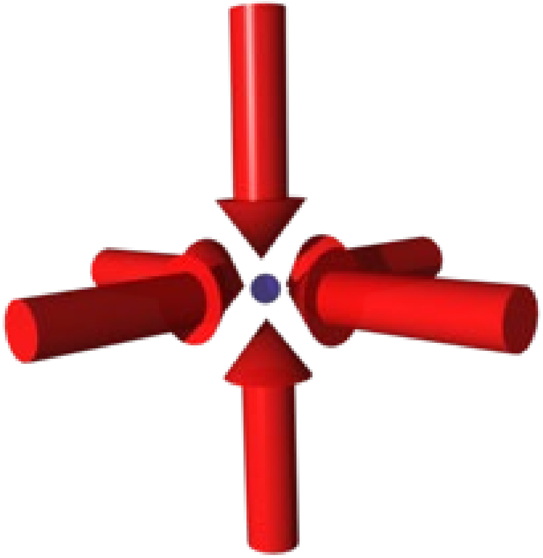
Cold atoms

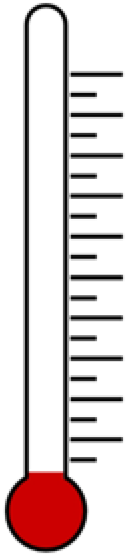


- Cold atoms are achieved from laser cooling down to micro-Kelvin temperatures
- Using photon momentum kicks, we take energy away from the atoms, making them slower and colder
- Orthogonal lasers used in 3 dimensions

Laser cooling







Importance of Chip-Scale Quantum Technology

Commercial atomic clocks

Thermal atoms

Commercial vapor cell clock
16 cm^3 [1]
125 mW
$<1\times10^{-11}$ @ 1000s

- Fast duty cycle for probing
- Readily available technology
- Buffer gas systems
- Paraffin coated cells

1 - https://www.microsemi.com/product-directory/clocks-frequency-references/3824-chip-scale-atomic-clock-csac

<u>University of Strathclyde</u>

Experimental Quantum Optics and Photonics Group
-
Compact Components Team

Micro-fabricated systems with the benefits of cold-atom stability and precision

Cold atoms

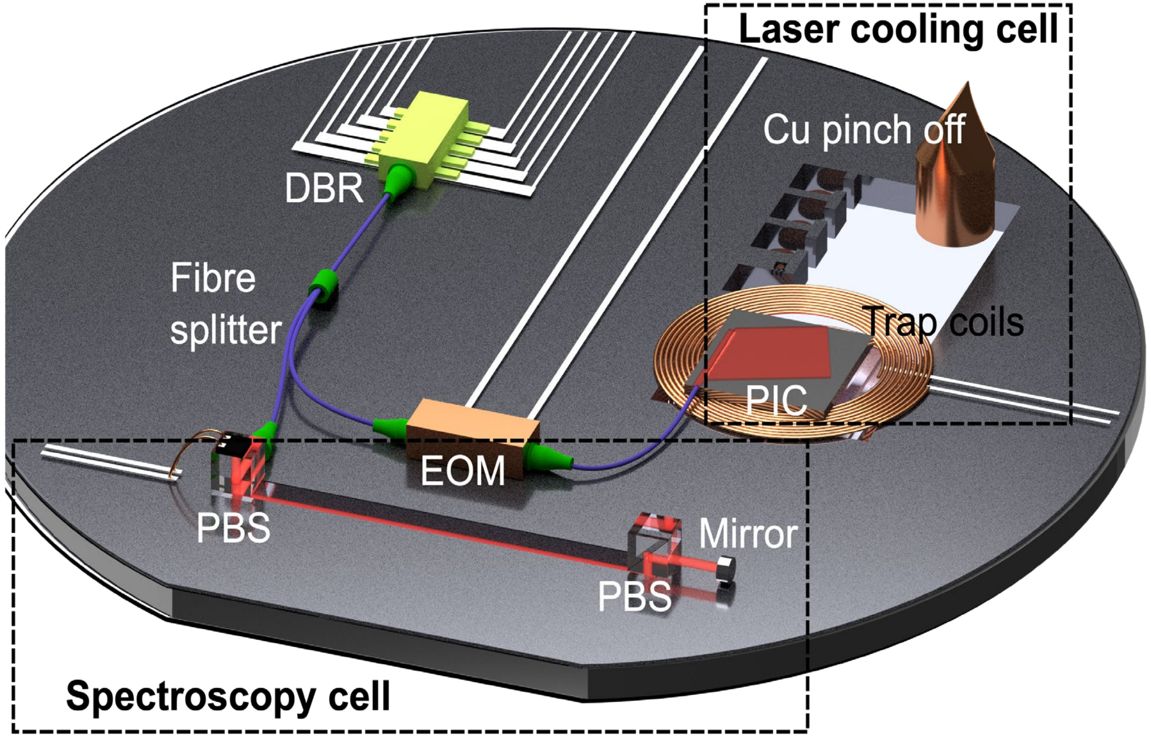
Commercial cold-atom clock
682000 cm^3 [2]
200 W
$<9.5\times10^{-15}$ @ 1000s

x42625 larger than CSAC

- Unperturbed sample
- Accurate and precise
- Long interrogation times
- Miniaturization required

2 - https://www.muquans.com/images/stories/muquans_muclock.pdf

Importance of Chip-Scale Quantum Technology



Vision for a fully integrated, cold-atom sensor

- Micro-machined vapour cell technology
- Micro-fabricated laser cooling components
- Mass producible, reproducible device

Key reason for chip-scale

- Mass producible – Lower cost for applications requiring reproducible sensor arrays
- Robust – Fully bonded components reduce damage risk for in field applications
- Low SWaP – Better suited to rocket launch (low size, weight) and satellite longevity (power consumption)

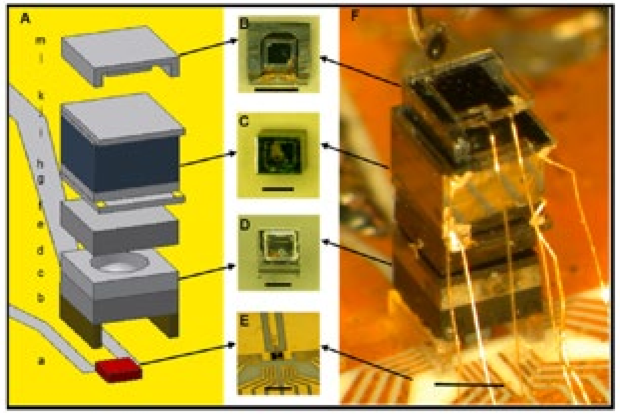
Technology development
Fully integrated cold atom platform

Chip-scale cold-atom vacuum cells

Micro-fabricated vacuum cells

MEMS (Micro-electro-mechanical-systems) vapour cells

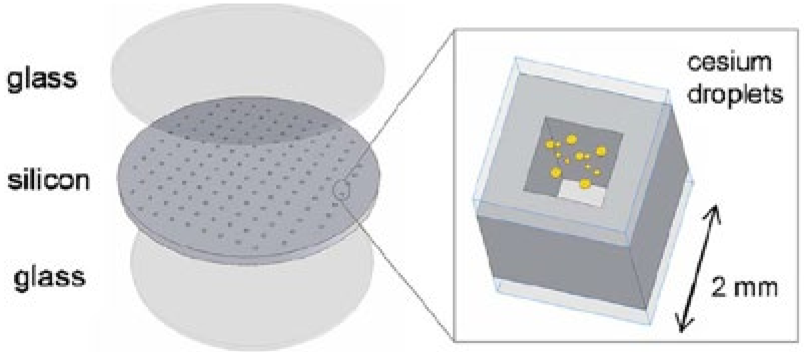
- Micro-fabrication of silicon body – Customizable
- Wafer glass-silicon-glass stack - Simple
- Silicon fabrication – mass producible



J. Kitching, ``Chip-scale atomic devices", Appl. Phys. Rev. **5** (2018)

Can this technology be directly transfer to cold atoms?

- Typical deposition methods produce background gasses and contaminants
- Cell pressure environment rapidly degrades due to helium permeation through glass windows
- Total background pressure $P>10^{-6}$ mbar

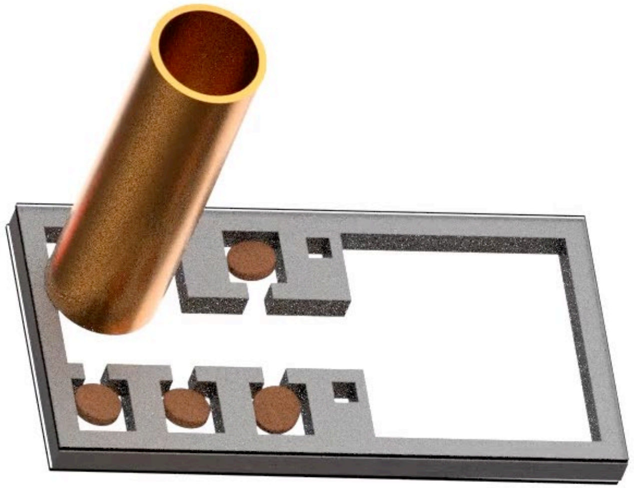


L. –A. Liew, et al, Proceedings of Eurosensors (2007)

How do we make MEMS compatible with cold atoms?

Chip-scale cold-atom vacuum cells

Laser cooling in a MEMS cell



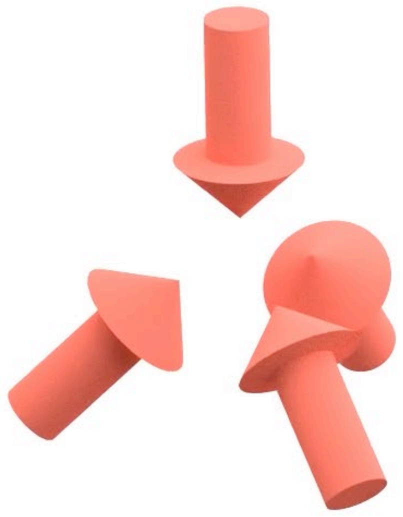
1. Bond glass to the lower silicon frame
2. Deposit alkali source and non-evaporable getters into the frame
3. Bond upper glass wafer to the silicon. This wafer has a hole and tube that is connected to a vacuum pump to achieve ~10^{-8} mbar inside the cell
4. An alkali background is dispensed, and a 6-beam retro MOT is aligned within the cell
   - $1/e^2$ diameter of 4mm, 1.5mW in each arm
   - Atom number of 6×10^5

<u>First demonstrated in the group of John Kitching</u>

- A. Dellis, et. al., "Low helium permeation cells for atomic microsystems technology" *Opt. Lett.* **41**, 2775-2778 (2016)
- J. P. McGilligan, et. al. "Laser cooling in a chip-scale platform" *Appl. Phys. Lett.* **117**, 054001 (2020)
- R. Boudot, J. P. McGilligan, *et al.* Scientific Reports, **10**, 16590, (2020)

Chip-scale cold-atom vacuum cells

The grating magneto-optical trap



- The micro-fabricated vacuum cell can be miniaturized further from 6 beam MOT

$$N_{beams} = N_{dimensions} + 1 \rightarrow 3D + 1$$

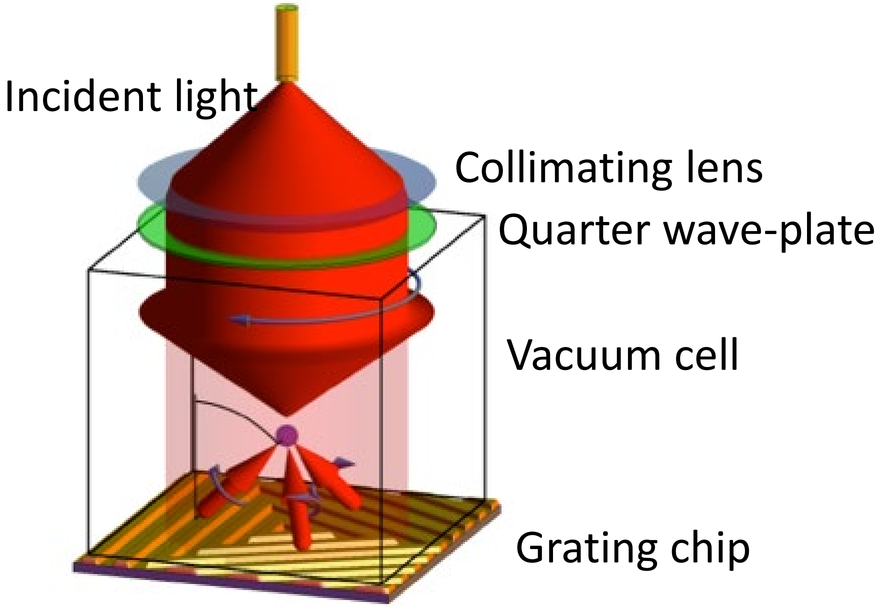
- The grating diffracts a single incident beam at an angle relative to grating period

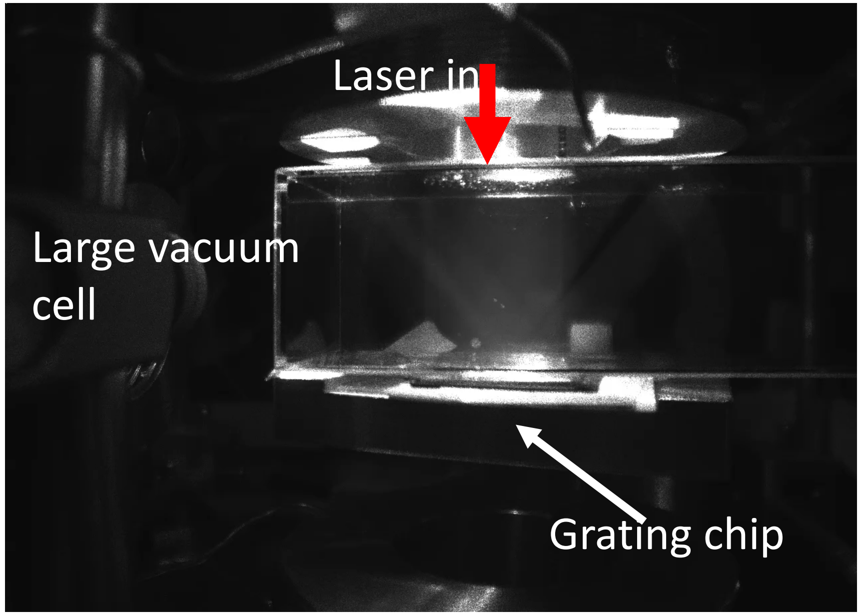
Bragg condition: $n\lambda = d\sin(\theta)$

- Reduces the optical footprint and is now fully a microfabricated package

Chip-scale cold-atom vacuum cells

The grating magneto-optical trap



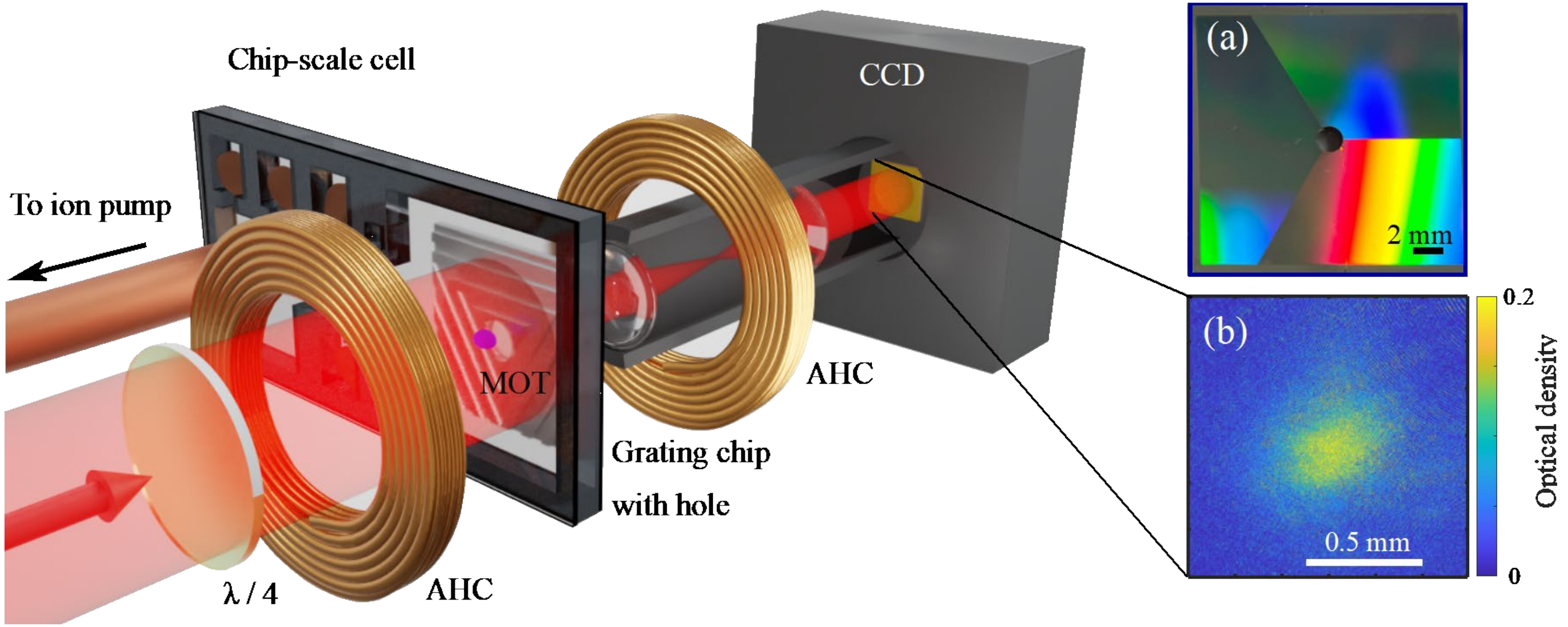


<u>First demonstrated in the group of Erling Riis</u>

- M. Vangeleyn, et. al. "Laser cooling with a single beam and a planar diffractor" Opt. Lett. 35, 3453-3455 (2010)
- C. C. Nshii, et. al. "A surface patterned chip as a strong source of ultracold atoms" *Nature Nano.* **8,** 321-324 (2013)
- J. P. McGilligan, et. al. "Diffraction grating characterization for cold atom experiments" *JOSA B* **33** (2016)

Chip-scale cold-atom vacuum cells

A micro-fabricated cold-atom platform



- A central hole is cut in the grating chip as an imaging axis
- Comparable atom number to our larger apparatus, N_{Atoms}~10^5
- Larger atom numbers are achievable with our thicker silicon cells

(Important: Clock instability $\propto \frac{1}{\sqrt{N}}$)

A. Bregazzi, et. al. "A simple imaging solution for chip-scale laser cooling" *Appl. Phys. Lett.* **119**, 184002 (2021)

Technology development
Part 2
On-chip laser frequency stabilisation

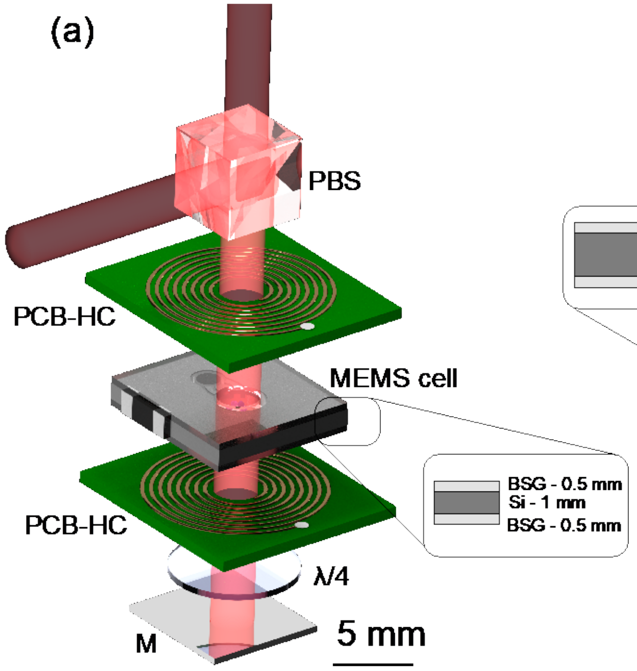
KELVIN NANOTECHNOLOGY
University of Strathclyde Science
INMAQS
Defence and Security Accelerator
University of Glasgow
UK Research and Innovation

Micro-fabricated vapour cells

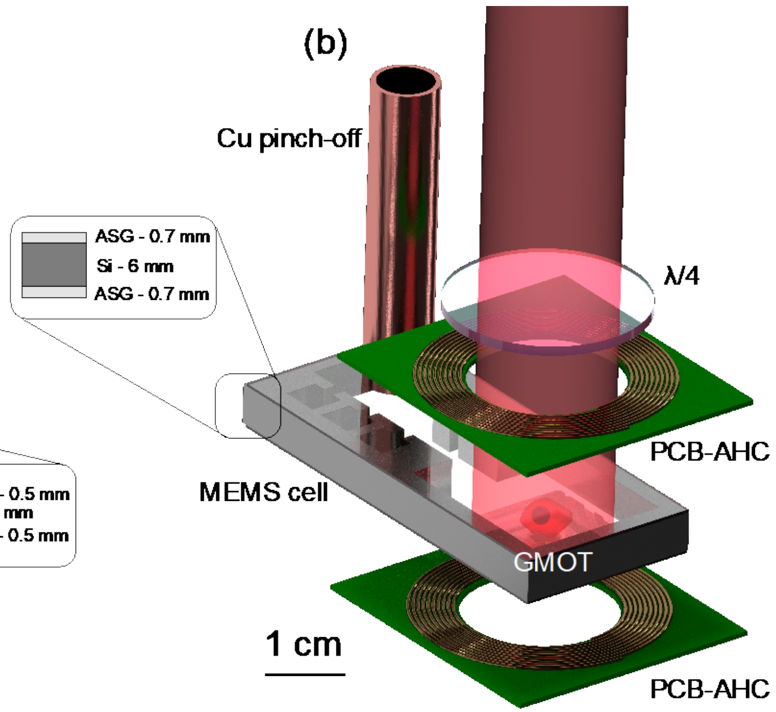
Fully chip-scale locking and cooling package

- Laser used for cold atom system is frequency stabilised in a planar stacked, chip-scale package with saturated absorption spectroscopy
- 2 mm total height cell is sandwiched between printed circuit board (PCB) coils to shift the atomic frequency and laser lock point when required
- Total amalgamated package can be reduced to a working volume on the order of cm^3

Laser locking chip stack



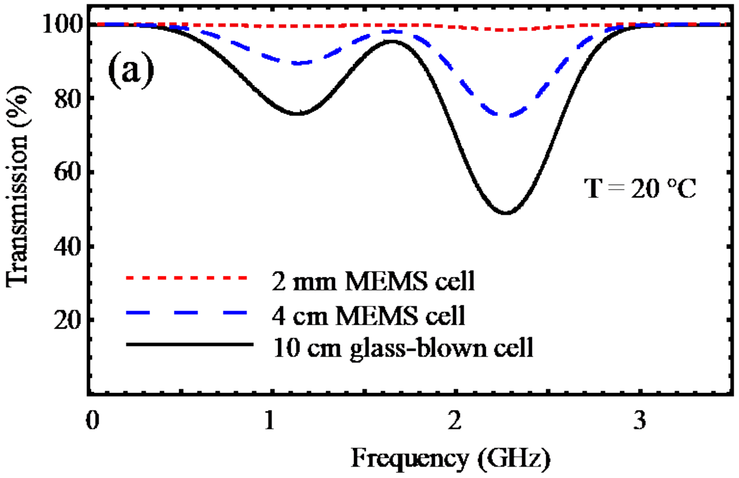
Laser cooling chip stack



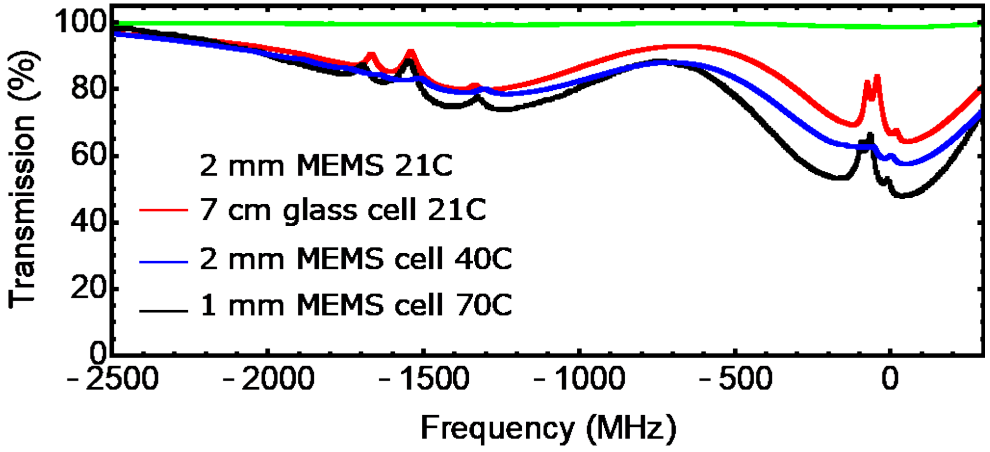
Microfabricated wavelength reference

Cell fabrication

Path length



Cell heating



- Straight 2 mm cell absorption is too low at room temperature, but has more comparable signal at 40 C
- Wet-etched, elongated cell with 4cm path length has sufficient SNR for laser locking without heating
- Standard glass blown cell is not mass producible or scalable to on-chip integration

Acknowledgements

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- <u>Dr James McGilligan</u>
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- Dr Paul Griffin
- Prof Erling Riis

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- Mr Sean Dyer

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- Dr Brendan Casey
- Dr Francesco Mirando

Glasgow University

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- Prof Douglas Paul

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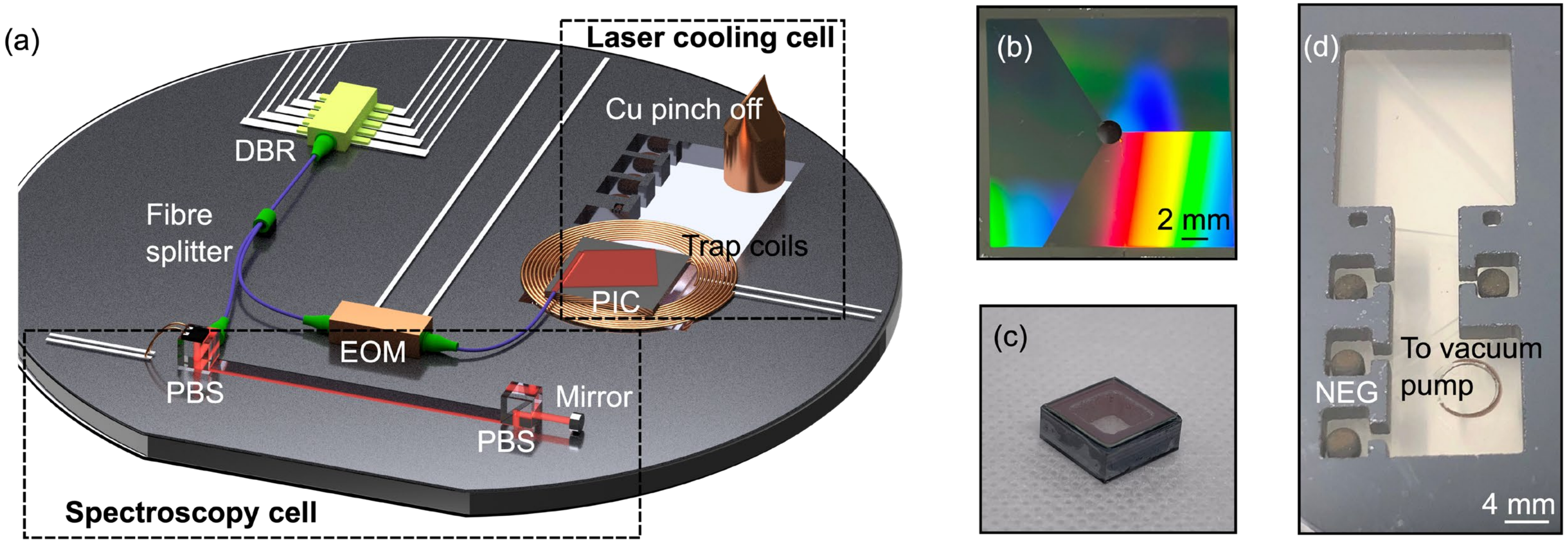
Conclusions

Summary

- Significant increase in application range achievable by miniaturizing the cold atom system at the core of atomic clocks and interferometers
- Novel microfabricated technology to miniaturize cold-atom sensor components for integrated laser cooling
- Once fully integrated, we can look forward to systems packaging and in field testing with focused applications



For more information on micro-fabricated atomic sensors please visit https://www.inmaqs.ac.uk/

INMAQS
International Network for Micro-fabricated Atomic Quantum Sensors

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