Chip-scale Optical Atomic Clocks and Integrated Photonics

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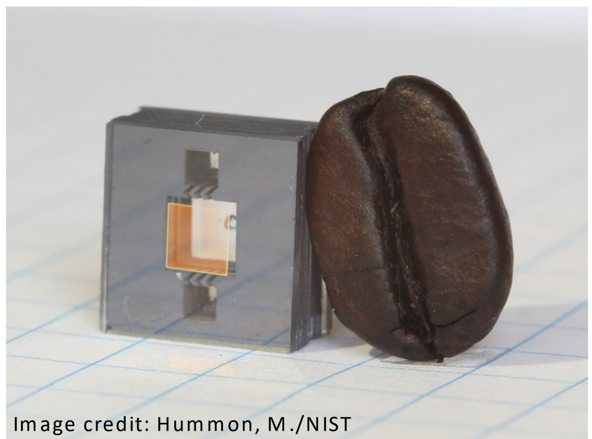

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Image credit: NIST

Outline

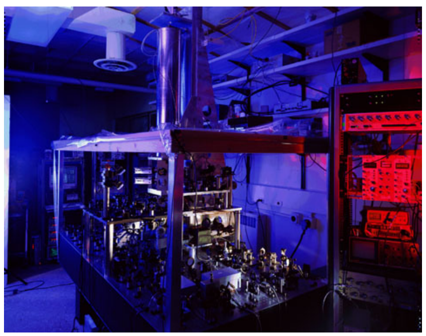
- Introduction to quantum sensors and atomic clocks
- Chip scale optical clock architecture
  - Design of microresonators
  - Atom-stabilized Optical local oscillator
- Photonic integration with atomic vapor cells

- References
  - arXiv:1811.00616 [physics.optics]. Photonic integration of an optical atomic clock. (2018).
  - Hummon, M., et al., Optica **5**, 443-449 (2018).

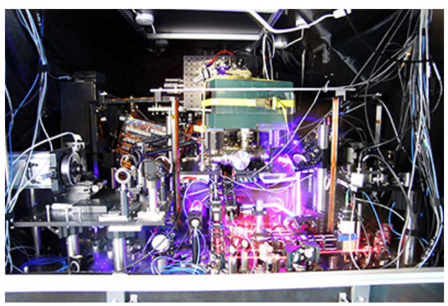
How are Photonics an enabling technology for atomic based quantum sensors?

State-of-the-art Laboratory Standards

- Highly accurate (to SI) , large and complex

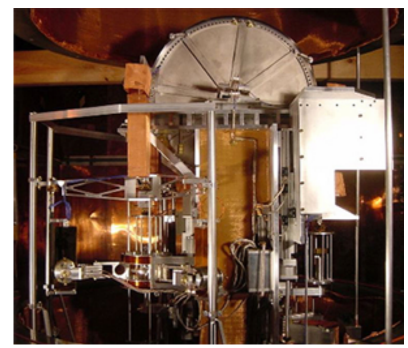


Cs fountain clock $\Delta f/f < 10^{-15}$



Sr optical clock $\Delta\lambda/\lambda < 10^{-17}$

JJ voltage standard $\Delta V/V < 10^{-10}$



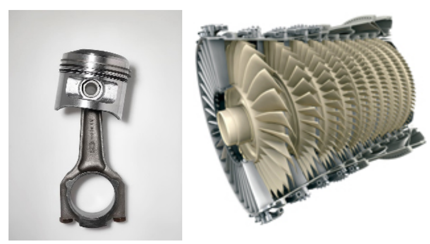
Watt balance $\Delta(P_{mech}/P_{elec}) < 10^{-7}$

Applications and Metrology

- Often driven by desire for interchangeability of parts and advanced, efficient manufacturing

Communications

Manufacturing

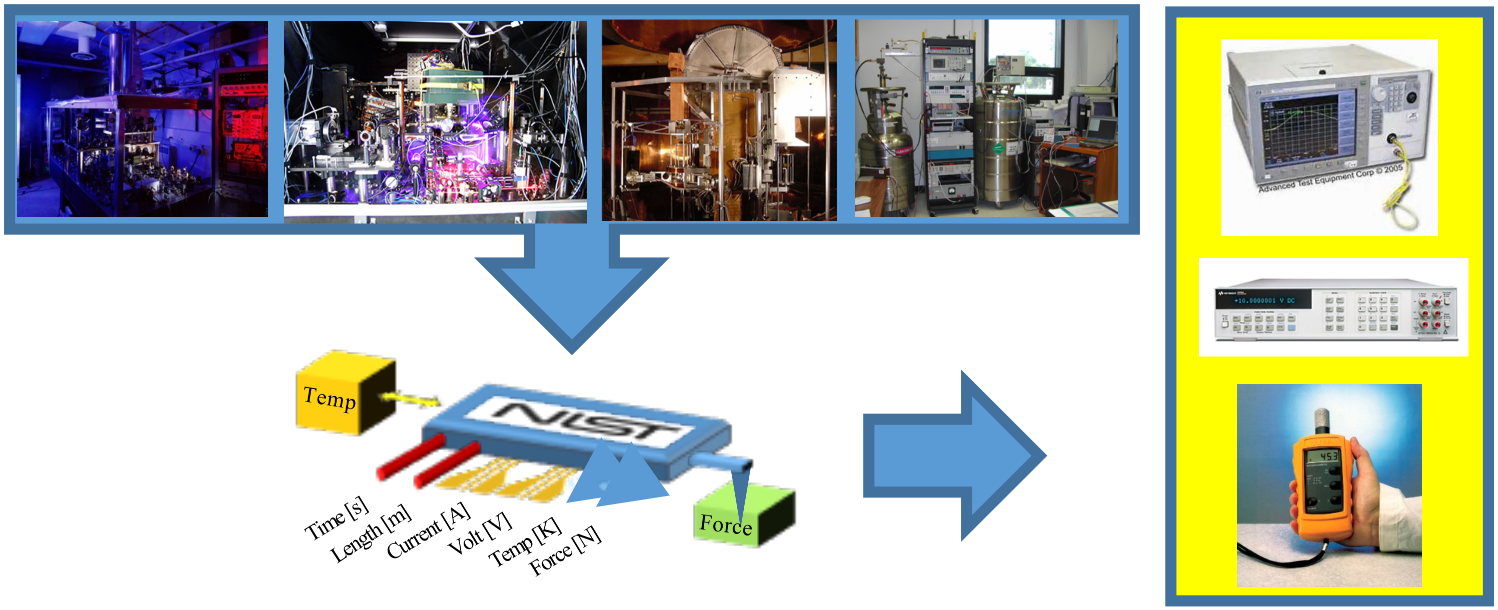


Navigation

Instrumentation

NIST on a Chip

- Measurement standards in chip format

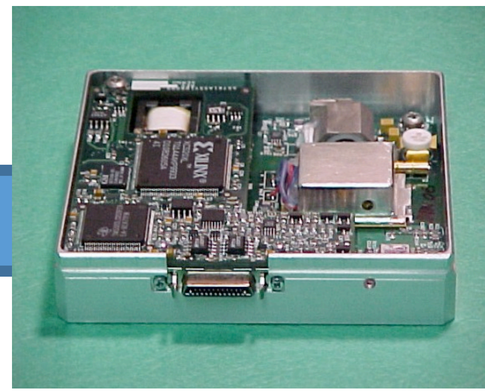


- Embedded, SI-traceable calibration built into instruments
- Goals: flexible, useful, manufacturable, deployable
- Get rid of the middle-man (us!)

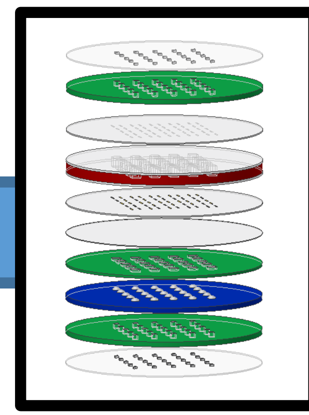
Parallel Fabrication

- To what extent can precision atomic instruments (clocks, magnetometers, etc.) be fabricated using low-cost processes similar to integrated circuits?

HP 5065 (1970)



Symmetricom X-72 (2005)

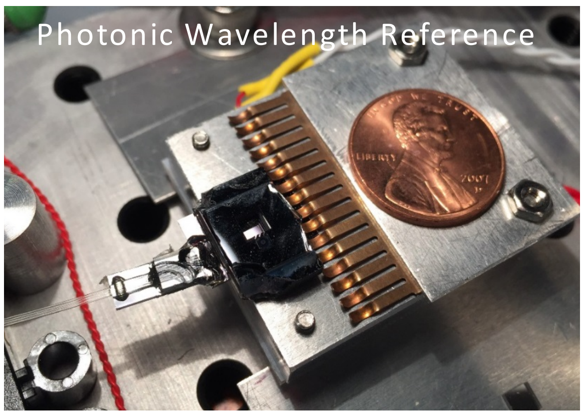


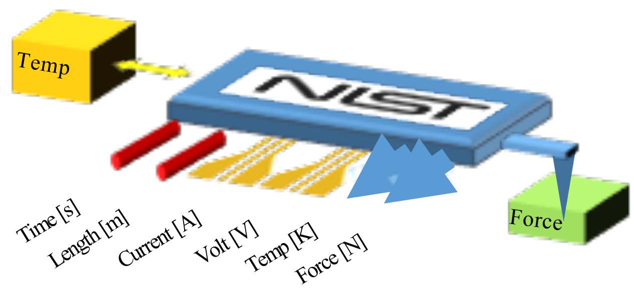
2030?

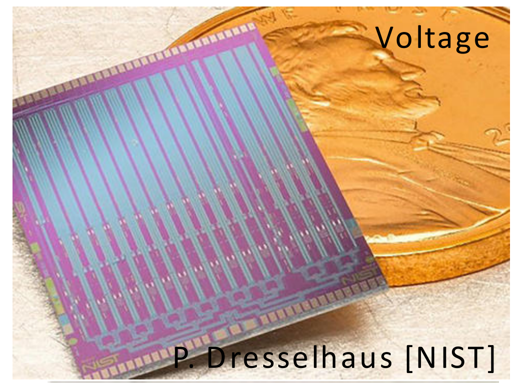
- Potential impact: an atomic clock on every desktop

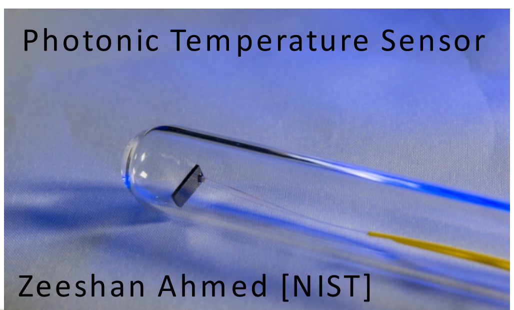
NIST-on-a-chip, Quantum based standards

- https://www.nist.gov/pml/productsservices/nist-chip-portal

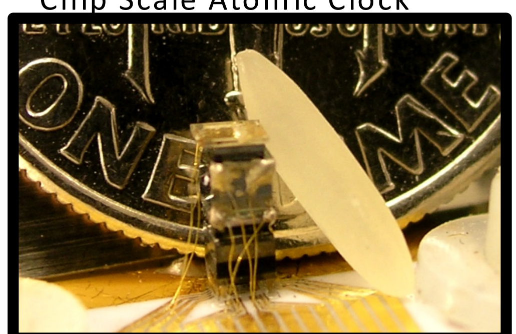








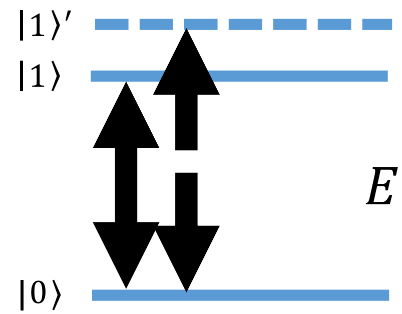
Chip Scale Atomic Clock



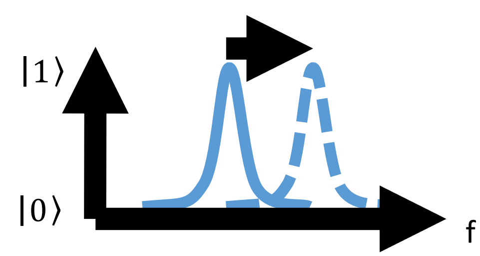
Atoms as quantum sensors

- 2-level system
- Measure energy splitting between two levels

- External Perturbation shifts levels
  - For atoms, energy spacing is the same, and based on fundamental constants (accurate)
  - Long coherence times → narrow linewidths, good sensitivity

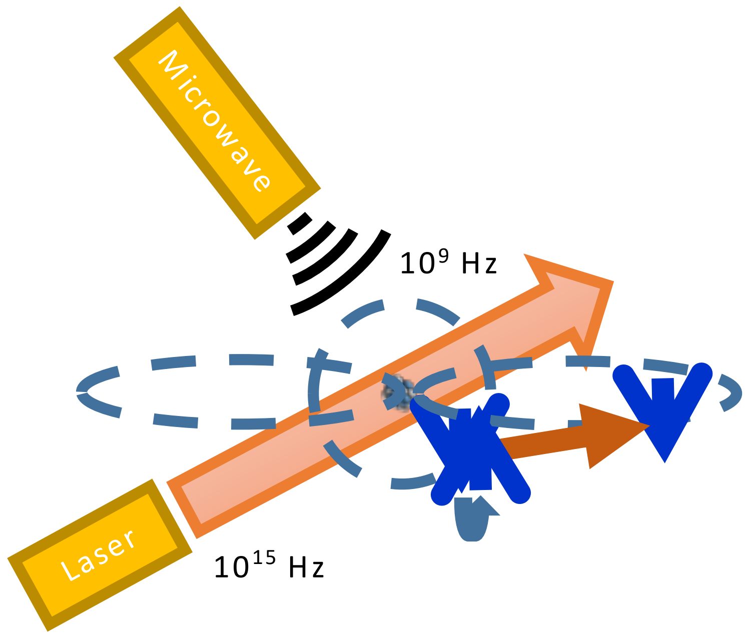


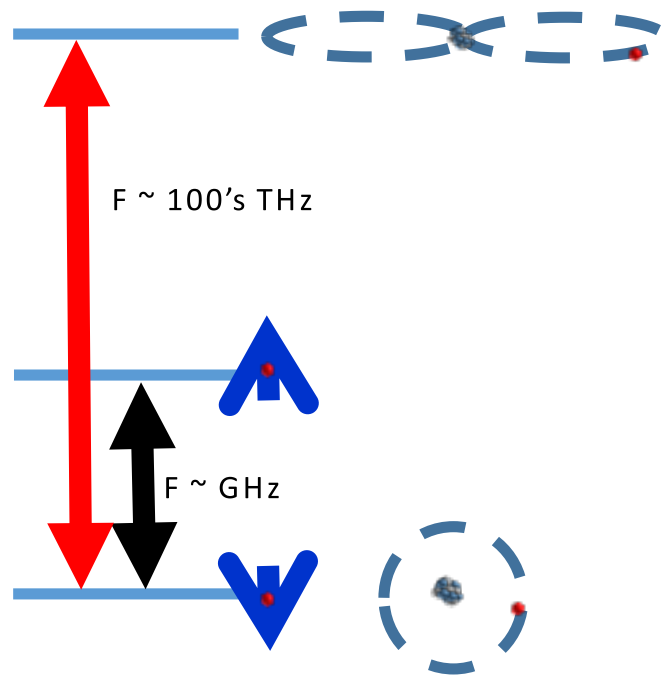
$$E = h \cdot f$$



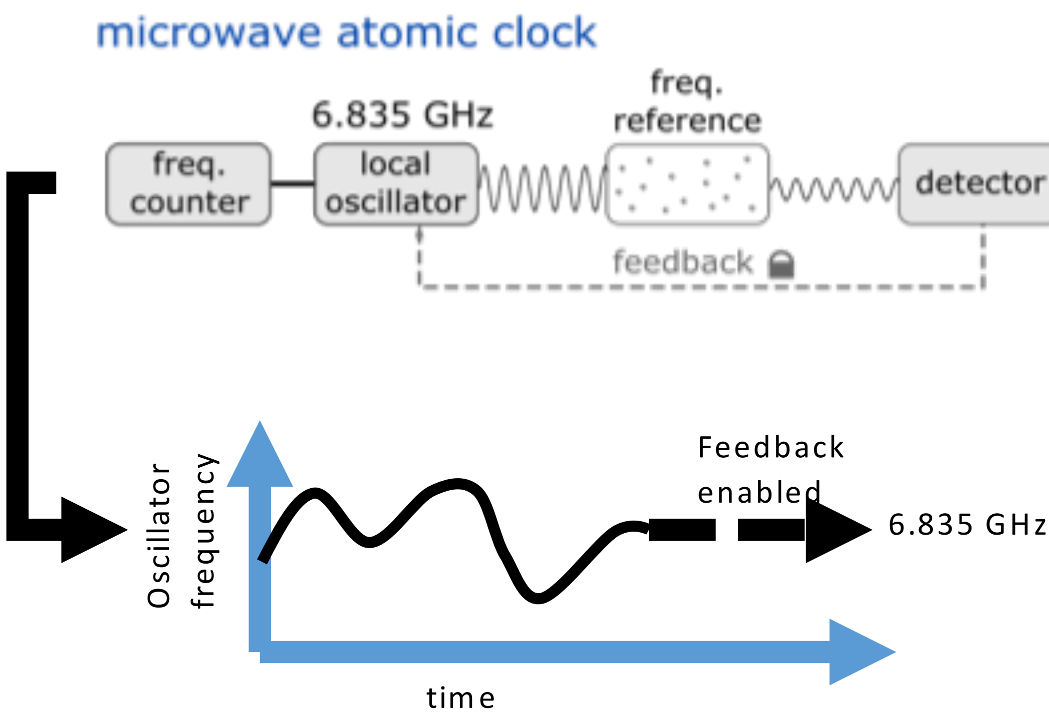
Degen, C.L., Reinhard, F., Cappellaro, P., “Quantum Sensing,” Rev. Mod. Phys. **89**, 035002 (2017).

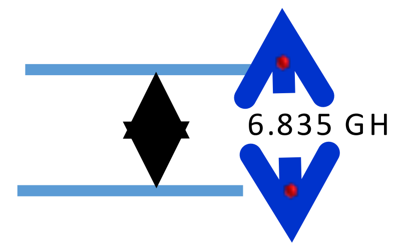
Atoms as quantum sensors

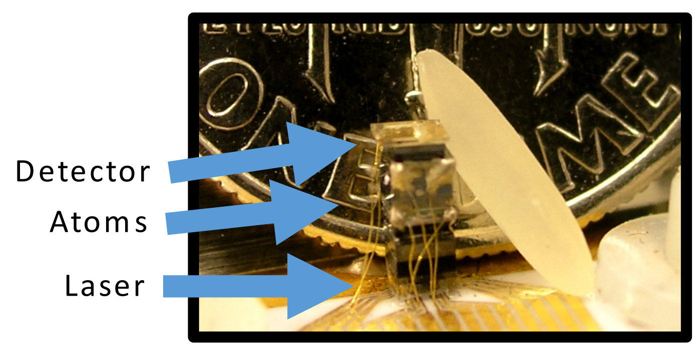




Atomic clock overview







1st gen. NIST physics package circa 2005
(Program development 2002)

How are (atomic) clocks used in the real world?

- Many real world devices rely on **1 µsec synchronization**
  - Communication networks
  - Power grids
  - Financial Timestamps
- 1 µsec synchronization achieved via GPS
  - GPS signal can be intermittent, noisy or jammed
  - "Holdover" clock
    - OCXO (crystal) can hold 1 µsec for ~several hrs
    - CSAC can hold 1 µsec for >~8 hrs
- Fieldable (operate outside the lab)
- Low Size, Weight and Power

GPS satellite, Image credit: US Govt. GPS.gov

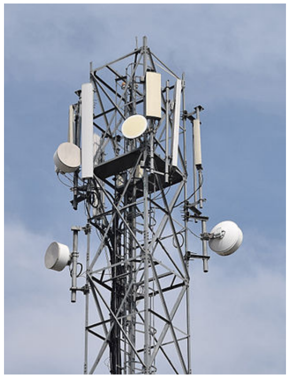
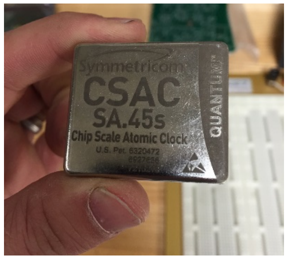


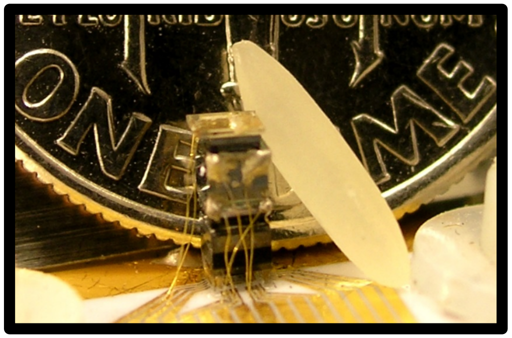
Image credit:
Nikhil B/Wikimedia Commons

Image credit: Wikipedia



Chip scale atomic clock

Chip scale atomic clock



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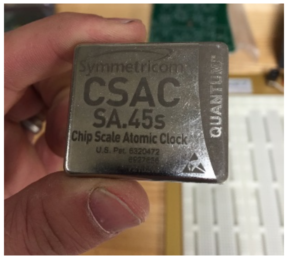
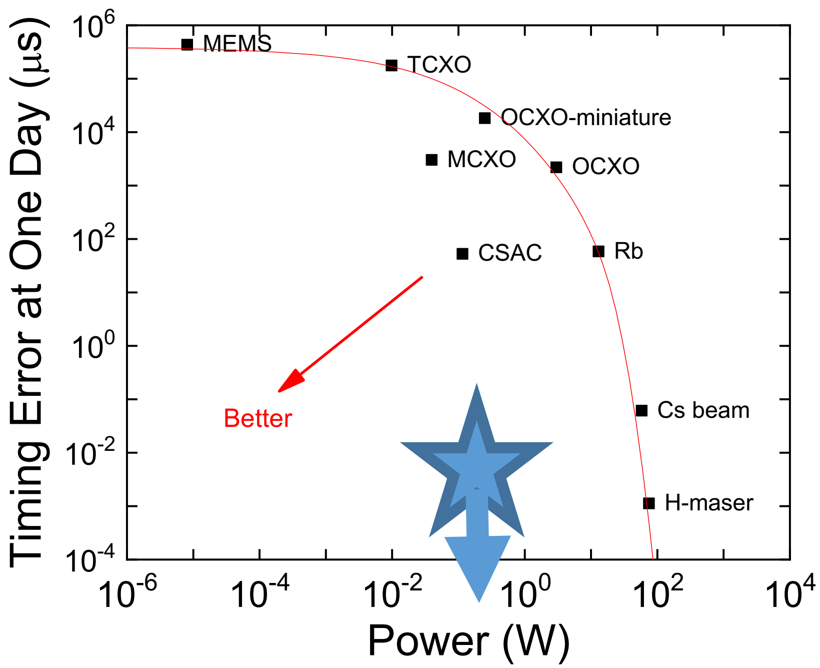
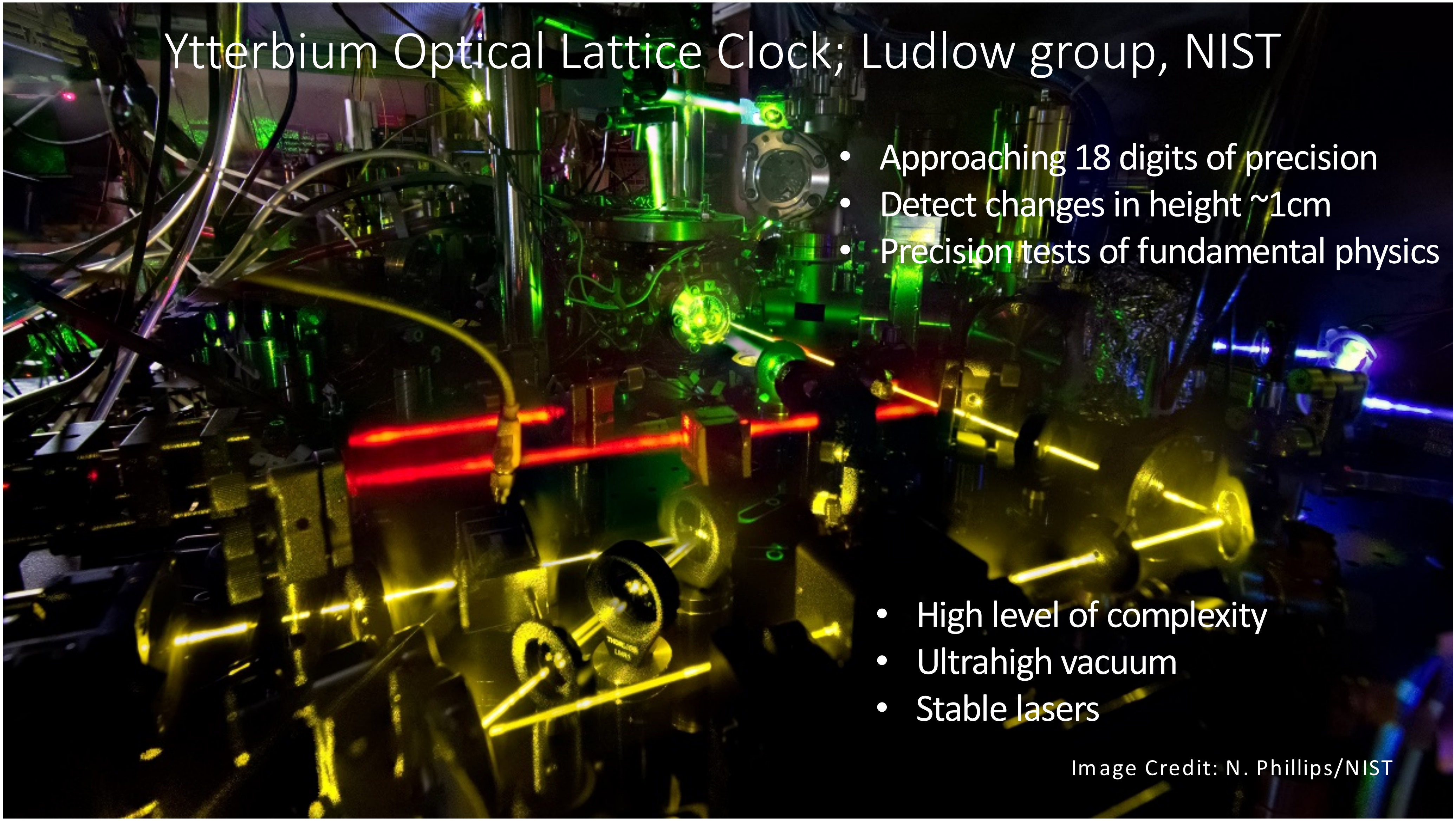


Chip scale atomic clock



Ytterbium Optical Lattice Clock; Ludlow group, NIST

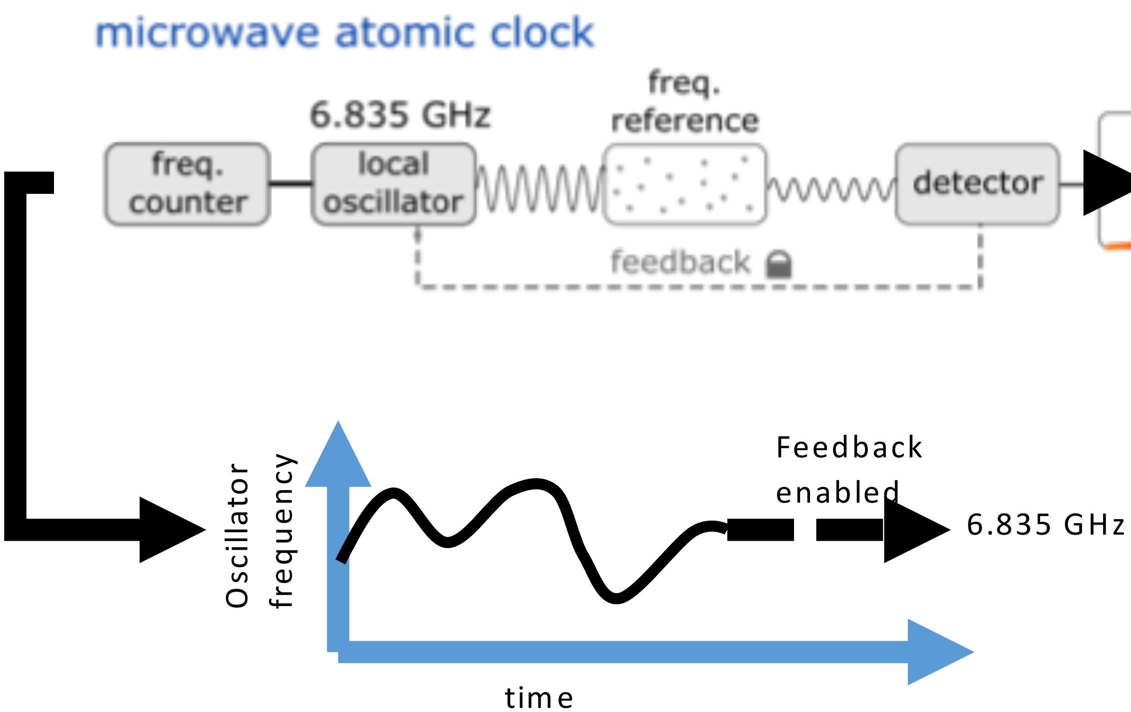


- Approaching 18 digits of precision
- Detect changes in height ~1cm
- Precision tests of fundamental physics

- High level of complexity
- Ultrahigh vacuum
- Stable lasers

Image Credit: N. Phillips/NIST

Atomic clock overview

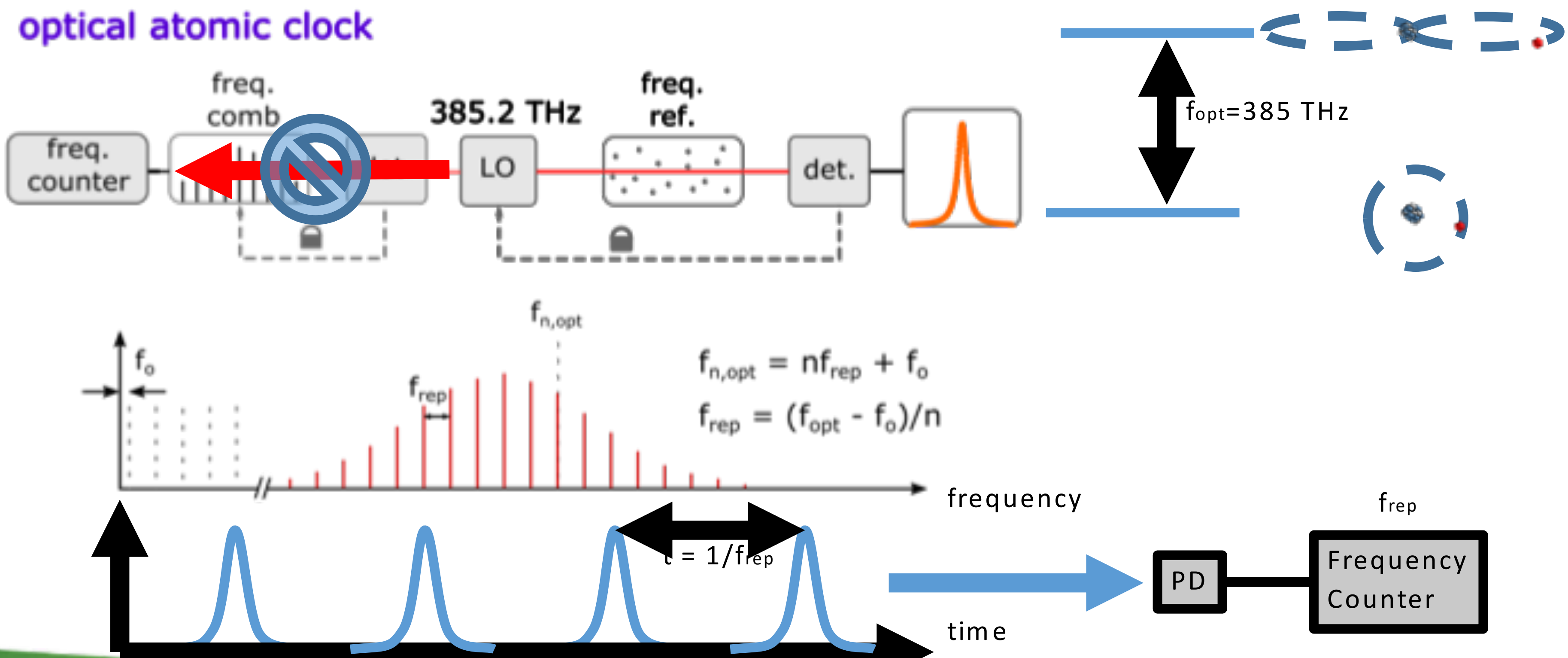


Clock Precision: (Δf/f)

Δf: instability of ticking → small
f: ticking rate → big

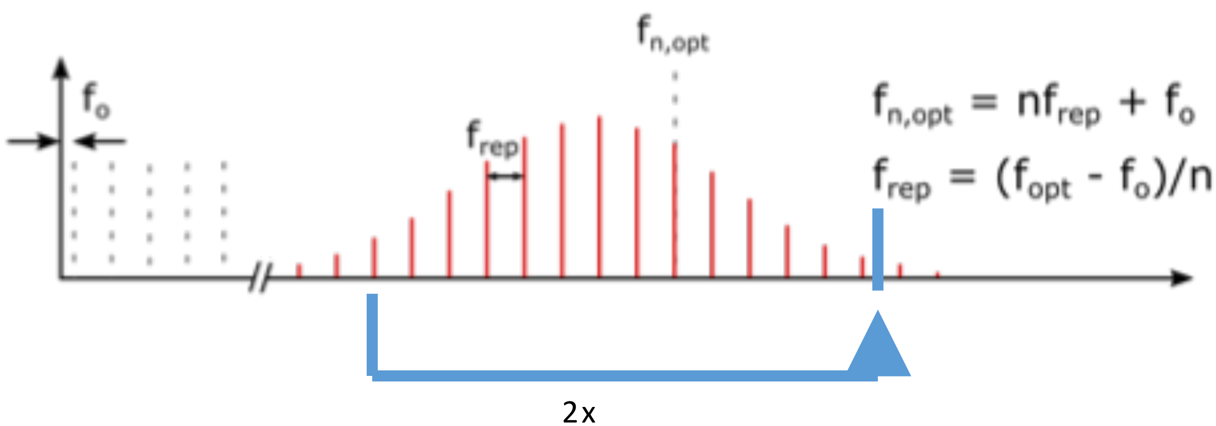
Solution: Go to larger F→optical transition

Optical clock overview



Requirements for frequency comb

- Octave spanning



$f_m = m\ f_{rep} + f_0$

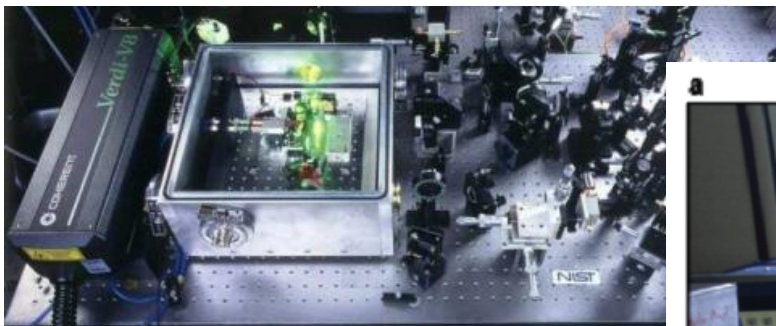
$f_{2x} = m\ f_{rep} + 2f_0$

$f_{2x} - f_n = f_0$

Miniaturization of optical frequency combs

Microresonator based combs

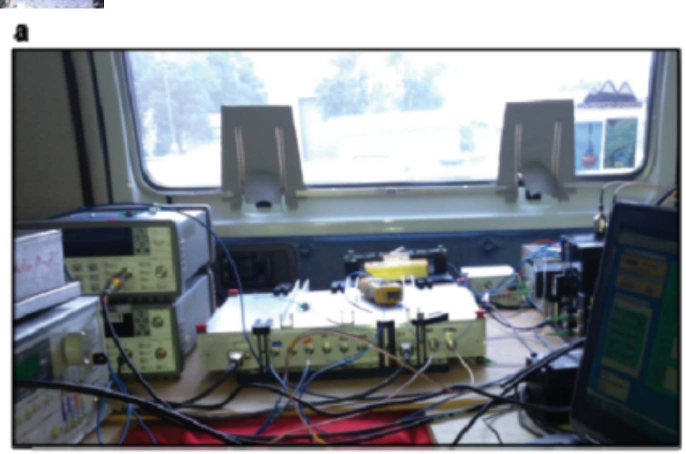
1 meter



Ti:Sapph Frequency Comb
OFM Group, NIST

100’s Watts

Diddams, S.A., et al., Science **293**, 825 (2001) [NIST}

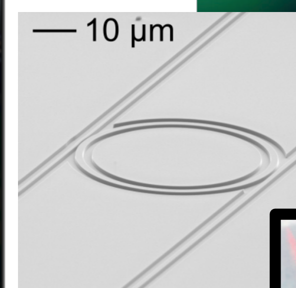


Transportable Fiber Comb
Fiber Sources & Applications Group, NIST

5 Watts

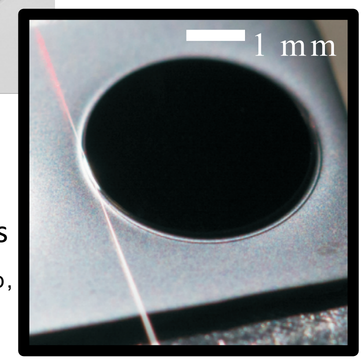
Manurkar, P., et al., OSA Continuum **1**, 274 (2018) [NIST}

Kippenberg Group, EPFL

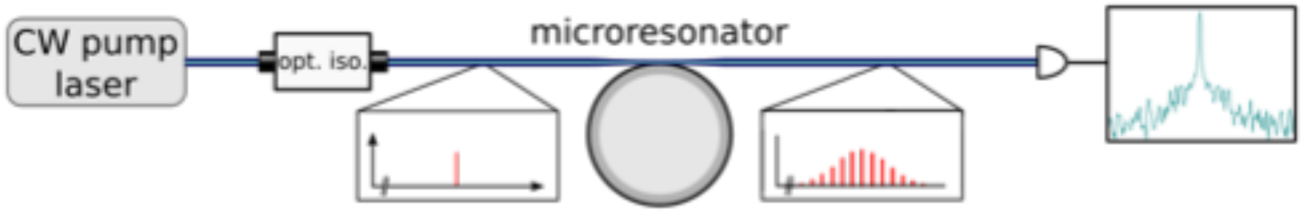


Nanofabrication Research Group NIST

< 100 mWatts

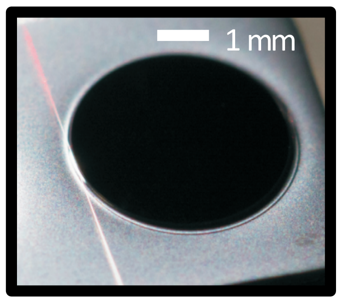


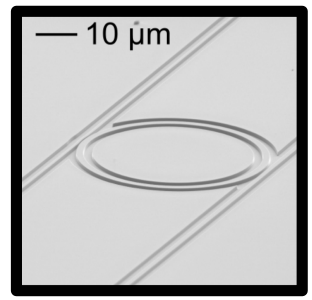
Vahala Group, Caltech



Silica (SiO_2) wedge resonator

Vahala [Caltech]

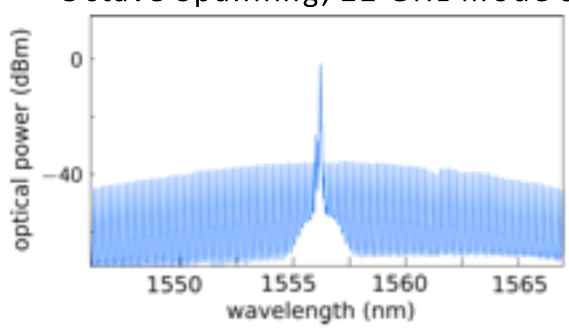




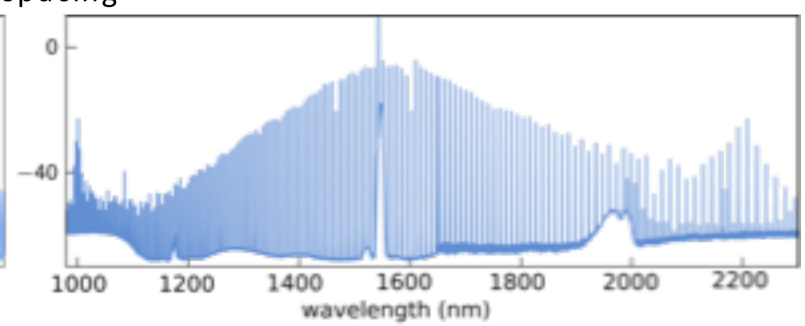
Si_3N_4 micro resonator

Srinivasan [NIST]

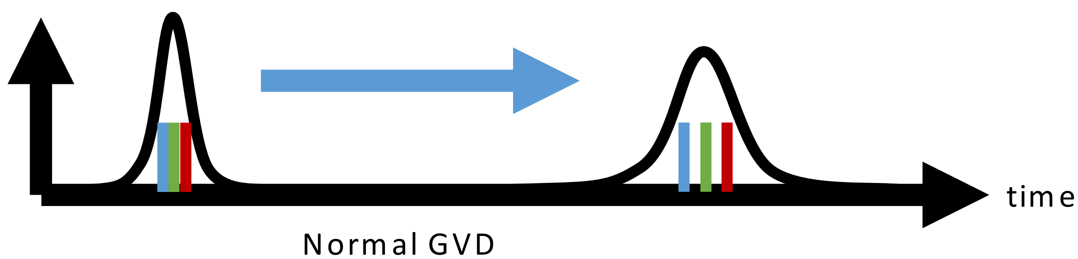
Octave Spanning, 22 GHz mode spacing

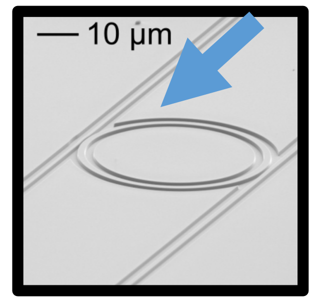


Octave Spanning, 1 THz mode spacing



Dispersion engineering for stable pulses





Stable Solitons/pulses

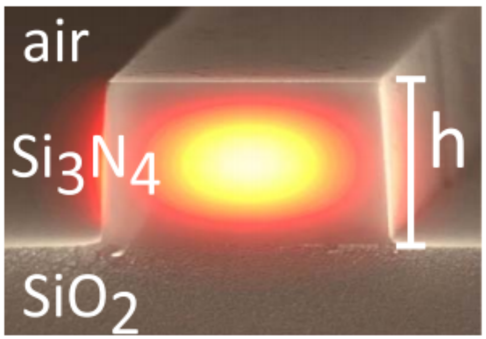
- Anomalous dispersion
- Kerr effect → Intensity dependent index of refraction

For octave spanning frequency comb,
Tune dispersion over large bandwidth

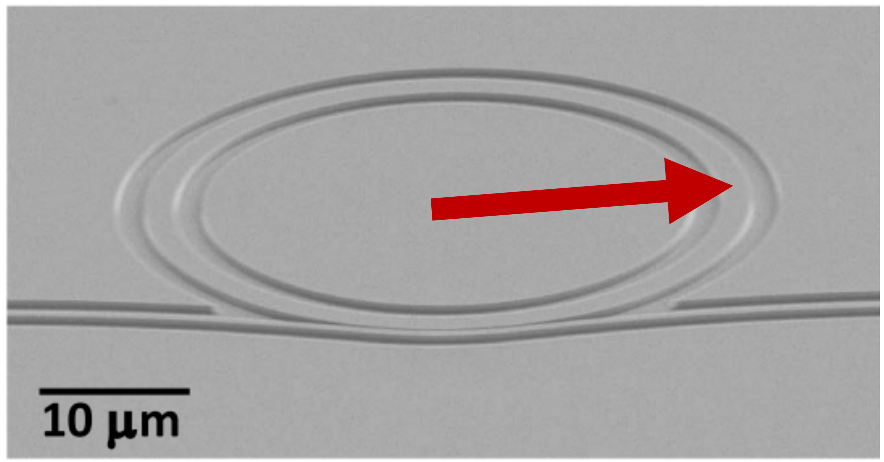
Kippenberg, T.J., Gaeta, A.L., Lipson, M., and M.L. Gorodetsky, Dissipative Kerr solitons in optical microresonators, Science **361**, eaan8083, 2018.

Dispersion engineering of comb...

WG cross section



Radius 23 micron→1 THz mode spacing



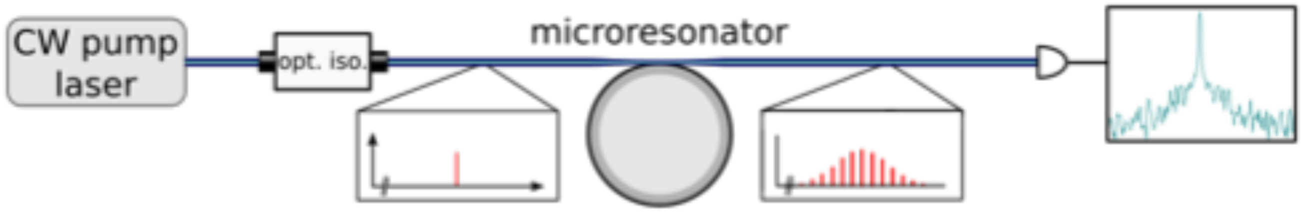
Radius determines mode spacing (1 THz)

Thickness (~600nm) determines GVD at pump wavelength (1550nm)

Width→controls higher order dispersion and location of dispersive waves.

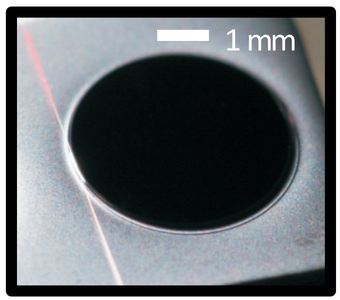
Image credit: Li, Q. et al., Optica **4**, 193-203 (2017). [NIST]

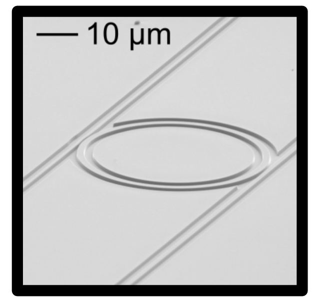
Pfeiffer, M.H.P, et al., Optica **4**, 684-691 (2017). [EPFL]
Okawachi, Y., et al., Opt. Lett., **39**, 3535-3538 (2014). [Cornell]
Yi, X., et al., Optica **2,** 1078-1085 (2015). [CalTech] 22 GHz, Q of 400 million



Silica (SiO_2) wedge resonator

Vahala [Caltech]

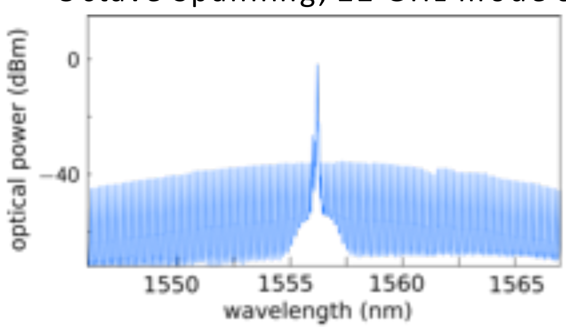




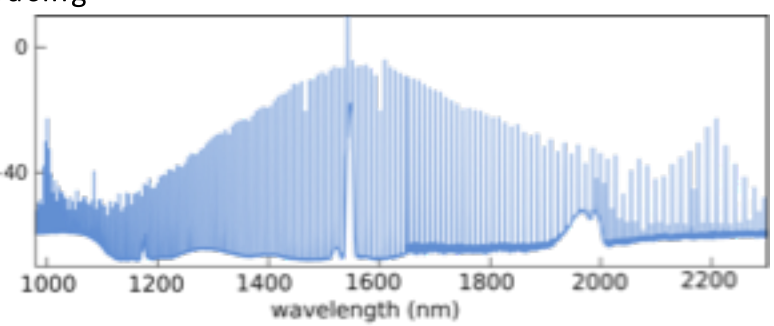
Si_3N_4 micro resonator

Srinivasan [NIST]

Octave Spanning, 22 GHz mode spacing



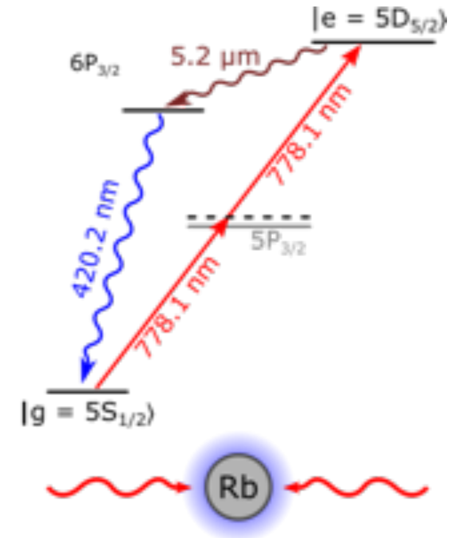
Octave Spanning, 1 THz mode spacing

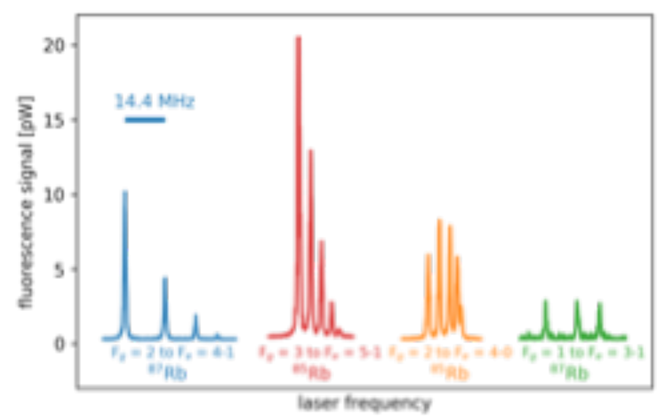


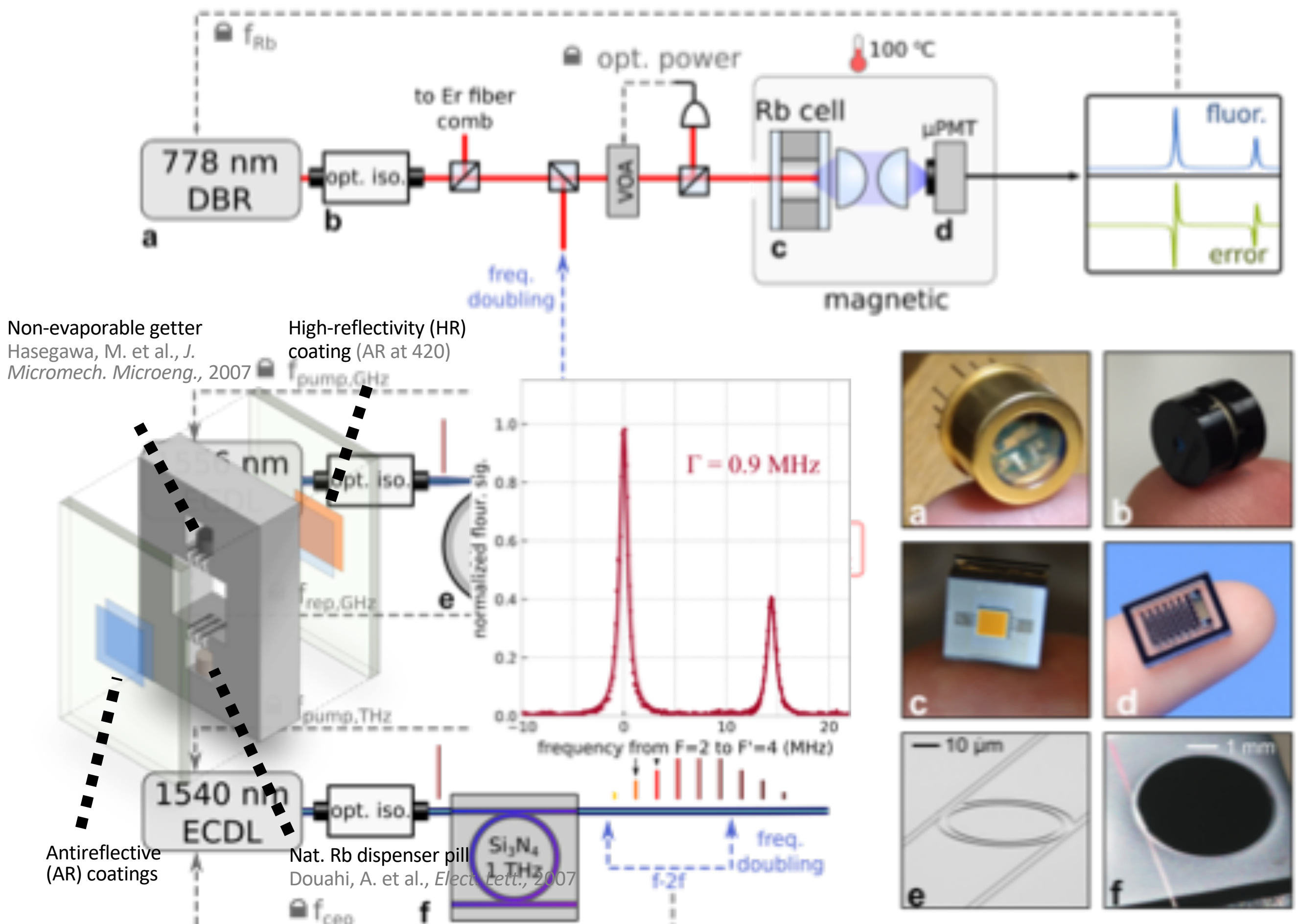
P_{opt} < 275 mW!

Rubidium two-photon transition

- Intrinsically **Doppler-free** for counterpropagating light fields; **all atoms participate** (typical Doppler Broadening ~ 300MHz)
- Vapor cell: low acceleration sensitivity, simple to implement
- Optical transition: high Q (385 THz/1MHz = 10^8), reduced systematics, low phase noise possible (narrow linewidth, $\Delta\nu \approx 300$ kHz)
- Well-studied metrologically, BIPM secondary representation of the second:
- Possibility of using well established telecom laser technology



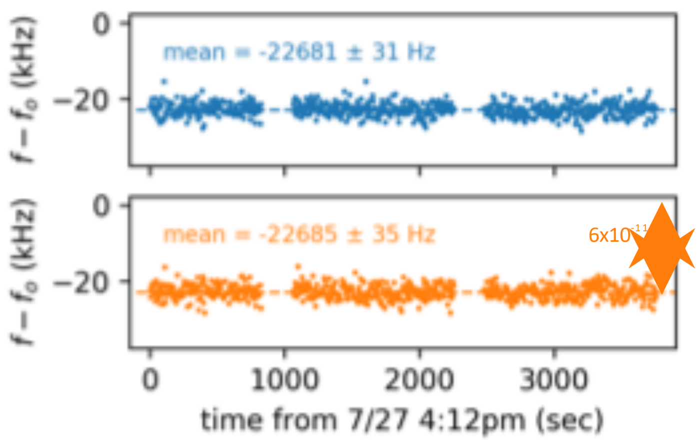


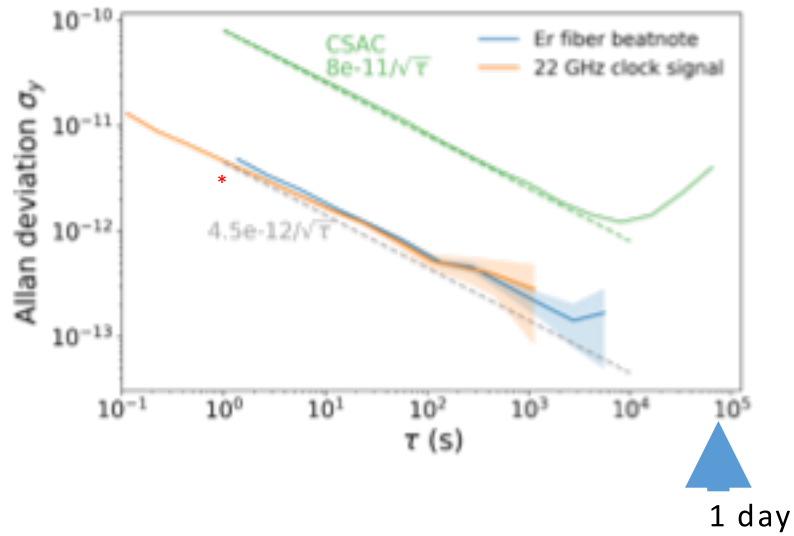


P_{tot} = **275 mW**

* Source: www.hamamatsu.com

Chip-scale optical clock performance





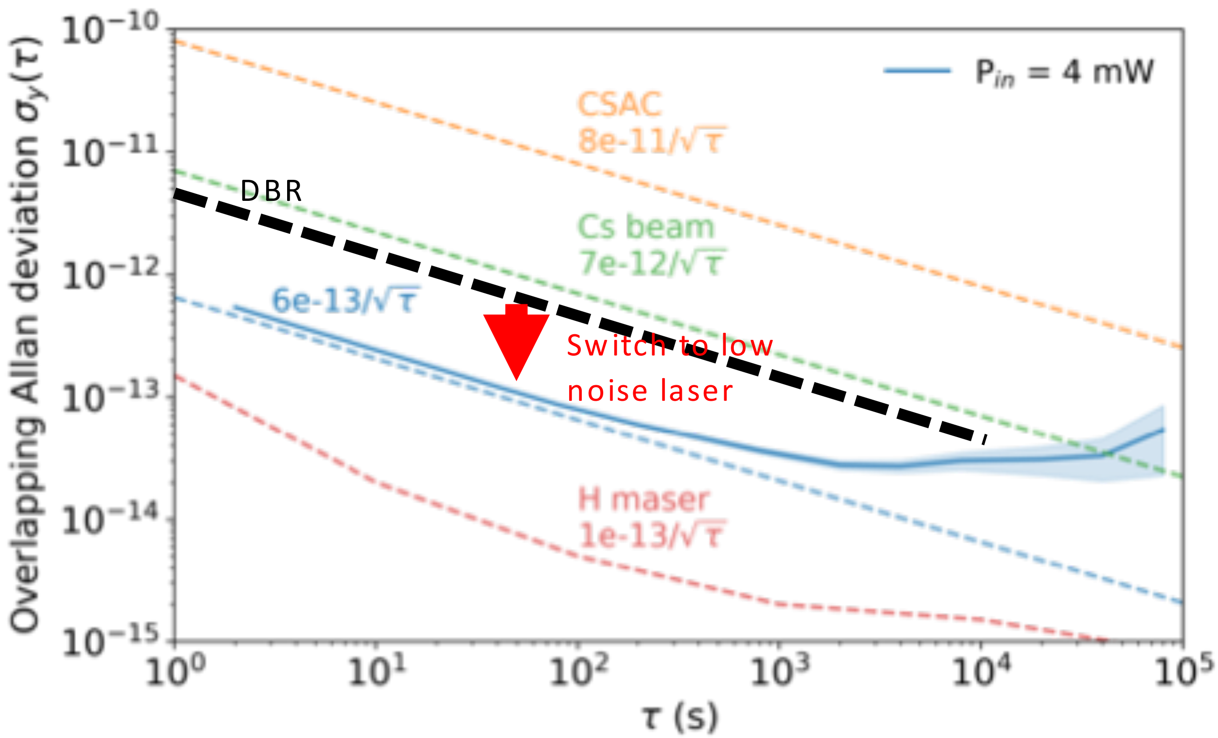
Linewidth contributions	Δf (kHz)
Natural linewidth (at 778 nm)	330
Laser linewidth	475
Time of flight	100
Collisional broadening	≈ 125
Total	≈ 1 MHz

Shift from [9]	Δf (kHz)
Light shift (-1.4 kHz/mW)	-23.4
He coll. shift [10]	≈ 3.5
Bkgnd. gas. coll. shift [10]	-4.5
Rb-Rb coll. shift (97 °C) [11]	≈ 1.27
Total	≈ 23.1

*intermodulation limited stability: $4x10^{-12}/\sqrt{\tau}$

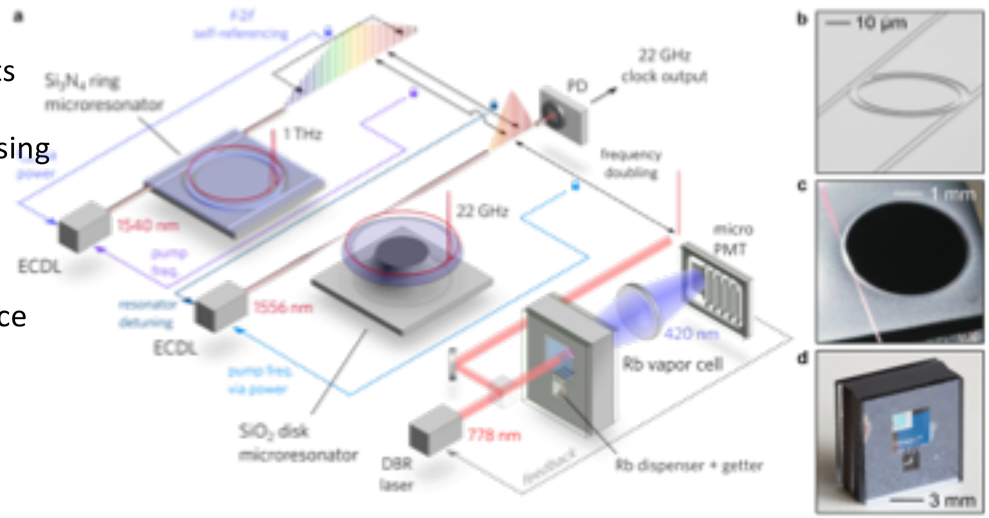
Stability limited by DBR laser noise (0.5 MHz linewidth)

Clock performance with low-noise clock laser



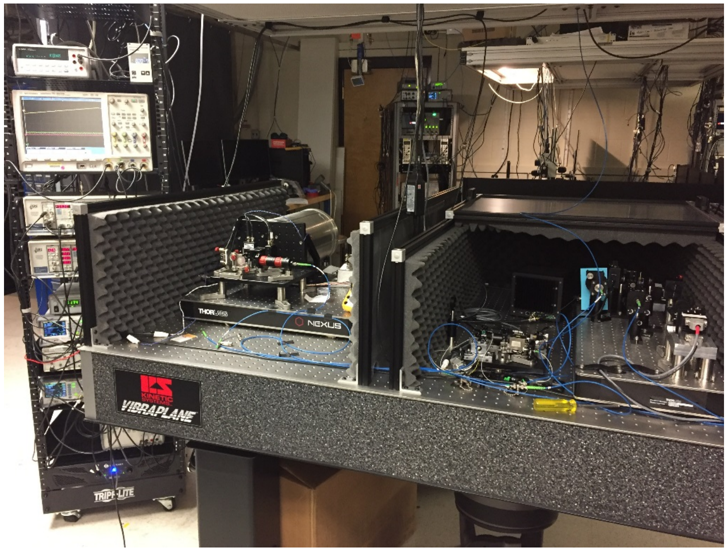
Summary

- Demonstration of an optical clock using microfabricated components
- Intermodulation limited clock stability at $4.4 \times 10^{-12}/\sqrt{\tau}$ to ~1000s using 275 mW of optical power (25x improvement over CSAC)
- Shot noise limited stability of $6.5 \times 10^{-13}/\sqrt{\tau}$ using a low-noise ECDL (100x improvement over CSAC, 10x better than Cs beam performance out to ~10^4 s)
- Future directions:
  - Development of an integrated clock package
    - Integrated, low noise lasers
    - On-chip optical frequency doubling

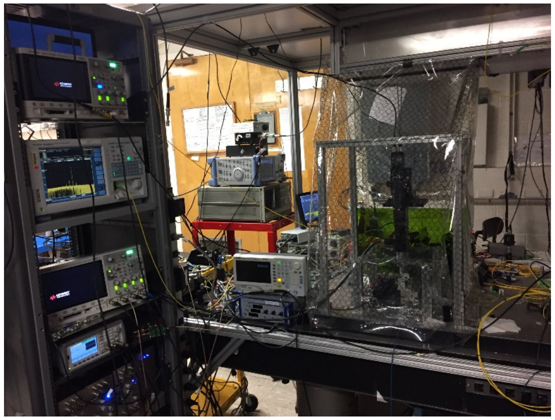


Future work: Integration

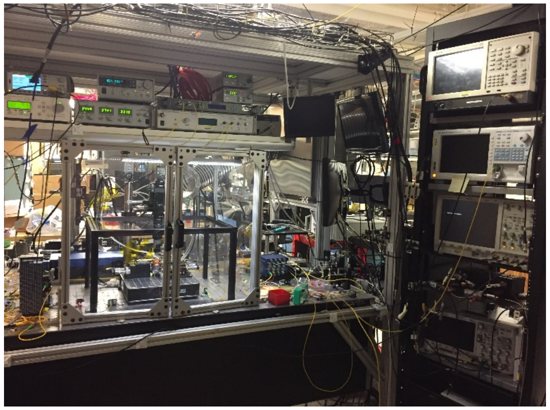
Clock Laser Setup

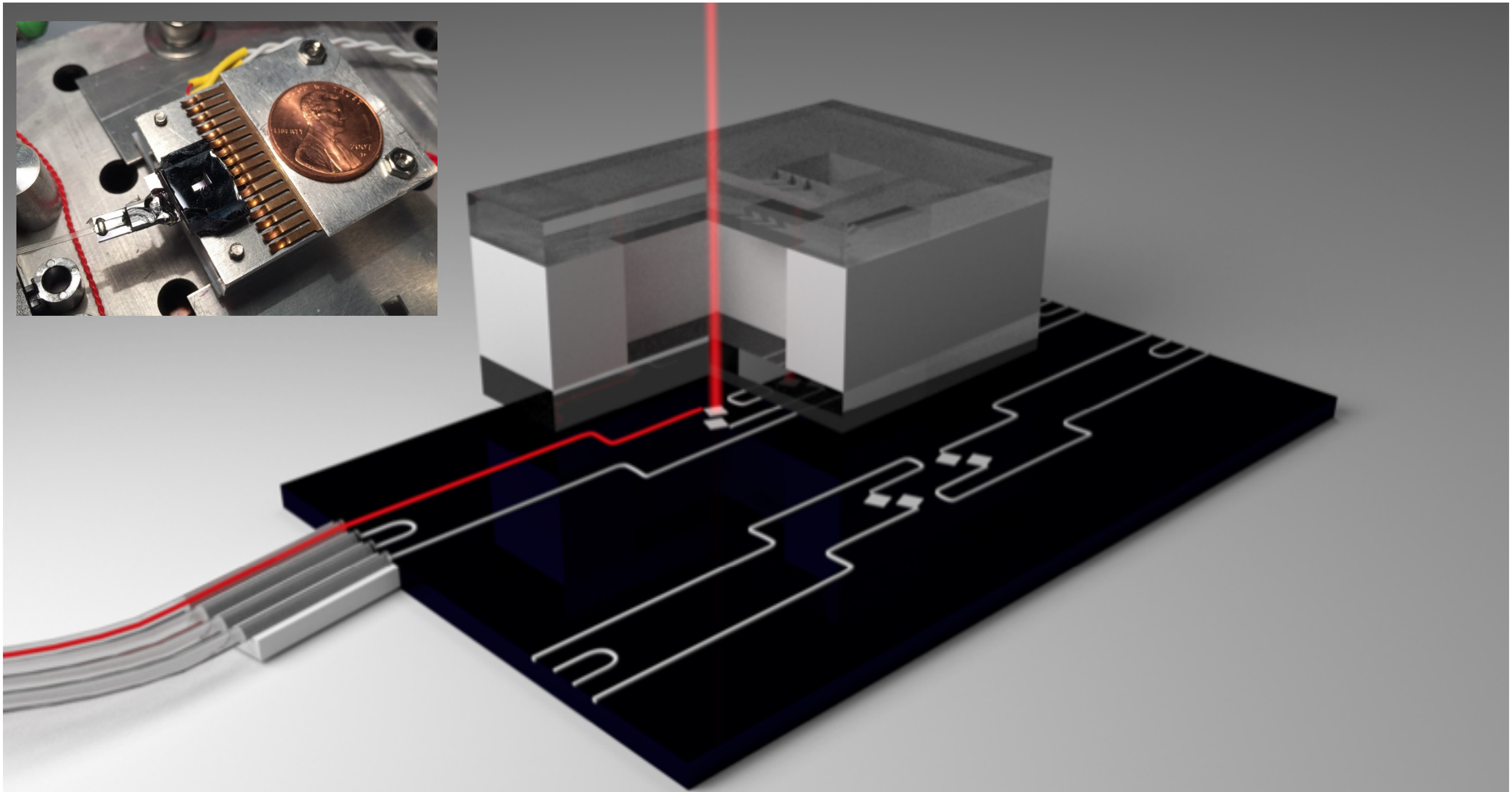


GHz Comb setup

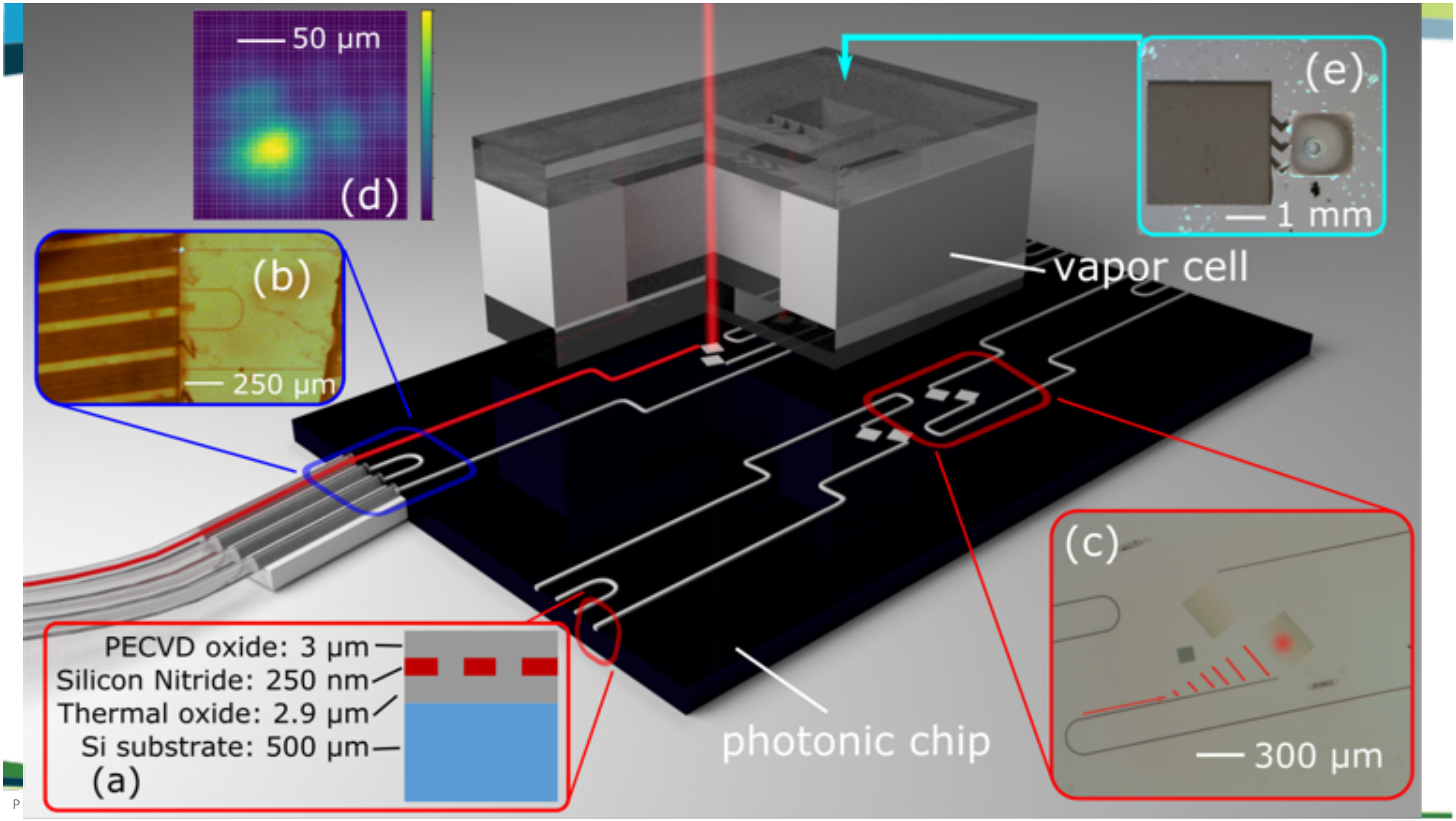


THz Comb setup





Hummon, M. T. et al., Optica **5**, 443-449 (2018)



50 µm
(d)
(e)
1 mm
(b)
250 µm
vapor cell
(c)
300 µm
PECVD oxide: 3 µm
Silicon Nitride: 250 nm
Thermal oxide: 2.9 µm
Si substrate: 500 µm
(a)
photonic chip

How are Photonics an enabling technology for atomic based quantum sensors?

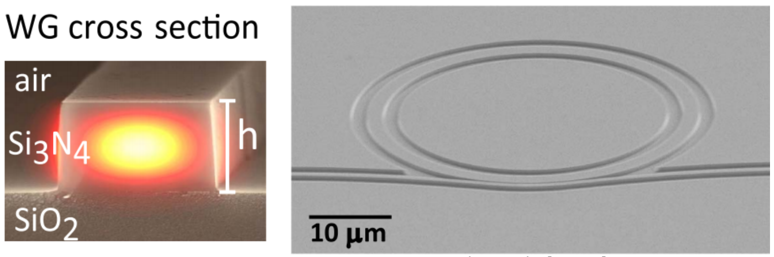
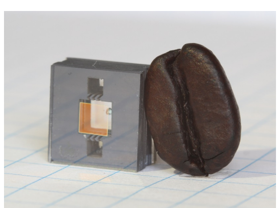
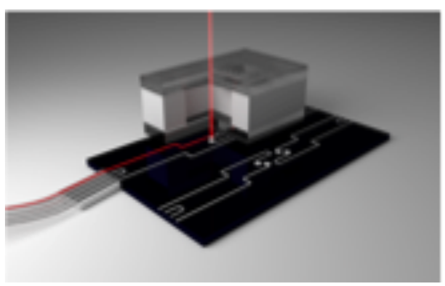


Image credit: Li, Q. et al., Optica **4**, 193-203 (2017). [NIST]

- Precision fabrication
  - Tune optical properties for desired applications
  - Access optical non-linearity at low powers

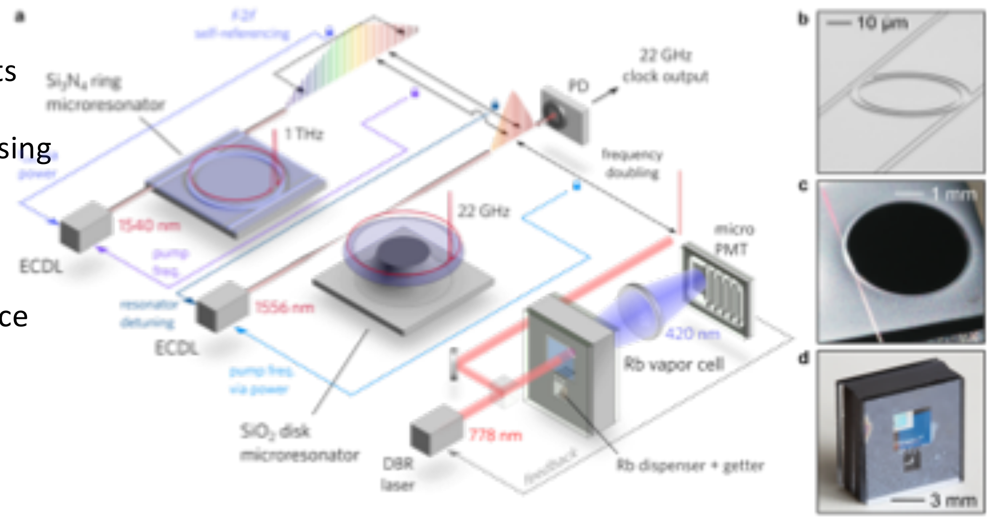


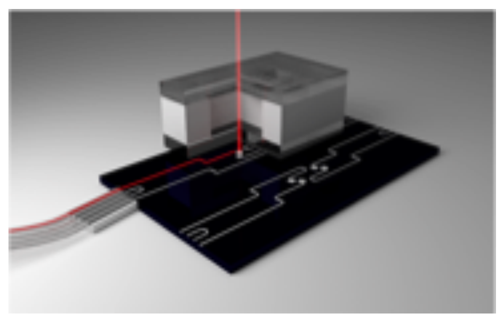


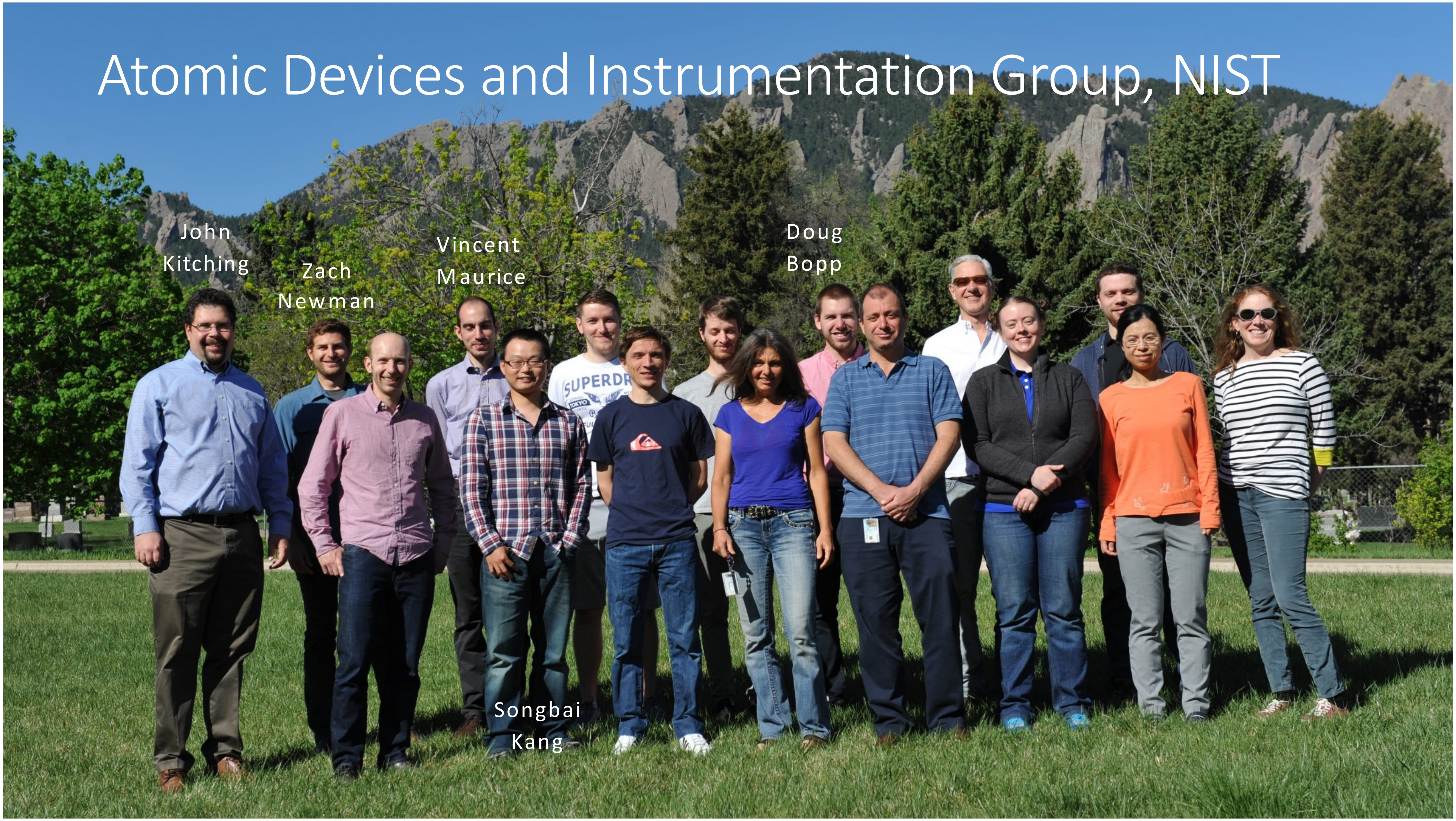
- Parallel wafer level fabrication for atomic vapors
- Optical tool box
  - Spatial mode, polarization, modulation
- Precision control & probing of atomic quantum states

Summary

- Demonstration of an optical clock using microfabricated components
- Intermodulation limited clock stability at $4.4 \times 10^{-12}/\sqrt{\tau}$ to ~1000s using 275 mW of optical power (25x improvement over CSAC)
- Shot noise limited stability of $6.5 \times 10^{-13}/\sqrt{\tau}$ using a low-noise ECDL (100x improvement over CSAC, 10x better than Cs beam performance out to ~10^4 s)
- Future directions:
  - Development of an integrated clock package
    - Integrated, low noise lasers
    - On-chip optical frequency doubling



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