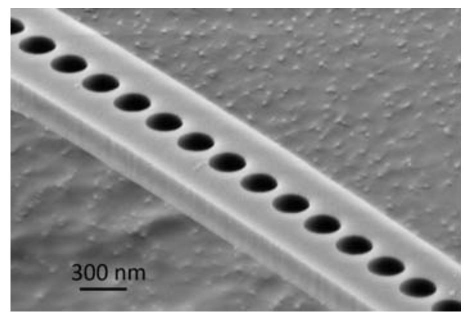
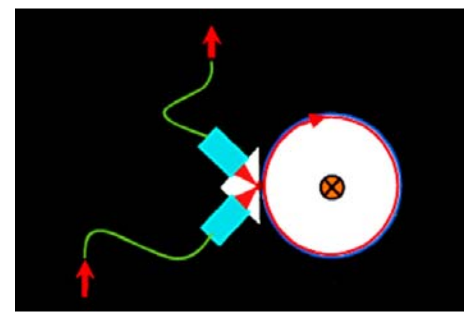
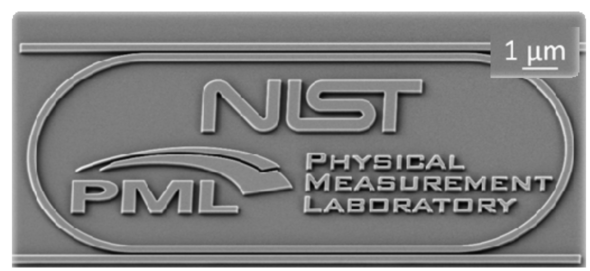
THERMODYNAMIC MINIATURIZED SENSORS AND STANDARDS AND THE QUANTUM SI





GREGORY F. STROUSE
Associate Director for Measurement Services
Physical Measurement Laboratory (PML)

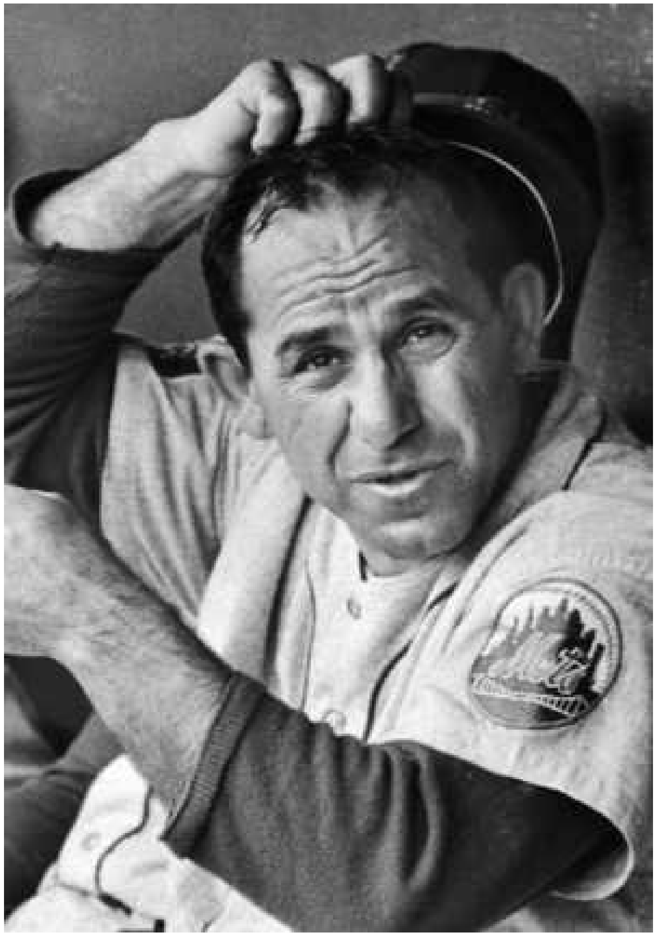
gregory.strouse@nist.gov



Future of Metrology?

"It's hard to make predictions, especially about the future"

Yogi Berra



Outline

- Few words on the Système international d'unités (the SI)
- Trend towards a "Quantum SI"
- Trend towards "Embedded Standards"
- Implications for measurement of thermodynamic quantities
- Final thoughts

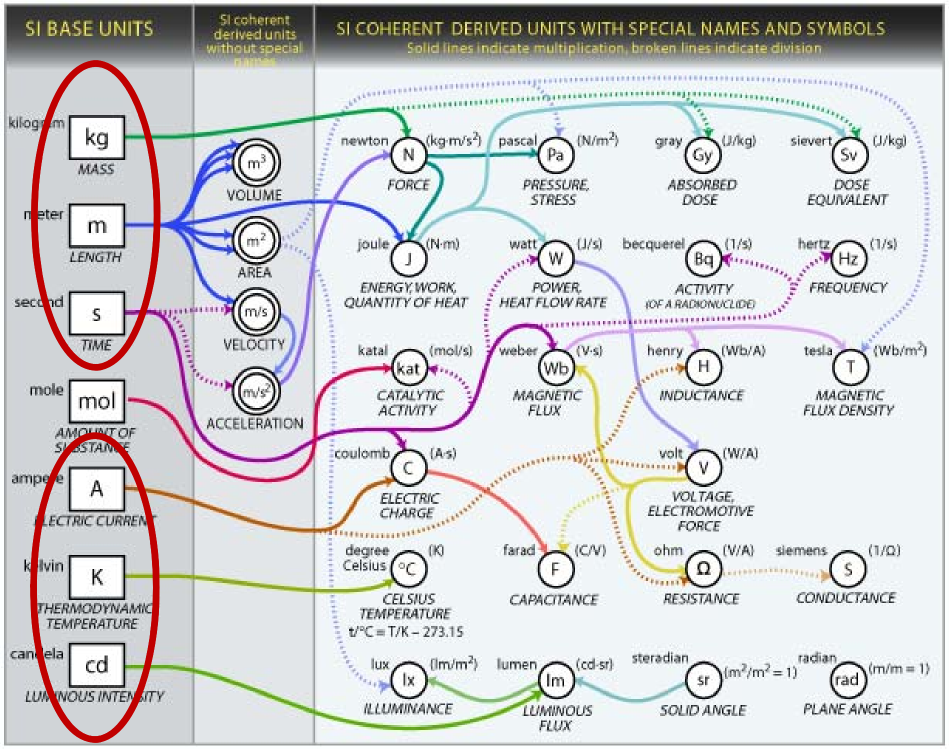
SI is the Modern, Harmonized Metric System

PML is responsible for 6 of 7 units

NIST seeks to ensure that SI is…

- Scientifically based
- Defined by consensus
- Realized in practice
- Disseminated for routine uses
- Disseminated for new and novel uses
- Maintained and improved

SI underpins *all* measurements, whether expressed in metric units or otherwise



Outline

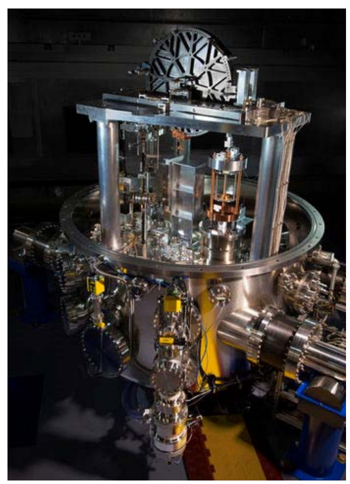
- Few words on the Système international d'unités (the SI)
- Trend towards a "Quantum SI"
- Trend towards "Embedded Standards"
- Implications for measurement of thermodynamic quantities
- Final thoughts

Classical to Quantum SI
Meeting the Metrology Challenges of the 21st Century

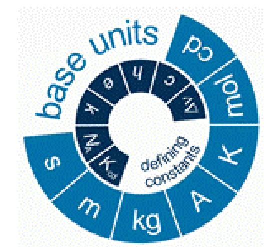
- **Quantum SI**
  - Quantum phenomena
  - Fundamental and atomic constants

- Tying metrology back to fundamental atomic quantities
  - Removing artifacts as defining the SI

NIST Watt Balance



- **kelvin**
  - Boltzmann constant
- **kilogram**
  - Planck constant
- **ampere**
  - Elementary electric charge
- **mole**
  - Avogadro constant



What do We Mean by "Quantum SI?" Consider th… History of the Meter:

1889: Internationa… …Meter (Artifact)

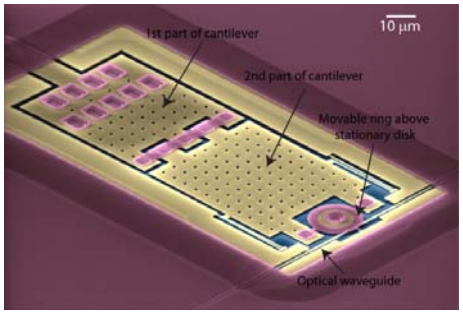
GOOD

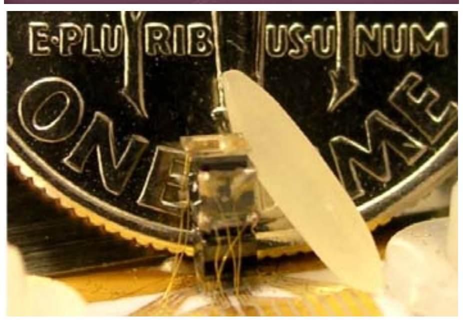
1960: *The meter is th… length … …al to* 1,650,763.73 *wavelengths in va… …e radiation corresponding to the transiti… …the levels* $2p_{10}$ *and* $5d_5$ *of the krypton 8…* … (11th CGPM, Resolution 6)

BETTER

1983: *The meter is the lengt… …he path travelled by light in vacuum during …val of* 1/299,792,458 *of a second.* (17th CGPM, …on 1)

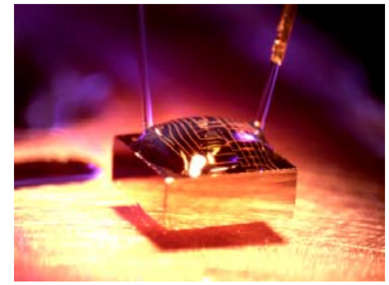
BEST

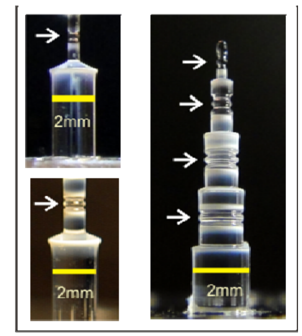


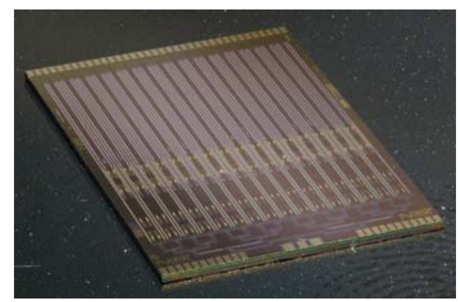


Quantum SI Metrology Areas

- Acceleration
- Electrical
- Fluid flow
- Humidity
- Length
- Magnetic field
- Mass and force
- Pressure
- Optical power
- Radiation
- Temperature
- Time and frequency





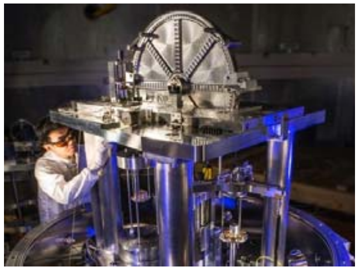


Outline

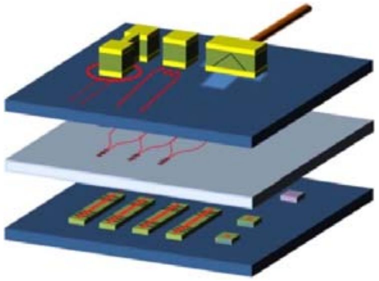
- Few words on the Système international d'unités (the SI)
- Trend towards a "Quantum SI"
- Trend towards "Embedded Standards"
- Implications for measurement of thermodynamic quantities
- Final thoughts

PML Priority
Advanced Measurement Dissemination

- Improving dissemination of national standards
  Using the "21st century toolkit" to reinvent best devices and modes for calibration services, e.g., greater stability, wider dynamic range



- Embedded sensors: "NIST on a Chip"
  Miniaturized devices that minimize the need for traditional calibration services by using quantum effects

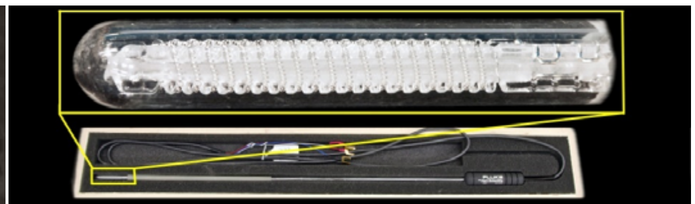


- Open metrology: Sharing what we know
  We commit to providing many, varied training opportunities to our customers to facilitate adoption of best practices

SI Dissemination Methodologies in Practice

Send us an artifact; We'll measure it and return it

Commercially available ITS-90 fixed-point cells

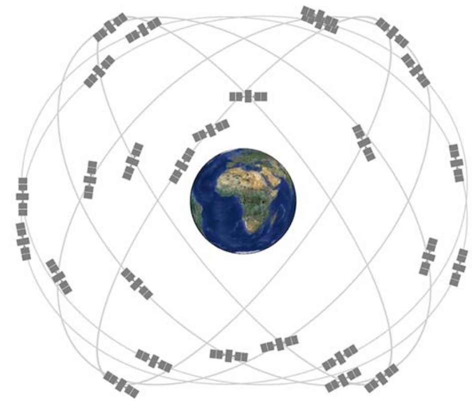


Send us an instrument; We'll calibrate it and return it

Standard Platinum Resistance Thermometer

Don't send us anything; Buy one, and we'll ship it to you

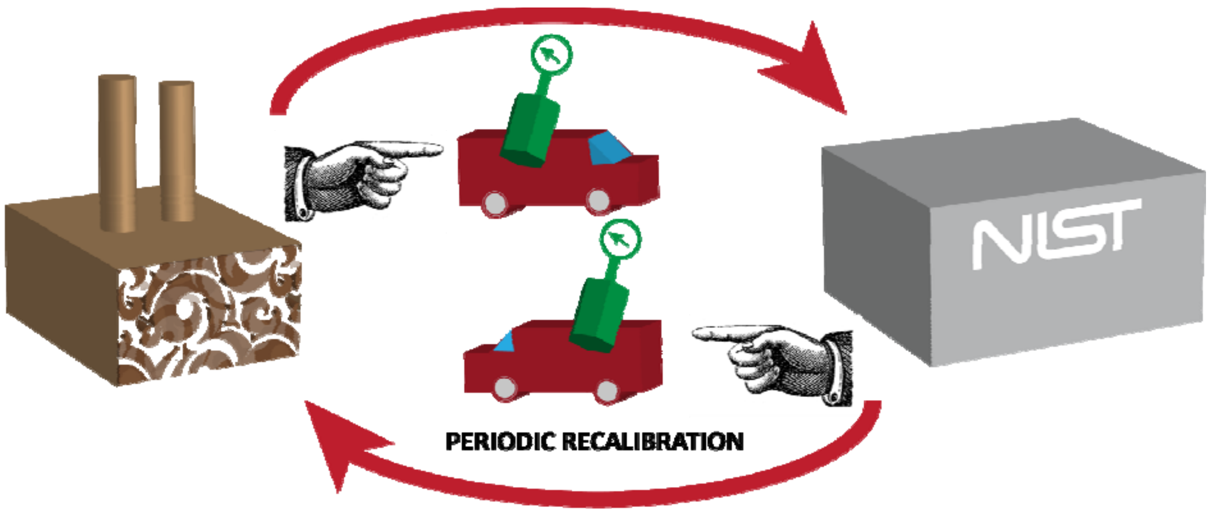
SRM 1968, Gallium Melting-Point Standard



Don't send us anything; We'll observe something together

GPS satellite constellation (atomic clocks in orbit)

Classical Calibration Dissemination Method



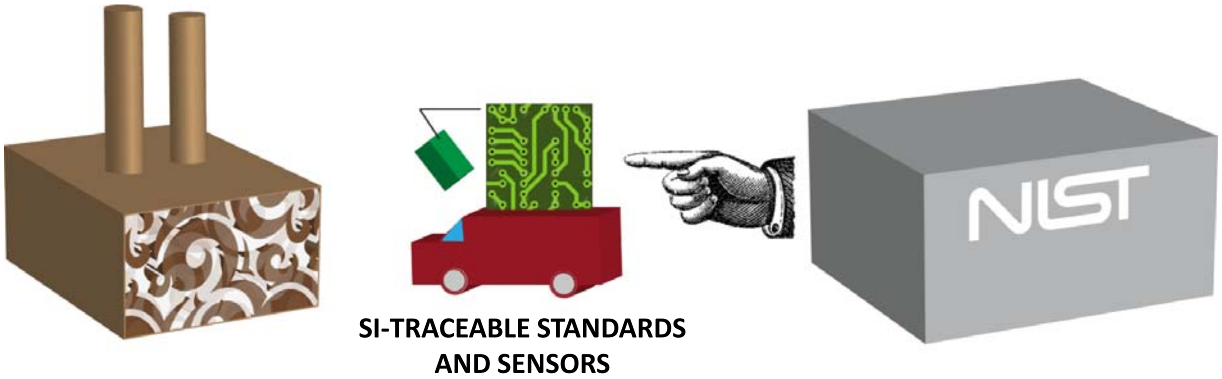
Delivery guy:
He likes things as they are

Routine shipment of artifacts
and instruments for calibration

Over 14,000 artifacts per year – Expensive modality

Advanced Measurement Quantum SI Dissemination

He’s got less work to do



Technology transfer

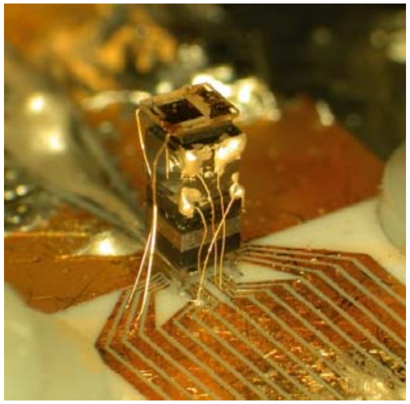
- Dual platform standards and sensors
- SI realization outside the walls of NIST
- New faster/lower cost calibration services – on factory floor
- Enhance economic impact through elimination of waste in industrial processes
- Number of calibrations approaches zero

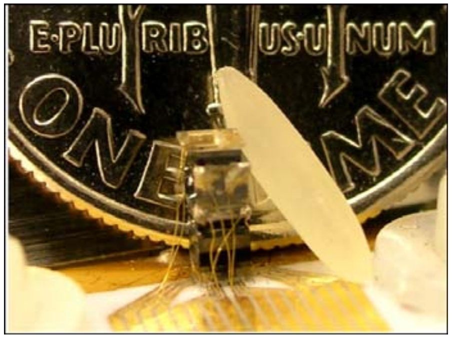
Emerging Technologies Enable Disruptive Change

- Solid state lasers (e.g., VCSELs)
- Microelectromechanical systems (MEMS)

Optical microresonators on a silicon wafer. (Premier issue of *Optica*)

Example: These technologies enabled the Chip Scale Atomic Clock (CSAC)

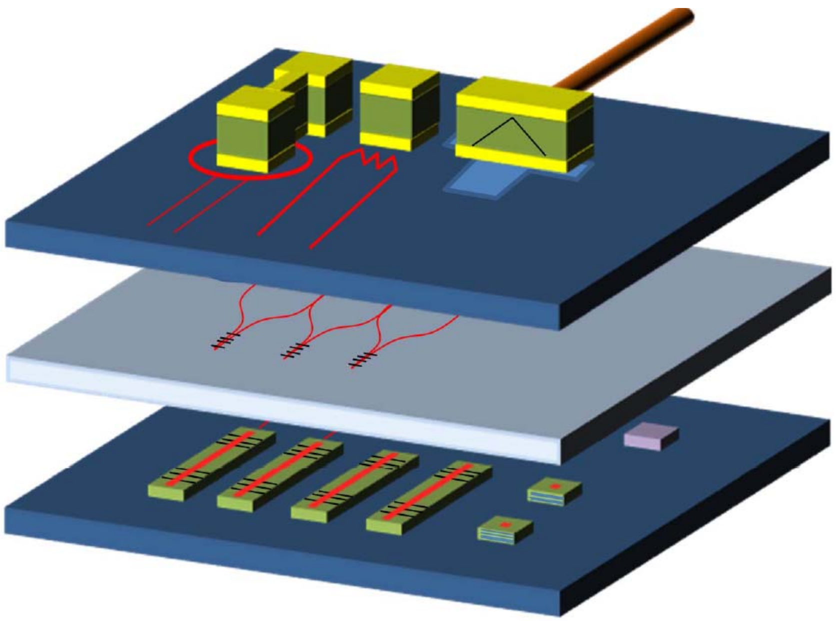




NIST Prototype (2004)

Commercialized (2011)

Embedded Metrology ("Chip Scale")



NIST Quantum SI Standards and Sensors
-Dual mode infra-technology

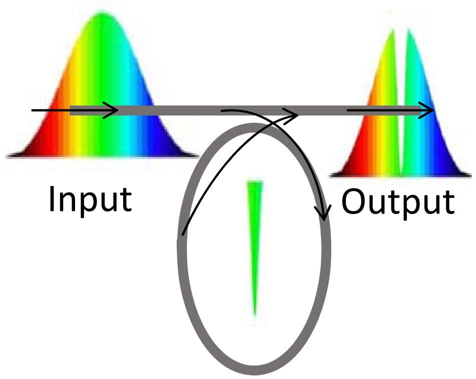
- Flexible
  - Integrated, multi-function standard and sensor platform
- Manufactural
  - Commercialization of designs / recipes to foundry
- Deployable
  - Quantum SI realization and zero-chain traceability
- Usable
  - Rugged and easy to use

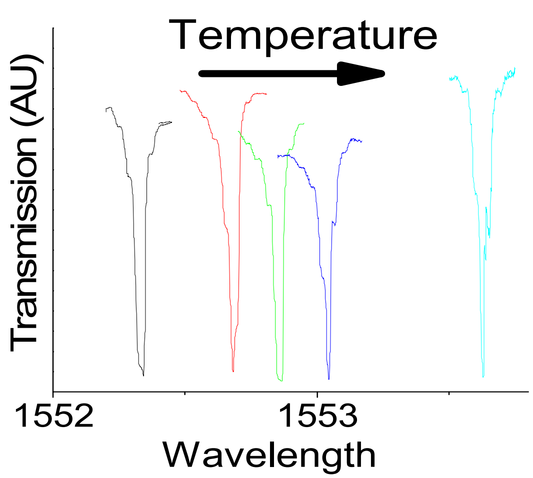
Outline

- Few words on the Système international d'unités (the SI)
- Trend towards a "Quantum SI"
- Trend towards "Embedded Standards"
- Implications for measurement of thermodynamic quantities
- Final thoughts

Photonic Sensors

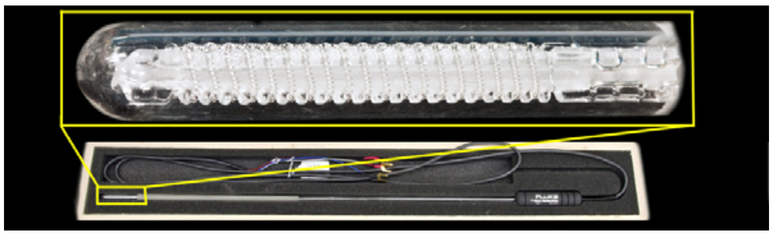
- Light based sensor
  - Change in physical property (e.g., index of refraction) creates a resonate frequency shift
  - Frequency notch-filter
- Frequency measurement advantages
  - More accurate than electrical
  - Low noise
  - Telecom industry components



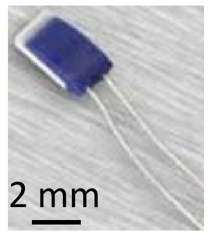


Photonic Temperature Sensor

Classical technology: Electrical temperature sensors



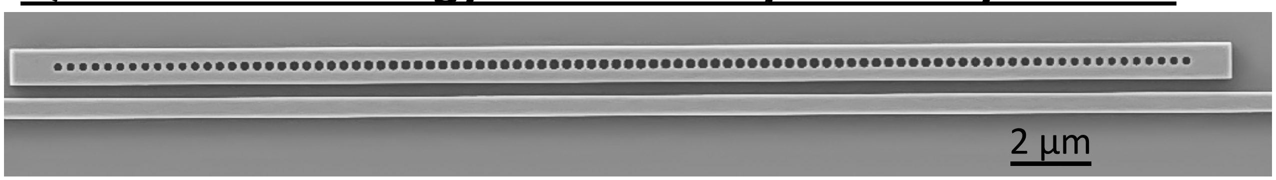
Standard platinum resistance thermometer

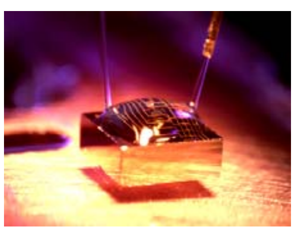


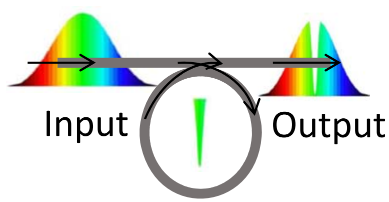
Industrial Pt PRT

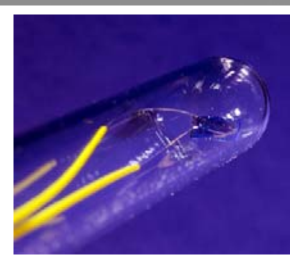
- *U* ≲ 10 mK @ (–196 °C to 500 °C)
- Hysteresis
- Mechanical or thermal shock

Quantum technology: Photonic crystal cavity sensors



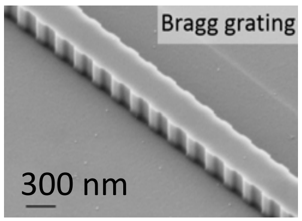




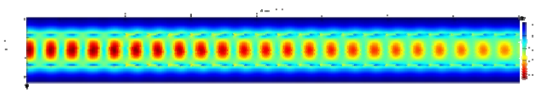


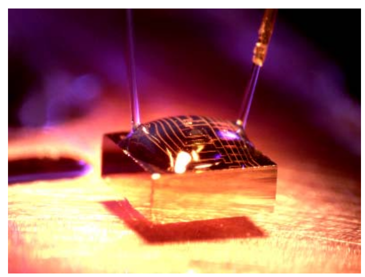
- Micro/nano-scale size
- Can be embedded
- Low cost and weight
- Immune to electromagnetic interference
- Negligible hysteresis
- Fast response time
- Can tolerate harsh conditions and treatment

Photonic Temperature Sensors

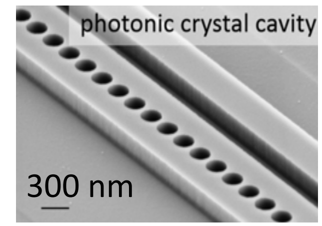


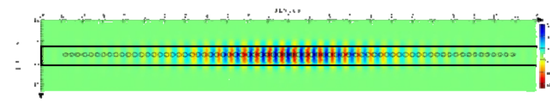
Si Bragg Waveguide
U < 1.25 °C

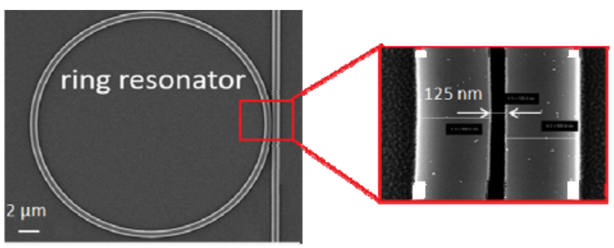




Si Crystal Cavity
U < 0.05 °C

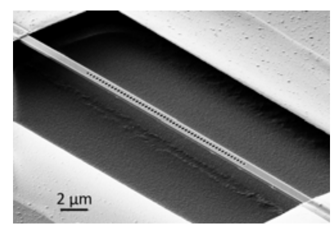


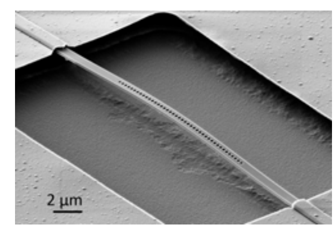




Si Ring Resonator
U < 0.01 °C

Si Nanobeam
U < 0.001 °C

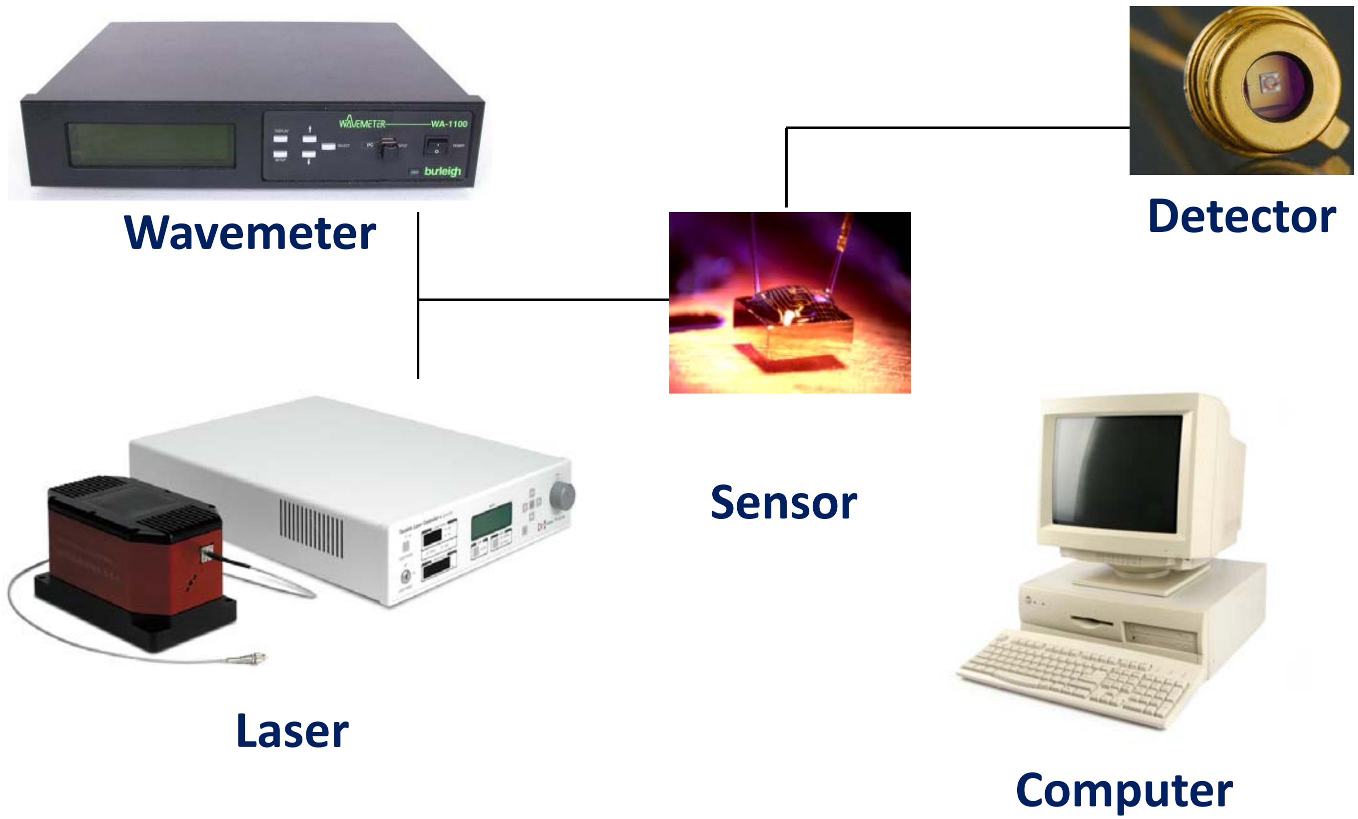




Integrated Photonics Currently

Sensor measurement "platform":

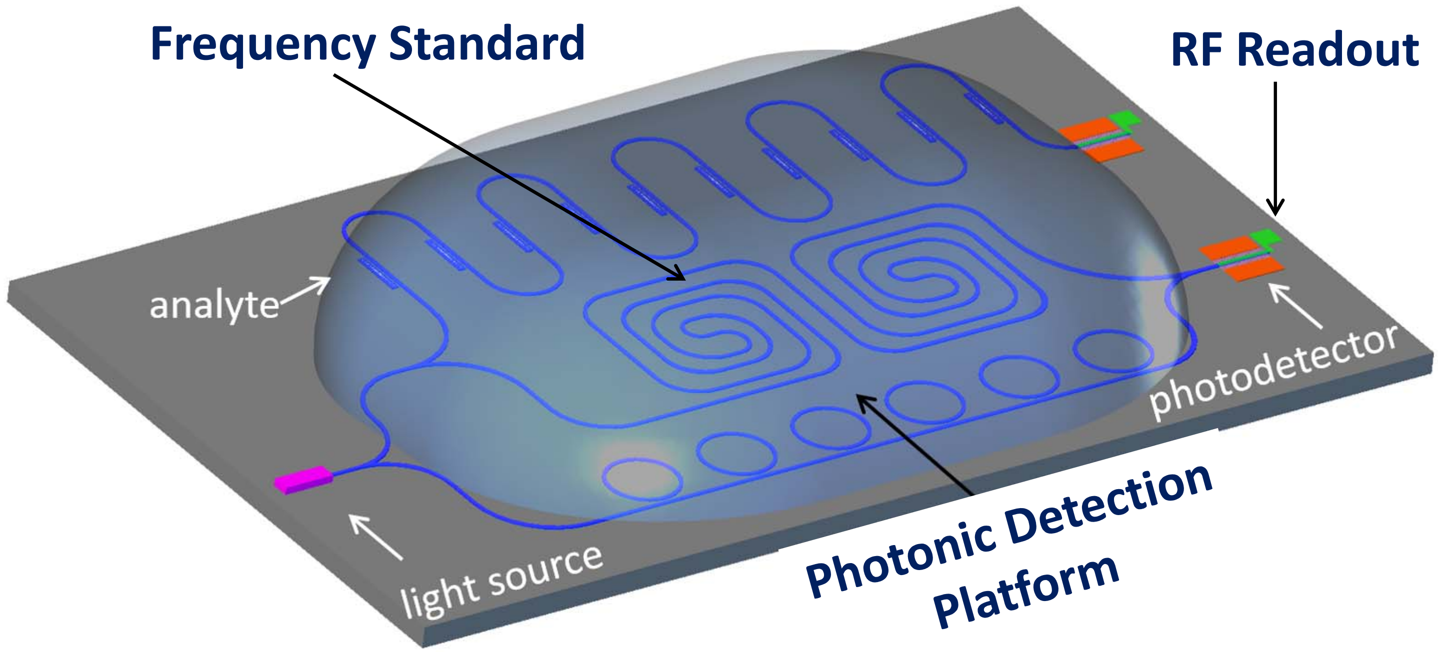
- Temperature
- Pressure
- Vacuum
- Humidity
- Strain
- Chemicals
- Radiation



Integrated Photonics
The Future for Mobile Sensing

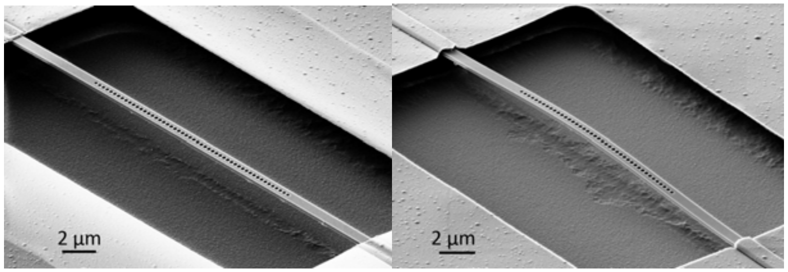
Sensor measurement platform:

- Temperature
- Pressure
- Vacuum
- Humidity
- Strain
- Chemicals
- Radiation



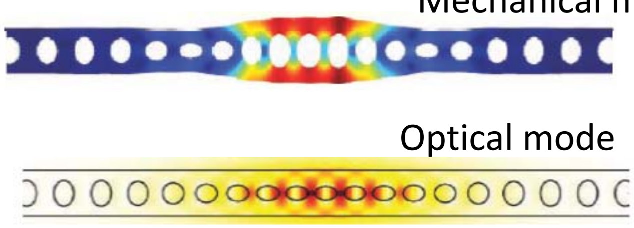
Possible Route to a Practical "Quantum Kelvin"

- Standard built into the sensor design
  - Nanoscale opto-mechanical silicon beam



Mechanical mode (standard)
- Phonon Boltzmann distributions of thermodynamic temperature states created to calibrate sensor temperature response

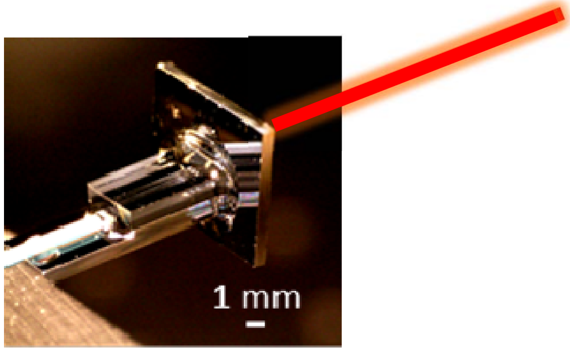
Optical mode (sensor)
- Temperature-dependent shift in sensor resonance is utilized to make temperature measurements

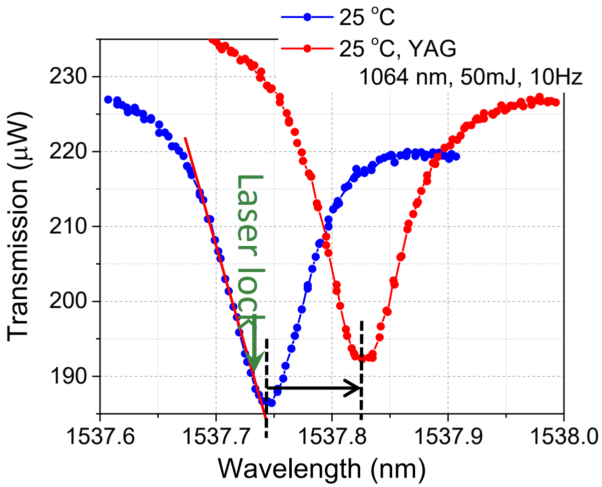


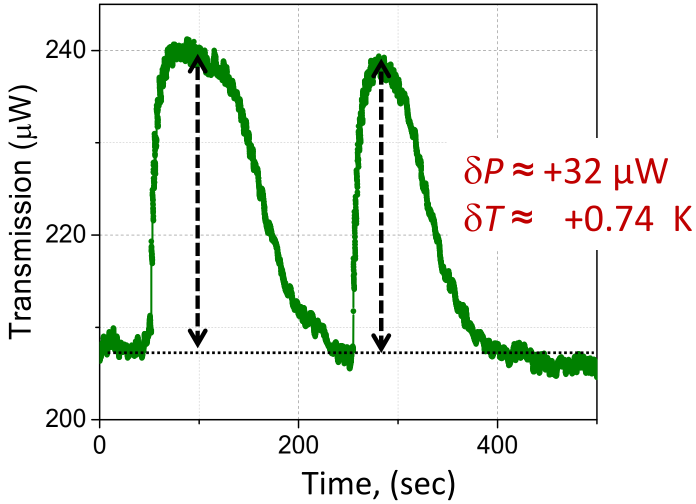
- Q ~ 1,000,000
- Resolution: $\delta\lambda_{MIN} \approx 0.1$ pm
  $\delta T_{MIN} < 1$ mK

Steps Toward Si Traceability to Dynamic Temperature

- Dynamic temperature
  - Developing laser temperature traceability (e.g., welding, chip manufacturing, eye surgery)
- First attempt – proof of concept
- YAG laser at 50 mJ
  - $\Delta P = 32\ \mu W$
  - $\Delta T = 0.74\ K$
- **SI traceable *T* through a photonic sensor**



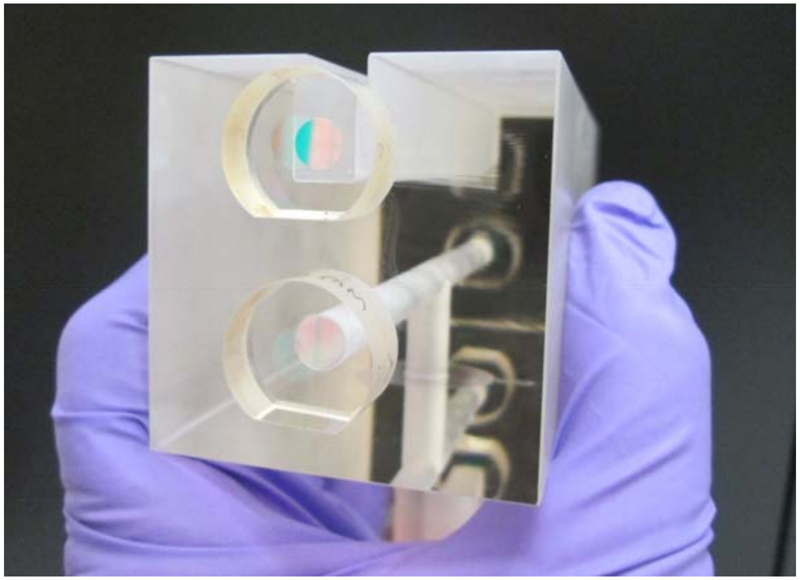




Quantum Pressure Standard and Sensor: FLOC (Fixed Length Optical Cavity)

- Compact, portable, quantum-based primary barometric pressure standard
- Replaces multiple commercial gauge technologies
- Range of 1 mPa to 1,000 kPa (10 atm)
  - Eight decades of pressure measurement in one instrument
- Based on refractive index of He (calculable to 0.1 ppm)

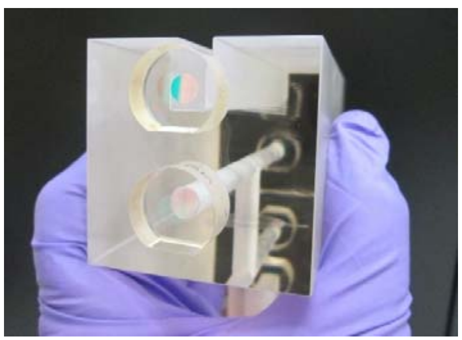
  $n - 1 \propto P \,/\, (k_B T)$



Fixed Length Optical Cavity (FLOC) gauge measures pressure from optical phase shift between lower channel (high vacuum) and upper channel (gas filled)

Key Advantages of Photonic Pressure

Hg manometer

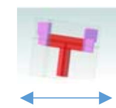


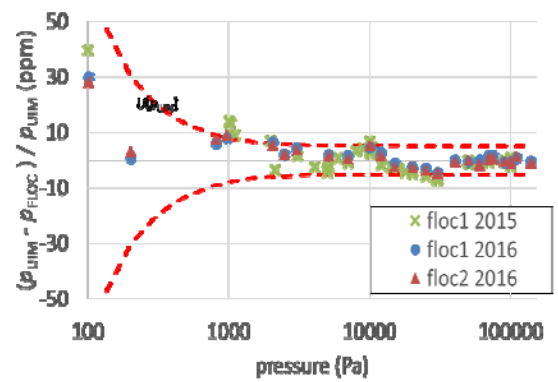
Photonic standard

- Elimination of mercury-based pressure standards
  - 400 year old technology
- 35× more sensitive
  - Resolution of 0.1 mPa
- 100× faster
  - Replaces inherently slow electrical-based measurements
- 1,000× lower pressure range
- Uncertainty smaller than Hg manometer
- Dual standard and sensor

Brings SI to the factory floor:
- **Pressure**
- **Length**

➢ **Reducible to size of cell phone**



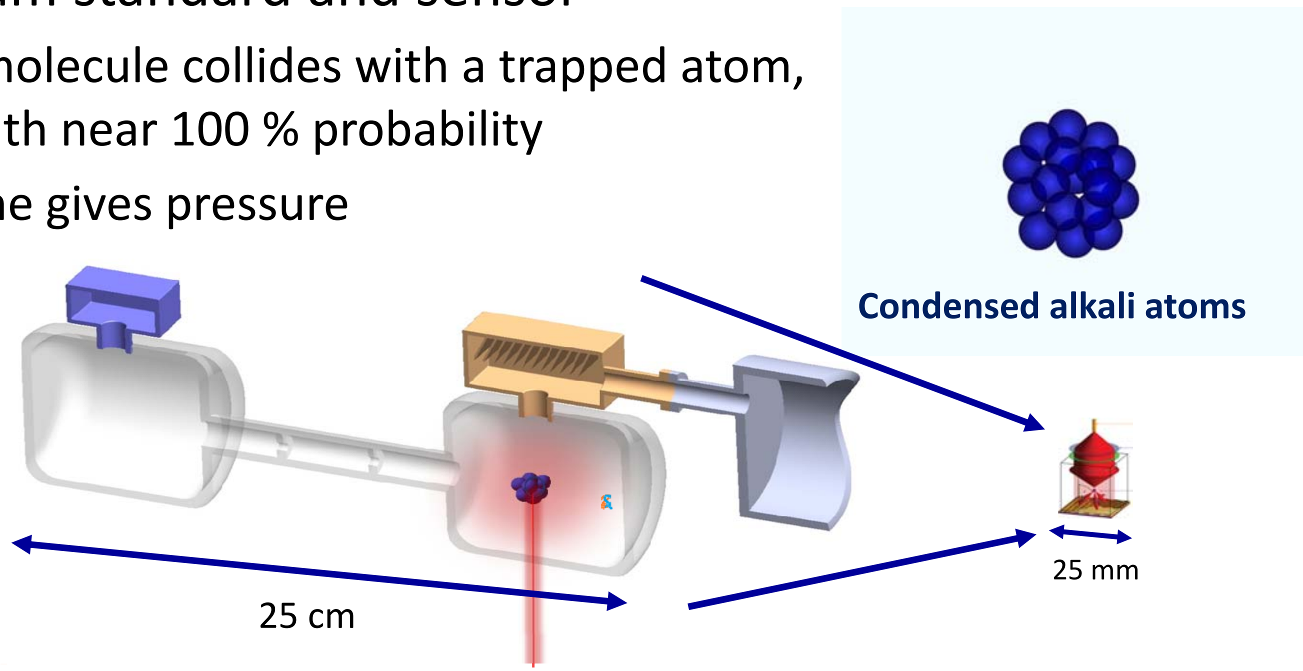


Cold Atom Vacuum Standard (CAVS)

- First-principle realization for UHV (10^{-6} to 10^{-9} Pa) and XHV ($\leq 10^{-10}$ Pa)
- Quantum-based vacuum standard and sensor
  - When a background molecule collides with a trapped atom, the atom is ejected with near 100 % probability
  - Measuring trap lifetime gives pressure

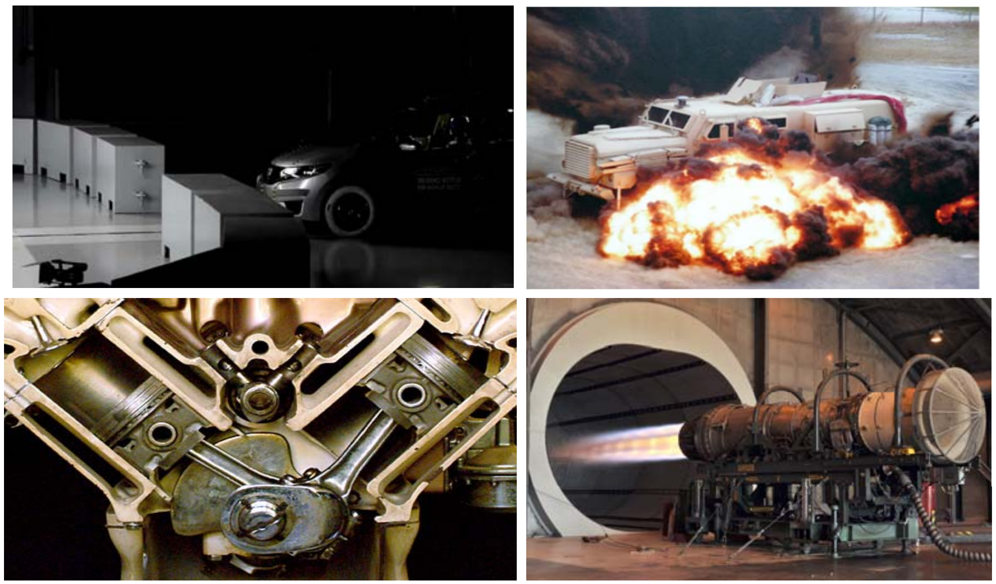
Quantum SI realization – reducible to cell-phone size

- Accelerators
- Semiconductor mfg
- Space sciences
- Surface sciences
- Quantum Information



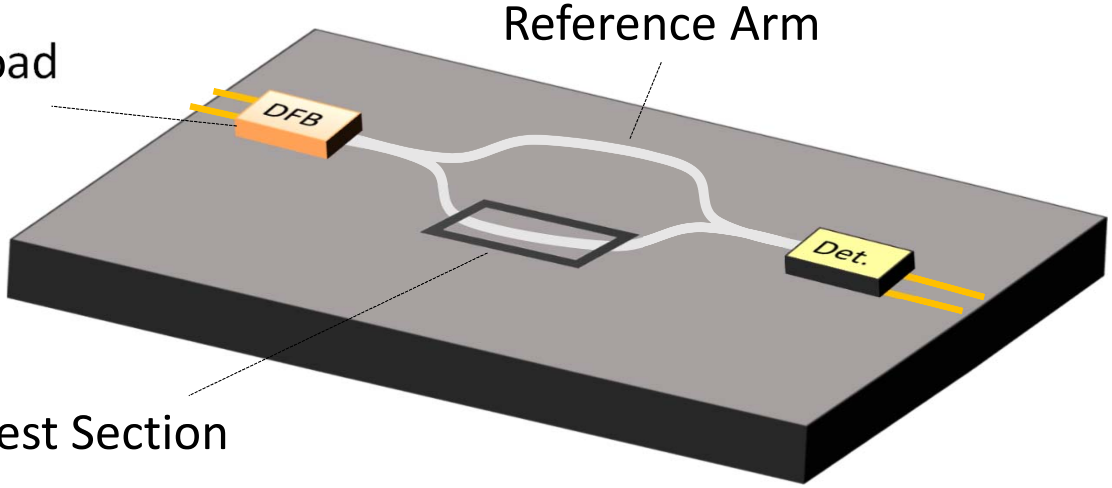
NIST pressure and vacuum standards

Dynamic Pressure – SI Traceability



- Static vs Dynamic SI Traceability
  - Dynamic is the next frontier
- Standards
  - SI traceable impulse standards and calibration methods are not available
- Sensors
  - Pressure sensors are only as good as their calibrations
- Develop new SI Traceable Standard and NoaC sensors

Next Frontier:
Dynamic, Impulse Measurement Standards

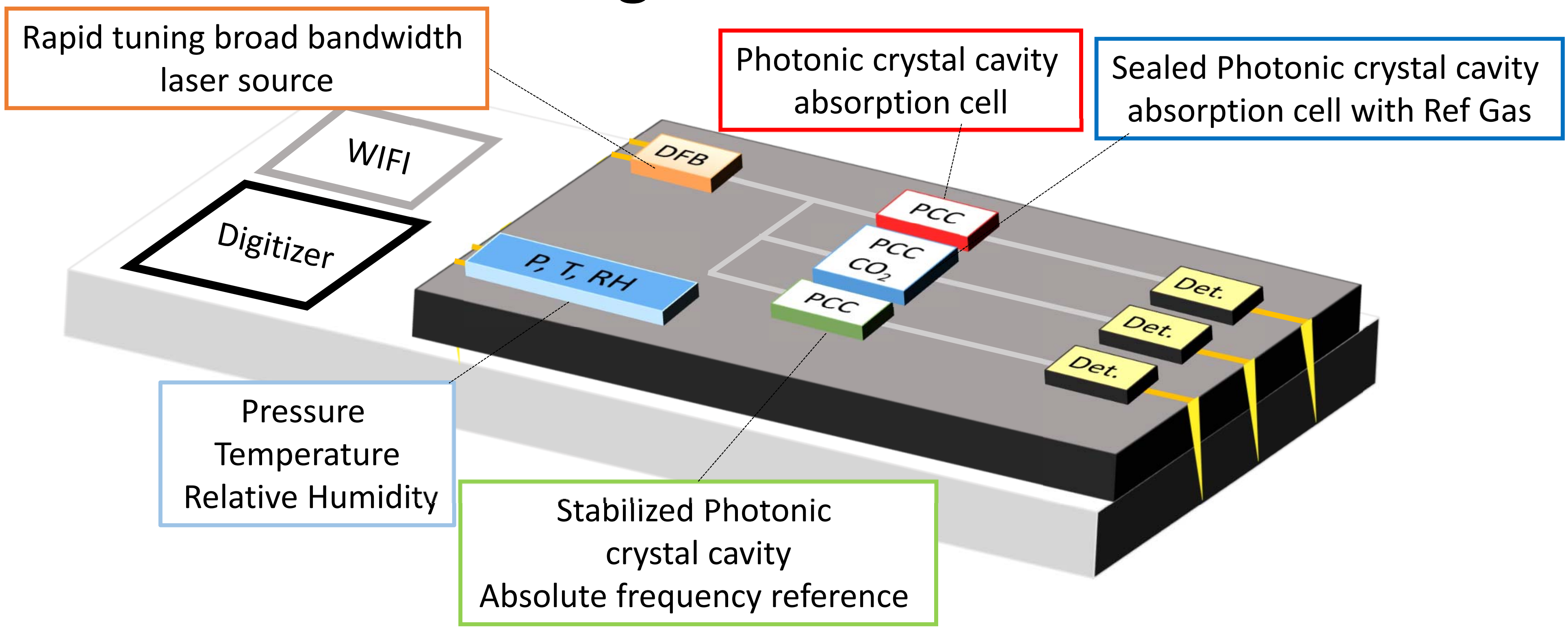


<u>Design Specifications</u>

- Size 2 mm × 1 mm
- High sensitivity
- High speed > GHz
- Dynamic range ≈ 10 % of operating pressure

Temperature Compensated, Dynamic Pressure Sensor
Mach–Zehnder based Design

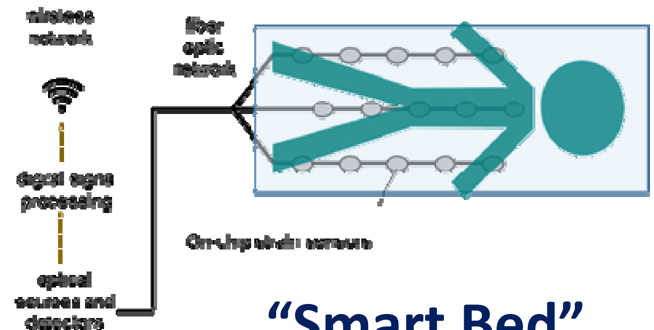
Long Term Vision



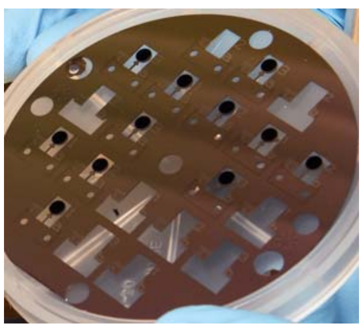
Fully integrated dynamic measurement sensor for pressure, temperature, relative humidity, and chemical species

Other Applications – Studies in Progress

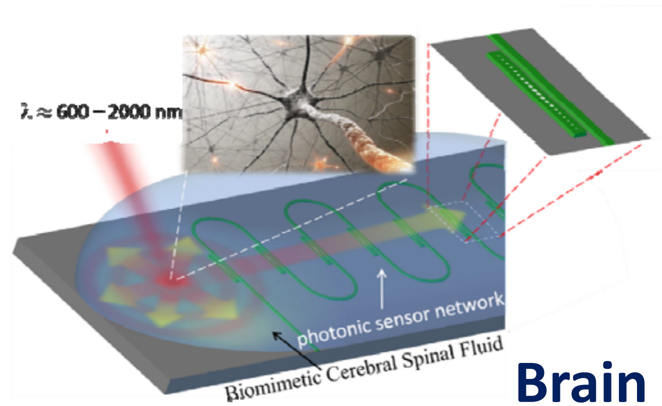
Infrastructure Monitoring



"Smart Bed"



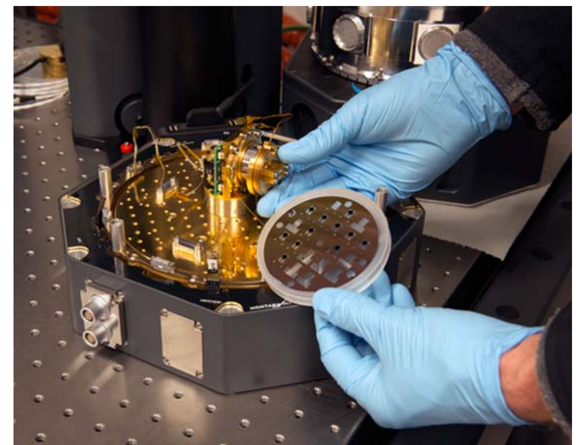
Laser Power Meters

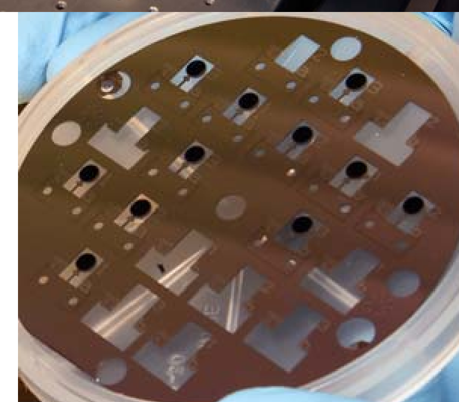


Brain Imaging

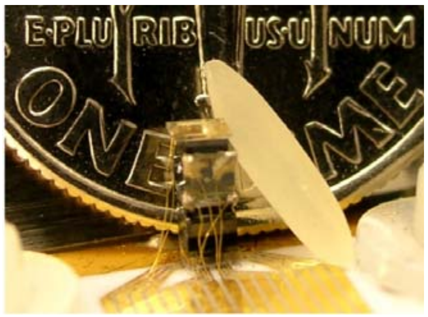
Nanotube Black—For Laser Power Meters

- >99 % conversion of light (broadband) to heat
- Enabling technology for high-accuracy optical (e.g., laser) power measurements
  - Terahertz [THz] radiation, currently a hot research topic for wireless communications
  - 300 nm to 500 µm
- Less expensive, more accurate, more portable than sensor technology it replaces
  - Zero-chain traceability
- Collaboration with PTB (Germany)





Deployed Quantum SI Enables Technology Infrastructure



Chip Scale Atomic Clock
(10^{-11} uncertainty)

As commercialized

Telecom networks
>$2 trillion/year globally

Outline

- Few words on the Système international d'unités (the SI)
- Trend towards a "Quantum SI"
- Trend towards "Embedded Standards"
- Implications for measurement of thermodynamic quantities
- Final thoughts

Possible Implications for NMIs

- For NIST
  - Focus shifts from artifact calibration to new deployable dual standards and sensors
  - Disruptive SI dissemination
  - Quantum-based metrology
  - Commercialization
- For international metrology
  - Traceability
  - Mutual recognition
  - Accreditation (think 17025)
- For NMIs in the “distant” future
  - What is the future of calibrations?
  - Will we still be necessary for traceability?
- For NIST
  - New metrology frontiers
  - Quantum-based SI everywhere
  - Expertise is still essential
  - Solve really hard problems
  - Training

Open Metrology – Key NMI Role

With dissemination of advanced measurement technology directly to the end user, training becomes even more critical

SIM Metrology School

Office of Weights and Measures (OWM) conducts training classes for trainers

National Institute of Standards and Technology

NIST
U.S. Department of Commerce

Enabling the **Next Generation** of **Metrology**

- Embedded Standards
- Ultrastable Lasers
- Optical Clocks
- Advanced Imaging
- Quantum Information
- Nanoscale Measurement
- Redefining the SI

Custom **Measurement Solutions**

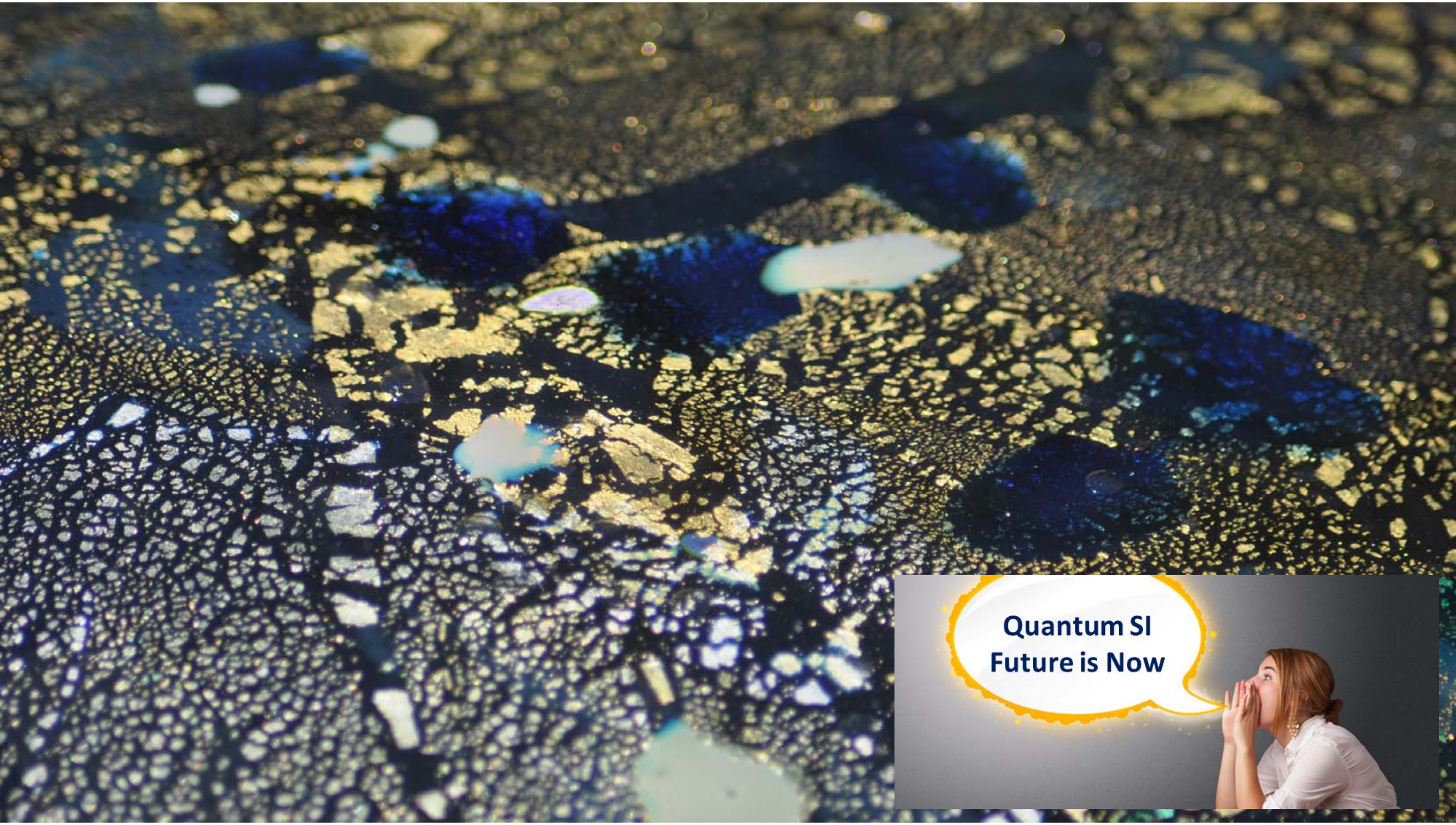
Take advantage of NIST's unparalleled depth of measurement expertise, world-class facilities, and one-of-a-kind instruments.

Our metrologists work directly with companies and organizations of all sizes, and have decades of experience in devising individualized measurement solutions.

Providing **Measurement Services**

- Calibrations
- Standard Reference Materials
- Standard Reference Data
- Standard Reference Instrumentation
- Training

PML


Quantum SI
Future is Now

National Institute of
Standards and Technology
U.S. Department of Commerce