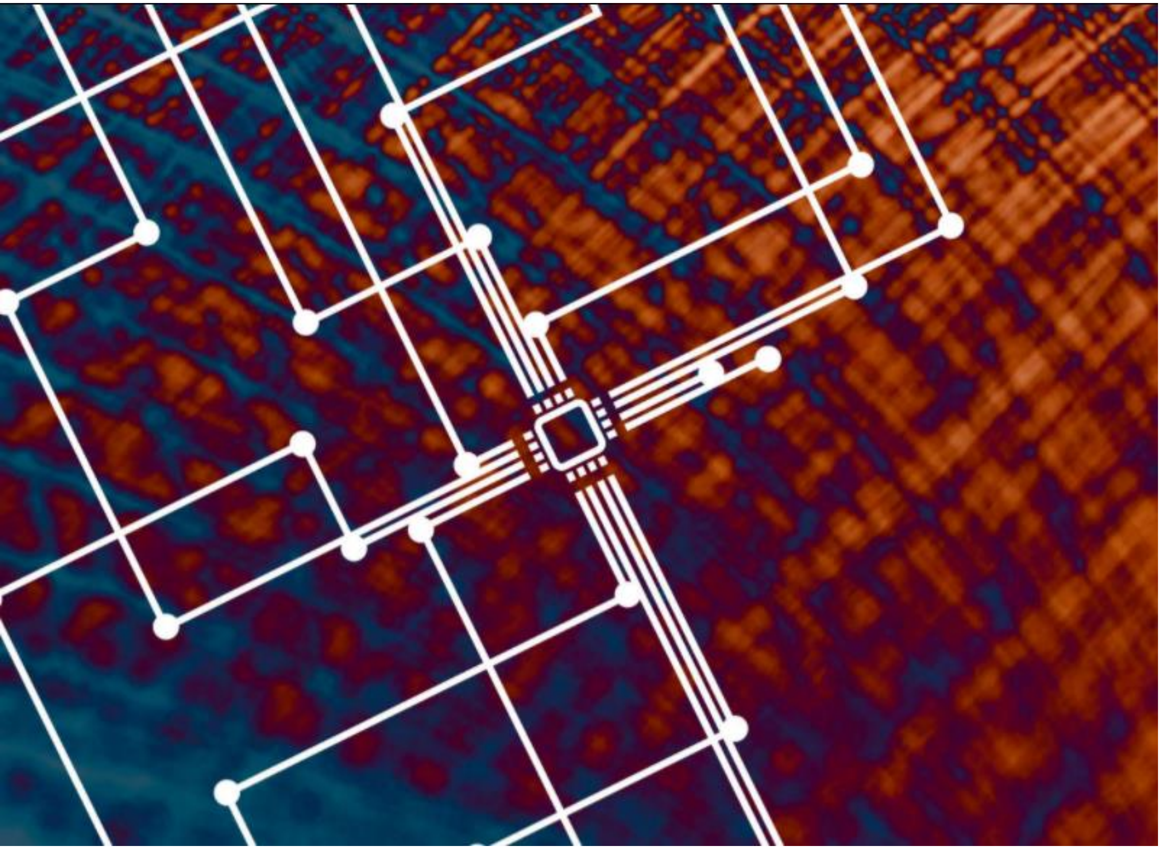

Quantum-based standards and trends in dissemination

NMI Directors Meeting

October 2021

https://www.nist.gov/noac

Barbara Goldstein
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Program Manager, NIST on a Chip
bgoldstein@nist.gov

This talk

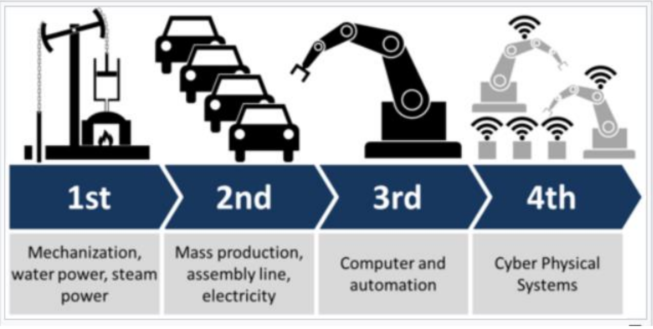
Global trends that are reshaping metrology

NIST on a Chip – a new vision for dissemination

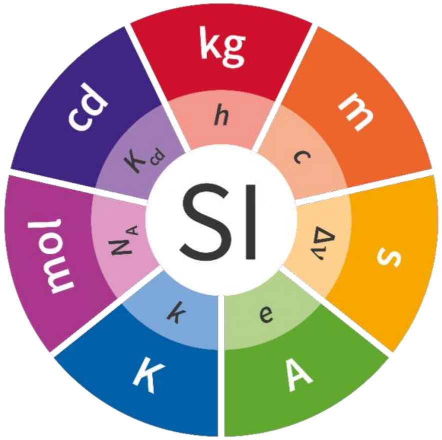
IMEKO TC25 – Quantum Measurement & Quantum Information

- Report out from Sept 1: “Growing the Quantum Economy through Metrology, Workforce, and Supply Chain Development”

Global trends are reshaping metrology

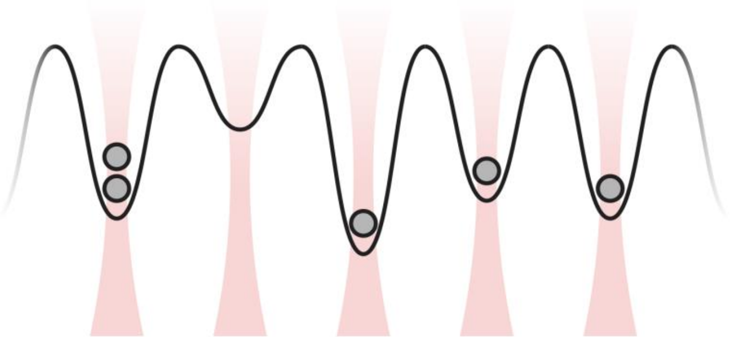


Industry 4.0 & Digitalization



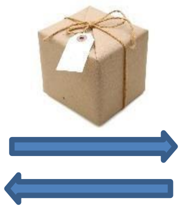
The redefinition of the SI

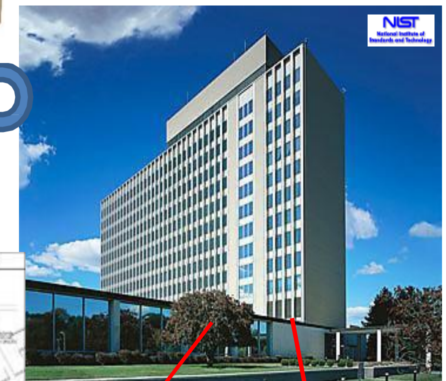
Miniaturization & Integrated Photonics

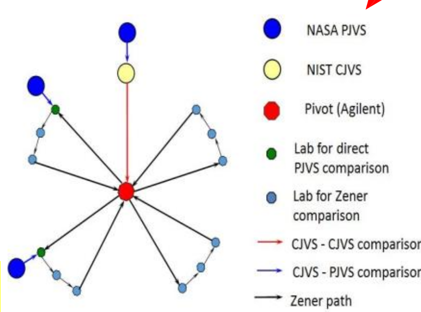


Quantum 2.0

Industry 4.0 & Digitalization





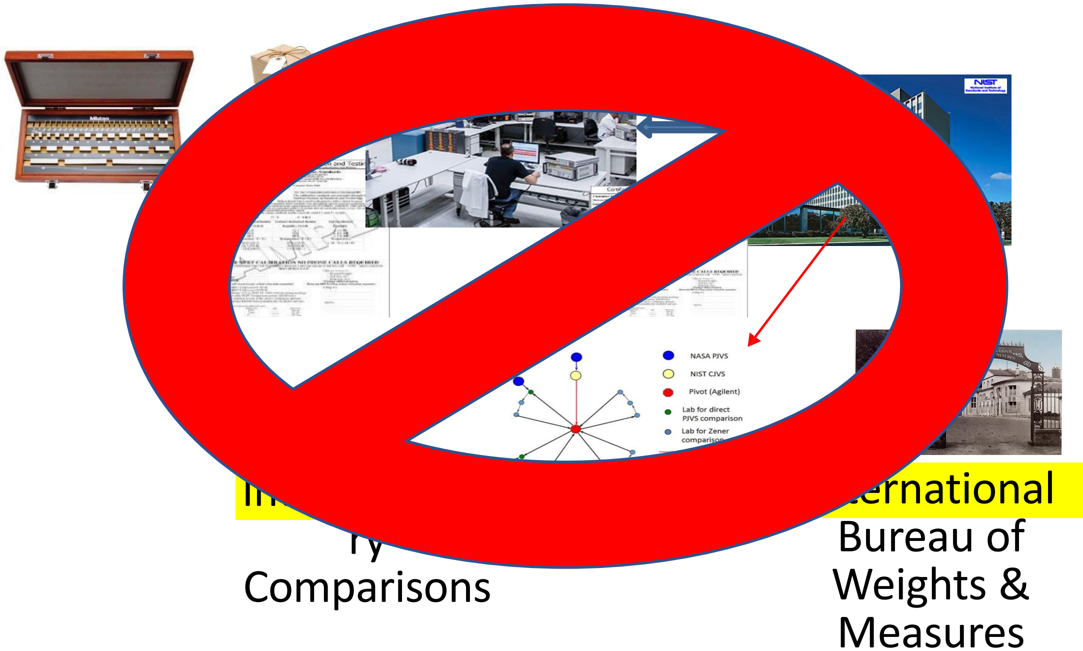


Interlaboratory Comparisons

International Bureau of Weights & Measures

Industry 4.0 & Digitalization

Industry 4.0 & Digitalization

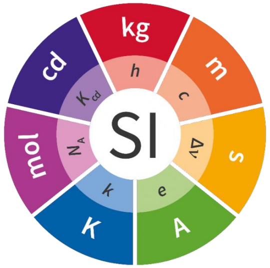


The traditional calibration chain doesn't meet Industry 4.0 needs!

- Machine-to-Machine decisions require reliable – traceable – sensors
- Users need in-situ, embedded measurements
- Remote operations need "zero chain" traceability for measurements
- Assurance will rely on automated digital handshakes

The SI redefinition untethers metrology

THE NEW SI IS BASED ON DEFINITIONS, NOT A PARTICULAR METHOD OR ARTIFACT



Base quantity	Base unit
Time	second
Length	meter
Mass	kilogram
Electric current	ampere
Thermodynamic temperature	kelvin
Amount of substance	mole
Luminous intensity	candela

Base quantity	Defining constant
Frequency	$\Delta\nu(^{133}\mathrm{Cs})_{\mathrm{hfs}}$
Velocity	c
Action	h
Electric charge	e
Heat capacity	k
Amount of substance	N_A
Luminous intensity	K_{cd}

THE NEW SI PROVIDES FLEXIBILITY

A primary realization of mass can use:

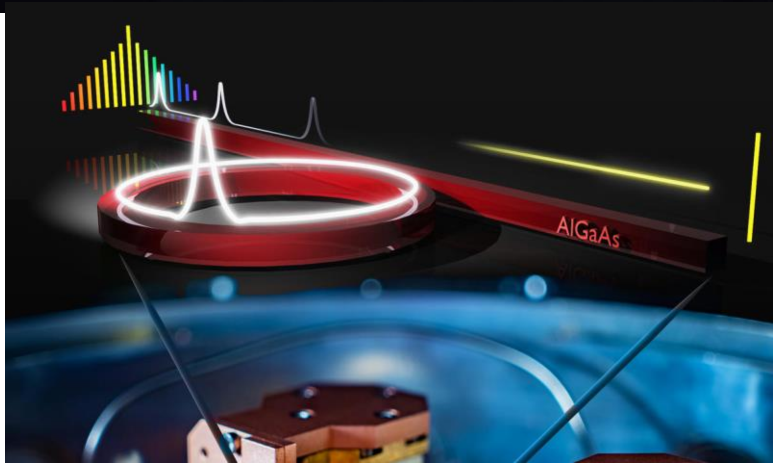
- the electromagnet in the Kibble balance
- the capacitor in the Electrostatic Force Balance
- laser power reflecting from a mirror

As long as it shows a direct link to Planck's constant, it can be considered a primary realization.

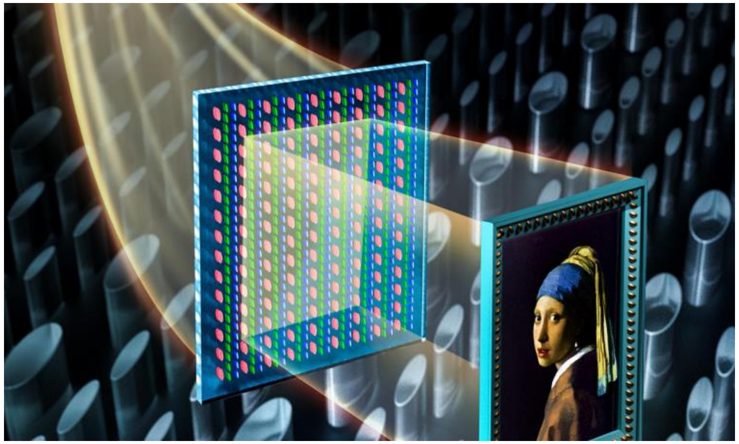
Miniaturization and Integrated Photonics

More tools in our toolbox :

- Wealth of knowledge and fabrication infrastructure from the semiconductor industry
- Integrated photonics
    - More capabilities on-chip – More than Moore
    - Enabling for quantum devices
    - New materials systems – a blessing & a curse
- Merging of materials & devices
    - Sometimes the material ***is*** the device



NIST Comb on a Chip / integrated nano-optics for optical clocks & quantum photonics



Meta-optics for arbitrary control of light

The quantum revolutions – are revolutionizing metrology

NIST

Quantum 1.0

- Exploit the quantum mechanical properties of materials as found in nature
  - Eg: transistors exploit band structure properties of materials

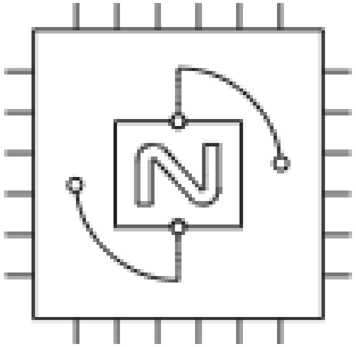
Quantum 2.0

- Engineer new materials that exhibit the quantum properties we want
- Control nature at the single particle level
  - Eg: use entanglement to beat the noise limits of independent atoms, to create more accurate clocks

The quantum advantage:

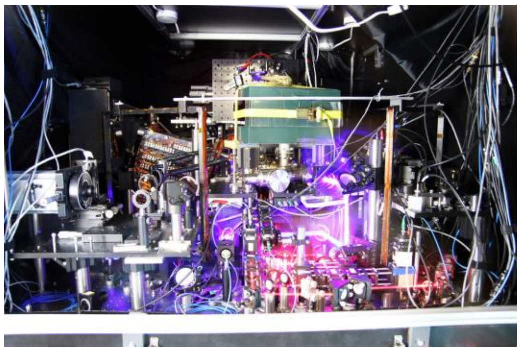
- Intrinsically accurate
- Lower noise limits for measurements and sensing

Introducing NIST on a Chip



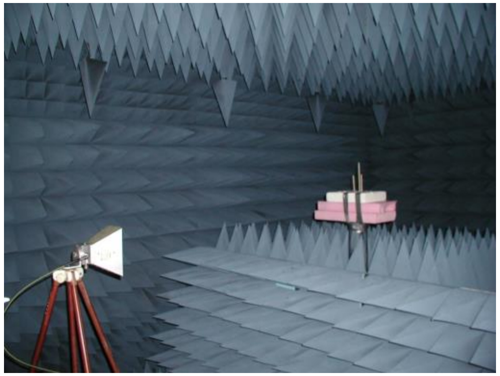
NIST on a Chip – the vision

To shrink measurement equipment like this…



NIST Strontium atomic clock

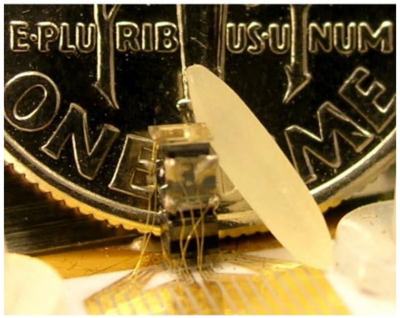
100 kW laser calorimeter
(ca. 2012)



Horn antenna in an
anechoic chamber

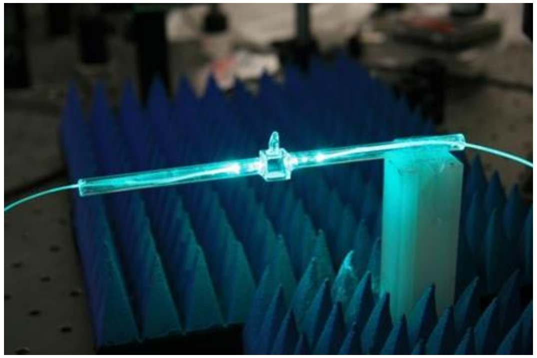
NIST on a Chip – the vision

To devices like this…

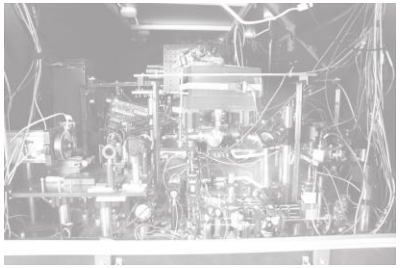


Chip-scale atomic clock

Optical power meter



Atoms as sensors



NIST Strontium atomic clock

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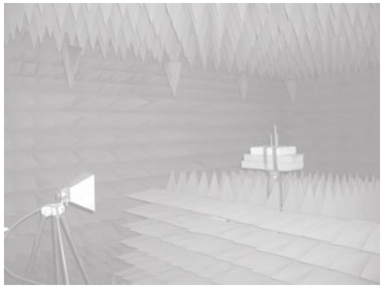
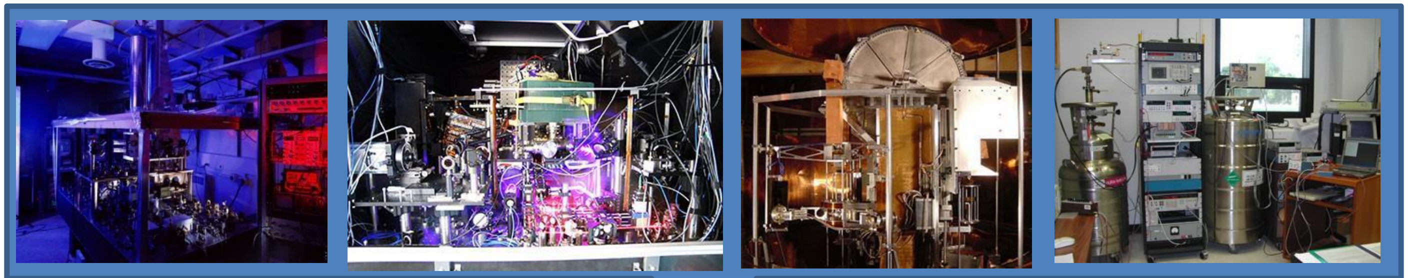
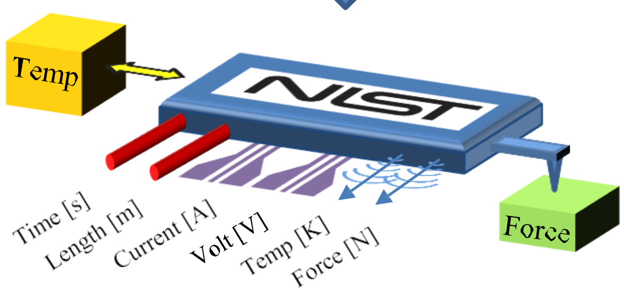


Horn antenna in an anechoic chamber

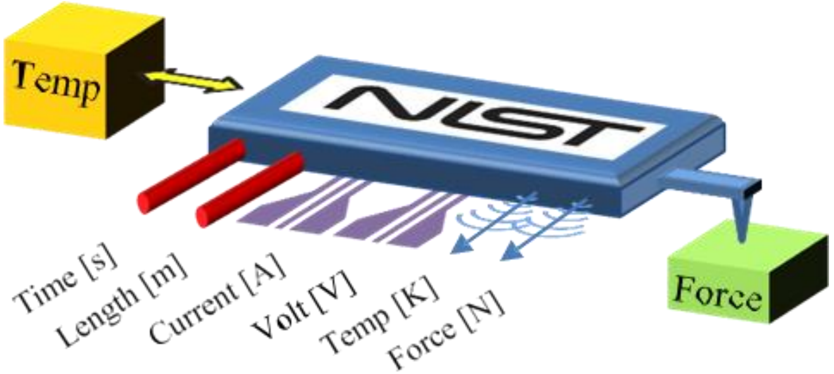
NIST on a Chip – the vision





Measurement standards in chip-scale format

Measurement standards in chip-scale format



- **Embedded** directly in equipment, deploy where needed
- Flexible, useful, **manufacturable**, deployable
- **Break the calibration chain**
    - Never need to be returned to NIST for calibration
- Give the **right answer or no answer** at all
- Based on fundamental (**quantum**) properties of nature

Technology readiness

NIST

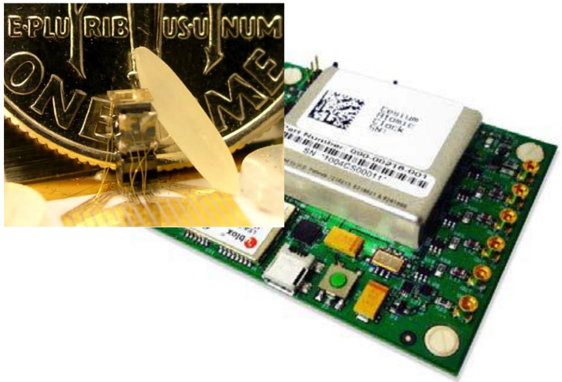
Basic Research | Feasibility Research | Prototype Development | Mature Technology

- Magnetic & Electrical Fields
- Quantum Optics & Radiometry
- Thermodynamics
- Fluid Measurement & Control
- Biochemical Sensing
- Radiation
- Mass & Force
- Dimensional Metrology
- Time & Frequency
- Vacuum
- Current, Voltage & Resistance

Chip-scale Atomic Magnetometers
SI-traceable E-field Metrology
Photonic Power Metrology
Microresonator Comb Technology
Electrical Substitution Bolometer
Quantum Light Sources & Circuits
Switches for Waveform Metrology
Photonic Thermometry
Microfluidics
Photonic Dosimetry
Emergency Response Dosimetry
Optomechanical Sensors
Cavity Optomechanics
Chip-scale Wavelength References
Integrated Cold-Atom Clocks & Sensors
Cold-atom Vacuum Standard
Silicon Quantum Ampere
Josephson Voltage Standard

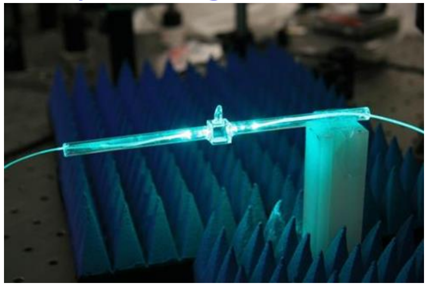
NIST on a Chip – example devices

Chip-scale Atomic Clock, Wavelength References



E-Field Sensing

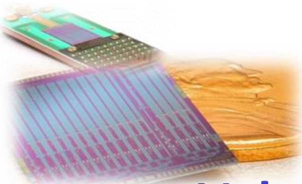
(Rydberg Atoms)



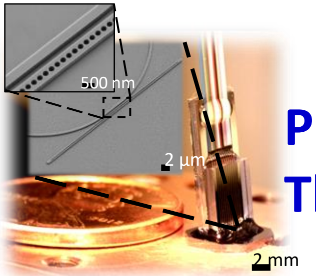
Laser Power

Resistance

Graphene QHR



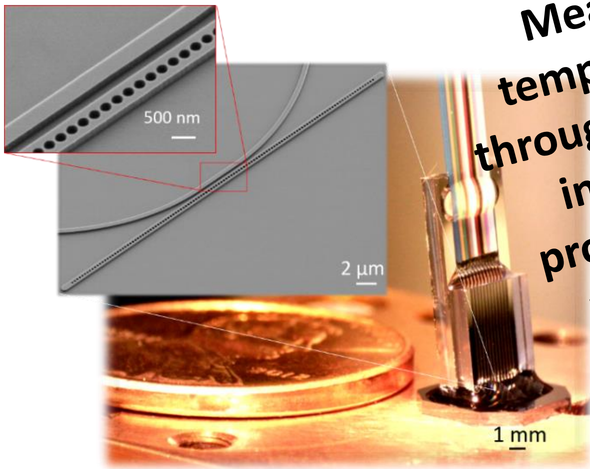
Voltage



Photonic Thermometer

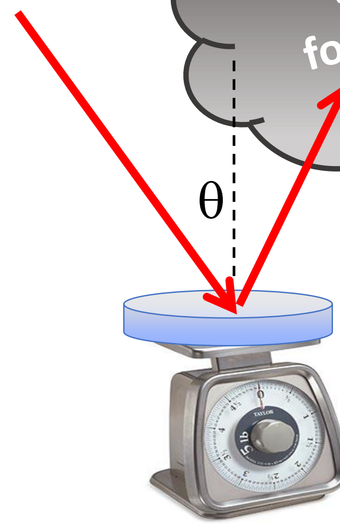
We don’t just make things smaller…

…we measure things in completely new ways

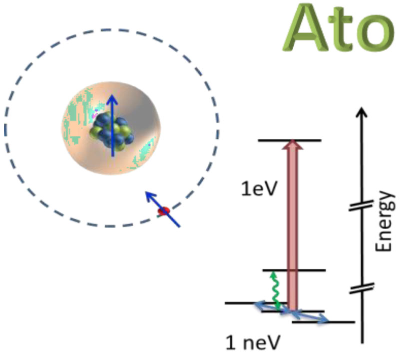


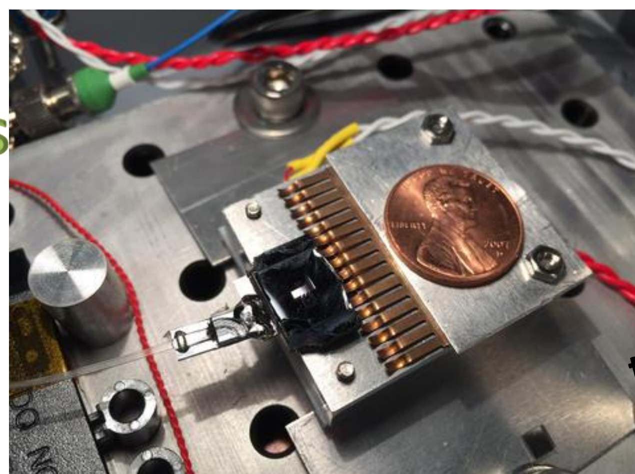
Measure temperature through changes in optical properties of materials

Measure power via the slight force light exerts on matter



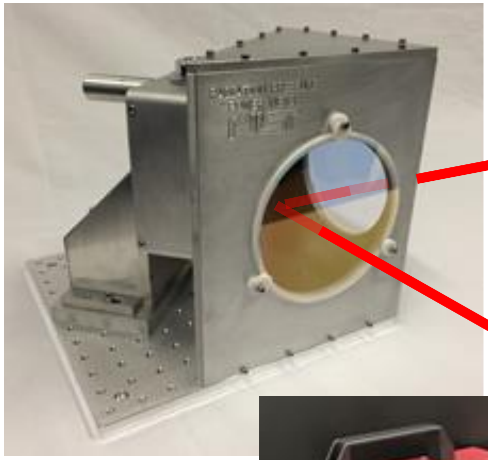
Atoms





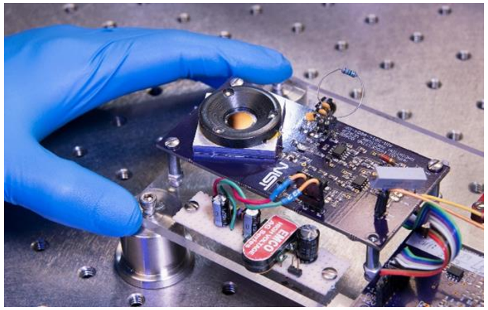
Measure distance using the frequency of atomic transitions

NOAC meets high energy laser metrology



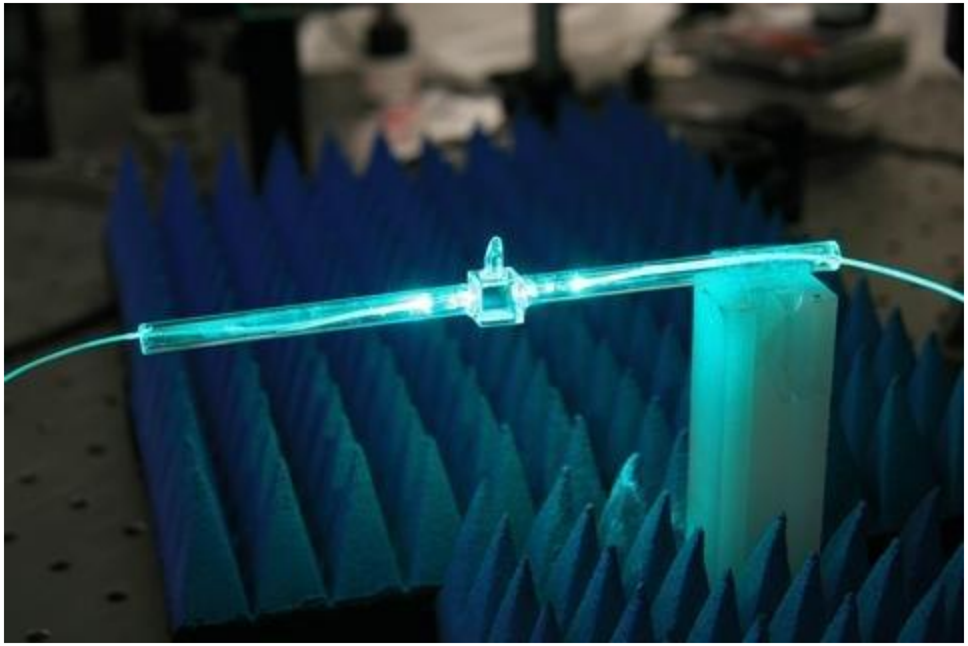
Radiation pressure power meter "RPPM"
Purpose: Free-space laser beams (up to 10 cm beam dia.)
Wavelength: 1070 nm – any wavelength with good mirrors
Power: 1 kW – above 100 kW
50 kW fully tested, 92 kW proof of principle, 200 kW planned
Uncertainty: 1.7 % (k=2)

"Beam Box"
Purpose: User-friendly operation (beams up to 7 cm dia.)
Wavelength: 1070 nm – any wavelength with good mirrors
Power: 1 kW – above 20 kW
Uncertainty: ~ 2 % (k=2)



"Smart Mirror"
Purpose: Embeddable, in-situ power meter for applications in welding or additive manufacturing

Applications of Rydberg atom sensors



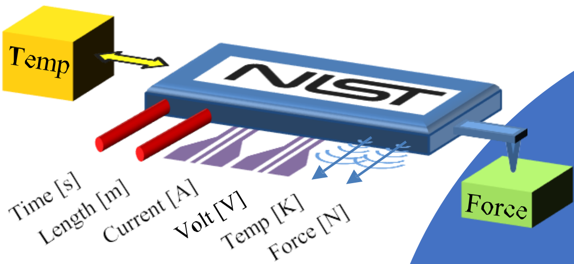
Fully characterize the RF electric field in one compact, room temperature vapor cell:

- Magnitude
- Phase
- Polarization

- High-power in-situ laser measurements
- Detecting the direction of incoming energy (angle of arrival)
- Atom-based receivers for phase-modulated signals
- RF imaging
- Voltage and current references

Power measurements and calibrations from 1 mW to 1MW, from UV to RF, with one traceability chain

NIST on a Chip – what it will take technically



Integration Platforms

- Modular platform
- Sensor networks
- …

Enabling technology

- On-chip lasers
- Microcombs
- Photonic readout
- Packaging
- …

Core sensors

- Time & freq
- Mag & e-field
- Temp, pressure
- Electrical
- Mass, force, acceleration
- …

NIST on a Chip – what it will take culturally?

NIST

Success requires commercial partners

- Taking a measurement innovation to a commercial product is expensive!
- Commercial entities will be ambassadors for NMIs
- What continuing role will NMIs provide for traceability in the wild?

Adoption by the international metrology community

- How do we trust each other’s measurements when they’re embedded in products produced by commercial partners?

NIST on a Chip – what it will take culturally?

NIST

Success requires commercial partners

- Taking a measurement innovation to a commercial product is expensive!
- We'll have trust a commercial entity to carry our NIST brand.
- How do we know it stays traceable in the field?

IMEKO TC25 Quantum Measurement & Quantum Information

Adoption by the international metrology community

- How do we trust each other's measurements when they're embedded in products produced by commercial partners?

IMEKO TC25 – Quantum Measurement & Quantum Information

NIST

Why IMEKO TC25?

- The second quantum revolution is revolutionizing metrology
  - In our labs
  - Through widely-deployed chip-scale sensors
- There are many forums to discuss quantum *technology*, but not many that focus on quantum *metrology*
- And there's a lot to talk about!
  - What does traceability mean – when its not *through* an NMI
  - How do we assure quality?
  - How do we provide mutual recognition?
  - The increasing of role of industry as a partner in dissemination

TC25: Growing the Quantum Economy through Metrology, Workforce, and Supply Chain Development

Panel: The changing role of the National Metrology Institute (NMI) - September 1, 2021

JT Janssen, Chief Scientist and Fellow, National Physical Laboratory (NPL), UK

Ivo Pietro Degiovanni, Chair, EURAMET European Metrology Networks – Quantum Technologies (EMN-Q); INRIM (Italy)

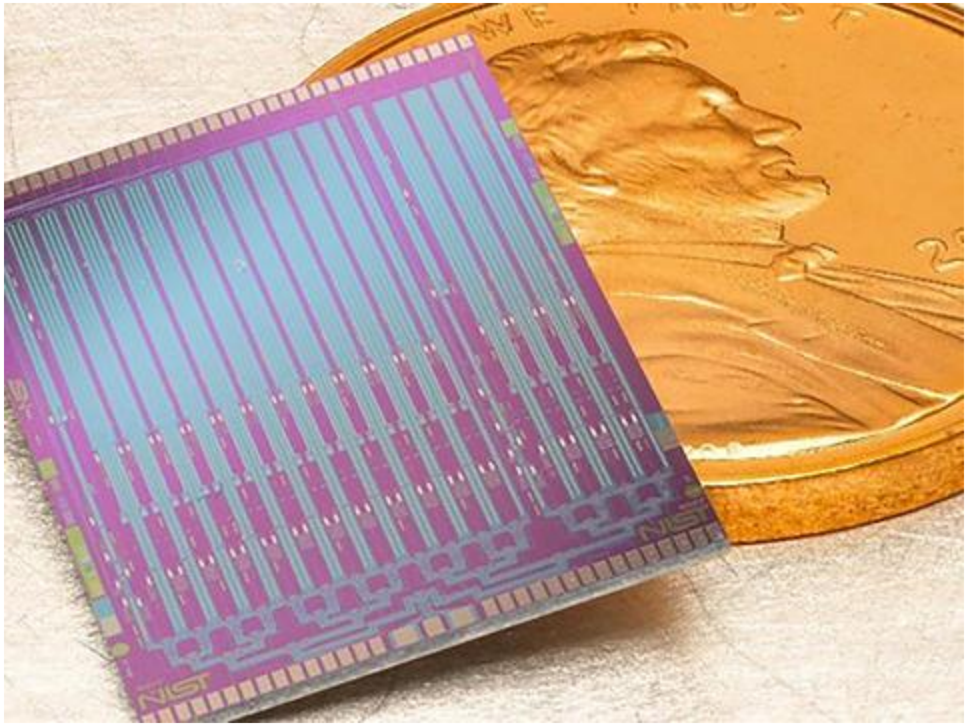
James Olthoff, Associate Director of Laboratory Programs, NIST (US)

Jörn Stenger, Chair, EURAMET Board of Directors; Member of the Presidential Board, MP, PTB (Germany)

Yuning Duan, Vice Director, NIM and member of CIPM (China)

KEY TAKE-AWAYS:

- NMI role hasn't ended with redefinition
- The role of the NMI hasn't changed but is ***expanding***
    - to support the emerging tech
    - to cover measurement beyond traceability
    - more focus on education, less on services
    - To quantify and measure novel quantities like quantum light
- Even quantum standards can give wrong answers
- First to benefit from Quantum will be developing NMIs



A NIST Josephson voltage chip next to a penny.

Thank you for your attention!

https://www.nist.gov/noac

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