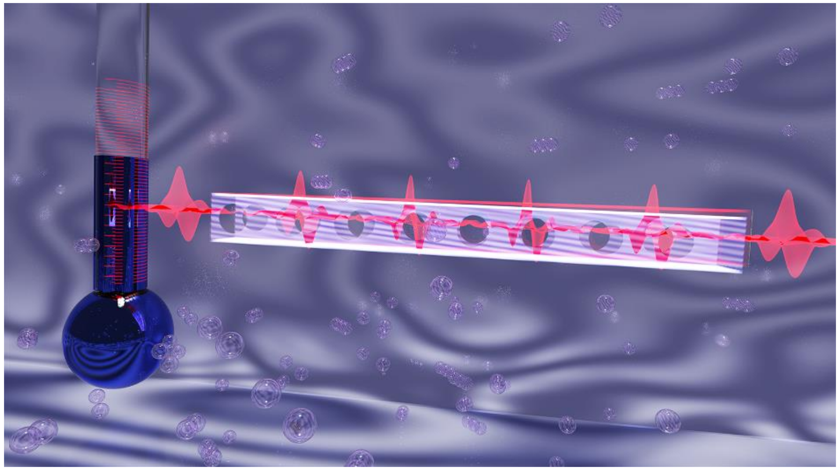
CCT/20-54



Landscape of Emerging Technologies in Thermometry

Presenter: Zeeshan Ahmed

Physical Measurement Laboratory
National Institute of Standards and Technology, USA

Disclaimer

Certain equipment or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available.

Opinions expressed are those of the speaker only

(Temperature)Sensing is Pervasive

Manufacturing

Energy Production

Petro-chemicals and pharmaceuticals

Armed Services

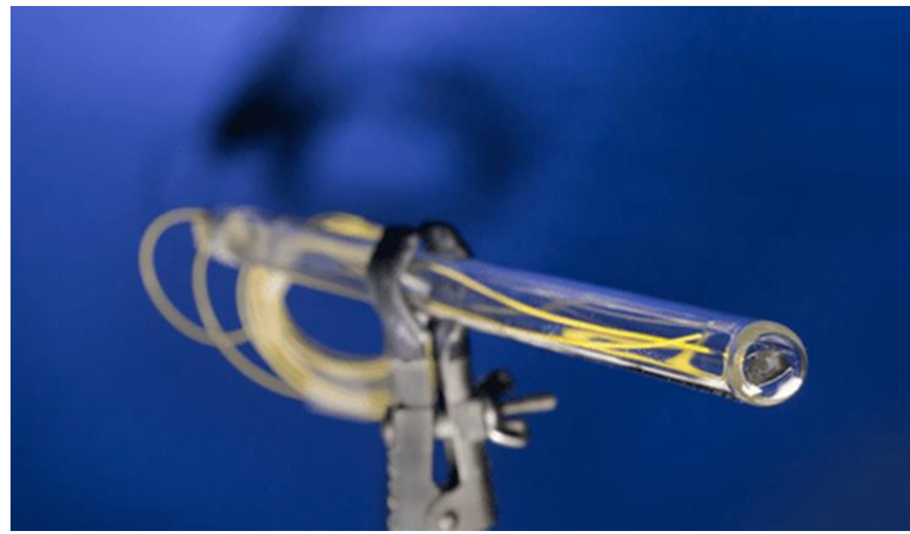
http://www.nbkls.com/the-emergence-of-injection-molding-in-plastic-industry.html
http://www.global-greenhouse-warming.com/biodiesel-from-algae.html

http://www.recallwarning.com/actos-warning.html
http://someinterestingfacts.net/how-big-is-an-aircraft-carrier/

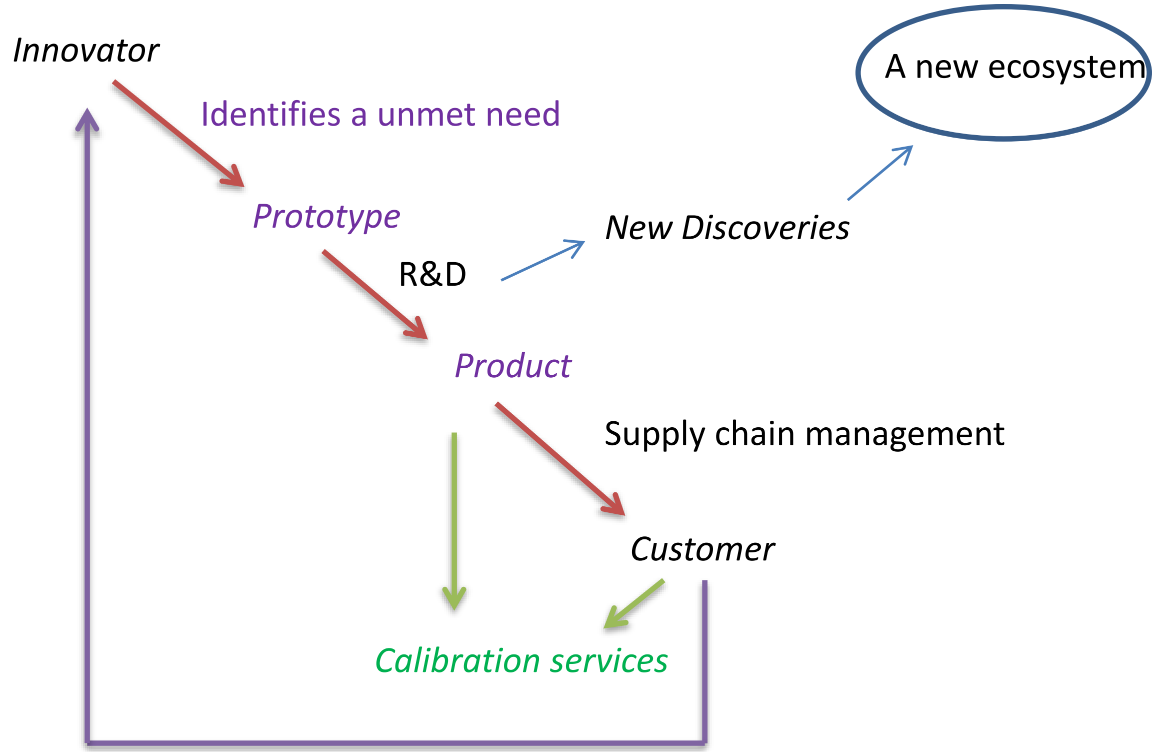
We live in interesting times

From a metrology perspective there are three key technologies that presents challenges and opportunities in the coming years:

- (nano)photonics and Quantum Technologies
- Additive Manufacturing
- AI or deep machine learning



All Roads Lead to Disruption



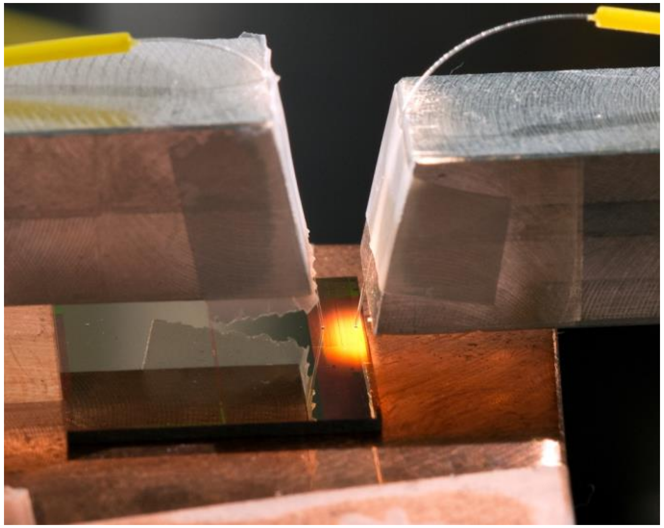
We see three pressure points in in the metrology ecosystem that one could use to bring disruptive change:

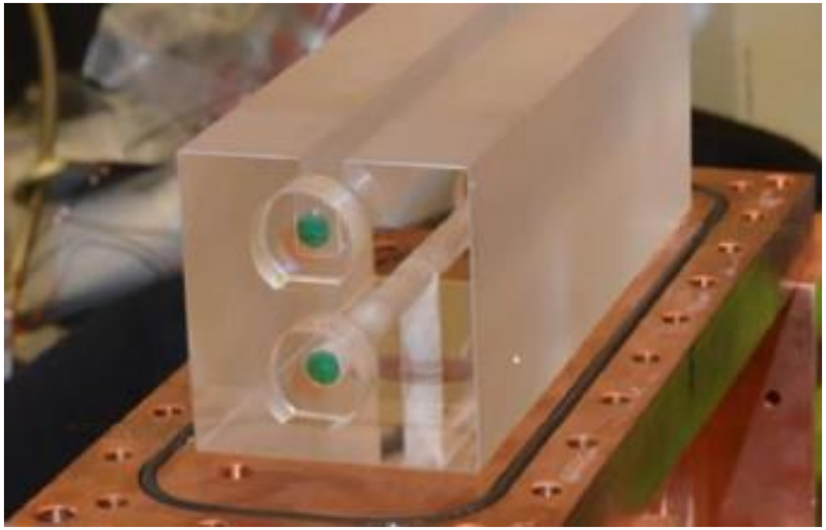
Photonics/Quantum – Transitioning from electrons to photons
(Deep) Machine Learning– Eliminate the "Phd-in-the-loop"
Additive manufacturing – shortening the innovation to consumption gap

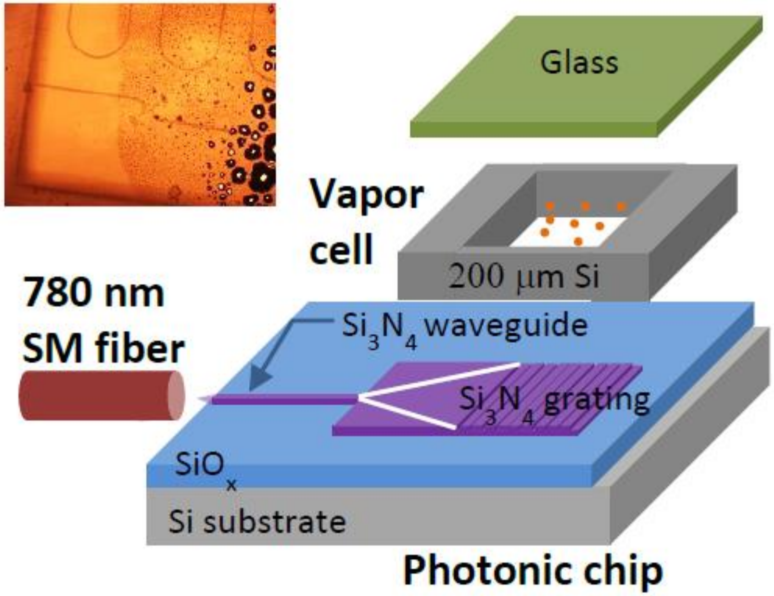
(nano)Photonics

How would you build a photonic thermometer

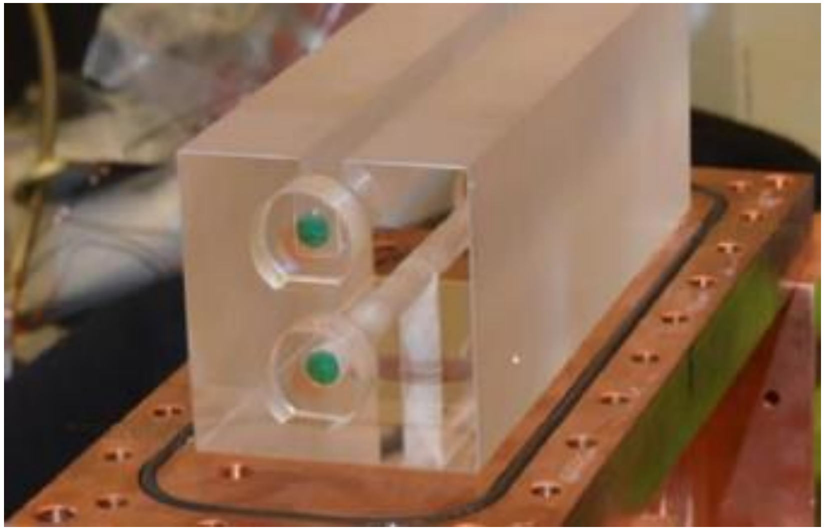
- Gas phase refractivity-based measurements
- Doppler Broadening measurements
- Light scattering-based measurements
- Solid-phase refractivity-based measurements
- Optomechanics-based measurements

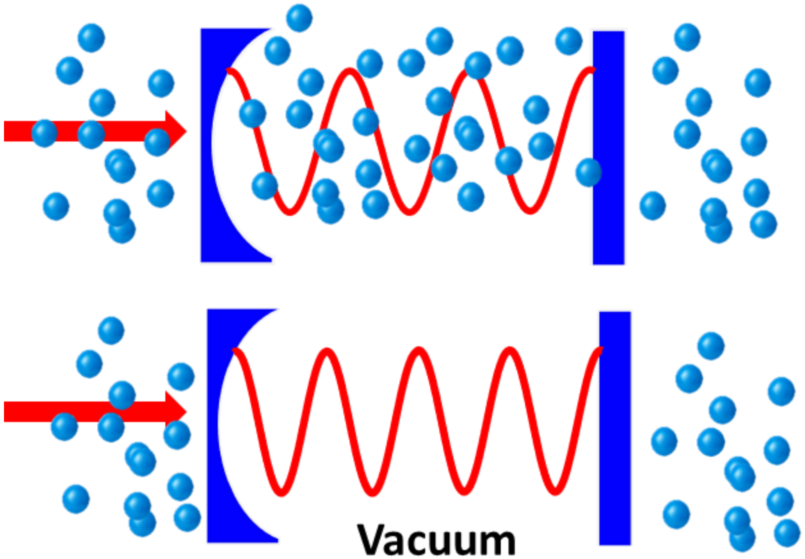






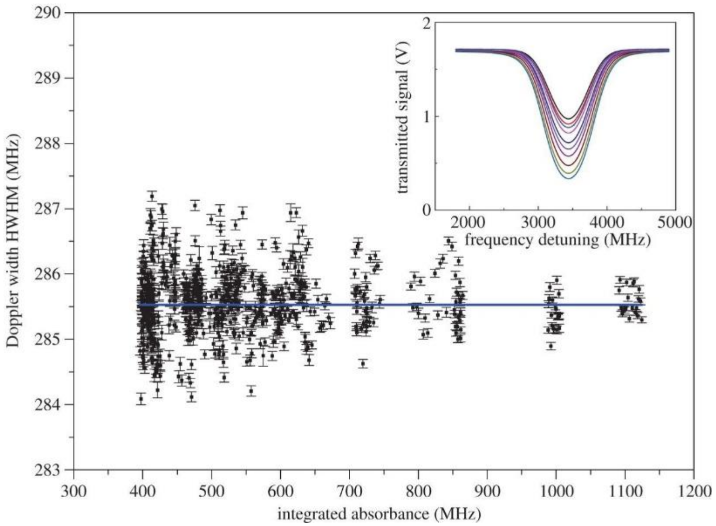
Optical thermometer based on gas refractive index

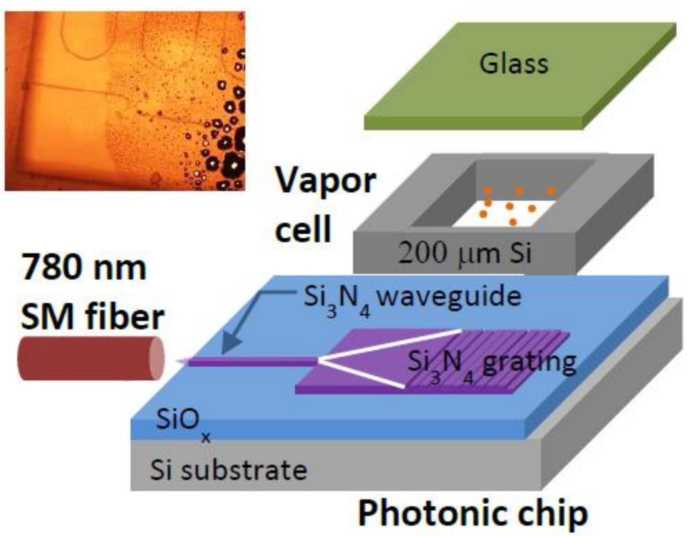




- Cavity enhanced refractometer
- Developed for Pressure metrology
  - Nearing commercialization
  - Relies on telecom COTS techonology
- Expected Uncertainty: 1-10 mK
- Advantages:
  - Thermodynamic Temperature
    - Traceable to frequency and pressure
  - Cross-platform utility
    - Pressure and dimensional metrology
- Disadvantages:
  - Centimeter scale footprint
  - Temperature < 150 °C (mirror coatings)
  - Working gas is susceptible to chemical contamination
- ETA: 3-5 years

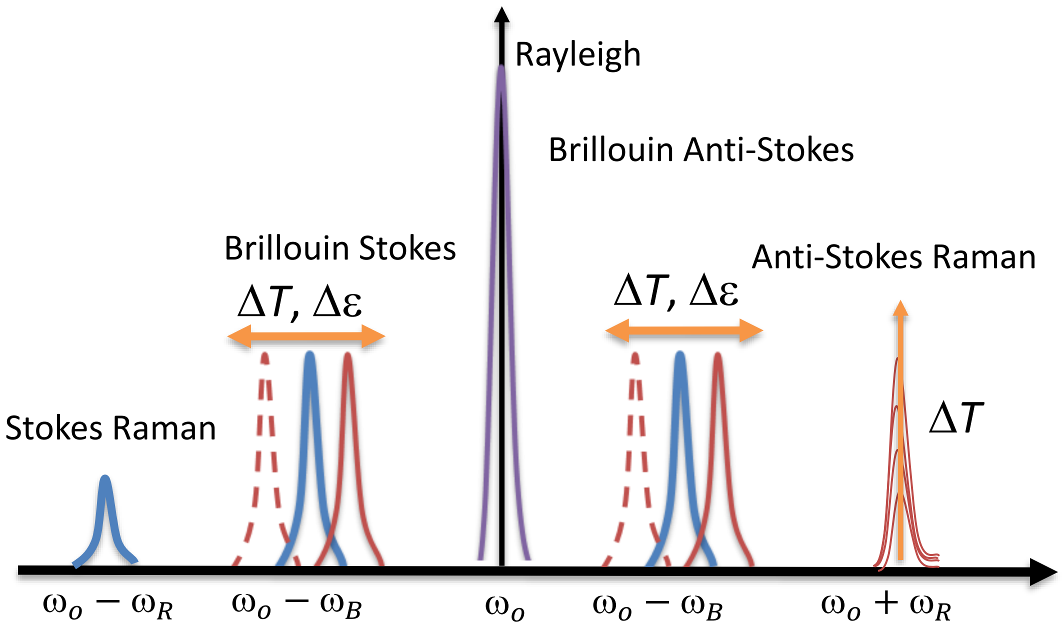
On-Chip Doppler Broadening Thermometer

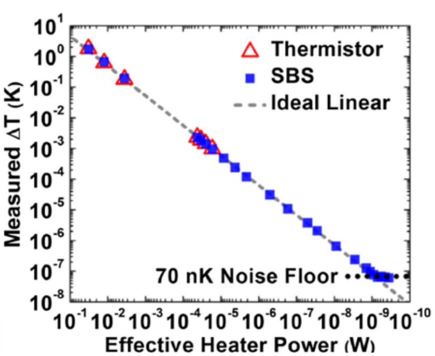


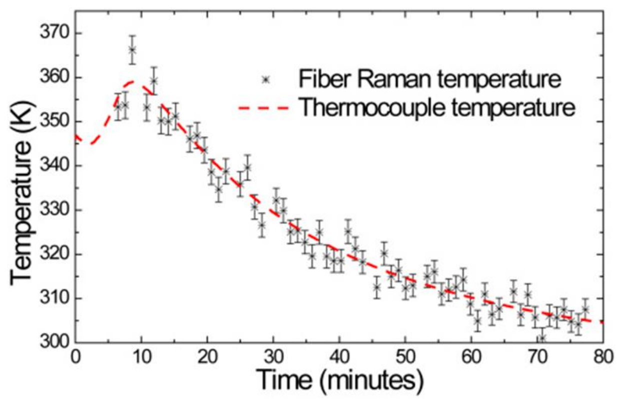


- Molecular spectroscopy-based Quantum SI realization
- Builds on history of free space DBT work
- Expected Uncertainty: 0.1 mK - 100 mK
- Advantages:
  - Thermodynamic Temperature
  - Small chip scale footprint
- Disadvantages:
  - Uncertainties likely to be in the 100 ppm
  - Susceptible to magnetic fields
- ETA: 5 years

Light Scattering Based Thermometry





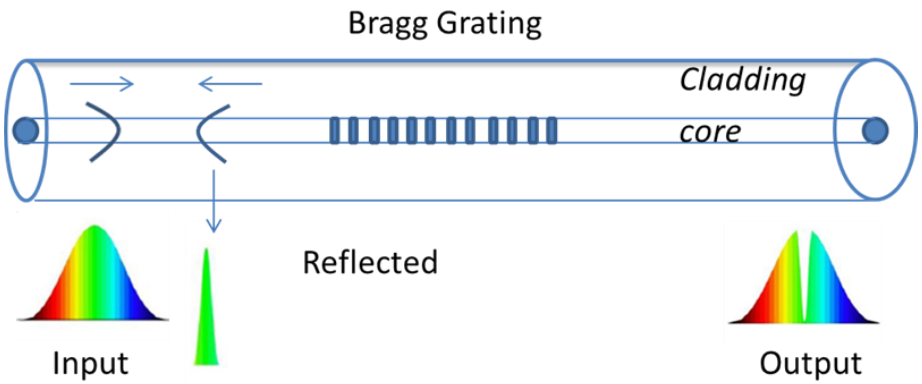


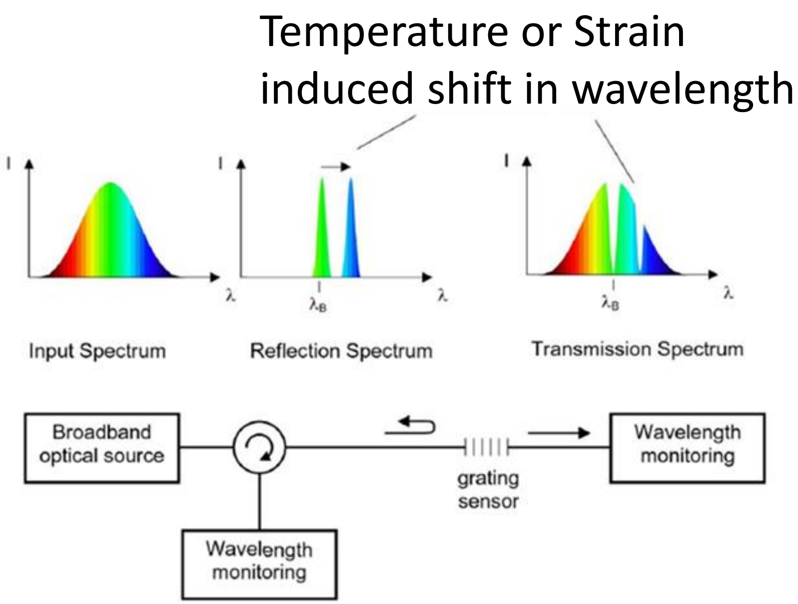
- Spectroscopic measurement
- Developed for Pressure metrology
  - Nearing commercialization
  - Relies on telecom COTS techonology
- Expected Uncertainty: 0.01 K – 10 K
- Advantages:
  - Spatial range covers several orders of magnitude (cm to km)
  - Suitable for static and dynamic measurements
  - Resistant to ionizing radiation and chemical corrosion
  - Thermodynamic Temperature
- Disadvantages:
  - Lower accuracy compared to most common temperature sensors
  - Susceptible to strain
  - Expensive and complex detection system
- ETA: available in some form

arXiv:1810.04781v1

https://doi.org/10.1364/OE.20.003456

Fiber Optic based Thermometry





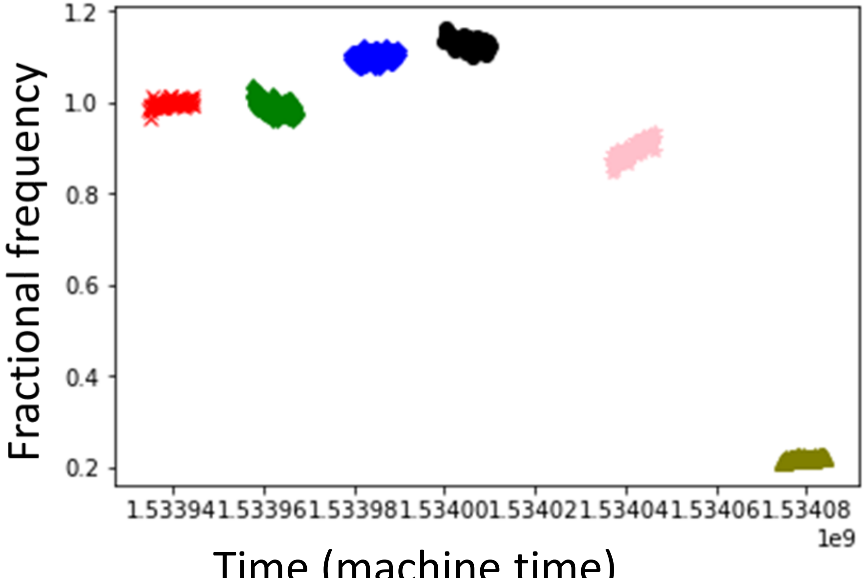
https://doi.org/10.1088/1361-6501/ab7611

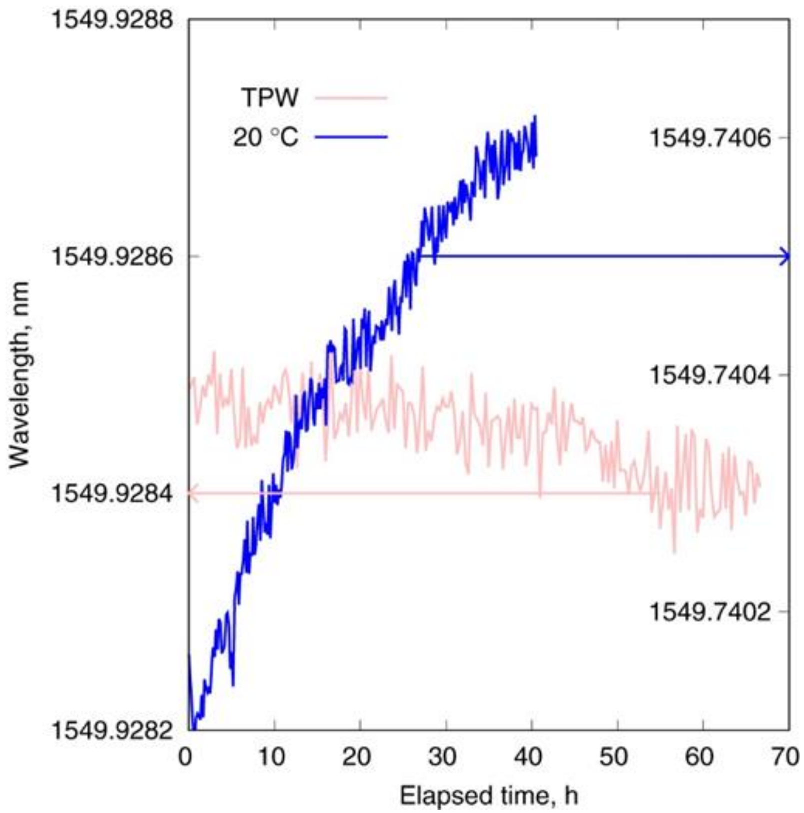
- Refractive index-based temperature transduction to frequency
- Expected Uncertainty: 100 mK – 500 mK
- Advantages:
  - Packaging can be made compatible with existing infrastructure
  - Point source-like temperature sensor
  - Multipoint sensing capability
  - Widely in use in telecom and sensor community
  - Large temperature range (100 K -1500 K)
  - ITS-90 Temperature
- Disadvantages:
  - Thermal hysteresis, long-term drift not well understood
  - Susceptible to ionizing radiation
  - Cross-sensitivity to stress and moisture
  - Large footprint (millimeter scale)
- ETA: on-market

What's holding back fiber thermometry?

Metrology specific understanding of device performance is *lacking*

- What's the uncertainty budget?
  - Over what temperature range?
- What is the *source* of uncertainty?
- Are these devices interchangeable?
- How stable are they?
- What's the measurement repeatability?





https://doi.org/10.1088/1361-6501/ab7611

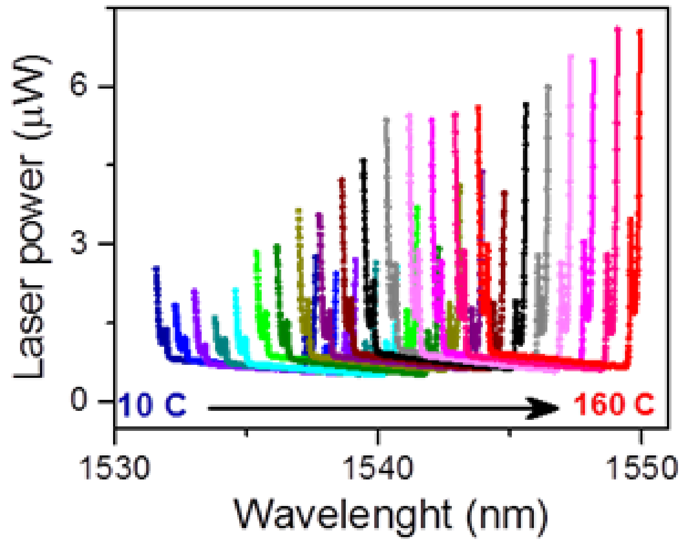
Si Bragg Thermometer shows a quadratic dependence on temperature

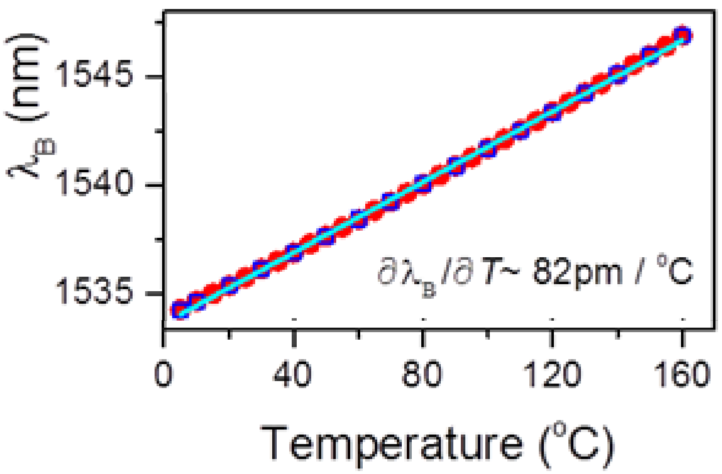
Silicon Bragg thermometer, compared to FBG sensor:

- ≈8x greater temperature sensitivity
- 50X smaller footprint
- impervious to moisture

Uncertainty = 1.25 °C (*k* = 2)

- driven by uncertainty in peak center measurement.

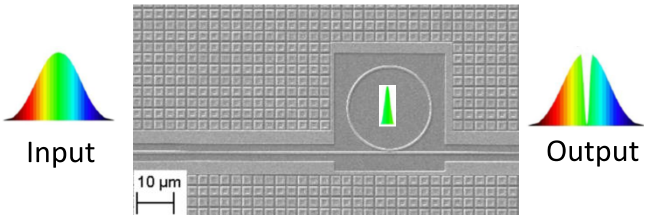




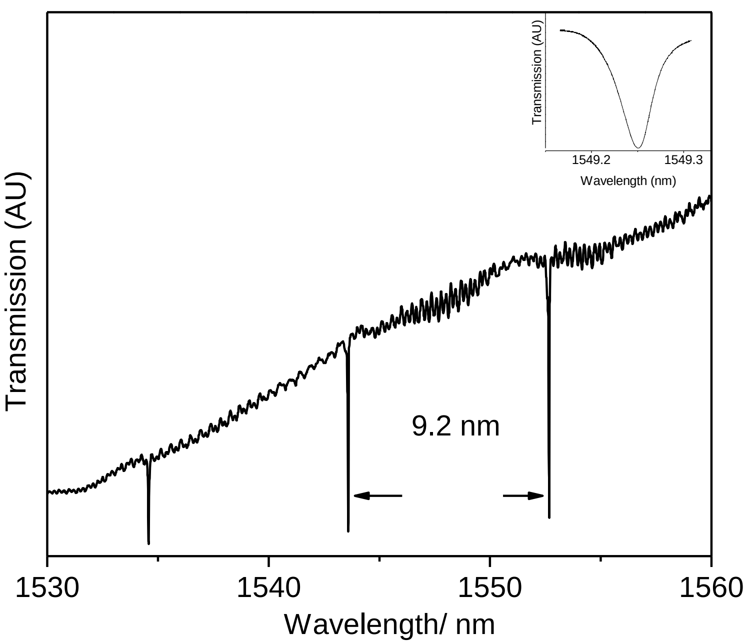
Optics Letters, 2015, vol 40, pg 3934-3936

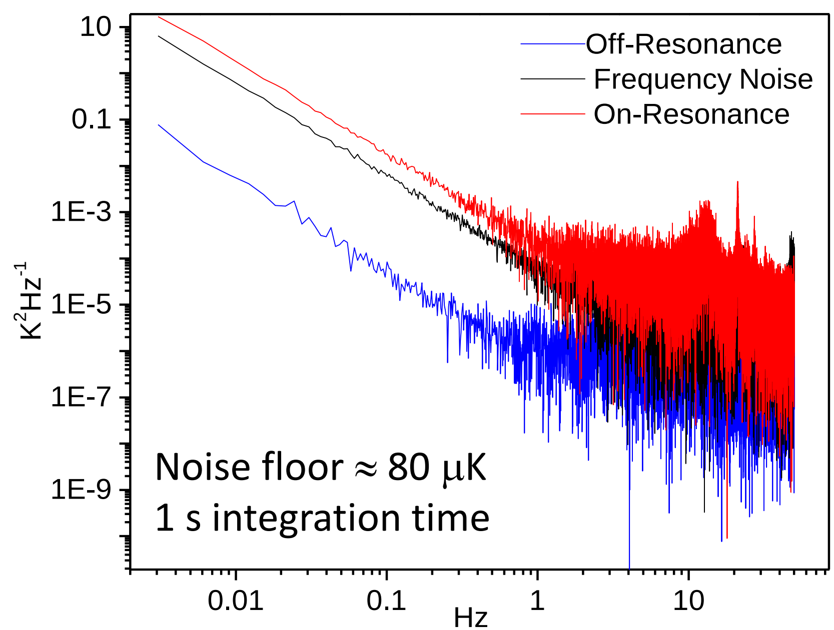
(Ring) Resonator Thermometry

Optical ring resonators exhibit a periodic notch-filter like response where the resonant wavelength shows a temperature-dependent shift in frequency



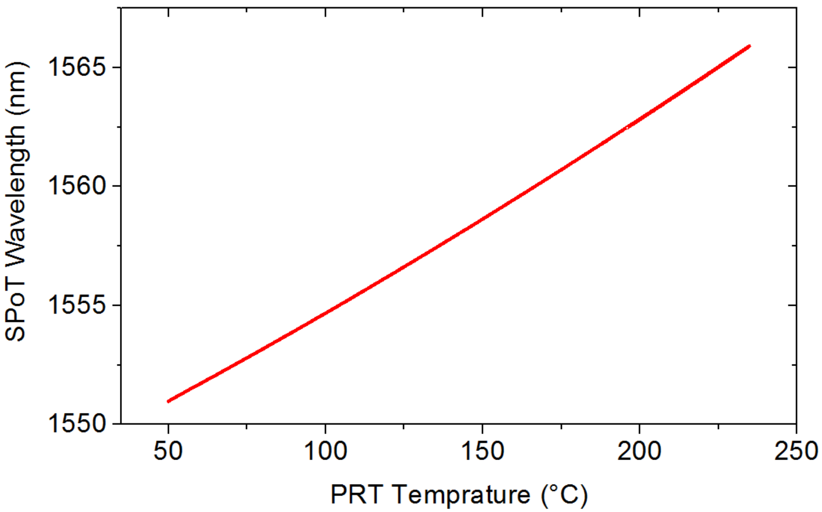
$$\lambda = \left\{ \left[\left(\frac{\partial n}{\partial T} \right) + n \left(\frac{\partial L}{\partial T} \right) \left(\frac{1}{L} \right) \right] \left(\frac{1}{ng} \right) \right\} * (\Delta \mathrm{T} * \lambda_{\mathrm{m}})$$





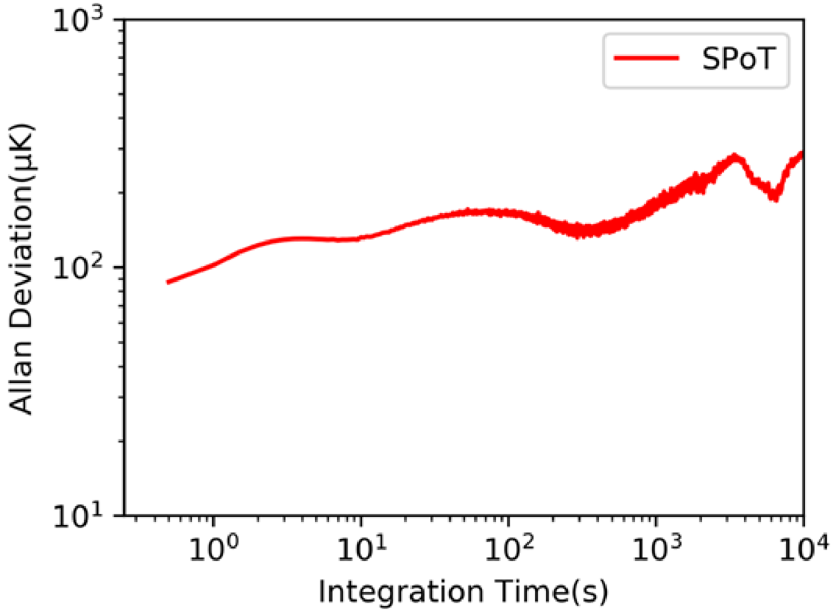
Opt. Express 22, 3098-3104 (2014)

Si Photonic Thermometry Continues to Improve

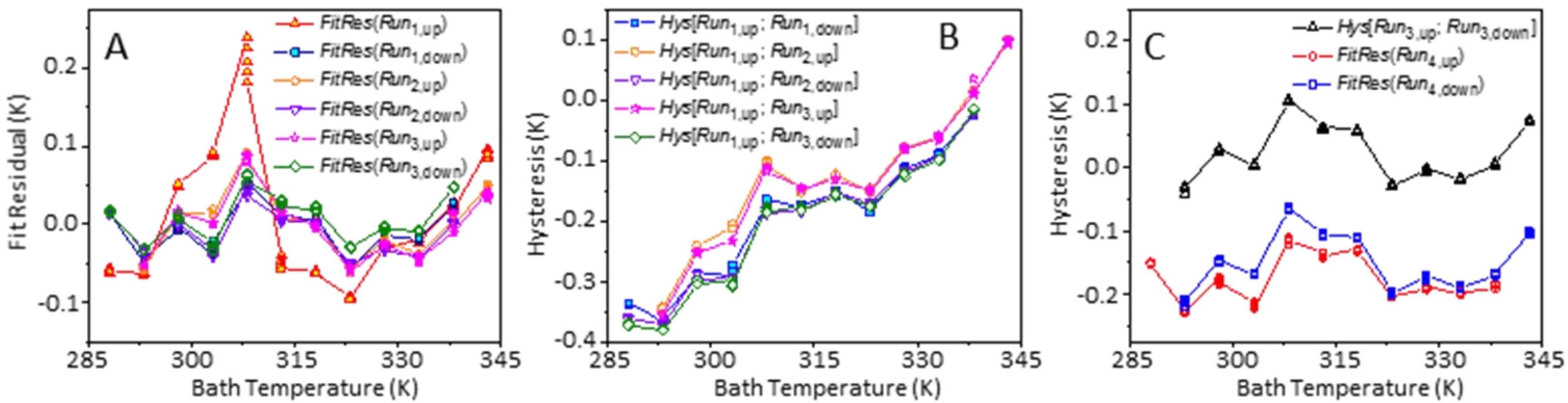


Continuous measurement over extended temperature range from room up to indium melting point temperature have been achieved

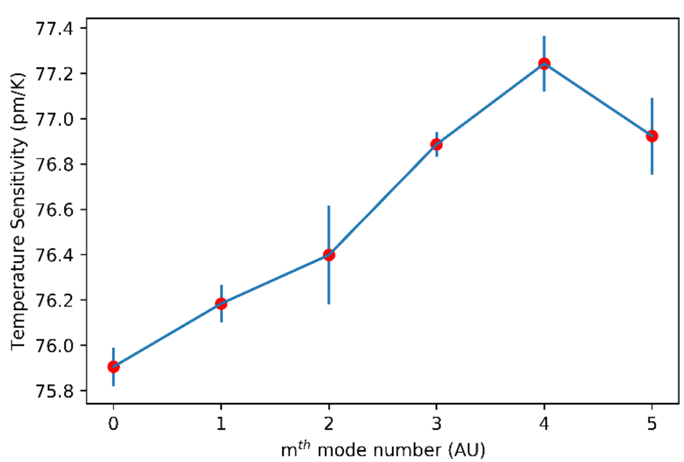
Long-term stability measured in WTP is less than 0.5 mK



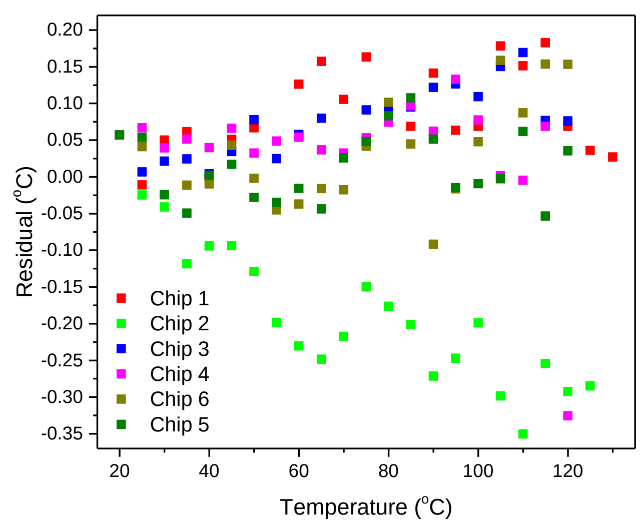
Devil's in the details



Packaging of the device and materials used in it, matter!



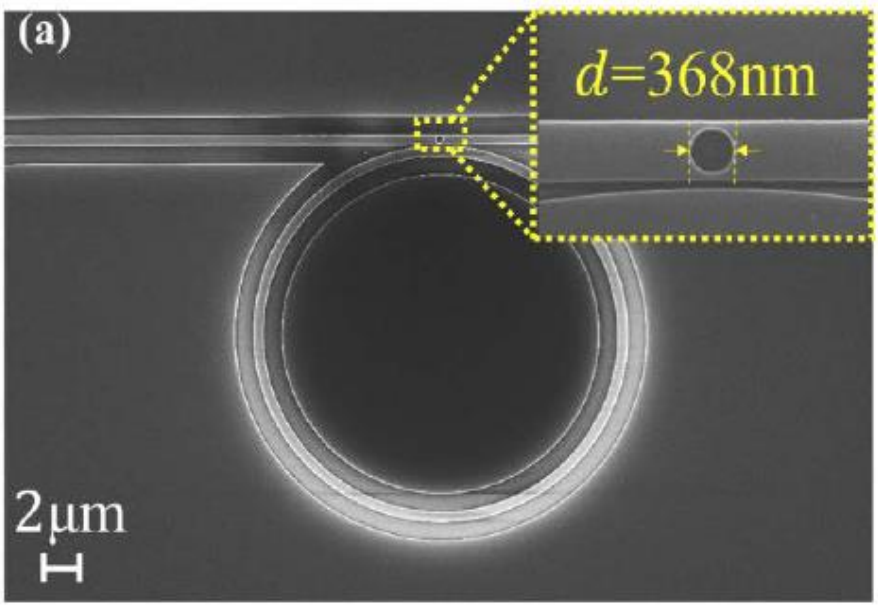
Mode interchangeability

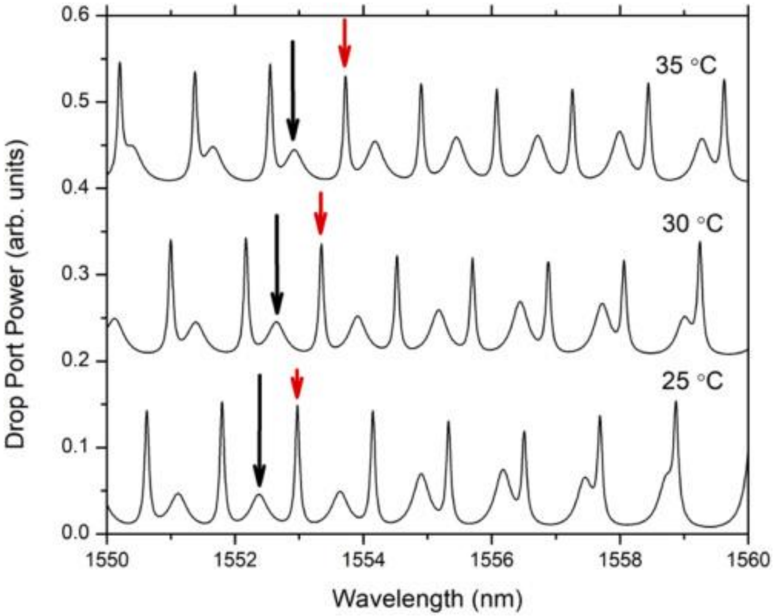


Device interchangeability

We Shall Overcome These Problems:

Because very smart people are taking a hard look at these problems



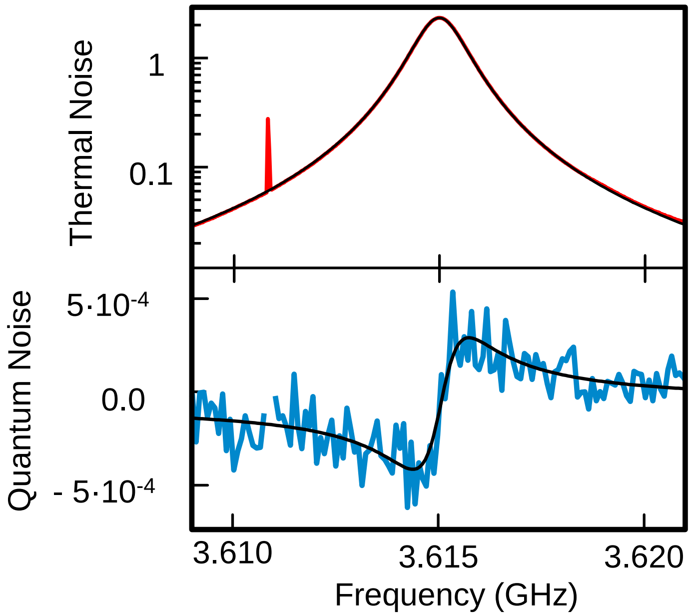


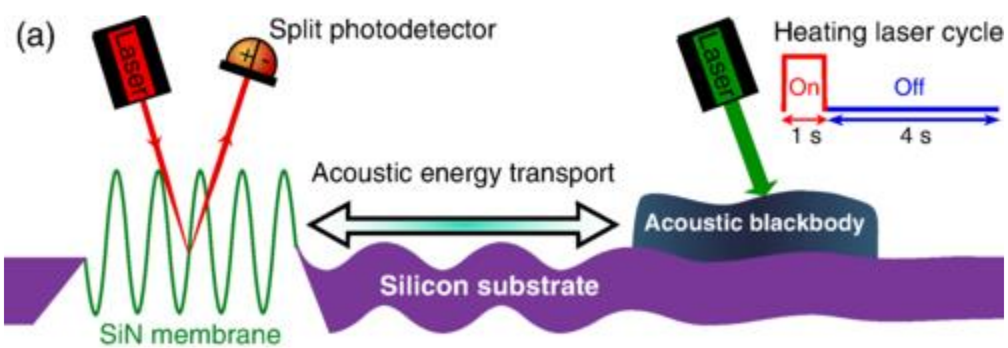
https://doi.org/10.1364/OE.390966

https://doi.org/10.1364/OE.394642

Quantum and Quantum-inspired Technologies

Opto-mechanical Thermometry





T. P. Purdy, K. E. Grutter, K. Srinivasan, J. M. Taylor, arXiv:1605.05664

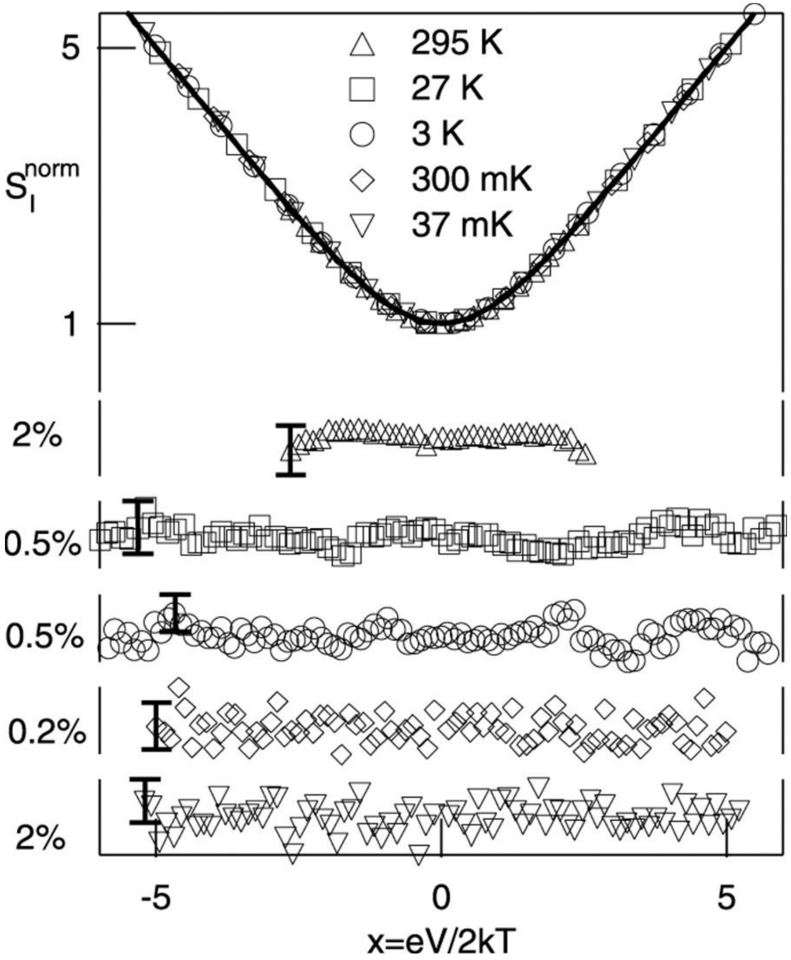
- Quantum realization of temperature
- Expected Uncertainty: 1 K
- Advantages:
  - On-Chip Thermodynamic temperature
  - Integrate-able with on-chip photonic thermometer
  - Easy integration into QIS
  - Unknown, unknowns
- Disadvantages:
  - Early stage of research
  - Current uncertainties on the order of few percent
  - Long-term device performance unknown
  - Unknown unknowns

- Bath engineering, new materials, longer wavelengths could be key to new breakthroughs
- ETA: 5+ years

10.1103/PhysRevLett.125.120603

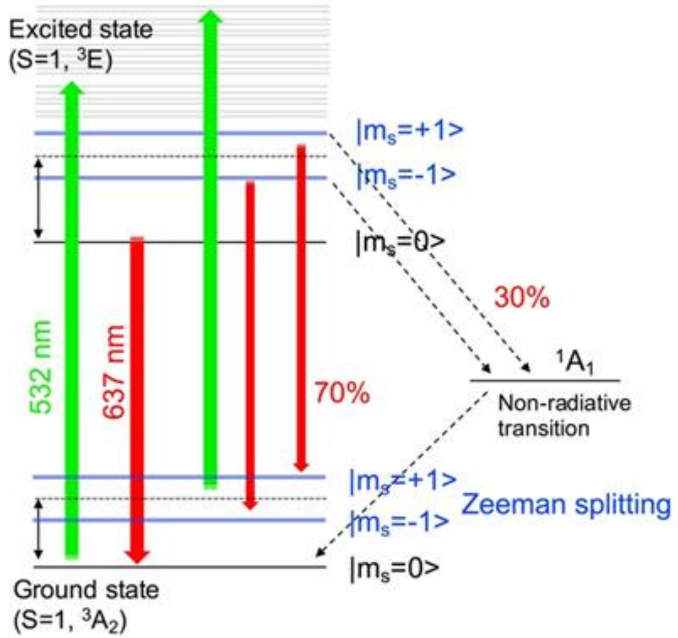
Tunnel Junction shot noise thermometer

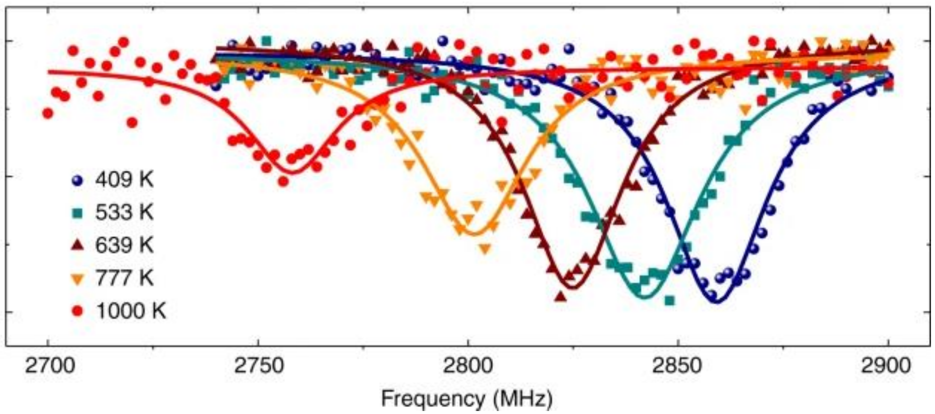
- Primary Thermometer
  - 0.1% accuracy at 1 K
  - Relies on electron charge, Boltzmann's constant, and assumption that electrons in a metal obey Fermi-Dirac statistics
  - Demonstrated range: 10 mK to 300 K



DOI: 10.1126/science.1084647

NV Diamond Thermometry



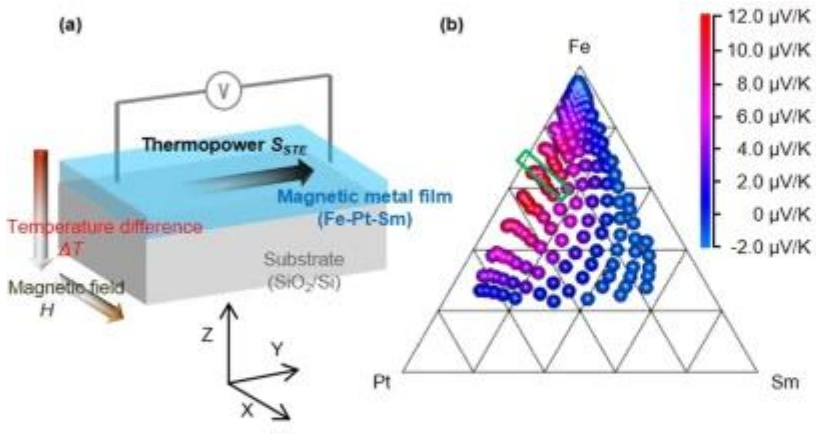


- Spectroscopy based
- Expected Uncertainty: 10 mK – 100 mK
- Advantages:
  - Nanometer spatial resolution
  - Wide temperature range 100 K-973 K
  - COTS components
  - QIS technology
  - Fiber-coupled devices have been demonstrated
- Disadvantages:
  - Relatively high uncertainties
  - Susceptible to environmental variables e.g:
    - Electric and Magnetic fields
    - Humidity
    - Local strain
    - Spin-spin interaction

Scientific Reports ,10, Article # 2483 (2020)
Nature Communications, 10, Article # 1344 (2019)

Machine Learning
(the completely speculative part of the talk)

Machine Learning and thermometry



Scientific Reports volume 9, Article number: 2751 (2019)

Potential areas of impact:

- Discovery of new materials
- Calibration-by-crowd sourcing
- Calibration over network of sensor
- Developing complex, physics-based models for novel sensors

Grand Challenges

How do we bring the rigor of metrology to emerging technologies?

How good are these devices? What are they good for?

What would an interpolation model look like?

Is interchangeability possible with these devices?

What does temperature mean at the nanoscale?

How do we communicate in a cross disciplinary field?

Temperature, frequency, photonics, communication, ML

How do we train the metrology workforce?

The next generation of temperature metrology experts will need to freely move amongst all these different technologies