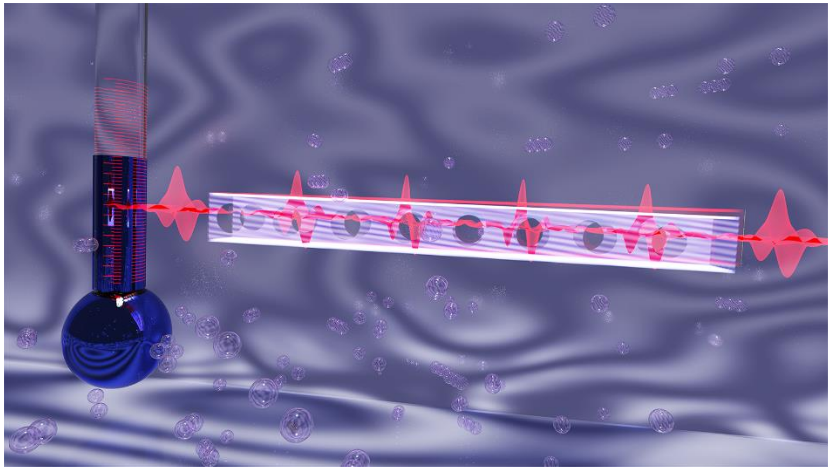
CCT/20-36



Emerging Technologies in Contact Thermometry

Emerging Technologies Task group

Task group's Mission

The task group was formed in 2017

TERMS:

The terms of reference of the CCT TG-CTh-ET are to identify, study and advise the CCT on matters related to the areas of emerging technologies.

TASKS:

- Review the field and report to the CCT on various emergent technologies for contact thermometry devices and measurement techniques
- Review and report on published data from various emergent technologies including a comparative study of the advantages, limitations, materials, and temperature ranges
- Review and report on the potential of some of these emergent technologies for primary thermometry

Task group's Membership

- Prof. Stéphan Briaudeau (LNE-Cnam)
- Dr Sergey Dedyulin (NRC)
- Dr Dolores Del Campo (CEM)
- Dr Efrem Kebede Ejigu (NMISA)
- Prof. Vito Fernicola (INRIM)
- Dr Victor Fuksov (VNIIM)
- Dr Martti Heinonen (MIKES)
- Dr Murat Kalemci (UME)
- Ing. Tomas Kopunec (SMU)
- Dr Stephan Krenek (PTB)
- Dr Farzana Masouleh (MSL)
- Dr Yijie Pan (NIM)
- Dr Jifeng Qu (NIM)
- Dr Chiharu Urano (NMIJ/AIST)
- Dr Eric van der Ham (NMIA)
- Dr Li Wang (NMC, A*STAR)
- Prof. Dr Davor Zvizdic (FSB-LPM)

- Dr. Zeeshan Ahmed (chairperson, NIST)

*new members

Emerging Technologies is a Growth Community

- EURAMET launched PhotOQuant, Project Number: 17FUN05. The program aims to develop photonic and optomechanical thermometry, calibration methods and future quantum-based primary thermometry methods
  - There is a new proposal submitted on "Combined photonic and quantum sensors for practical thermometry"

- NRC-Canada and NIM have stood up active research program in photonic thermometry

- MSL is developing a photonic humidity measurement capability

Technology Landscape: Possible Realities

Primary Thermometers:

- Optomechanical Thermometry
- Refractometry based Thermometry
- Spectroscopic Thermometry
- ~~Nanoelectronics based thermometry~~
  ~~(e.g. Coulomb Blockade thermometry, JNT)~~
- ~~Quantum Conductance~~

ITS 90 Traceable Thermometry

- Photonic Thermometry
  - In-Fiber
  - On-Chip

Draft Report

EMERGING TECHNOLOGIES IN THE FIELD OF THERMOMETRY

A PREPRINT

Emerging Technologies Taskgroup Contact Thermometry
Consultative Committee on Thermometry
BIPM

October 23, 2020

1 Summary/Outlook

Over the past few years, optical, photonic and quantum optomechanical based thermometry techniques have garnered considerable attention. Motivations behind the development of these emerging technologies are multi-faceted, ranging from the desire for low cost, *in-situ* temperature sensors for critical infrastructure monitoring applications (fiber optic thermometry), to embedded sensors for quantum computing and quantum information systems (photonic and quantum optomechanical thermometry), to the development of portable thermodynamic temperature sensors (on-chip doppler broadening, optical refraction and quantum optomechanical thermometry). Leveraging the vast economies of scale provided by the telecommunications industry's infrastructure, and metrology expertise developed for frequency metrology, these techniques hold the promise of enabling fit-for-purpose, cost-effective measurement solutions that can meet or out-perform legacy devices. In particular, the development of ultra-stable photonic thermometers that show minimal drift over decadal time spans or thermodynamic temperature sensors based on quantum properties of matter could dramatically disrupt the calibration centered metrology ecosystem.

In this document we have focused on techniques that are currently either not under study within another CCT working group (optical refraction/optical fiber thermometry) or are in the earliest stages of research (photonic thermometry/quantum optomechanical thermometry) but have shown considerable promise and merit further consideration by the community. Briefly, we find that techniques such as optical refraction and on-chip doppler broadening thermometry have shown considerable improvements over the past decade. Optical refraction, developed as a primary pressure metrology technique and could be deployed as a primary thermometer over a limited temperature range of 253 K to 423 K in metrology labs in the next 5 years. The temperature range is entirely limited by the thermal stability of mirror coatings. Similarly, on-chip Doppler Broadening thermometry is continuing to evolve and could provide access to primary thermometry in a range of industrial applications with uncertainties of 100 mK or better. On the other hand, optical fiber thermometry techniques such as light scattering thermometry (Raman and Brilloin thermometry) and fiber Bragg grating thermometry are already commercially available from several vendors. These techniques have found a foothold in civil infrastructure and industrial applications. For example, Brillion fiber thermometry is being used in fire research to measure temperature gradients in concrete structures during a fire while FBGs have been utilized in aircraft engines to get a better temperature profile of engine parts during operation. Despite their commercial appeal, little is known about the metrological performance of these devices including device inter-changeability, long-term thermal stability, uncertainty budget and optimum operating conditions. On-Chip photonic thermometry is potentially a more powerful alternative to both fiber and resistance thermometry. The technique, though still relatively new, has seen significant developments. Over the last decade, researchers have demonstrated that at room temperature whispering gallery mode resonators can be used to measure temperature with noise floor of 30 nK or better. Silicon photonic thermometers have been demonstrated to measure temperature over broad ranges (4 K to 500 K) with temperature resolution of as low as 10 μK at the triple point of water . Preliminary results indicate that measurement repeatability at the triple point of water and triple point of Gallium is comparable to that of a SPRT. It is anticipated that these devices could cover the range from triple point of hydrogen to aluminium freezing point or higher. Currently the packaging of the devices limits the temperature range and their long-term stability.

Lastly, opto-mechanical thermometry, an outgrowth of fundamental research in quantum optomechanics, has shown promise as an on-chip route to realizing thermodynamic temperature. At cryogenic temperatures it already outperforms traditional stalwarts such as Coulomb Blockade Thermometry. Recent developments utilizing correlation analysis have successful extended the range up to 300 K. Improvements in opto-mechanical coupling of the device, minimization of self-heating in the nanophotonic device and other related improvements could improve the measurement uncertainty to the point of making quantum optomechanics competitive with resistance thermometry while provide thermodynamic temperature.

In Table 1 we have summarized the metrology-specific attributes of the emerging technologies. A brief summary of each technique's advantages and drawbacks is given in Table 2. A detailed description of each technique including materials, device description and the state of the art is given in Section 3. Given the size of the surveyed field, the amount of information required, and rapidly-evolving nature of the field the list of the emerging technologies described below is not exhaustive and the performance metrics provided are best available estimates that will hopefully be updated on a regular basis.

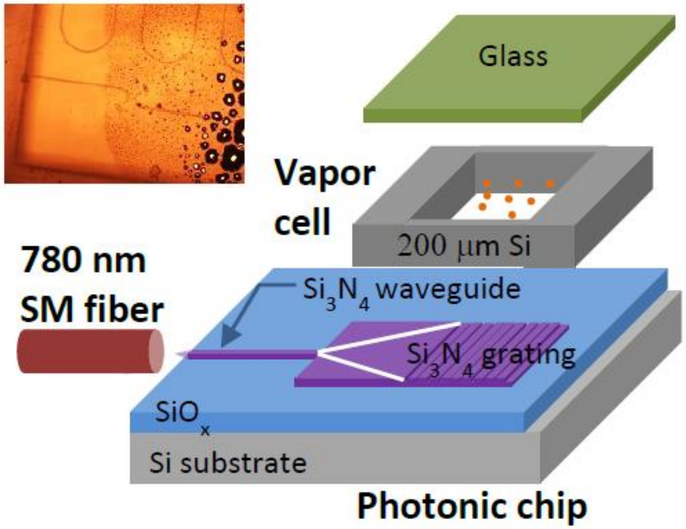
Emerging technologies Vs. State of the Art

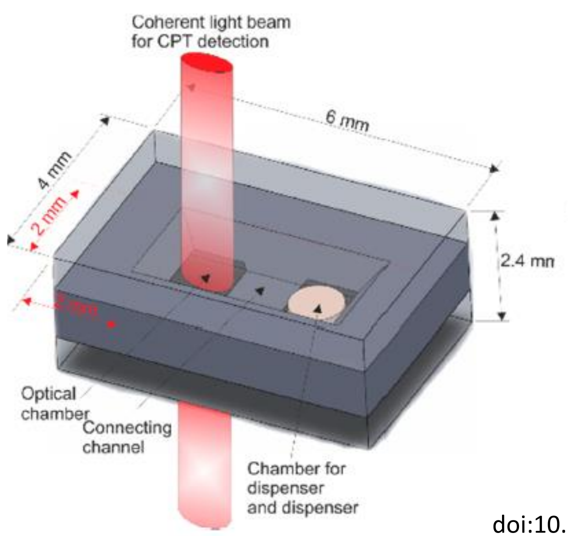
Technology	Primary	Probe Material	Sensitive Element Size	Temperature Range	Typical Sensitivity	Expected Uncertainty	Commercial
Optical Refraction	y	He/N_2	10 mm - 100 mm	100 K - 420 K	3 pm/K	1 mK - 10 mK	n
On-chip DBT	y	Rb/Cs	0.1 mm^3	300 K - 1000 K	0.8 Hz/Torr/K	0.1 mK - 100 mK	n
FBG	n	SiO_2[a]	0.1 mm - 10 mm	80 K - 1300 K	10 pm/K[b]	100 mK - 500 mK	y
Brilloiun Scattering	n	SiO_2	0.1 m - 100 m	250 K - 350 K[c]	1 MHz/K	0.5 K - 10 K	y
Raman Scattering	y	SiO_2	0.001 m - 10 m	250 K - 350 K	xxx	0.01 K - 10 K	y
Ring Resonator/Photonic Crystal Cavity	n	Si[d]	0.1 mm - 1 mm	3 K - 1000 K	100 pm/K[b]	1 mK - 100 mK	n
Optomechanical Thermometry	y	Si_3N_4/Si	0.1 mm - 1 mm	0.05 K - 300 K	60 pm/K	1 K - 10 K	n
Long-Stem SPRT	n	Pt	40 mm - 60 mm	75 K - 950 K	0.1 Ω/K	0.1 mK - 1 mK	y
Type S Thermocouple	n	Pt(Rh)	0.5 m - 1 m	300 K - 2000 K	10 μV/K	100 mK - 500 mK	y
Johnson Noise Thermometry	y			50 nK - 2500 K			n

Why and Why Not of Emerging Technologies

Technology	Advantages	Drawbacks
Optical Refraction	✓ Measures thermodynamic temperature (traceable to frequency and pressure)	× Centimeter scale footprint × Working gas is susceptible to chemical contamination × Limited to temperatures below 150 °C (mirror coating)
on-chip DBT	✓ Measures thermodynamic temperature (traceable to frequency)	× Susceptible to magnetic field
FBG	✓ Packaging can be made compatible with the existing calibration infrastructure ✓ Point-like temperature sensor ✓ Multi-point sensing capability (singal multiplexing)	× Thermal hysteresis, long-term drifts are not well understood × Susceptible to ionizing radiation × Cross-sensitivity (stress, humidity)
Brilloiun/Raman Scattering	✓ Spatial range covers several orders of magnitude (cm to km) ✓ Suitable for static and dynamic measurements ✓ Resistant to ionizing radiation and chemical corrosion ✓ Measures thermodynamic temperature (single photon detector)	× Lower accuracy compared to the most common temperature sensors × Susceptible to strain; special device handling and installation protocol are necessary × Detection systems are often complex and expensive (increased training time)
nanophotonic resonators	✓ Wide range of materials, wavelengths and device design parameters available for fit-for-purpose device development ✓ Resistant to chemical contamination ✓ Uncertainties expected to be comparable to SPRT or better	× Low drift packaging needs to be developed × Susceptible to manufacturing imperfections
Optomechanics thermometry	✓ On-chip thermodynamic temperature ✓ Integrateable with on-chip photonic thermometers	× Early stage of research × Uncertainties estimated to be on the order of 1 K

On-Chip Doppler Broadening Thermometer



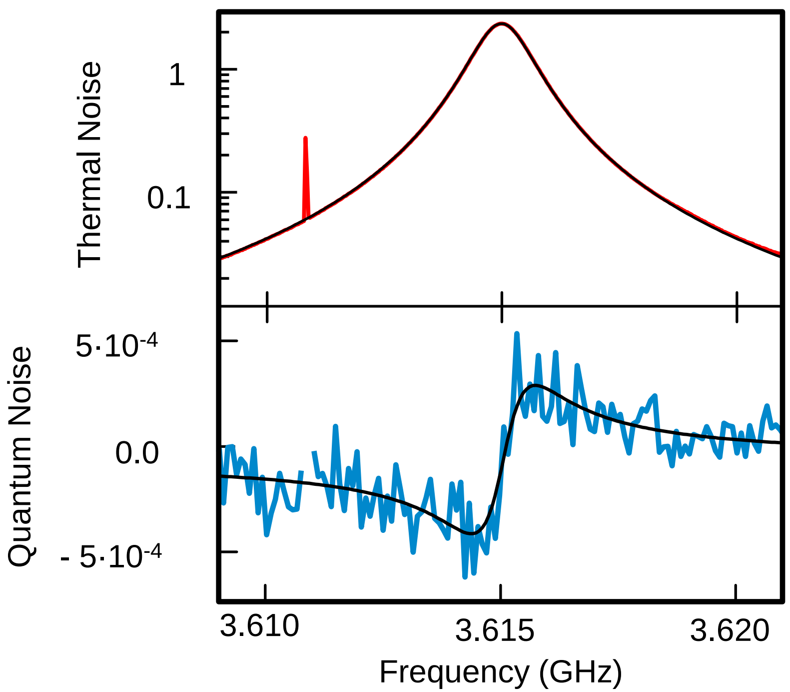


- Molecular spectroscopy-based Quantum SI realization
- Builds on history of free space DBT work
- Expected Uncertainty: 0.1 mK - 100 mK
- Advantages:
  - Thermodynamic Temperature
  - Small chip scale footprint
- Disadvantages:
  - Uncertainty likely to be in the 100 ppm range
  - Susceptible to magnetic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

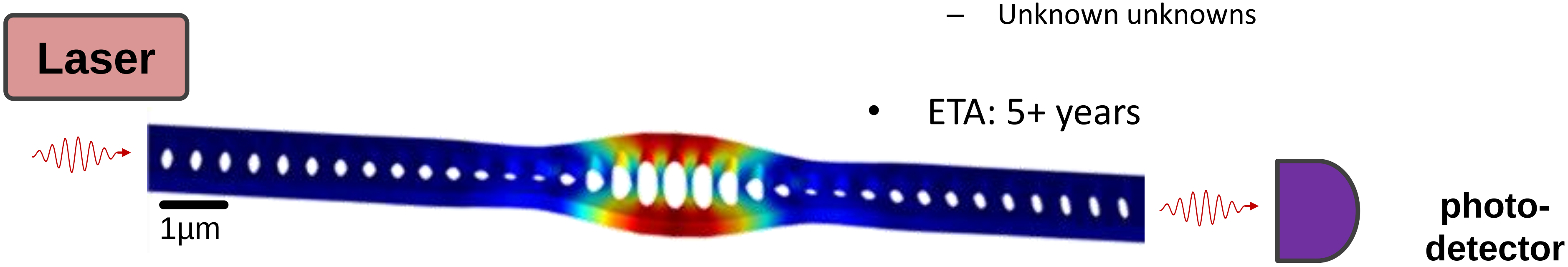
doi:10.1088/1742-6596/723/1/012056

doi: 10.3390/mi9080405

Opto-mechanical Thermometry

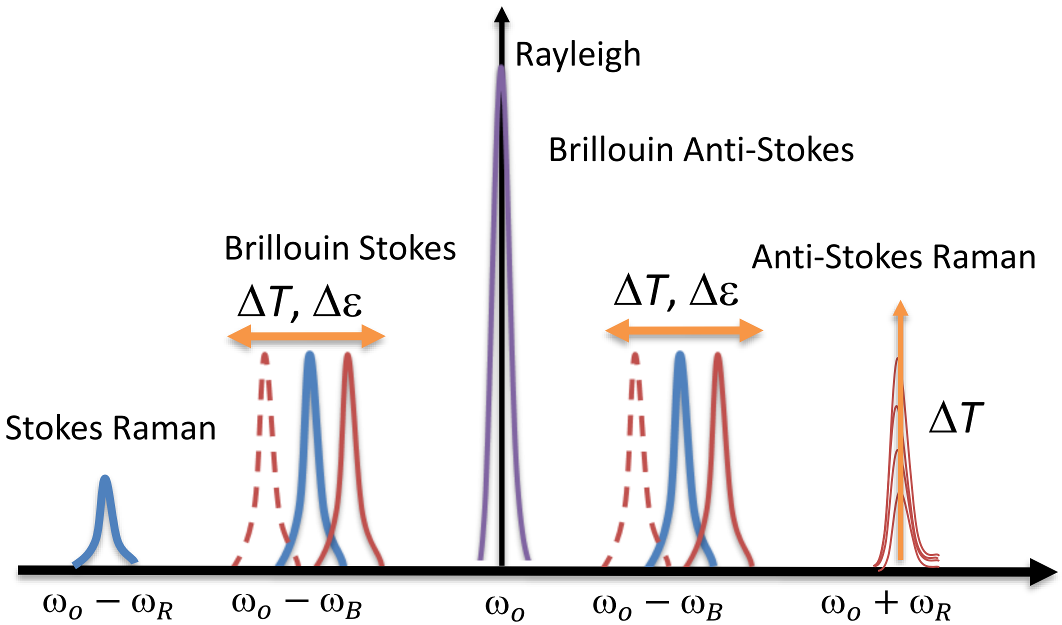


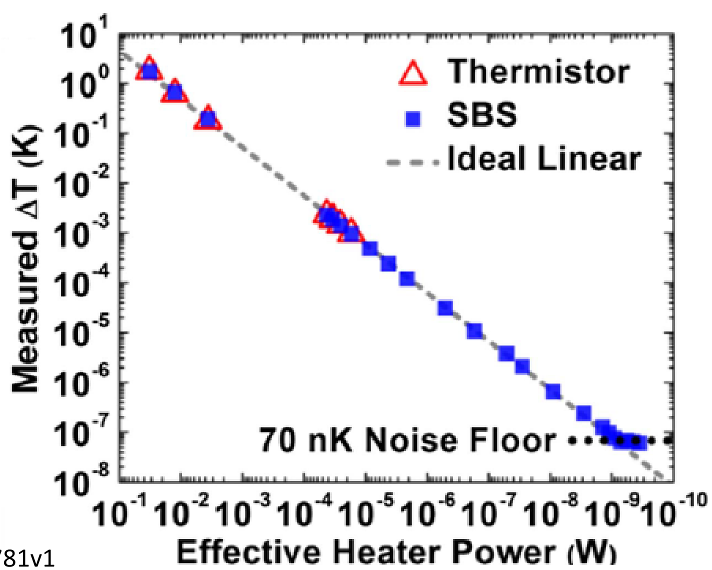
- Quantum realization of temperature
- Expected Uncertainty: 1 K
- Advantages:
  - On-Chip Thermodynamic temperature
  - Integrate-able with on-chip photonic thermometer
  - Easy integration into QIS
  - Unknown, unknowns
- Disadvantages:
  - Early stage of research
  - Current uncertainties on the order of few percent
  - Long-term device performance unknown
  - Unknown unknowns
- ETA: 5+ years



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

Light Scattering Based Thermometry

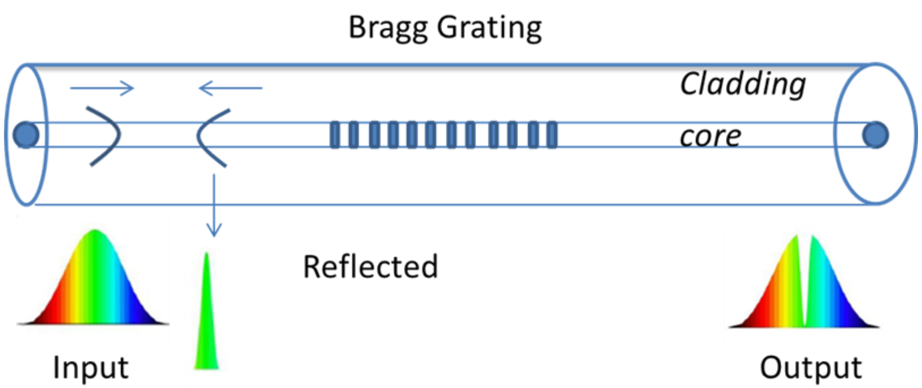


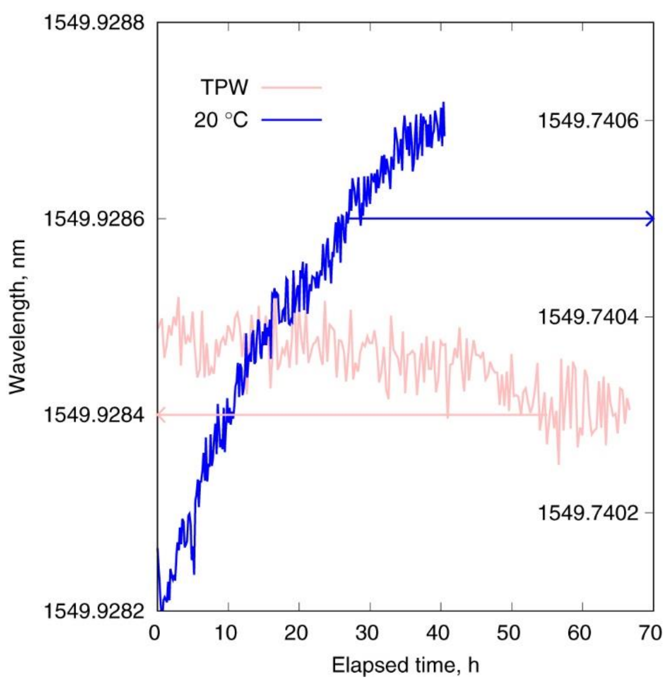


arXiv:1810.04781v1

- Spectroscopic measurement
- 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

Fiber Optic based Thermometry



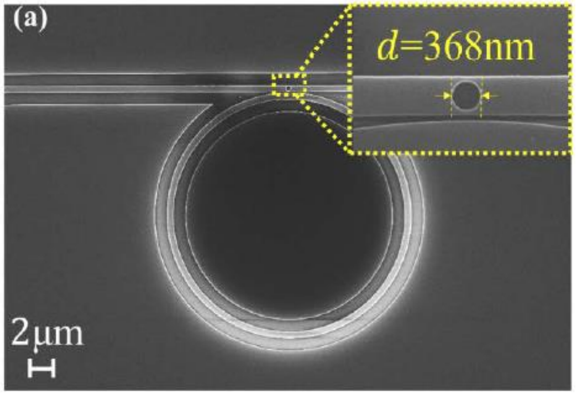


https://doi.org/10.1088/1361-6501/ab7611

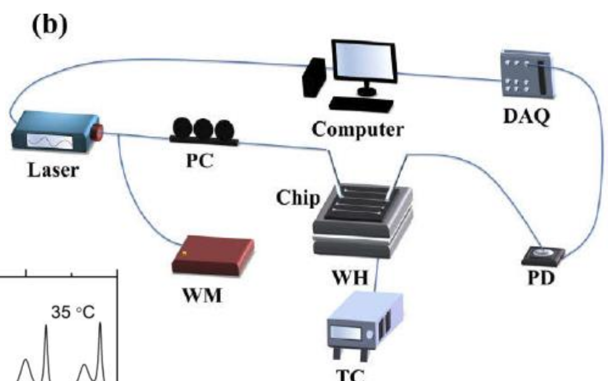
- Refractive index-based temperature transduction to frequency
- Expected Uncertainty: 100 mK – 500 mK
- Advantages:
  - Packaging can be made compatible with existing infrastructure
  - Point source-like temperature sensor
  - Multipoint sensing capability
  - Widely in use in telecom and sensor community
  - 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)

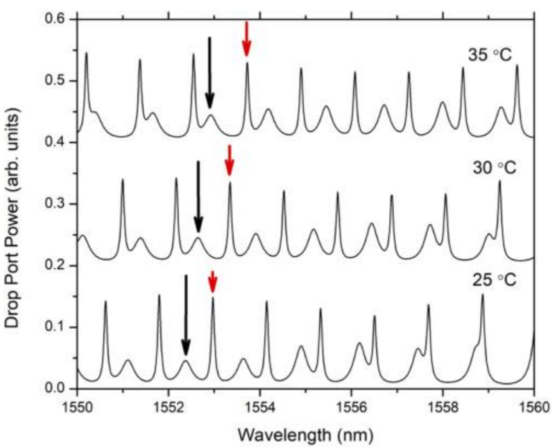
- ETA: on-market

On-Chip Thermometry



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





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

- Refractive index-based temperature transduction to frequency
- Expected Uncertainty: 1 mK – 500 mK
- Advantages:
  - Wide range of materials, wavelengths and device design parameters possible
  - Moisture resistant
  - Uncertainties expected to be comparable to SPRT or better

  Disadvantages:
  - Low drift packaging needs to be developed
  - Susceptible to manufacturing imperfections
  - Lack of physics-based models
  - Cost of interrogator; user training
  - Temperature range limited by packaging
- ETA: 5 years

Re-orienting the Taskgroup

- Publish the document as review article to make the information as widely available as possible
- Continued literature surveillance
  - Maintain the report as a living document, updating the references and discussion to address breakthroughs in core technology areas;
  - Add new technology areas as they appear
- Document best practices that ensure these new thermometers are:
  - Deployable
  - Practical
  - Stable
  - Allow comparison between different technologies, E*merging* and *Legacy* alike
    - Study and recommend minimum frequency metrology requirements
    - Figures of merits and best practices for calculating them
    - Uncertainty budget development
    - Lessons and best practices drawn from existing technologies and on-going activities for designing experiments
      - Ex: Considering the growth of IoT sensors and on-going efforts to understand the traceability of MEMS temperature sensors as part of EMPIR "Metrology for the factory of the future" project, we propose to study sensor networks, role of emerging technologies in enabling traceable measurement using sensor networks and lessons that can be drawn from on-going work in MEMS network to accelerate new technologies