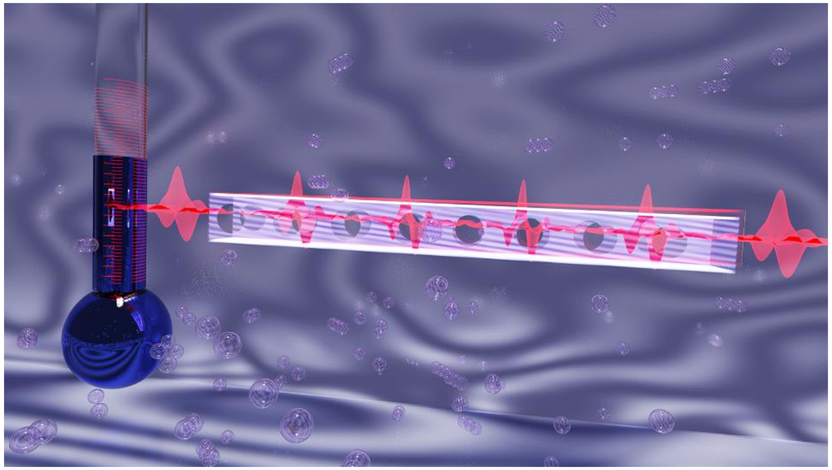


Emerging Technologies in Contact Thermometry

Emerging Technologies Task group

Task group's Mission

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; *(Table 1 and 2)*
- Review and report on published data from various emergent technologies including a comparative study of the advantages *(Table 1 and 2),* limitations *(Table 1 and 2)*, materials *(section 3.4.2 and table 1),* and temperature ranges *(Table 1 and section 3.1,3.2, 3.3, 3.4.3, 3.5, 4.1 and 4.2)*;

- Review and report on the potential of some of these emergent technologies for primary thermometry *(Table 1, section 3.1, 3.2, 3.5, 4.2)*

Task group's Membership

Dr. Zeeshan Ahmed (chairperson, NIST)

- Prof. Stéphan Briaudeau (LNE-Cnam)
- Dr Sergey Dedyulin (NRC)
- Dr Efrem Kebede Ejigu (NMISA)
- Prof. Vito Fernicola (INRIM)
- Dr Victor Fuksov (VNIIM)
- Dr Maria-José Martín Hernández (CEM),
- Dr Murat Kalemci (UME)
- Ing. Tomas Kopunec (SMU)
- Dr Stephan Krenek (PTB)
- Dr Sergey Osadchiy (VNIIFTRI),
- Prof. Graham Machin (NPL)
- Dr Yijie Pan (NIM, observer)
- 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)

(past members)

- Steffen Rudtsch (PTB)
- Michael de Podesta (NPL)
- Dr Dolores del Campo Maldonado (CEM
- Edgar Mendez (CENAM)
- Andrea Peruzzi (VSL)
- Dr Martti Heinonen (MIKES)
- Dr Farzana Masouleh (MSL)
- Dr Dolores Del Campo (CEM)

Technology Landscape: Possible Realities

Primary Thermometers:
- Optomechanical Thermometry
- Refractometry based Thermometry
- On-chip Doppler Broadening Thermometry

ITS 90 Traceable Thermometry
- Optical thermometry
- Photonic Thermometry
  - Light scattering
  - Refractometry
    - In-Fiber
    - On-Chip

New Technologies and Trends
- NV diamond and Quantum Dots
- Rydberg Atoms
- Photonic Interrogator

A detailed review paper covering a broader range of technologies, discussed in greater depth was published.

Along with the report it provides a detailed map of the literature to any new user interested in emerging technologies in contact thermometry

Emerging technologies Vs. State of the Art (Table 1)

Table 1: Emerging technologies in thermometry compared to standard platinum resistance thermometer (SPRT) and type S thermocouple

Technology	Primary	Probe Material	Sensitive Element Size	Temperature Range	Typical Sensitivity	Expected Uncertainty	Commercial
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	—	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

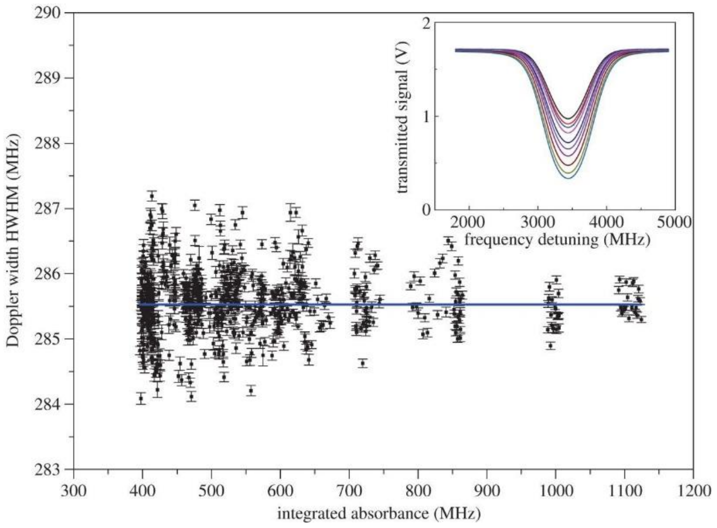
[a] Fiber Bragg grating can be inscribed in sapphire (Al_2O_3) in which case the temperature range can be extended to 2000 K.
[b] Typical resolution of a tunable laser used for interrogation is 0.1 pm.
[c] The range can be potentially extended to 1 K - 1100 K.
[d] See Section 3 for complete list of materials.

Why and Why Not of Emerging Technologies (Table 2)

Table 2: Advantages and drawbacks of emerging technologies described in Table 1

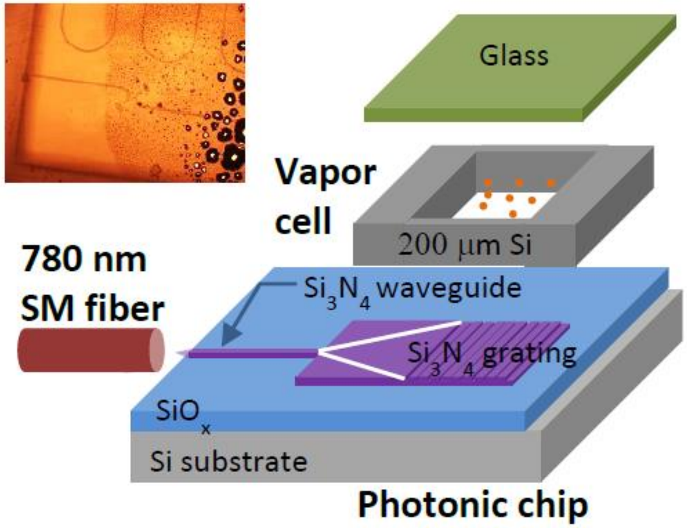
Technology	Advantages	Drawbacks
Optical Refraction	✓ Measures thermodynamic temperature (traceable to frequency and pressure)	× Centimeter scale footprint × Working gas is susceptible to chemical contamination × Limited to temperatures below 150 °C (mirror coating)
On-chip DBT	✓ Measures thermodynamic temperature (traceable to frequency)	× Susceptible to magnetic field
FBG	✓ Packaging is 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)
Optical resonators	✓ Smallest uncertainty / resolution compared to other emerging technologies; expected uncertainties comparable to SPRT ✓ Wide range of materials, wavelengths and device design parameters available for fit-for-purpose device development	× Low-drift packaging needs to be developed × High-temperature packaging needs to be developed × Manufacturing imperfections contribute to device-to-device variability
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



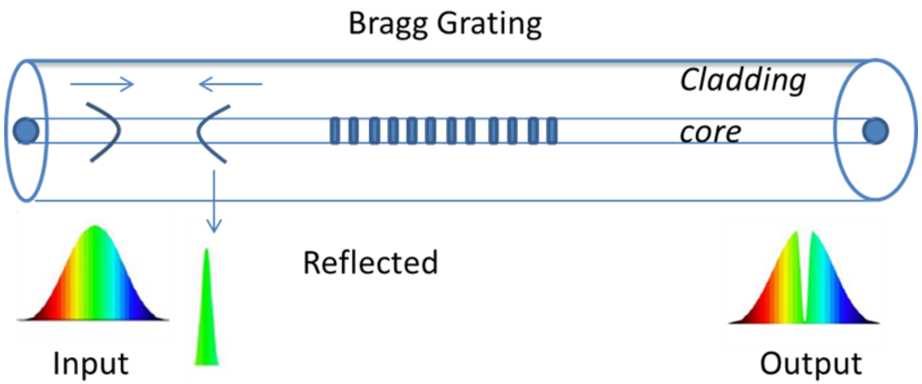
- Molecular spectroscopy-based Quantum SI realization
- Builds on history of free space DBT work
- Expected Uncertainty: 0.1 mK - 100 mK

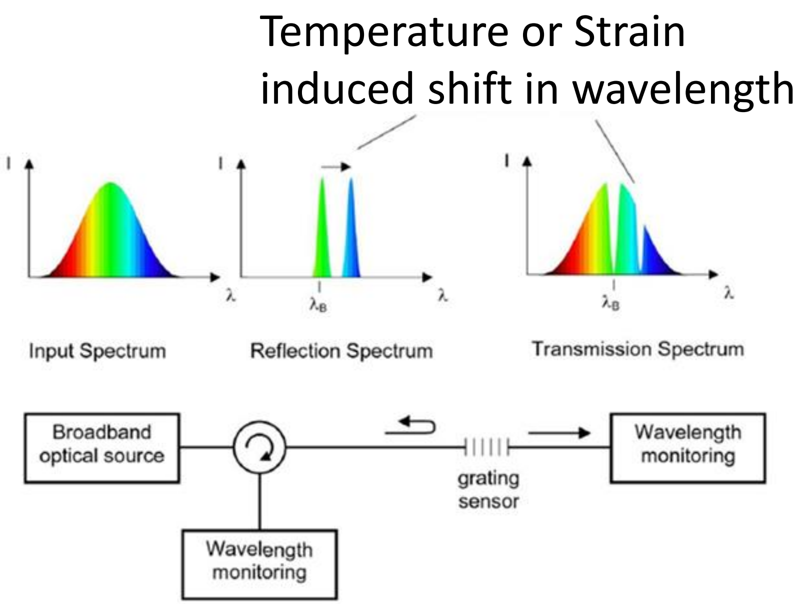
- Advantages:
  - Thermodynamic Temperature
  - Small chip scale footprint



- Disadvantages:
  - Uncertainties likely to be in the 100 ppm
  - Susceptible to magnetic fields
- Thermalization of atomic vapour in nano-volume requires greater scrutiny; wall effects need to be quantified
- ETA: 5+ years

Fiber Optic based Thermometry





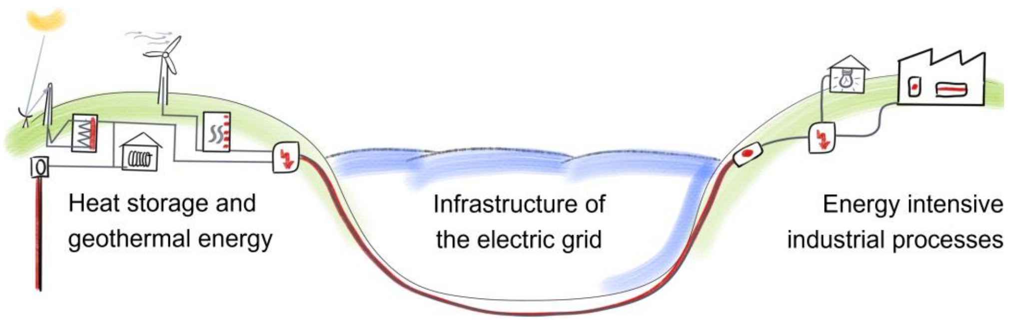
- Refractive index-based temperature transduction to frequency
- Expected Uncertainty: 100 mK – 500 mK
- Advantages:
  - Packaging can be made compatible with existing infrastructure
  - Point source-like temperature sensor
  - Multipoint sensing capability
  - Widely in use in telecom and sensor community
  - Large temperature range (100 K -1500 K) with sapphire fiber (u = 1 K – 5K)
  - ITS-90 Temperature
  - Green Energy applications
- 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

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

What's holding back fiber thermometry?

Metrology specific understanding of device performance is *lacking*

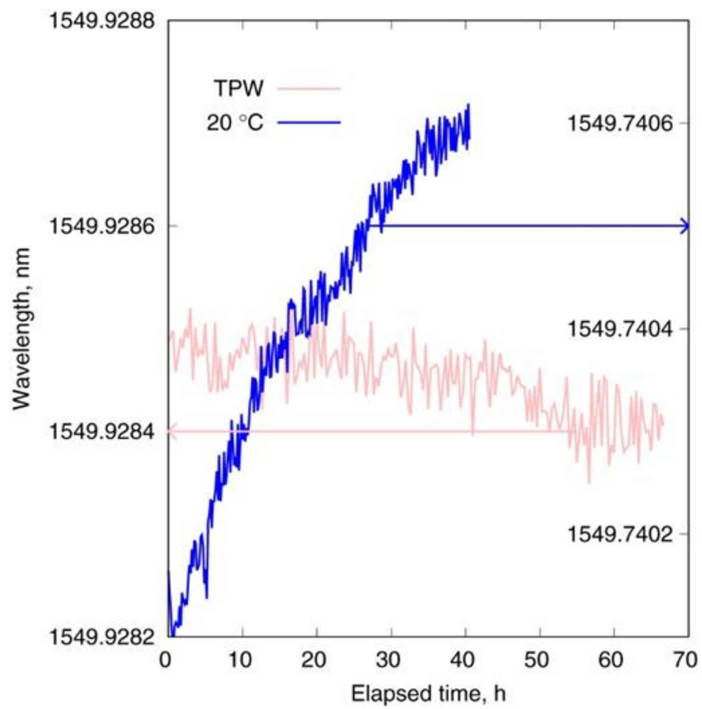
- What's the uncertainty budget?
  - 100 mK - 10 K- depends upon grating type and temperature range



- What is the *source* of uncertainty?
  - Hysteresis
  - Peak center
  - Environment (e.g. moisture)

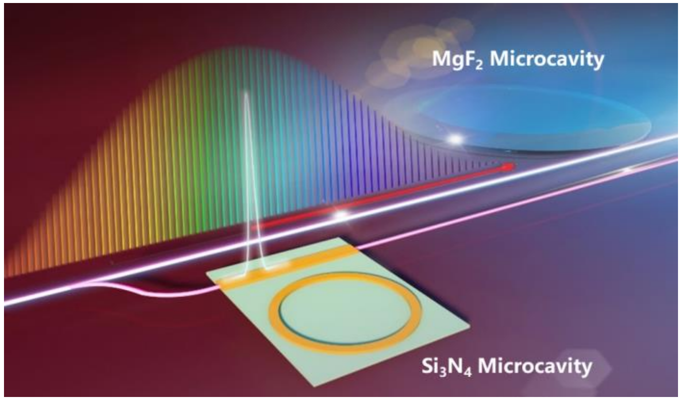
- Are these devices interchangeable?
- How stable are they?
- What's the measurement repeatability?

- The European INFOTherm project runs from 2023 to 2026 and aims to address several of these issues. (www.infotherm.ptb.de)

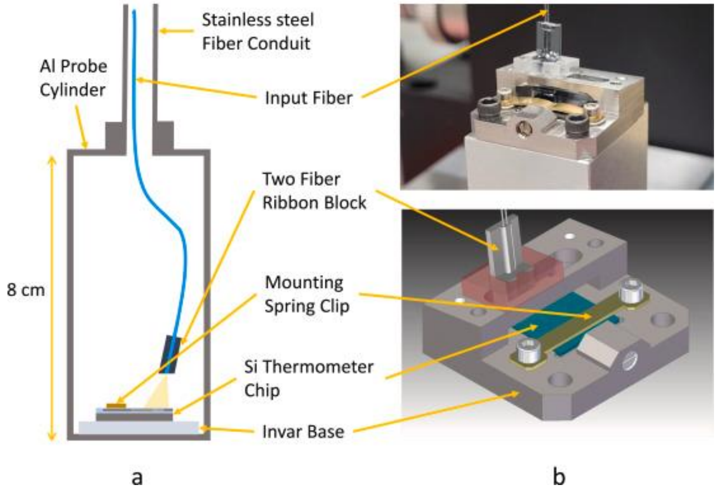


https://doi.org/10.1088/1361-6501/ab7611

On-Chip Thermometry



Jin Wang, Yijie Pan, Jifeng Qu, et al. Photonic Research, 11(2023),



https://doi.org/10.1016/j.measurement.2023.113453

- Refractive index-based temperature transduction to frequency
- Expected Uncertainty: 1 mK – 100 mK (*current: 9.2 mK*)
- Resolution floor: ≤ 50 µK
- Advantages:
  - Packaging can be made compatible with existing infrastructure
  - Point source-like temperature sensor
  - Large temperature range (cryogenic temps to >500 K)
  - ITS-90 Temperature
- Disadvantages:
  - Thermal hysteresis/long-term drift not well understood; self-heating/non-linear effects limit accuracy
  - Accuracy under thermal gradients need to be understood
  - May be susceptible to ionizing radiation
  - Cross-sensitivity to stress and moisture (packaging dependent)
  - Interrogation instrument's C-SWAP could be limiting

Adoption of III-V materials could increase rad-hardness, increased sensitivity and ease PIC instrumentation development

New Trends and Technologies

- NV diamond and Quantum Dots:
  - Finding utility in microscopy of biological and semi-conductor matrices.
  - Metrology specific questions similar to photonic thermometry need to be addressed
- Rydberg Atoms
  - Holds the promise of primary thermometry with uncertainties in the 1-4% range; immediate future depends on further development of spectroscopic and theoretical methods
- Photonic Interrogator:
  - The cost and complexity of photonic interrogator is likely to prove to be a limiting step in wider adoption of the technique. Development of fit-for-purpose, cost-effective solution will help accelerate technology adoption.

https://doi.org/10.48550/arXiv.2203.07906 10.1088/1367-2630/abe8f5 10.1088/1361-6501/ac75b1

Grand Challenges

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

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

What does temperature mean at the nanoscale?

How do we communicate in a cross disciplinary field?

Temperature, frequency, photonics, communication, QIS, humidity, ML

How do we meet the user community where it is?

C-SWAP, complexity of technology/training

Au Revoir/Auf Wiedershen/Good bye

- Deliverables:
  - Report concisely reports a survey on broad range of primary and ITS-90 relevant technologies
  - Report presents a comparative analysis of each technology’s advantages and backdraws
  - Reports highlights the need for harmonization of measurement metrics and need for standards to promote these technologies
  - Report highlights trends and technologies to watch beyond the techniques extensively studied
    - Quantum technologies are continuing to evolve with new opportunities emerging e.g. NV diamond and quantum blackbody radiation thermometry
- Other noteworthy publications:
  - *Emerging technologies in the field of thermometry (and refs within)* https://doi.org/10.1088/1361-6501/ac75b1
  - Practical ring-resonator thermometer with an uncertainty of 10 mK https://doi.org/10.1016/j.measurement.2023.113453
  - Soliton microcomb-assisted microring photonic thermometer with ultra-high resolution and broad range https://doi.org/10.1364/PRJ.496232
  - Photonic contact thermometry using silicon ring resonators and tuneable laser-based spectroscopy https://doi.org/10.1515/teme-2021-0054
- That taskgroup has completed its task and will be shutdown down.