The Future of Temperature Sensing
Room 320 - Session TS-WeM

The Future of Temperature Sensing II
Moderators: Dr. Graham Machin, NPL, **Dr. Stephan Krenek**, PTB

8:00am **TS-WeM-1 Utilizing the SI Redefinition and "NIST on a Chip" to Ensure Readiness Across the United States Air Force, Army, and Navy*, Jeremy Latsko,*** United States Air Force Metrology and Calibration **INVITED**

The U.S. military's metrology and calibration programs rely on a complex global calibration chain that is prone to disruption, posing a risk to military readiness. To mitigate these vulnerabilities, the Air Force, Army, and Navy are investing in advanced technologies, particularly Quantum-Based Intrinsically Accurate Technology (QB-IAT). This technology is enabled by the 2019 redefinition of the International System of Units (SI) and the "NIST on a Chip" program. QB-IAT reduces reliance on the traditional calibration chain by providing intrinsic accuracy based on fundamental physical constants. By implementing QB-IAT, the military has the potential to decrease equipment damage, improve measurement confidence, and ensure operational readiness at the point of use. This paper details the military's strategy to integrate these quantum-based technologies, encourages industry partnership for commercialization, and provides an overview of currently funded projects.

8:30am **TS-WeM-3 Air Force Temperature Metrology and Photonic Thermometer Applications*, Kaleb Reed,*** Air Force Research Lab

Temperature sensing devices in Air Force inventory are required to be calibrated to ensure operational readiness and effectiveness. To do this there is a long calibration chain of increasingly accurate thermometers providing traceability and accuracy. Existing platinum resistance thermometers (PRTs) are a key part of that chain. However, they are fragile, prone to drift, and require labor-intensive calibrations.

Photonic thermometers could be able to match PRT accuracy while being more robust, stable, and having longer calibration intervals. The successful introduction of photonic thermometer technology would reduce or eliminate the calibration chain for thermometers in the USAF. This presentation will discuss how the USAF Temperature Metrology Program could benefit from accurate, stable, and more robust thermometers to increase readiness.

8:45am **TS-WeM-4 The Standard Photonic Thermometer (SPoT) program at NIST***, Pavan Challa, Michal Chojnacky, Kevin Douglass, Thinh Bui, Klaus Quelhas, Daniel Barker, Nazanin Hoghooghi, Franklyn Quinlan,* ***Nikolai Klimov,*** National Institute of Standards and Technology (NIST)

Temperature underpins modern technology, and resistance thermometers remain the primary means of realizing the SI kelvin. However, their inherent limitations – most notable calibration drift over time and the resulting need for frequent recalibration – have motivated the search for alternative approaches such as integrated photonic thermometry.Photonic thermometry offers a compelling alternative, but practical adoption has been limited by the lack of packaged, infrastructure–compatible systems that combine SI–traceable interrogation, a rigorous uncertainty framework, and millikelvin–level performance. Achieving this combination is necessary for photonic sensors to serve as viable metrological replacements for resistance standards.

Building on these needs, The Standard Photonic Thermometer (SPoT) program at NIST is developing a chip–scale, SI–traceable temperature standard that overcomes the drift, fragility, and calibration burdens of resistance–based thermometry. SPoT leverages integrated silicon photonics to realize narrow linewidth resonant structures whose temperature–dependent optical frequency response provides a stable and reproducible thermometric signal. This presentation will provide an overview of the SPoT program, including device–level design, advanced packaging approaches, and the frequency–metrology framework that defines the absolute frequency scale for SPoT thermometry.

9:00am **TS-WeM-5 From SPRT Comparison to SI-traceable Photonic Thermometry with SPoT*, Michal Chojnacky**, Pavan Challa, Kevin Douglass, Thinh Bui, Klaus Quelhas, Frank Quinlan, Alessandro Restelli, Nikolai Klimov,* National Institute of Standards and Technology (NIST)

Photonic thermometry offers a promising alternative to resistance-based temperature sensing, but its adoption for precision metrology requires an SI-traceable relationship between optical frequency and temperature. We present the initial metrological evaluation of the Standard Photonic Thermometer (SPoT), a fully packaged silicon microring-resonator thermometer designed for use in conventional thermometric baths and fixed-point-cell infrastructure. Using four months of side-by-side measurements with a calibrated standard platinum resistance thermometer (SPRT) over 10 °C to 90 °C, we developed SI-traceable calibration functions relating SPoT resonance frequency to temperature and evaluated the uncertainty contributions associated with the comparison. The SPoT resonance frequency was measured using two independent interrogation methods: resonance scanning and offset-sideband laser locking. The uncertainty framework includes contributions from the SPRT reference measurement, bath stability and uniformity, frequency-axis determination, resonance peak fitting, and offset-lock noise, yielding combined standard uncertainties of 1.67 mK and 2.61 mK for resonance scanning and offset-sideband locking, respectively. The uncertainty budget identifies key limitations from both the reference temperature environment and the offset-lock readout, highlighting clear pathways for improvement through fixed-point-cell measurements, frequency-comb-based metrology, and alternative interrogation systems. This work establishes the calibration-function and uncertainty-analysis framework that supports ongoing efforts toward practical, deployable, SI-traceable photonic temperature measurement.

9:15am **TS-WeM-6 Optical Frequency Comb Metrology for Assessing the Ultimate Stability of SPoT in a Water Triple-point (WTP) Cell*, Thinh Bui,*** *Pavan Challa, Michal Chojnacky, Kevin Douglass, Nikolai Klimov,* NIST-Gaithersburg

Reliable and long-term measurement of SI-traceable temperature is a fundamental challenge due to drifts in standard, calibrated resistance-based thermometers. The Standard Photonic Thermometer (SPoT) is a chip–scale, SI–traceable thermometry platform that has potential to achieve long-term stability and high accuracy. Using an optical frequency comb stabilized to an ultra-stable cavity reference, we determine the ultimate temperature accuracy and precision of SPoT, only limited by the stability of the water triple-point (WTP) cell rather than the optical reference. We report on SPoT's long-term stability and reproducibility in a WTP cell using our frequency comb-based methodology.

9:30am **TS-WeM-7 Dual Mode-Locked Comb Readout Method for Chip-Scale Silicon Photonic Thermometer*, Nazanin Hoghooghi,*** NIST-Boulder*; Pavan Challa, Nikolai Klimov,* NIST-Gaithersburg

We present a dual mode-locked laser comb-based readout method for Standard Photonic Thermometer (SPoT), a chip-scale silicon photonic thermometer platform. In this work, we demonstrate how fiber mode-locked frequency combs enable a tunning-free, SI-traceable optical readout method for SPoT devices with no moving parts. The broad bandwidth and high resolution of the combs allow precise detecting of SPoT resonance-frequency shifts over a wide temperature range and with high sensitivity.

In our experiments, two self-referenced fiber frequency combs centered at 1550 nm, with slightly different repetition rates, are used to probe and track the SPoT resonance transmission spectrum. Light from fiber mode-locked combs is optically filtered and coupled into a fiber-coupled SPoT device. The SPoT chip is hermetically sealed in a miniature metal capsule and placed in a drywell capable of providing a stable temperature environment. Using the dual-comb readout system, we track SPoT resonance-frequency shift over -25°C to 140°C range. The dual–comb readout exhibits sensitivity at ≈ 200 MHz–level; however, in the present setup the achievable temperature–measurement resolution is primarily limited by the drywell stability (≈ 20 mK), rather than by the SPoT device or the comb–based readout.

9:45am **TS-WeM-8 Developing Portable Tools for Photonic Thermometry*,* *Kevin Douglass,*** NIST-Gaithersburg*; Michal Chojnacky, CH. S. S. Pavan Kumar, Thinh Q Bui, Nikolai Klimov,* NIST

As part of the photonic thermometry program at NIST we are developing a Standard Photonic Thermometer (SPoT) as a drop-in replacement for resistance-based thermometry devices.One of the major challenges of this program is to make the system portable and to minimize costs.To achieve this goal, we are developing new optical readout tools based on high accuracy optical frequency metrology to interrogate the temperature dependent frequency shifts of the SPoT.We have combined a broadband rapidly sweeping laser with a gas cell and etalon to provide an absolute frequency axis with high precision.We demonstrate measurement repeatability over a range of 20 °C to 80 °C of nearly 10 mK.This approach also gives us the ability to track multiple modes of the ring resonator simultaneously, which can be used to determine the free spectral range and group index, n_g, as a function of temperature. Recent results will be reported along with potential pathways to further improve the accuracy and precision of the portable readout methodology.

11:00am **TS-WeM-13 A Lighter Footprint: The Evolution of Ring-Resonator Thermometer Design at NRC*, Sergey Dedyulin*,** *Siegfried Janz, Dan-Xia Xu, Ross Cheriton, Shurui Wang, Martin Vachon, John Weber,* National Research Council Canada **INVITED**

Over the past decade, ring-resonator thermometers have emerged as promising candidates for high-accuracy temperature metrology, offering small footprint, resistance to electromagnetic interference, and on-chip photonic integration. At the National Research Council Canada, our work over the past several years has focused on evaluating the metrological performance of these devices and on understanding how resonator design and packaging influence measurement accuracy and long-term stability.

This presentation traces the evolution of silicon ring-resonator thermometer design at NRC, from early prototype characterization to the development of smaller and lower-uncertainty implementations. During this time, we characterized the short- and long-term stability of the ring-resonator thermometer in a stirred liquid bath between 20 °C and 80 °C, investigated various packaging options, measured the influence of self-heating, optimized the interrogation methods, tested the resolution and time response, varied the gas atmosphere, and created the full uncertainty budget for the packaged RR thermometer. The combined 10-mK standard uncertainty was found to be consistent with the repeatability reported previously for an unpackaged device and includes a long-term stability component evaluated over the course of 3 years. The presentation draws parallels with the development of the platinum resistance thermometer and concludes with an outlook on the remaining challenges toward routinely achieving millikelvin-level accuracy.

11:30am **TS-WeM-15 Chip-Based Photonic Thermometers: In-Situ Calibration and Si Traceability*, David Pabst*,** *Daniel Schmid, René Eisermann, Bruno Rohloff, Stephan Krenek,* Physikalisch-Technische Bundesanstalt (PTB), Germany

Highly integrated lab-on-a-chip applications such as on-chip optical clocks or ion traps require integrated temperature sensors, as many of these applications are sensitive to temperature, so accurate temperature control is essential for high-level scientific and industrial applications. Yet conventional electronic thermometers based on platinum resistance or thermocouples face fundamental limitations in mechanical stability and immunity to electromagnetic interference. Chip-based photonic temperature sensors, which exploit the temperature dependence of the resonance wavelengths of ring resonators and Bragg gratings, are emerging as a compelling alternative in many applications. Lab-on-a-chip applications in particular require integrated temperature sensors, as many of these applications are influenced by temperature and therefore require temperature-dependent corrections.

A major factor in the practical implementation and design of ring resonator and Bragg-grating-based photonic thermometers is the development of a data acquisition and processing method that combines accurate in-situ determination of the circuit's resonance wavelengths
with a high acquisition speed in a small form factor. Additionally, traceability to the International System of Units (SI) is required to guarantee long-term comparability and absolute accuracy. This requires very stable wavelength determination schemes or in-situ calibration with each measurement. As part of the pan-European PhoQuS-T project, we designed and manufactured Si- and SiN-based photonic integrated circuits as temperature sensors. They were packaged for use with the temperature calibration infrastructure of the PTB (the German National Metrology Institute). We developed novel techniques based on a multi-peak fit model, with which we achieve accurate in-situ calibration over a span of 100 nm while maintaining a high acquisition speed. This includes SI traceability to different reference gas cells, as well as advanced data analysis for temperature determination.

In this work, we will present our findings on the implementation of these methods and compare them with current state-of-the-art approaches under realistic thermometer calibration conditions.

11:45am **TS-WeM-16 Band-Edge Optical Microthermometers for Ultrahigh-Resolution Temperature Sensing*, Alex Shoghi Tekmedash*,** *Amin Reihani,* Rutgers University

Ultrahigh-resolution thermometry at room temperature is critical for emerging applications in bio-calorimetry, bolometry, infrared imaging, and characterization of electronic, optoelectronic, and quantum devices. In this presentation, we discuss the development and future scaling of optical microthermometers based on semiconductor band-edge thermoreflectance. We first present a GaAs band-edge microthermometer that utilizes the strong temperature dependence of optical absorption near the semiconductor band edge. Using a suspended asymmetricFabry–Pérot resonator and a wavelength-stabilized probe laser, the device achieves at hermoreflectance coefficient exceeding 30 K^{-1}, enabling a thermometry noise floor ofapproximately 60 nK.Hz $^{-1/2}$ and sub-100 nK temperature resolution at room temperature. We then discuss how multilayered nanostructures can further miniaturize band-edge thermometers while simultaneously enhancing sensor sensitivity. These advances establish new opportunities for high-resolution thermal metrology at the microscale.

12:00pm **TS-WeM-17 Quantitative Temperature Mapping with Nanometric Resolution***, Rituparna Mohanty,* ***Amin Reihani,*** Mechanical and Aerospace Engineering, Rutgers University

Quantitative nanoscale thermal imaging is critical for understanding energy transport and dissipation in emerging technologies, including nanoelectronics, plasmonics, quantum systems, and high-frequency microelectronics. In this presentation, we discuss recent advances in scanning thermal microscopy (SThM) techniques that enable quantitative mapping of both lattice and electron temperature fields with nanometric spatial resolution under practical operating conditions. First, we present Contact Resistance-Resolved Scanning Thermal Microscopy (CR-SThM), a technique capable of quantitatively mapping unmodulated surface temperature fields while simultaneously resolving the local tip–sample thermal resistance. Using custom-fabricated scanning thermal probes with integrated heater/thermometers and sharp tips (~25 nm radius), the approach achieves ~7 nm spatial resolution and ~50 mK temperature resolution in a 1 Hz bandwidth. By introducing a modulated heat input to the probe and measuring both AC and DC thermal responses, CR-SThM enables accurate thermometry even in the presence of strong topography-dependent variations in thermal contact resistance. We then present Electron-Scanning Thermal Microscopy (E-SThM), a novel technique for imaging nonequilibrium electron temperature distributions on conductive surfaces. The method employs a metal–insulator–metal tunneling junction formed using a Pt-coated thermal probe with an ultrathin Al_2O_3 tunneling barrier. Variations in electron temperature modify the tunneling current through broadening of the Fermi–Dirac distribution, enabling nanoscale mapping of hot-electron transport with sub-kelvin sensitivity. Together, these techniques provide powerful new capabilities for probing coupled thermal and electronic nonequilibrium phenomena at the nanoscale.

Author Index

Bold page numbers indicate presenter