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

The Future of Temperature Sensing I

Moderators: Dr. Nikolai Klimov, National Institute of Standards and Technology, **Dr. Sesha Challa**, NIST-Gaithersburg

4:00pm **TS-TuA-8 Keynote Talk: The Transformation of Temperature Traceability***, **Graham Machin FREng FRS**,* National Physical Laboratory, U.K. **INVITED**

In May 2019 the kelvin was redefined in terms of a fixed value for the Boltzmann constant, *k*. Since then global temperature traceability has been regulated through the Consultative Committee of Thermometry (CCT) *mise-en-pratique* for the definition of the kelvin (*MeP*-K-19).

The *MeP*-K-19 introduced a gradualist but transformational approach to temperature traceability. Whilst allowing for continuity in temperature traceability through the long defined temperature scales of ITS-90 and PLTS-2000, it opened, for the first time, the possibility for temperature traceability to be derived directly from the kelvin definition through use of a *MeP*-K-19 approved primary thermometry approach, such as acoustic gas thermometry or dielectric constant gas thermometry. Some of these approaches are currently close to maturity and likely to be implemented and trial comparisons in train before the end of the decade.

However, that form of traceability is essentially still traditional in that reference thermometers would still be calibrated at National Metrology Institutes (NMIs) and sent to calibration laboratories to act as reference standards for the calibration of user thermometers. The only difference, from a user perspective, is that thermodynamic temperature, *T*, rather than a defined scale (T_{90} or T_{2000}) would be disseminated to them. More radical traceability approaches, envisaged in the CCT Strategy 2030+, is the development of temperature sensors that provide traceability at the point of measurement. These could be conventional based self-validating thermometers, or reliable practical primary thermometers, that require no calibration, based on fundamental physical principles that would provide trustworthy thermodynamic temperature values for the lifetime of the application.

In this talk I will outline the kelvin redefinition, introduce the concept of traceability, describe the *MeP*-K-19 and its function and then go on to speak about emerging approaches to temperature traceability. This will be illustrated with examples ranging from traditional approaches to temperature traceability that disseminate *T*, to more radical approaches under development such as self-validating thermometers and practical primary thermometry such as Doppler broadening or ring-resonator thermometry.

4:45pm **TS-TuA-11 Dual-Mode Fiber-Optic Refractive-Index Gas Thermometry for Primary Calibration and Continuous Temperature Tracking to 1000 K***, Musaddeque Syed, **Ming Han**,* Michigan State University

Accurate, drift-resistant temperature measurement is essential for harsh industrial processes, where conventional secondary sensors often degrade under sustained thermal and mechanical stress or experience radiation-induced drift in nuclear reactor environments. Refractive-index gas thermometry (RIGT) provides a driftless primary route to thermodynamic temperature measurement, but practical deployment has been limited by pressure-cycling requirements that reduce measurement speed and complicate field operation. Here, we advance an argon-filled, fiber-optic Fabry-Perot (FP) RIGT sensor into a dual-mode temperature metrology platform that combines absolute primary calibration with continuous temperature tracking up to 1000 K.

The thermometer consists of an external FP cavity formed at the end of a single-mode optical fiber and filled with argon gas. In primary mode, absolute thermodynamic temperature is determined from spectral fringe shifts measured between two pressure states and interpreted using a virial-coefficient refractivity model, eliminating dependence on empirical calibration. In secondary mode, the same fiber-optic FP sensor operates at a fixed pressure to continuously track temperature-induced optical path-length changes with faster temporal response. This mode provides practical monitoring capability between primary calibration points while retaining traceability to the underlying RIGT measurement framework.

We develop working equations for both primary-mode and secondary-mode operation, establishing a unified analytical framework for absolute temperature determination and continuous temperature tracking using the same fiber-optic FP sensor. The dual-mode operation is experimentally demonstrated from room temperature to 1000 K. The resulting architecture links the driftless accuracy of a primary gas thermometer with the compactness, remote interrogation capability, and deployment advantages of a fiber-optic FP sensor. This work establishes a practical pathway toward high-accuracy temperature metrology for extreme industrial, energy, nuclear, and process-control environments.

5:00pm **TS-TuA-12 A Projected Refractive Index Gas Thermometer Revisited***, **Patrick Egan**,* National Institute of Standards and Technology (NIST)

In 1974, Colclough of the National Physical Laboratory UK lamented the difficulties associated with the primary thermometry methods: constant volume gas thermometry, acoustic gas thermometry, and Johnson noise thermometry. As an alternative to those established methods, Colclough projected a refractive index gas thermometer as a viable alternative for primary thermometry.

There were two oversights in Colclough's projections. The first is merely a minor point that the proposed refractometer system (gas cell in a Michelson interferometer) never worked! The second issue is that Colclough did not foresee the 2025 breakthrough "dispersion gas barometry" which derives thermodynamic temperature using simultaneous measurements of refractive index at widely separated wavelengths. Fifty year's after Colclough's original projection, I would now argue that refractive index gas thermometry has become superior to every other primary thermometry methodology.

My presentation will explain some key advantages of dispersion gas barometry. I will present a roadmap for primary thermometry covering the range 4 K to 1234 K using only two refractometers.

1. A. R. Colclough, "A Projected Refractive Index Thermometer for the Range 2--20 K," Metrologia 10, 73 (1974). https://doi.org/10.1088/0026-1394/10/2/006
2. Y. Yang, J. A. Stone, and P. F. Egan, "Demonstration of dispersion gas barometry," Physical Review Applied 23, 064041 (2025). https://doi.org/10.1103/z9zz-lqzh

5:15pm **TS-TuA-13 Wide-Temperature-Range Luminescence Thermometry***, **Yuanbing Mao**,* Illinois Institute of Technology

Luminescence-based temperature sensing holds great promise thanks to their attractive properties including rapid response, high spatial resolution, and remote non-invasive detection, ultimately their applicability in chemically and electromagnetically harsh environments. Relevant to their practical use, a wide temperature sensing range is urgently required for thermometric phosphors along with high relative sensitivity. Herein, we have designed several thermometric phosphors for wide-temperature-range sensing in recent years. In this talk, I will focus on discussing relevant strategies to broaden the working range of thermometric phosphors with enhanced temperature sensitivity, such as intervalence charge transfer and thermally stable hosts, particularly negative thermal expansion compounds. Our work provides inspiration for exploring desirable wide-temperature-range thermometric phosphors insensitive to surface emissivity and reflected radiation with broad application potential.

5:30pm **TS-TuA-14 Group V Metalates as High-Temperature Thermosensitive Phosphors***, **Federico Rabuffetti**,* Wayne State University

Refractory niobates and tantalates are ideal hosts for high-temperature thermosensitive phosphors activated with rare-earths.A distinct feature of these materials is their chemical tunability, which makes them ideal platforms to understand the interplay between crystal structure, electronic structure, and luminescence thermal quenching. This understanding provides the basis to exercise synthetic control over temperature-dependent luminescence and thermometric response.

In this talk I will use group V metalates to illustrate how we are approaching the challenge of establishing a set of crystal-chemical principles that enable the design of high-temperature thermosensitive phosphors. Synthesis, high-end structural analysis, and luminescence studies of dysprosium-doped $Ba_3MgTa_2O_9$ and Y_3NbO_7 will be described to demonstrate how chemical substitutions may be used to rationally tune structural and electronic features governing thermal quenching. From a luminescence thermometry standpoint, I will show that both phosphors are capable of temperature sensing up to 1200 °C, thus expanding the compositional library of high-temperature thermosensitive phosphors [1,2].

[1] M.R. Imer, A. Afugu; Z.-F. Liu; and F.A. Rabuffetti. Luminescence of Triple Perovskite $Ba_3MgTa_2O_9:Dy^{3+}$ Up to 1100 °C. *The Journal of Physical Chemistry C* **2024**, 128, 16628–16639.

[2] M.R. Imer and F.A. Rabuffetti. Luminescence of Y_3NbO_7:Dy Up to 1000 °C. *Journal of Luminescence* **2025**, 278, 121017.

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.

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

The Future of Temperature Sensing III

Moderators: Dr. Olga Kozlova, LNE-CNAM, **Dr. Nikolai Klimov**, National Institute of Standards and Technology

2:15pm **TS-WeA-1 Enabling New Measurement Capabilities with Fiber-Optic Thermometry***, **Stephan Krenek**, René Eisermann,* Physikalisch-Technische Bundesanstalt (PTB), Germany*; Guillaume Failleau,* Laboratoire National de métrologie et d'Essais (LNE), France*; Xin Lu,* Bundesanstalt für Materialforschung und -prüfung (BAM), Germany*; Peter Thomas,* Norwegian Research Centre AS (NORCE), Norway*; Henrik Kjeldsen,* Danish Technological Institute (DTI), Denmark **INVITED**

Accurate temperature measurement and control are fundamental to advancements in industry and the energy sector. Transitioning to a clean industry is essential for ensuring future competitiveness. This transition necessitates not only the reduction of carbon emissions but also the assurance of reliable and affordable clean energy. Accurate thermometry is an enabling technology that facilitates the optimization of energy safety, storage, and transmission. It also contributes to the enhancement of industrial efficiency. Fiber optic thermometry has emerged as a promising solution for applications where conventional electrical temperature sensors are impractical. This technology offers unique advantages, including immunity to electromagnetic interference and the ability to make spatially distributed measurements over long distances. However, the lack of metrological characterization, and thus SI traceability, currently hinders its widespread adoption. As with all sensors, fiber optic sensors exhibit cross-sensitivities and aging effects that must be investigated, quantified, and minimized to ensure low uncertainty temperature measurements.

Over the past three years, the European project INFOTherm has begun to unlock the full potential of fiber optic thermometry by addressing current limitations and implementing calibration methods and infrastructure. A key aspect of this project was demonstrating fiber optic thermometry in real-world scenarios. Industrial case studies examined the ability of fiber optic thermometry to optimize energy infrastructure and improve the efficiency of processes in high-temperature industrial environments.

Case studies have been performed in thermal energy storage in molten salt tanks, geothermal systems, submarine cable monitoring, high-voltage component diagnostics, and silicone and glass production. These successful case studies were made possible by improving fiber optic thermometry throughout the project, particularly by enabling the traceable calibration and reducing measurement uncertainties, while extending the operational temperature range.

This presentation will provide a comprehensive overview of the INFOTherm project, with a focus on the practical implementation of fiber optics in the energy and industrial sectors. Recent progress will be highlighted. This includes improved calibration techniques for distributed sensing methods and advancements in fiber optic sensors for high temperatures.

2:45pm **TS-WeA-3 Distributed Fiber-Optic Thermometry for High-Fidelity Temperature Metrology in Harsh and Thermally Heterogeneous Environments***, KOUSTAV DEY, Grant Whitham, **Laura Bartlett**, Rony Kumer Saha, Farhan Mumtaz, Ronald J. O'Malley, Jeffrey D. Smith, Rex E. Gerald II, Jie Huang,* Missouri S&T

Recent advances in distributed optical fiber sensing are enabling transformative approaches for high-resolution temperature metrology in harsh manufacturing environments. In this work, we developed a scalable, high-resolution distributed thermometry platform based on Rayleigh backscattering (RBS)-enabled optical frequency domain reflectometry (OFDR) for real-time spatial thermal mapping during the aluminum casting process. The system utilzed silica optical fibers (UHNA1, Thorlabs) interrogated with a high-speed OFDR platform, enabling high-density thermal metrology with a resolution of approximately 0.65 mm (~1538 points m^{-1}) and acquisition rates up to 62 Hz. The sensing approach was successfully integrated into elevated-temperature casting environments, including the casting of AA356 aluminum in 3D-printed investment shells. Distributed thermal data were acquired throughout the full casting cycle, including shell preheating, molten metal pouring, and subsequent solidification at temperatures approaching 700 °C, showing trends consistent with thermocouple measurements. The platform effectively captured localized thermal gradients, transient heat-transfer phenomena, and the spatio-temporal evolution of temperature during solidification, while the optical fiber remained intact after molten metal pouring and was reusable for subsequent measurements, demonstrating the robustness of the sensing platform in harsh casting environments. Unlike conventional thermocouple-based systems, the distributed fiber-optic approach provided near-continuous thermal measurements along the length of a single optical fiber, significantly improving spatial sensing capability while remaining minimally invasive. The results demonstrate the strong potential of RBS-enabled distributed fiber-optic sensors as robust thermometry platforms for metal casting and other advanced manufacturing applications operating in extreme environments. This work further establishes a foundation for intelligent process monitoring, real-time thermal diagnostics, and digital twin-enabled manufacturing systems, while highlighting the broader applicability of distributed fiber-optic thermometry for next-generation harsh-environment sensing technologies.

3:00pm **TS-WeA-4 Toward SI-Traceable Photonic Thermometry using Dual-Comb Spectroscopy***, **Peter Chang**, Nathan Brooks, Tsung-Han Wu,* Chi3 Optics

Precise measurements of temperature are an important requirement in many fields, with functions ranging from process control in manufacturing, to disease treatment in medicine, to military applications. Whereas the Standard Platinum Resistance Thermometer (SPRT) is a robust and simple method to measure temperature to uncertainties less than 10mK, their sensitivity to mechanical shock and need for routine calibration has motivated research to establish platforms based on photonic thermometry [1]. A photonic thermometer is composed of an element highly sensitive to temperature (a photonic thermistor), and a means to reference the device to a primary standard. For example, a prominent platform is the silicon photonic thermometer (SPoT), which uses the narrow resonance of a photonic crystal cavity that can be calibrated against the thermal Brownian motion of its nanomechanical resonator [2]. Here, we propose a platform based on dual-comb spectroscopy (DCS), where the absolute frequency axis retrieved in DCS is used to provide a primary standard. In particular, by leveraging developments in low SWaP and compact fully self-referenced frequency combs, we aim to employ a high resolution 50MHz dual-comb spectrometer covering 30nm of optical bandwidth in the C-band. This spectrometer can be paired with a fiber Bragg grating [3] or a NIST standard reference gas-cell [4] to resolve temperature-dependent frequency shifts below 100MHz with direct SI traceability. Its high resolution targets the 10 mK sensitivity range, while SI traceability can be provided either in the RF by locking the repetition rate to a reference oscillator, or in the optical domain by locking a comb line to an optical standard. Together, these capabilities point toward a compact and fieldable thermometry platform relevant to precision metrology in demanding environments.

References:

1. N. Klimov, T. Purdy, and Z. Ahmed, "Towards replacing resistance thermometry with photonic thermometry," Sens. Actuators Phys. 269, 308–312 (2018).
2. T. P. Purdy, K. E. Grutter, K. Srinivasan, and J. M. Taylor, "Quantum correlations from a room-temperature optomechanical cavity," Science 356, 1265–1268 (2017).
3. A. J. Fleisher, Z. Ahmed, T. Herman, and M. R. Hartings, "Dual electro-optic frequency comb photonic thermometry," Opt. Lett. 48, 2210 (2023).
4. Y. Pang, L. Xu, X. Zhang, Z. Cao, Y. Ding, and G. Wang, "Accurate gas temperature measurement via iterative fitting of dual-comb spectral absorbance versus lower-state energy dependence," Opt. Express 33, 37913 (2025).

3:15pm **TS-WeA-5 A Practical Approach to Johnson Noise Thermometry***, Robert Crabtree,* Isothermal technology Ltd, UK*; **Carl Baines**,* Isothermal Technology Ltd, UK

Johnson Noise Thermometry (JNT) offers a primary, electrically traceable approach to temperature measurement.

Achieved by directly linking the Johnson noise voltage across a resistive probe to temperature as defined by the Johnson-Nyquist equation. Presented is aconcise overview of JNT from its theory, through prior arts to modern techniques, and outlining real-world applications. Topics include noise signal acquisition and processing, andpractical challenges of implementation across laboratory and industrial environments. Recent advances in JNT development to realise a practical Johnson noise thermometer will also be examined, with a discussion of its evolving role within the broader landscape of precision thermometry.

3:30pm **TS-WeA-6 Validated Dissemination: What Makes a Primary-Standard Bridge Trustworthy in a Post-Redefinition Traceability Chain***, **Abhishek Sengupta,*** WIKA Group, UK

Since the 2019 kelvin redefinition, thermodynamic temperature can be realized directly through methods anchored to the Boltzmann constant. Realization, however, is not dissemination - and dissemination determines whether a primary realization becomes a deployable, qualified measurement in the field. A calibrated kelvin still reaches accredited laboratories and industrial processes through standard platinum resistance thermometers and the ratio bridges that read them.

This contribution is from the manufacturer of one such instrument: the WIKA CTR9000, an AC resistance ratio bridge built on the ASL technology deployed at most national metrology institutes for ITS-90 realization and dissemination. One reason it occupies that role at parts-per-billion scale is architectural. Top-tier bridges derive accuracy from transformer-based ratio determination set by integer winding counts that cannot drift. The CTR9000 implements this in AC - continuously alternating excitation, inductive voltage divider ratio determination, quadrature balancing - where thermal EMFs sit at DC and never enter the measurement bandwidth, so each reading is a continuous measurement rather than a composite of two opposite-polarity readings combined by symmetry.

What gives the 20 parts-per-billion specification its standing is the framework of independent validations behind it: zero and unity checks, complement measurements by swapping resistors and evaluating the reciprocal, ratio test units against a calculable network, resistance bridge calibrators against a combinatorial standard, and long-term stabilization during manufacture. Each catches an error the others would miss, each works by physical manipulation of real ratios, independent of internal references. This carries the instrument from factory specification to qualified field deployment.

Drawing on a current cooperation with PTB on the CTR9000, the talk frames the AC bridge as the interface between primary realization and accredited dissemination. Of the methods enabled by the redefined kelvin, Johnson noise thermometry sits closest: a quantum voltage noise source provides the reference against which a sense resistor's thermal noise is compared, and the resistance contributes directly to realized temperature. As photonic, optomechanical, and noise-based primary thermometers move from laboratory demonstration toward deployable, qualified systems, each will face the question the bridge has answered over decades: not how accurate it can be in principle, but what architecture and framework will make the trust transferable.

4:15pm **TS-WeA-9 Fiber Optic Phosphor-Based Temperature Sensors: Can It Replace Industrial Platinum Resistance Thermometers (IPRTs)?***, Noah J.J. Johnson,* ***Michael Goldstein,*** Accelovant Technologies Corporation, Canada

IPRTs are the industrial standard for highly accurate, reliable and repeatable temperature measurement in the range of -200°C to 650°C. Despite their rugged construction, IPRTs do suffer from drift due to mechanical shock and vibration necessitating costly routine recalibration. Fiber optic phosphor-based temperature sensors can potentially achieve drift free performance that require no recalibration over time. These sensors are also unaffected by electromagnetic fields, RF, MRI, and microwave radiation making them attractive for medical and high-voltage environments. The all optical sensing tip eliminates sparking and electrical hazards making them suitable for oil, gas, and mining industries. In this talk, we will present our successful effort towards commercializing fiber optic phosphor-based temperature sensors that outperform the tolerance specification of commercial IPRTs. Temperature measurement range (-200°C to 650°C), drift (<0.05°C for 1000 hours at 450°C) and repeatability (within ±0.01°C) measurements show they can potentially match current industrial performance standards. The presentation will highlight the technology and its overall suitability as an easily scalable, cost effective replacement of IPRTs in various industrial applications.

4:30pm **TS-WeA-10 Industry Panel Discussion - Scaling Up Temperature Innovation: Challenges, Opportunities, and Global Adoption -- Panelists: Isotech, WIKA, Fluke, Chi3 Optics, U.S. Air Force**

Panelists: Isotech, WIKA, Fluke, Chi3 Optics, U.S. Air Force

This industry panel brings together leaders from Isotech, WIKA, Fluke, Chi3 Optics, and the U.S. Air Force to examine how next–generation temperature–sensing technologies can move from laboratory innovation to broad industrial deployment. Panelists will discuss commercialization challenges, key roadblocks, and practical strategies to accelerate worldwide adoption of advanced temperature–metrology solutions.

Thursday Morning, November 12, 2026

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

The Future of Temperature Sensing IV

Moderators: Dr. Nikolai Klimov, National Institute of Standards and Technology, **Dr. Sesha Challa**, NIST-Gaithersburg

8:00am **TS-ThM-1 Magnomechanical Noise Thermometry***, **John Davis**,* University of Alberta, Canada **INVITED**

Virtually every quantum technology needs to be operated at some level of low temperatures to generate and protect low energy quantum states.As a result, cryogenics has become a critical enabling tool in the race to develop quantum technologies.Yet little attention has been paid to the thermometry that allows us to quantify these low temperatures.As an example, most users of a dilution refrigerator simply take for granted that the resistive temperature sensor they use to measure millikelvin temperatures is accurate (and actually represents their experimental temperature).A such, we believe that a renewed focus must be put on primary temperatures sensors in the sub-kelvin regime to ensure that quantum technologies and their enabling cryogenics can be accurately measured and compared between laboratories.To this end, we are working on a type of mechanical noise thermometry using the techniques of cavity optomechanics.I will provide the background and context of this temperature sensor and where we are in its development.

8:30am **TS-ThM-3 Compact Blackbody Radiation Atomic Sensor (CoBRAS)***, Eric Norrgard,* National Institute of Standards & Technology*; **William Newman**,* National Institute of Standards and Technology

The NIST Fundamental Thermodynamics group is leveraging the physical properties of atoms to provide accurate metrology of radiative temperature. Atoms are quantum systems whose interactions with electromagnetic radiation have been characterized with exquisite precision and, in many cases, are amenable to ab initio calculation. Compact Blackbody Radiation Atomic Sensor (CoBRAS) uses fluorescence detection of optically excited atoms in vapor cells to determine temperature. A CoBRAS temperature measurement is fast, with statistical uncertainty as low as 0.1% in one second. We provide an update on the temperature precision, range, and sensitivity of the CoBRAS. We also describe a new fiberized CoBRAS sensor with a form factor similar to traditional four-wire resistance thermometers.

8:45am **TS-ThM-4 Electro-Optic Frequency Comb Doppler-Broadening Thermometry***, **Sean Bresler**,* University of Maryland, College Park/National Institute of Standards and Technology (NIST)*; Erin Adkins,* National Institute for Science and Technology (NIST)*; Stephen Eckel,* National Institute of Standards and Technology (NIST)*; David Long,* National Institute for Science and Technology (NIST)*; Benjamin Reschovsky, Daniel Barker,* National Institute of Standards and Technology (NIST)

We demonstrate Doppler-broadening thermometry based on direct optical frequency comb spectroscopy of an 85Rb vapor with a chirped electro-optic frequency comb (EOFC). The direct EOFC Doppler-broadening thermometry measurements are accurate to within their approximately K statistical uncertainty. We experimentally compare direct EOFC spectroscopy with conventional Doppler spectroscopy using a single-frequency, step-scanned laser probe. Our results show that direct EOFC spectroscopy mitigates transit-induced optical pumping distortion of the atomic lineshape, which is the dominant systematic temperature shift in alkali atom Doppler-broadening thermometry. Optical Bloch equation simulations of conventional and direct EOFC Doppler spectroscopy confirm that EOFC spectroscopy can use higher optical power to reduce statistical noise without optical pumping distortion. Our results indicate that EOFC Doppler-broadening thermometry is a promising approach to realizing a primary thermometer with size and measurement rate sufficient for applications including pharmaceutical manufacturing and nuclear waste monitoring.

9:00am **TS-ThM-5 Towards Practical Integrated Primary Thermometry with Optomechanical and Photonic Techniques***, **Olga Kozlova**,* LNE-Cnam, France **INVITED**

Temperature is one of the most commonly measured physical quantities and influences nearly every physical, chemical, and biological process. Photonic and quantum-based approaches have the potential to transform practical thermometry by enabling *in-situ* traceability without requiring sensor removal for recalibration. A further advantage of these optical methods is their compatibility with silicon photonics, allowing on-chip integration thus to have the potential to radically improve thermal management of semi-conductor devices.

In this presentation, I will give an overview of the progress of European Partnership in Metrology Joint Research Project: Photonic and Quantum Sensors for Practical Integrated Primary Thermometry (PhoQuS-T) [1]. This project aims to develop integrated optical practical primary thermometry from 4 K to 500 K to enable *in-situ* traceability for practical applications.To achieve this, we combine several techniques: photonic thermometry using ring resonators; optomechanical noise thermometry and quantum correlation thermometry with opto-mechanical resonators. In addition, key challenges such as robust packaging over a wide temperature range are being addressed, along with metrological validation of the developed sensors and the exploration of future application possibilities.

At the current stage of the project, recent progress in photonic thermometry and optical noise thermometry from 4 K to 300 K, using 1D- and 2D- optomechanical sensors, will be presented. The next steps toward self-calibration using quantum thermometry (quantum correlation techniques [2]) will also be discussed. An overview of advances in high-resolution photonic sensors based on ring resonators operating over an extended temperature range (80 K to 500 K) will be given, along with updates on the development of a novel active thermometry approach [3]. Progress in packaging techniques (including gluing, welding, and mechanical support) for the developed sensors will also be presented.

Finally, developments toward practical application of such photonic sensors (including temperature monitoring of photonic integrated chips for optical clocks and assigning temperature in quantum-based pressure measurements) will be discussed.

References:

[1] https://www.mdpi.com/2673-8244/5/3/44

[2] https://www.science.org/doi/10.1126/science.aag1407

[3] https://doi.org/10.1098/rsta.2024.0459

9:30am **TS-ThM-7 Two-Dimensional Silicon Optomechanical Crystals for Quantum-Referenced Temperature Sensing***, **Daniel Ramos**,* CSIC, Spain*; María José Martin Hernandez,* CEM, Spain*; Irene Castro,* CSIC, Spain*; Iago Sanchez,* CEM, Spain

Accurate temperature sensing at the nanoscale remains a central challenge for emerging quantum, photonic and nanomechanical technologies, where local heating, weak thermal anchoring and limited calibration accuracy can strongly affect device performance. Optomechanical systems offer a route to temperature sensing based on the thermal occupation of mechanical modes, enabling local, contactless and potentially self-calibrated thermometry through the optical readout of mechanical motion.

Here we present the design and first experimental realization of a two-dimensional silicon optomechanical crystal engineered as a platform for temperature sensing across the transition from the classical thermal regime toward the quantum regime. The device integrates a telecom C-band optical cavity and a co-localized GHz radial-breathing mechanical mode within a two-dimensional phononic shield. This architecture combines strong optical–mechanical confinement with improved thermal anchoring to the substrate compared with conventional one-dimensional optomechanical cavities, reducing absorption-induced heating while preserving high displacement sensitivity.

The geometry was optimized using three-dimensional simulations and machine-learning-assisted parametric sweeps to achieve operation in the resolved-sideband regime, high optical and mechanical quality factors, and strong optomechanical coupling. These characteristics enable sensitive monitoring of the mechanical noise spectrum as a function of temperature and provide the basis for sideband-resolved thermometry at low phonon occupation. In this regime, the Stokes and anti-Stokes sidebands provide a direct route to absolute quantum thermometry, since their asymmetry is determined by the mean phonon population rather than by an external thermal calibration.

We discuss how this two-dimensional optomechanical platform can be used for temperature sensing from elevated temperatures down to cryogenic conditions, with particular emphasis on quantifying local optical heating, calibrating phonon occupation, and approaching the quantum ground state. By combining heterodyne sideband readout, optomechanical cooling and sideband-asymmetry thermometry, the device provides a route toward quantum-referenced nanoscale temperature sensing. These results position two-dimensional silicon optomechanical crystals as a promising integrated platform for future temperature sensors operating beyond conventional calibration limits.

9:45am **TS-ThM-8 Developing Thermal Magnetic Imaging for Advanced Semiconductor Packaging**, ***Frank Abel***, *Thinh Bui, Mahadi Rajib,* National Institute of Standards and Technology (NIST)*; Brian Donovan,* United States Naval Academy*; Solomon Woods,* National Institute for Science and Technology (NIST)

As the number of transistors on a single chip has approached its physical limit, the architectural complexity of semiconductor packaging in the form of heterogeneous 3D integrated components has been developed to meet the demand for high performance computing. However, with increased complexity comes significant thermal management issues, which are a crucial factor in designing new high-density semiconductor packages. These challenges require new measurement techniques to quantify temperature and heat flow during operational conditions through opaque materials with greater than 1 mm of depth penetration. For the past 5 years, our team at NIST has been developing magnetic imaging instrumentation and magnetic nanoparticle thermometers for 3D temperature imaging. Here, we present our progress in designing temperature- and signal-sensitive magnetic nanoparticle tracers integrated into proxy semiconductor materials, including silicon substrates, thermal interface materials (TIMs), and underfills. Along with the demonstration of solid-state imaging of embedded tracers in silicon imaging phantoms.

The Future of Temperature Sensing
Room Ballroom A - Session TS-ThP

The Future of Temperature Sensing, Poster Session

TS-ThP-1 Progress Towards Simplified Measurement Schemes for Optomechanical Quantum-Correlation Thermometers*, **Daniel Barker,*** National Institute of Standards and Technology*; Ana Rakonjac,* Measurement Standards Laboratory, New Zealand*; Biswarup Guha, Kartik Srinivasan, Nikolai Klimov,* National Institute of Standards and Technology*; Thomas Purdy,* University of Pittsburgh

Optomechanical thermometry is a promising route to portable primary thermometry from room temperature down to a few kelvin. Quantum noise arising from the zero-point motion of a mechanical oscillator can provide *in situ* calibration of the oscillator's thermal motion. In an optomechanical system, the resonator undergoes thermal Brownian motion, driven motion from the light in the cavity, and optomechanical backaction. Noise correlators can be employed to separate thermal and quantum signals, thereby forming a quantum-correlation thermometer and enabling primary temperature measurements. The optomechanical cavity is chip-scale, which allows for integration with other chip-scale sensors. Fiber-optic readout makes optomechanical thermometers suitable for a variety of applications, including those in which conductive sensor leads cannot be used. However, the measurement precision of quantum-correlation thermometers is not presently competitive with existing secondary thermometers, and reducing systematic uncertainties is an ongoing challenge.

We use a waveguide-coupled GaAs nanobeam resonator with an optical resonance in the telecom wavelength range and a mechanical resonance around 2.6 GHz as our optomechanical thermometer. The optomechanical resonator is installed in a low-vibration cryostat along with a resistive cryogenic thermometer that independently monitors the temperature. Our detection scheme utilizes a double-mix-down technique, where optical carrier sidebands generated by an electro-optic modulator mix with the mechanical signal in the resonator and are then combined with a local oscillator in a heterodyne measurement. This method requires only a single channel for data acquisition, with subsequent phase-sensitive signal processing performed entirely in software. We report on progress towards primary thermometry using this simplified measurement scheme and provide an outlook for future work.

TS-ThP-2 Progress Towards Doppler Thermometry in Microfabricated Vapor Cells*, **Ryan Johnson**, Yu-Ting Chen, Sean Bresler, Erin Adkins, Matthew Hummon, Benjamin Reschovsky, Vladimir Aksyuk, Stephen Eckel, Tobias Herman, John Kitching, Daniel Barker,* NIST

We report on our effort to develop Doppler thermometers using microfabricated atomic vapor cells. The Doppler broadening of spectral lines relates gas temperature to physical constants and immutable gas properties, enabling primary thermometry. We present measurements of the Doppler broadening in a microfabricated rubidium vapor cell from 25 °C to above 100 °C. The accuracy of the fitted Doppler temperature is limited by parasitic etalons in the vapor cell. To reduce the temperature uncertainty, we are implementing improved physical models of the etalon transmission. We also discuss prospects for improving the accuracy and increasing the operating temperature range of atomic Doppler thermometers using microfabricated cesium and ytterbium vapor cells.

TS-ThP-3 Thermal Noise Measurements in a Cavity Electro-Optic System*, **Griffin O'Neal-Freeman,*** University of Pittsburgh

Resonant electro-optic transducers are a promising platform for high-sensitivity microwave detection and quantum frequency conversion. By utilizing a fully-resonant, all-dielectric architecture, we achieve high photon-number conversion efficiencies, enabling the up-conversion of thermal microwave photons into the optical domain. In this work, we explore the application of these transducers as high-precision temperature sensors. We are interested in investigating Raman sideband asymmetry thermometry, a technique employed in spectroscopy, fiber optic sensing, and cavity optomechanics to make calibrated temperature measurements. We present preliminary experimental results demonstrating the optical detection of the thermal occupation of a 16GHz microwave mode with a signal-to-noise ratio of a few. Ongoing efforts focus on mitigating material losses and optimizing resonator geometry to enhance coupling and further suppress technical noise. Ultimately, this electro-optic platform offers a path toward precision temperature sensing, quantum-limited radiometry and quantum communication.

TS-ThP-4 The Recent Advancement of Crystalline Core and Crystalline Cladding Sapphire Fibers for Extreme High Temperature Environment Sensing*, **Shizhuo Yin,*** Penn State University

In this paper, we report the recent progress of crystalline core and crystalline cladding sapphire fibers and its potential applications for extreme high temperature >1500 oC sensing. In particular, we will discuss the single-transverse-mode clad sapphire fiber.

TS-ThP-5 Chip-Scale Photonic AC –DC Thermal Transfer Device*, **Pavan Challa**, Kevin Douglass, Michal Chojnacky, Thinh Bui, Tam Duong,* NIST-Gaithersburg*; Michael Sherman, Dorin Shapira, Leeya Engel,* Technion Israel Institute of Technology, Israel*; Stefan Cular,* Howard Community College*; Nikolai Klimov,* NIST-Gaithersburg

We present a chip-scale photonic ac–dc thermal transfer device that provide an alternative to conventional multijunction thermal converters (MJTCs) for establishing the traceability link between dc electrical units and practical ac voltage and current measurements. While MJTCs offer the highest accuracy available today, they exhibit intrinsic ac–frequency–dependent transfer errors arising from parasitic capacitive coupling between the resistive heater and the thermocouple array. To overcome these limitations, we introduce an integrated photonics-based architecture that replaces the thermoelectric sensor with an electrically passive, silicon photonic microresonator thermometer – the Standard Photonic Thermometer (SPoT). In the SPoT sensor, Joule heating under ac or dc excitation produces a highly sensitive shift in the optical resonance frequency. Because the optical readout is electrically isolated from the heater, the device measures Joule-heating-induced temperature rise without capacitive pickup, thus eliminating fundamental error mechanics present in MJTC-based thermal-transfer metrology.

We report the first prototype of photonic ac–dc thermal transfer standard device, termed the thermal-transfer SPoT (T-SPoT). The device integrates a waveguide-coupled SPoT sensor with an on-chip microheater and is interrogated using resonance-scanning optical readout. Ac–dc difference measurements are performed as a function of ac frequency at fixed voltage and benchmarked against a calibrated MJTC standard using a drift-rejecting triplet measurement sequence. The initial T-SPoT results demonstrate performance consistent with expectations for a first-generation photonic thermal transfer device and reveal clear pathways for further improvement through enhanced optical-frequency readout and thermally optimized device architectures. These results establish a foundation for next–generation photonic ac–dc transfer standards with improved robustness, scalability, and long–term stability.

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