XXIII IMEKO World Congress "Measurement: sparking tomorrow's smart revolution"
August 30 – September 3, 2021, Yokohama, Japan

EMERGING TECHNOLOGIES IN THERMOMETRY

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Abstract – Today's resistance thermometers can routinely measure temperatures with uncertainties of >1 mK to 100 mK over multiple decades of temperatures. As the modern economy continues to evolve, so does the measurement infrastructure. In recent years, there has been a considerable progress in the development of novel temperature sensing technologies driven by advances in quantum information science and nano-photonics. Quantum technologies in particular hold the promise of field-deployable primary thermometry whilst ultra-stable nanophotonic thermometers could displace resistance thermometers as commodity sensors.

Keywords: quantum opto-mechanics, Doppler Broadening thermometry, NV Diamond, photonic thermometry

1. BASIC INFORMATION

Temperature measurements encompass almost every aspect of modern life ranging from advanced manufacturing of microprocessors to medicine to baking a soufflé [1] (see ref within). In all these varied activities temperature stands as a proxy for measurement of thermal energy in the system – a simple and accurate measurement of thermal energy of the system is non-trivial and as such, temperature sensors have become a ubiquitous stand-in. Many thermometry techniques have been developed to meet the varied needs of the user community including resistance-based devices, such as thermistors and platinum resistance thermometers, as well as other sensing modalities including thermocouples and diodes. Standardized manufacturing of these devices ensures an acceptable uncertainty (100 mK to few kelvin) over the given temperature range using nominal coefficients. Tighter uncertainty performance (< 100 mK) requires time consuming calibrations of each individual sensor.

Given the ubiquity of temperature measurements in modern commerce and the impracticality of realizing thermodynamic temperature in the field, a rigorous protocol- the International Temperature Scale of 1990 (ITS-90) published by the Consultative Committee for Thermometry (CCT) of the International Committee for Weights and Measures (CIPM)- has been developed to ensure measurement reproducibility and repeatability across the world. Presently, measurements of thermodynamic temperatures are often achieved by laborious primary gas thermometry using acoustic measurements in a gas of known purity, pressure and volume. Alternative approaches demonstrated during the redefinition effort include Doppler broadening thermometry (DBT) and Johnson noise thermometry. The ITS-90 uses a practical measurement scheme to closely approximate true thermodynamic temperature laying out the *mise en pratique* for the realization and dissemination of temperature [2, 3]. ITS-90 leverages the universality of thermo-physical properties of pure materials such as elemental metals (e.g. gold, silver and tin) or molecular species (e.g. water) to ensure that this scale can be implemented anywhere and produce calibrated sensors that are completely interchangeable. Specifically, the ITS 90 defines the freezing, melting or triple point temperature for a series of materials ranging from the triple point of hydrogen at 13.8033 K to the freezing point of copper at 1357.77 K. At temperatures between 0.9 mK to 1 K, the provisional low temperature scale of 2000 (PLTS-2000) is used. Once a thermometer is measured at two or more of these "fixed-point," the ITS 90 defines an interpolating function to allow the calibrated sensor to provide consistent temperature measurements that closely approximates true thermodynamic temperature and ensure comparability of temperature measurements around the globe [2, 3].

2. EMERGING TECHNOLOGIES

The temperature sensor market is a multi-billion-dollar enterprise and is expected to grow as the use of temperature sensors continues to proliferate [4]. The ubiquity of temperature sensors, i.e. the size of the market, is a powerful motivation for developing novel technologies targeted towards meeting present and future measurement needs of the user community. The existing metrology infrastructure and user expectations of performance metrics, low cost of sensor ownership, small footprint and low power budget represent formidable barriers to wide-spread adoption of any new technology. As such, any emerging technology will have to not only provide a novel utility but will likely have to be backwards compatible with existing infrastructure e.g. any potential SPRT (standard platinum resistance thermometer) replacement in ITS-90 thermometry will need to be have a SPRT-like form-factor. A larger device would require significant redesign of existing infrastructure, an expense that may deter interested users. Similarly, the technology must be amenable to automation to lower cost of operation.

2.1. Quantum Enabled Thermometry

Infrastructure being developed to enable Quantum 2.0 technologies has fostered growth in thermometry techniques as advance technologies become ubiquitous and new problems emerge. For quantum technologies arguably the most impact has been made in electrical noise thermometry where development of quantum-based voltage waveform synthesizer has been instrumental in enabling precision measurement of the Boltzmann constant opening up an avenue for primary realization of temperature [5].

Alternatives to JNT include primary electrical shot noise thermometry (SNT) [6] and magnetic tunnel junction thermometry (MJT) [7]. SNT is being explored as an embedded primary thermometer for measuring temperature in super conducting qubits used in quantum computing applications where temperature of the qubit informs on its initial state. SNT uses the voltage-dependent electrical noise from a tunnel junction to relate temperature to voltage using the ratio of electrical charge to Boltzmann constant (e/kB) and the assumption that electrons in a metal obey Fermi-Dirac statistics. SNT has been demonstrated from room temperature down to 50 mK with accuracies of 103 ppm at 1 kelvin-level temperatures and 200 ppm at 0.5 K. While these results represent a factor of five improvement in absolute accuracy over the state-of-the-art Coulomb Blockade thermometers, they currently fall well-short of being competitive with resistance thermometry. Any application of SNT beyond the niche application will require significant improvements in precision and accuracy of the measurement, especially at temperatures above 80 K.

In recent years MJT has garnered interest as an embedded temperature probe in complex, 3D microchips. A MJT device is composed of two magnetic layers separated by a thin oxide layer. The tunnel resistance is strongly dependent on the orientation of the magnetization relative to layer across the tunnel barrier. A small change in the magnetization direction, e.g. due to thermal effects can result in significant changes in resistance. The resistance in MJT device is inversely correlated with increasing temperatures and has been used to demonstrate fast temperature readouts in embedded devices in electronic devices [7].

While electrical-based quantum technologies may have had a leg up on the competition, photonics and phononics-based technologies are rapidly gaining ground. Laboratory scale DBT [8] and optical gas refractivity[9] measurement systems were successfully used to realize the Boltzmann constant to within 24 ppm and 2.2 ppm of the CODATA (Committee on Data for Science and Technology) value. A practical deployment of these devices, however, requires scaling down of the active “sensor” area by a few orders of magnitude, an endeavour more amiable to DBT than gas refractivity, where efforts in DBT will benefit from on-going work in frequency metrology to produce fiber-coupled vapor cells [10].

Arguably, the most exciting development in quantum-based thermometry techniques has been in optomechanical thermometry as this technology is amiable to being embedded into quantum computing infrastructure to determine a qubit’s initial state by measuring is phonon occupation state.

Optomechanical sideband ratio thermometry has been used to measure thermodynamic temperature of nano-mechanical devices over an extended range of temperatures from 500 μK up to 50 K [11], while quantum cross-correlation technique probing side band asymmetry extend temperature measurements up to 300 K [12]. Realization of a practical optomechanical primary thermometer with acceptable uncertainty will require overcoming several challenges including the need to significantly increase the optomechanical transduction factor, to develop robust vacuum-compatible packaging, and to characterize systematic temperature effects such as self-heating and the quantum properties of the cavity optomechanical systems (e.g., cavity chaos and characterization of energy flow between the bath and mechanical modes of the resonator).

Another quantum technology quietly making inroads in the world of thermometry is Nitrogen Vacancy (NV) diamond. Optical detection of magnetic resonance (ODMR) in NV diamond has been extensively studied as a potential room-temperature quantum-computing platform[13-15]. Over the past decade, numerous groups have demonstrated proof-of-concept quantum NV sensors for electrometry, magnetometry, velocimetry, pressure sensing, in vivo MR imaging, and thermometry [16] (and ref within). In thermometry application, NV is limited to 1000 K as the ODMR contrast vanishes at higher temperatures. At low temperatures, NV thermometry is being used to understand thermal transport at the nanoscale.

As our understanding of quantum information systems increases, new technologies continue to emerge. In recent years, phonon transport in narrow, phononic waveguides have garnered attention as possible quantum information buses. Tools being developed for quantum acoustics present an unexplored avenue for realizing primary thermometry based on the thermal quantum of conductance (QTC) [17]. The QTC describes the rate at heat transport in a channel through single ballistic phonon. This universal limit on the rate of heat transport through a quantum mechanical link, first measured in 2000, is given by $G = T^*g_o$, where $go = \pi^2k^2/h^2 = 9.456 \times 10^{-13}$ W/K^2. A realization of temperature based on G would be based on transport and hence be fundamentally distinct from existing measurement schemes based on noise measurements (e.g., electronic, photonic or phononic) or equation of state measurements (e.g., acoustic gas thermometry). This measurement scheme is best understood in analogy to the quantum Hall effect: by passing a known power through a quantum link a known temperature difference will be realized. Because the conductance itself is linearly dependent on the mean temperature of the two reservoirs, it could provide a path to absolute thermometry. Any QTC-based measurements, however, will undoubtably face significant challenges related to minimization of phonon backscattering. Since a QTC based realization is based on measurement of net phonons transported from the bath to the reservoir, any backscattering from fabrication errors, material non-uniformities or electronic systems and their inter-connects with the phononic system will degrade measurement quality.

2.2 Photonics-Enabled, Defined-Scale Thermometry

Nano-photonics infrastructure developed to support the telecommunication industry and the emerging quantum industry has been harnessed to provide new avenues for the realization and dissemination of ITS-90. Commonly referred to as photonic thermometry, photonic temperature sensors rely on light-matter interactions to transduce temperature changes into frequency changes [18]. To meet the immediate temperature sensing needs of the consumers, researchers have focused on the development of fiber-optic (silica) and chip-based silicon photonic sensors [18-27] Regardless of the device materials or geometry, photonic devices typically use spectroscopic techniques to detect temperature-induced changes in a substrate's refractive index and physical dimensions. The changes in effective length of the resonator directly alter the resonance frequency of the photonic element. A temperature resolution of a few microkelvin can be readily achieved over integration times ranging from 1 second to few thousand seconds. The ultimate limit to the noise floor is set by fundamental processes such as thermo-refractive noise, thermo-elastic noise, Brownian noise, photothermal noise, pondermotive noise and Kerr-effect non-linearities [28]. On a practical level the working noise floor is typically elevated due to contributions of self-heating (photo-thermal noise), laser noise, wavelength measurement scheme limitations, and long-term thermal drift due to chemical and/or physical changes in the sensor and/or packaging.

To date, research in this area has been driven by metrology specific aims such as the determination of measurement range, noise floor, and uncertainty [20, 22, 29]. While delivering a high resolution, low uncertainty measurement is an important metric, it ignores the economic realities of use-case applications which are equally likely to guide technology adoption. The largest driver of size, weight, power, and cost for a photonic thermometry is the need for a broadly tunable laser to track the resonance frequency of a single mode over a wide temperature range. In classical optics, the free spectral range of an optical cavity, evacuated or filled with ideal gases, is routinely tracked using a narrowly tunable laser as the dispersion-induced changes in mode characteristics are negligible. Such an approach was used by Egan *et al* [30] to demonstrate primary measurements of pressure using optical refractometry with Helium-Neon lasers. In photonic thermometry the picture is complicated by strong material and modal dispersion, scattering induced mode mixing and avoided mode crossings, and modal dependence of mode volume [18] (and ref within), which often results in consecutive resonance modes exhibiting an overall trend towards increasing temperature sensitivity with mode number (Fig 1). Results such as these suggest that any measurement approach relying on mode interchangeability will incur large uncertainty penalties. Ongoing efforts to develop cost-effective broadband interrogators and fast data processing routines that take the multiple bands into consideration [31] will go a long way to making photonic thermometry accessible to a wider user community.

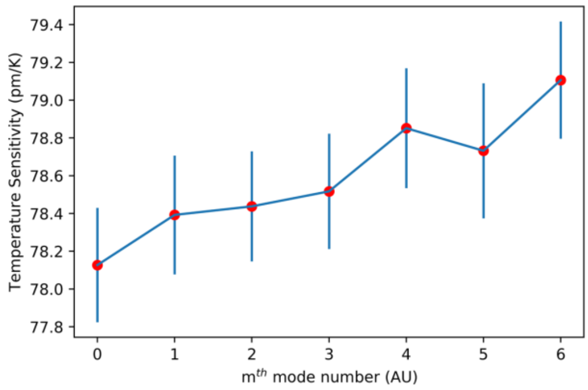

Figure 1: Temperature sensitivity shows a statistically significant dependence on mode number

3. CONCLUSIONS

The rise of quantum 2.0 technologies and the redefinition of temperature based on the Boltzmann constant has opened up new avenues for making high-accuracy temperature measurements more broadly available. Quantum technologies such as JNT, on-chip DBT, optomechanical thermometry, cavity-enhanced optical refraction, and NV diamond have demonstrated tremendous growth over the past decade and spurred numerous new investments at national, academic, and industrial labs. On the other hand, photonic thermometry techniques such as light scattering thermometry (Raman and Brillouin thermometry) and fiber Bragg grating thermometry are already commercially available from several vendors.

On-chip photonic thermometry as a potentially more powerful alternative to both fiber and resistance thermometry has seen significant developments. Over the last decade, researchers have demonstrated temperature measurements with a noise floor of 30 nK or better. It is anticipated that if an adequate packaging solution are developed, these devices could cover the range from triple point of hydrogen to the aluminium freezing point or higher.

ACKNOWLEDGMENTS

The authors acknowledge Weston Tew and Stephen Eckel for helpful discussions.

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