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One-Step Traceability with NIST on a Chip: A Case for the Emergence of Quantum-Based Methods for Metrology and Sensing of Pressure, Vacuum, Temperature, Electric Fields, Mass, Force, and Torque, all enabled by the New SI.

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Summary:
The world is changing. Measurements are everywhere. As sensors are embedded into everyday products and electronics, the importance of sensors that give “the right answer” or “none at all” is of growing importance. The traditional role of the national metrology institute (NMI) is also changing with the 2019 revision of the international system of units. This revision removed long-standing artifact-based standards in favor of fundamental constants of nature. Sensors that are built on fundamental physics, constants of nature, and in many cases quantum-based systems will open a new paradigm for metrology. NIST has developed the “NIST on a Chip” program with a far-reaching vision that the future of metrology will be based on a new suite of sensor technologies that effectively removes the need for calibration instruments or artifacts to be returned to the NMI for periodic recalibration. This will be due to the inherent stability of these sensors that ideally will be small, compact, take advantage of nanomanufacturing, nanophotonics, future development of on-chip lasers, frequency combs, photon sources and detectors, etc. This paper will briefly discuss the promise for sensors and standards of pressure, vacuum, temperature, electric field, mass, force, and torque.

Keywords:

NIST on a Chip, NOAC, pressure, vacuum, cold atoms, fixed length optical cavity, Fabry Perot, quantum, nanophotonics, national metrology institute, temperature metrology, thermometry, photonics, Rydberg atoms, electrometry, revised SI, radio frequency, sensing, communications, Kibble balance, revised SI, force measurements, torque measurements

Introduction

The role of NIST as a National Metrology institute (NMI) is changing due to a world-wide redefinition of units that occurred on May 20th, 2019. The re-definition of units is now aligned with physical constants of nature and fundamental physics which has now opened new realization routes with quantum-based sensors and standards. The NIST on a Chip program (NOAC) is strategically positioned to take advantage of this change. The re-definition of the SI units enables new ways to realize the units for the pascal (pressure and vacuum), the kelvin (temperature), and the kilogram (mass). These quantum-based systems, however exciting, do raise new challenges and several important questions. Can these new realizations enable the size and scale of the realization to be miniaturized to the point where it can be imbedded into everyday products? What will be the role of metrology institutes in this new ecosystem of metrology and measurement? What will be the NMI role for quality systems and measurement assurance for these new quantum-based systems? [1] This paper will briefly review several emerging technologies for measurements of pressure, vacuum, temperature, electric fields, mass, force and torque. These methods are viewed through the redefinition of units that occurred in 2019 and the overall viewpoint of potential impact to the NIST on a Chip (NOAC) program.

Pressure

The next generation of pressure standards will provide a new route of SI traceability for the pascal. By taking advantage of light interacting with a gas the pressure-dependent refractive index of helium can be precisely predicted from fundamental, first-principles quantum-chemistry calculations. This enables a new route for realizing the pascal which has now been demonstrated.

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From a metrology standpoint, the new quantum-based SI pascal will move us from the classical force/area definition to an energy density (joules per unit volume) definition. Should the technique be further miniaturized, it will lead to a revolution in pressure metrology, enabling a photonics-based device that serves both a gas pressure sensor and a portable gas pressure standard all in one. In the future, the mercury barometer will be replaced with a new standard based on quantum chemistry calculations.

Figure 1: Fixed Length Optical Cavity developed under a CRADA (Collaborative Research and Development Agreement) with MKS Instruments. The FLOC will enable the replacement of artifact-based mercury manometers world-wide. Photo courtesy of MKS Instruments.

The new method relies on a pair of optical cavities, each consisting of a set of mirrors on a spacer with the gas/vacuum filling the space between the mirrors. To improve upon this design, the reference cavity is always kept at vacuum to help eliminate noise and other systematic errors. This device, referred to as a Fixed Length Optical Cavity (FLOC), is shown in Figure 1. The FLOC is made of a glass with Ultra-Low thermal Expansion (ULE) to prevent changes in interferometer length with temperature. The upper cavity consists of a slot to allow gas to easily flow in and out, whereas the reference cavity is a hole drilled through the glass block and sealed at either end via mirrors.[2-5] The FLOC shown in Figure 1 was developed under a CRADA (Collaborative Research and Development Agreement) between NIST and MKS Instruments.

Vacuum

For vacuum measurements, NIST efforts to develop a new vacuum standard for measuring and understanding the pascal at the lowest pressures is underway. To achieve this, the Cold-Atom Vacuum Standard (CAVS) has been developed which uses a cold atom trap to sense pressure. [6] Since the earliest days of neutral atom trapping, it has been known that the background gas in the vacuum limits the trap lifetime (the characteristic time that atoms remain trapped). NIST is taking advantage of this well-known effect to create a quantum-based standard and sensor for vacuum measurement.

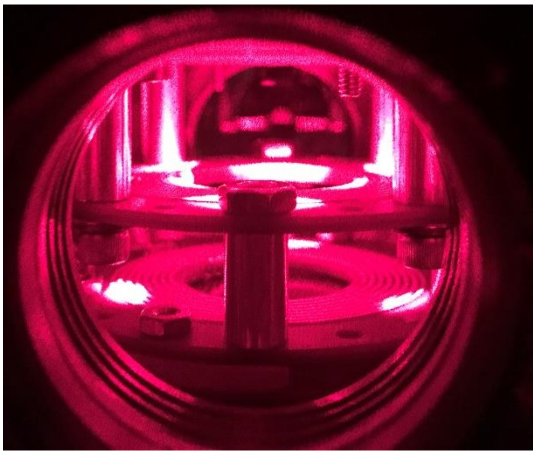

Figure 2: NIST CAVS table-top prototype version with a cloud of trapped Li atoms.

Because the measured loss-rate of ultra- cold atoms from the trap depends on a fundamental atomic property (the loss-rate coefficient, related to the thermalized cross section) such atoms can be used as an absolute sensor and primary vacuum standard. Researchers have often observed that the relationship between the trap lifetime and background gas can be an indication of the vacuum level, and several research groups have pursued using cold atom traps as vacuum sensors. [8,9] However, an absolute vacuum standard, sufficient for use as an international standard, has not yet been realized. To do this requires rigorous attention to all potential error sources, from both the atomic perspective and the vacuum perspective. Moreover, a primary CAVS requires the collision cross section between trapped ultra-cold atoms and the background gas to be traceable to an ab initio theoretical determination. NIST has built a laboratory-scale CAVS apparatus, developed the measurement scheme, and done preliminary theoretical calculations, all of which show promising early results. In addition, NIST is developing a small, portable version that uses a grating-based trap (shown in Figure 2) that will eventually enable users to realize and measure vacuum pressures in their lab without relying on calibrated sensor artifacts.

Temperature

For temperature measurements, NIST efforts to develop a method of measuring temperature using a photonic-based method are underway. Temperature measurements and sensors play a crucial role in various aspects of modern technology ranging from medicine and manufacturing process control to environmental borehole monitoring. Among various temperature

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measurement solutions, resistance-based thermometry is a time-tested method of disseminating temperature standards. [10]

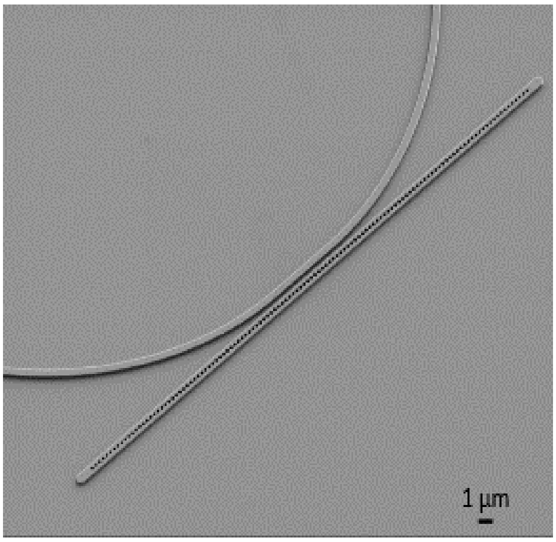

Figure 3. Silicon photonic crystal cavitythermometer fabricated at NIST

Although industrial resistance thermometers can routinely measure temperatures with uncertainties of 10 mK, their performance is sensitive to multiple environmental variables such as mechanical shock, thermal stress and humidity. These fundamental limitations of resistance thermometry, as well as the desire to reduce sensor ownership cost, have ignited a substantial interest in the development of alternative temperature measurement solutions such as photonics-based temperature sensors [11,12]. These sensors are Fabry-Perrot cavity type silicon photonic devices that are based on a Photonic Crystal nanobeam Cavity (PhCC), whose high-Q resonant frequency mode is highly sensitive to even ultra-small temperature variations. Measurement results show the NIST photonic nanothermometers can detect changes of temperature as small as sub-10 µK and can achieve measurement capabilities that are on-par or even better than the state-of-the-art platinum resistance thermometry.

Electric Field Measurements

Absolute measurements of electric fields are vital in various applications, such as precision metrology, communications, and sensing. However, measuring the electric field's strength accurately is a challenging task due to the lack of reliable calibration standards. The traditional calibration methods rely on accurate measurements of the geometry of the sensing probe and a chain of calibrations to determine absolute field strength with an order of 5 % uncertainty. NIST is developing an alternative approach that utilizes Rydberg atoms for measuring electric fields with improved accuracy and simplicity.

Rydberg atoms made with alkali atoms such as rubidium have a single valance electron which enables the accurate calculation of the quantum mechanical response of these atoms to radio frequency electric fields. The researchers employ a spectroscopy technique known as electromagnetic induced transparency (EIT) and a resonant effect known as Autler-Townes (AT) splitting to measure the Radio Frequency (RF) field strengths exposed to the atoms [13].

The Rydberg atom-based technique provides a direct traceability path for RF electric field strength to be determined directly from fundamental units of the SI, namely the Planck constant accomplished through the calculable response of the atoms given by the dipole moment and dictated by quantum mechanics.

Using this technique, Rydberg atom sensors have been shown to achieve sensitivities down to 5 $\mu Vm_{-1}Hz_{-1/2}$ [14] and as receivers of amplitude, frequency, and/or phase modulated signals [15,16].

Mass, Force and Torque

The reciprocity in Maxwell's equations that Bryan Kibble saw in 1975 [17] proved to be a powerful principle for high-precision metrology and allows the precise comparison of electrical power to mechanical power with relative uncertainties close to 1 part in 10^8. With the 2019 redefinition, the kilogram (kg) is now defined in terms of the Planck constant. This eliminated the artifact-based standard for mass. NIST has built systems based on the Kibble principle [18,19] that are high accuracy, full laboratory scale instruments. With the 2019 redefinition, NIST is now showing that the Kibble principle has fantastic potential be useful in mass-produced devices for mass, torque, and force. NIST has developed table-top prototype instruments that calibrate mass, force, and torque using Kibble's principle. For the torque project, NIST researchers have shown the performance on a device that can measure torques ranging from order 1 mN·m to 18 mN·m.

Conclusion

Sensors that are built on fundamental physics, constants of nature, and in many cases quantum-based systems are being developed worldwide at National Metrology Institutes. NIST has developed the NIST on a Chip program with a long-term vision that the future of metrology will be based on a new suite of sensor technologies. While the example technologies discussed in this paper are emergent, NIST has demonstrated several tabletop versions. Should these be further developed by industry, reduced in size, weight and power and integrated into commercial products, a new paradigm will emerge that will reduce or eliminate the need for instrument recalibration. This will be due to the inherent stability of these sensors that ideally will be small, compact, take advantage of other quickly developing fields and technologies, including nanomanufacturing, nanophotonics, future development of on-chip lasers, frequency combs, photon sources and detectors, to name a few.

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