17FUN05 PhotOQuanT

Publishable Summary for 17FUN05 PhotOQuanT
Photonic and Optomechanical Sensors for Nanoscaled and Quantum Thermometry

Overview

Photonic sensors use light-matter interaction to measure temperature and other physical quantities via temperature-dependent material properties. A particularly promising new development is the possibility of using optomechanical sensors to produce quantum primary standards. Photonic and optomechanical temperature sensors enable a spatial resolution adapted for the measurement of temperature at micrometer length scale where usual sensors are unsuitable. These sensors will have optimised sensitivity as well as robustness to mechanical constraints and chemical species, and will be of prime importance for the future dissemination of the kelvin following its forthcoming re-definition in 2018.

Need

Driven by new technologies such as “lab on a chip”, microelectronics, optoelectronics or microfluidics, the demand for advanced manufacturing metrology is growing. Currently, intelligent embedded sensors are widely integrated into production processes, measurement and inspection of manufactured products, as well as in aerospace and transportation applications.

Temperature is probably the most important physical variable of state, influencing almost every physical, chemical, and biological process. Surprisingly, the world’s most accurate temperature sensors, standard platinum resistance thermometers (SPRTs), rely on antiquated technologies that do not lend themselves to miniaturisation, portability, or wide dissemination. Moreover, SPRTs are sensitive to mechanical shock, thermal stress and environmental variables such as humidity and chemical contaminants that cause irreproducibility and drifts. These fundamental limitations have stimulated the quest for improved temperature sensors. Photonic temperature sensors are inexpensive, lightweight, portable, and resistant both to mechanical shock and to electromagnetic interferences. However, such sensors require the development of specific calibration and characterisation systems to provide traceability where usual macroscopic metrological standards are not applicable.

Despite their high accuracy, primary thermometers e.g. acoustic gas thermometers, dielectric gas thermometers, Johnson noise thermometers, doppler broadening thermometers) are complex and fragile thus inappropriate for dissemination purposes, whereas optomechanical devices provide a small, reliable and cost-effective primary temperature sensing method. Such sensors use zero-point motion vacuum noise as a quantised standard to scale thermal noise, and recent improvements enable to assess the feasibility of this method at room temperature using miniaturised devices.

The high quality needed for photonic and optomechanical resonators depends on photoelastic properties of the involved materials and the losses of the guided modes. However, the existing database on photoelastic properties and losses (mechanical and optical) come from studies on bulk materials, which is not sufficient for the optimisation of the resonators used in this project.

Objectives

This project aims at exploring the potential of high resolution photonics and optomechanical sensors in terms of sensitivity, uncertainty and resolution for realising future quantum and nanoscaled temperature standards. The specific objectives are:

1. To design and fabricate different photonic and optomechanical devices dedicated to temperature metrology at the nano- and micro-scale: photonic crystal cavities, micro-rings, micro-disks and membrane resonators with high optical (for photonic sensors: $Q_o>10^5$; for optomechanical sensors: $Q_o>10^8$) and mechanical quality factors ($Q>10^4$).

2. To investigate the optical and mechanical performance (photo-elastic properties) of several silicon-based and diamond-based materials, and their influence on the quality factor (*Q*) of the optical and mechanical resonators. To study the viability of using these materials in quantum optomechanical resonators.

3. To characterise the metrological repeatability, sensitivity and stability of both photonic and optomechanical devices, and demonstrate quantum-based read-out protocols for optomechanical devices as quantum primary temperature standards up to ambient temperature.

4. To develop methods for calibrating the developed mesoscopic sensors traceable to the practical International Temperature Scale of 1990 (ITS-90) including the evaluation of the uncertainty. Target uncertainties are below 1 mK for photonic sensors and below 1 K for optomechanical sensors in quantum regime (below 10 K).

5. To facilitate the adoption of the technology developed in the project by end users of thermometry and nanoscale technology.

Progress beyond the state of the art

One important objective of this project is to develop a quantum temperature standard using an optomechanical resonator. Thus far, only one laboratory (NIST) has produced and tested such a device up to room temperature. These results come from the first attempt of a single research group. The challenge of this quantum measurement is the detection of a very small quantum correlation between optical and mechanical states hidden by the strong Brownian motion growing with temperature. This explains why this project will first develop quantum thermometry and complex read-out technique at cryogenic temperature before scaling it to room temperature. The key points with quantum thermometry are not yet the temperature resolution but rather the temperature systematic effects and the quantum regime itself. This project will study the systematic effects associated with photonic and optomechanical sensors and will provide a full uncertainty budget of these high-performance temperature sensors. This project will provide the first uncertainty budget on quantum thermometry with optomechanical resonators, none having been reported before.

Two different types of mesoscopic temperature sensors will be developed in this project. Photonic sensors aim at overcoming SPRTs drawbacks (drift, low spatial resolution, sensitivity to mechanical shocks, electromagnetic field and chemical environments), while optomechanical sensors aim at providing a quantum standard for primary thermometry. Each of them addresses a different state of the art. Photonic devices will exhibit ultra-high resolution and stability, while optomechanical sensors will run in quantum regime to realise quantum measurement of temperature. Both types of sensors require high-Q optical resonators although they rely on different physical principles. For photonic sensors, the frequency of the optical resonance depends on temperature while for optomechanical sensors, the optical resonance is modulated (Raman sidebands) by the thermal vibrations (phonons). Then each of these two complementary temperature sensors follow a specific state of the art.

Results

Objective 1: In recent years a wide variety of novel photonic thermometers have been proposed including photosensitive dyes, fibre Bragg gratings (FBG), and on-chip integrated silicon photonic (Si-Ph) nanostructures. This project will design and construct photonic and optomechanical sensors with optical quality factors beyond the state of the art (photonic sensors: $Qo>10^5$; optomechanical sensors: $Q_o>10^8$). Within this project, photonic silicon resonators will be developed with the aim to outperform prior technologies by enhancing microscale sensor design, and using materials with improved stiffness and thermal conductivity.

Objective 2: Silicon photonic nanostructure devices can potentially compete with resistance-based standards and be manufactured using existing technologies. However, the ultimate limitations in optical and metrological performance of these technologies have yet to be reached, and no attempts have been made to explore other materials with better characteristics. This project will study the photoelastic parameters of the used samples, thus including effects of its geometry, of the mechanical stress applied to the membrane. These parameters will be evaluated with diamond, SiN and silicon resonators, for optimisation of their optical *Q* factor.

Objective 3: The sensors to be developed in this project will not only be more accurate, but also smaller, more robust and less sensitive to shocks and external variations than the more macroscopic platinum resistance thermometers. In addition, a procedure for quantum scale sensor calibration will be developed for the first time, where optomechanical resonators are calibrated at low temperature by linking them to primary quantum standards, and thermal noise thermometry is used to extend the temperature range towards room temperature without the need for further calibration.

Objective 4: Traceability to the kelvin has yet to be demonstrated for existing photonic thermometers. Their systematic effects will be studied to assess a realistic uncertainty budget depending on the used method (classical, quantum mechanical) and the device (photonic, optomechanical). Since quantum-based thermometry is most accurate near cryogenic temperatures where the thermal energy equals the quantum zero-point energy ($k_B T \approx h.f$), optomechanical devices with different mechanical resonance frequencies f will be fabricated to maximise accuracy of a large number of temperature ranges (product $f.Q > 10^{12}$ Hz with Q mechanical quality factor).

Impact

Impact on industrial and other user communities

The development and the metrological validation of optomechanical quantum temperature sensors solves the problem of drift of embedded sensors. These mesoscopic sensors will enhance the reliability of temperature measurement for applications in fields such as transportation industry, space instrumentation, engine monitoring, power plant safety and consumer electronics. More generally, photonic sensors developed in this project will have two advantages: robustness (to mechanical shocks, electromagnetic field, high energy particles, nuclear irradiation, chemical species) and high resolution.

Future on-chip optical communication applications face major issues with temperature management and require localised temperature measurements. With metrologically validated photonic sensors that are distributed over the silicon chip, one can envision more accurate power distribution and temperature control. Another rapidly growing product is the power transistor, more ubiquitously used for converting electric power in applications ranging from mobile phone chargers and solar panels to electric cars. Heat generation in these transistors causes thermomechanical stresses that can lead to dangerous short circuits that can cause fires or explosions in battery-driven applications. Accurate, distributed temperature sensors can prevent these failures and their related dangers.

Impact on the metrology and scientific communities

The measurement of thermodynamic temperature has been pushed to its ultimate performance for the determination of the Boltzmann constant and the forthcoming redefinition of the kelvin. This collaborative research project is the first European attempt to develop a quantum standard for temperature metrology. Optomechanical sensors will provide a primary temperature sensor of easy access to end users. This project also pave the way to high accuracy temperature measurement on a mesoscopic scale. With an improved robustness and sensitivity, photonic sensors could replace standard platinum resistance thermometers.

Impact on relevant standards

The performance and reliability of the sensors developed in this project and their robustness compared to Standard Platinum Resistance Thermometers in the realisation of a practical temperature scale will be presented to the Consultative Committee for Thermometry (CCT). The viability of optomechanical sensors as new primary thermometers and their inclusion in the mise-en-pratique for the definition of the kelvin will be also discussed.

Longer-term economic, social and environmental impacts

A wider impact of these sensors is foreseen in the field of metrology as the sensors based on quantum standards may renew thermometric methods in future years. As such sensors do not require any calibration against standard artefacts, metrological skills will shift from calibration services to sensor integration and expertise on systematic effects. These sensors are expected to have a wide impact on temperature metrology standardisation, in the same way as photonic sensors, which may one day replace the platinum resistance thermometers so widely used in process control or inspection at present. These primary thermometers operating at mesoscopic scale may push advances in biology research, health, environment and nuclear safety. The demonstration of the viability of these sensors in thermometry will also open the way to their use in other metrology fields as pressure or nano-force measurements.

Project start date and duration:	1st June 2018, duration 36 Months	
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