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

Overview

This project addressed the emerging technologies for temperature sensing, particularly in scope of precise temperature measurements up to nano-scale level and in scope of their application for future dissemination of the kelvin following its re-definition in 2018. During this project, different photonic and optomechanical systems were designed, fabricated, and characterised. Calibration methods have been developed to ensure the traceability to the International Temperature Scale of 1990 (ITS-90). Photonic sensors aim at overcoming standard platinum resistance thermometers (SPRTs) drawbacks (drift, low spatial resolution, sensitivity to mechanical shocks, electromagnetic and chemical environments), while optomechanical sensors aim at providing a quantum standard for primary thermometry. This project provided a systematic study (including an uncertainty budget) of these sensors, pointing out their potential, limitations and perspectives.

Need

For a wide range of processes, from consumer electronics to space instrumentation, a growing need to make temperature measurements at smaller scales has been evident. The range of currently available thermometers, however, cannot meet the challenge. Nanotechnology offered the possibility of innovative ‘photonic’ and ‘optomechanical’ sensors capable of measuring temperature on micrometre length scales. Not only could these new temperature sensors replace the standard high-accuracy platinum resistance thermometers but, embedded into production processes, many industrial users could benefit from the technology. Whereas temperature is probably the most important physical variable of state, influencing almost every physical, chemical, and biological process; the world’s most accurate temperature sensors, 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. This project has developed and studied photonic temperature sensors which are inexpensive, lightweight, portable, and immune to electromagnetic interferences. Such sensors required the development of specific calibration and characterisation systems to provide traceability where usual macroscopic metrological standards were hardly 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 enabled 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) came from studies on bulk materials, which has been insufficient for the optimisation of the resonators used in this project and required further investigation.

Objectives

The overall objective of the project was to provide a quantum temperature standard for self-calibrated embedded optomechanical sensor applications, as well as optimised high resolution and high reliability photonic sensors to measure temperature at the nano and meso-scales and as possible replacement for the Standard Platinum Resistance Thermometers broadly used in temperature metrology.

The specific objectives of the project were:

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 Mach–Zehnder interferometer and membrane resonators with high optical (photonic sensors: $Q_o>10^5$; optomechanical sensors: $Q_o>10^8$) and mechanical quality factors ($Q>10^4$). A high f-Q product (f.Q>10^{12} Hz) of the mechanical resonator (product of resonance frequency and quality factor) is targeted in this project to reach quantum regime with high quantum correlations between optical and motion states.

2 To investigate the optical and mechanical performance (photo-elastic properties) of several silicon-based and diamond-based materials and their influence in the quality factor 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. The target uncertainties on temperature measurement are below 1 mK for photonic sensors and below 1 K for optomechanical sensors in quantum regime (below 10 K).

5 To facilitate the take up of the technology, developed in the project, by end users in the field of quantum and nanoscaled technology.

Progress beyond the state of the art

Two complementary types of mesoscopic temperature sensors have been developed in this project. Photonic devices exhibit ultra-high resolution and stability (aiming at overcoming SPRTs drawbacks), while optomechanical sensors can 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 and follow a specific state of the art. 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). During this project, strong efforts have been made to push the state of the art of fabrication of photonic and optomechanical sensors following complementary strategies (materials, geometries, mechanical frequencies) for a most effective comparison. The investigation properties of silicon-based and diamond-based materials undertaken in frame of this project can serve as a basis for the material comparison illustrating the excellent properties of silicon devices in mass production with state-of-the-art technology and the potential of silicon nitride and diamond for thermometry approaching fundamental limits. The fabricated high-quality photonic sensors could ensure a temperature resolution at the level of 1 mK and was able to challenge the most accurate temperature sensors available (SPRT). Up to now, only one laboratory (NIST) has produced and tested a quantum temperature standard using an optomechanical resonator up to room temperature. The challenge of this quantum measurement was 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 had to develop complex read-out technique and test noise thermometry before testing quantum thermometry, starting from low temperatures (below 10 K). The key points with quantum thermometry are not yet the temperature resolution but rather the systematic effects related to this technique. First of all, the quantum regime requires small thermal damping i.e. a very high value (above THz) of the product "*Q.f*" ("*Q*" being the quality factor of the mechanical resonator and *"f"* being its mechanical resonant frequency). Within this project the fabricated optomechanical resonators went beyond the published state of the art for phononic shielding technology and showed *Q.f* product at the level of 10^{14} Hz. Secondly, the self-heating must also be kept reasonable, below few kelvins. Finally, optical detuning must be zeroed at a very high precision (1/1000th of the width of the optical resonance at 10 K, 1/10 000th at 100 K) as the sensitivity of quantum correlation to optical detuning is proportional to the temperature. Thus, with in this project a study the systematic effects associated with photonic and optomechanical sensors was carried out and an uncertainty budget associated to these emerging technologies has been provided.

Results

Objective 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 Mach–Zehnder interferometer and membrane resonators with high optical (photonic sensors: $Q_o>10^5$; optomechanical sensors: $Q_o>10^8$) and mechanical quality factors ($Q>10^4$). A high f-Q product (f.Q>10^{12} Hz) of the mechanical *resonator (product of resonance frequency and quality factor) is targeted in this project to reach quantum regime with high quantum correlations between optical and motion states.*

This project was designing and constructing 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 have been developed with the aim to outperform prior technologies by enhancing microscale sensor design, using materials with improved stiffness and thermal conductivity.

Photonic resonators made of silicon mononitride (SiN) with over 120 individual micro-ring resonators operating in optical telecom wavelength C-band (1520-1590 nm) have been designed with different combination of ring diameters and coupling efficiencies for their optimisation. Their high optical quality factor (Q_0 ~10^5) provides sharp optical resonance (~10pm) required for high temperature resolution measurements thanks to the resonator optical refractive index (~74 pm / K). The photonic resonators exhibit also a near perfect Notch optical filter with a residual transmission below 5 % level. These high-quality resonators ensured a temperature resolution at the level of 1 mK (equivalent to a fraction of 0,07 % of the resonance width), able to challenge the most accurate temperature sensors available (standard platinum sensors). Chip temperature and electromagnetic field distributions have been simulated including self-heating caused by optical absorption for different materials, and resonator geometries.

Diamond photonic resonator has been designed using specific softwares developed for the numerical simulation of physical properties of microring diamond resonators (temperature sensitivity, self-heating). These computations showed a sensitivity about 13 pm / K, with small self-heating but also a high stiffness and thermal conductivity, very promising for optomechanical thermometry. Fabricated polycrystalline diamond photonic crystal exhibits too high optical and mechanical losses for thermometric application in this project. Thus, first prototypes of diamond optomechanical resonators made on single crystal (monocrystalline) have been fabricated by CSIC.

The optomechanical sensors fabricated for this project have been designed for quantum measurement up to room temperature. A quantum correlation read-out protocol scales the thermal fluctuation directly in terms of quantum fluctuations and yields a temperature etalon. This strategy requires the thermal fluctuations mechanical oscillation to keep small over one period i.e. mechanical product of quality factor and mechanical frequency must satisfy $Q.f > 10^{12}$ Hz for a temperature range up to 100 K.

While the resonators fabricated for this project both satisfy this requirement, two complementary strategies have been implemented by SU - CNRS and TUD partners.

SU - CNRS have developed a 1D nanobeam optomechanical resonator having a high mechanical frequency (f~3 GHz) but moderate quality factor (Q~2 10^3) for keeping the mechanical oscillator closer to its ground state whereas TUD has developed a low frequency (f~1 MHz) but ultimate quality (Q~10^8) mechanical resonator, thus breaking the published state of the art for phononic shielding technology together with Q.f level (10^{14} Hz). The capability of this optomechanical resonator has been demonstrated with the optical cooling of its resonant mechanical mode below 1,5 mK which shows its ability for quantum thermometry, at least below 0.1 K.

As a conclusion, strong efforts have been made to push state-of-the-art photonic and optomechanical sensors following complementary strategies (materials, geometries, mechanical frequencies) for a most effective comparison. The objective 1 has been successfully achieved.

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

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 prior to this project no attempts have been made to explore other materials with better characteristics. This project studied the photoelastic parameters of the used samples, thus including effects of its geometry, of the mechanical stress applied to the membrane. These parameters have been evaluated with diamond, SiN and silicon resonators, for optimisation of their optical *Q* factor.

A setup for absolute measurement of photoelastic constants of macroscopic samples has been designed and measured at room temperature on a silicon sample at a wavelength of 1550 nm with a relative uncertainty of 0.3 % which is one order of magnitude better than other measurement techniques in literature. Specific test structures dedicated to the measurement of photoelastic constants in small samples have been fabricated. Mechanical losses with different aspect ratios and clamping have been estimated. Measurements of mechanical losses have been realised on microcantilever arrays (SiO_2) with ring down technique from 5 K to 300 K. An analytical model has been developed for self-heating, temperature field and mechanical stress simulation in photonic microrings and microdisk resonators, with the following input parameters: material properties, resonator geometry, two-photon absorption.

The characterisation of photo-elastic material properties and mechanical loss investigations on silicon, silicon nitride and diamond have been finalised. In addition, photothermal properties have been successfully extracted from transmittance measurements in silicon photonic microring resonators. These experimental activities have been complemented by numerical and semi-analytic modelling of self-heating due to material absorption. All the results served as a basis for the material comparison illustrating the excellent properties of silicon devices in mass production with state-of-the-art technology and the potential of silicon nitride and diamond for thermometry approaching fundamental limits. The objective 2 has been successfully achieved.

Objective 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.

The photonic sensors developed in this project can be more accurate, but also smaller, more robust and less sensitive to shocks and external variations than the more macroscopic platinum resistance thermometers. A fibre optic set-up based on a tuneable laser, traceable to an acetylene stabilised laser, together with a nm-positioning system has been developed for the read-out of photonic sensor temperature. Read-out protocol has allowed to demonstrate the very high Q factor (Q=1.6 10^5) of the fabricated optical resonators together with a high contrast of the notch filter (-12 dB). The temperature sensitivity was about 72 pm / K^{-1}, quite linear from 25° C to 40 °C with a good repeatability (about 1 pm / ~14 mK). The reproducibility has been enhanced with active feedback loops for laser power and frequency stabilisation.

Preliminary to the quantum correlation technique, a noise thermometry experimental set-up has been developed and studied from 4 K to 300 K. The thermal fluctuations of the high frequency (Ω=3 GHz), high quality (Q=2500) mechanical resonator of the optomechanical sensor, are transduced into optical phase noise. Using a probe laser detuned from the optical resonance, the optical resonator converts its thermal phase noise into thermal intensity noise. The reflected laser power spectrum is then simply observed with a fast photoreceiver loaded onto an electrical spectrum analyser. Thus, the observed spectrum exhibits the mechanical resonances of the optomechanical sensor. The temperature is then simply proportional to their area. This optical noise thermometry technique requires rigorous calibration of the mechanical susceptibility of the device using a frequency tone close to the mechanical resonance. At high temperature, thermal noise dominates quantum noise so that quantum correlation technique is limited in practice to low temperature range. Nevertheless, the temperature of the device may be extrapolated from low temperature using optical phase noise thermometry technique.

Noise thermometry read-out protocol has been tested on two complementary geometries of optomechanical sensors: a “2D” geometry and a “1D” geometry. The temperature of a “2D” SiN square membrane optomechanical sensor (mechanical resonance frequency: 1.34 MHz, mechanical quality factor:10^6, width: 80 nm, side-length: 250 μm) has been determined from 5 K to 260 K with this read out technique. The temperature of a “1D” GaP nanobeam optomechanical sensor (mechanical resonance frequency: 2.7 GHz, mechanical quality factor: 1 000, length: 20 μm long, lateral size: 700 nm) has been determined from 5 K to 300 K with this read out technique. Noise thermometry technique is much more sensitive with low frequency “2D” membrane resonator than with high frequency 1D” nanobeam resonator. Nevertheless, a repeatability of the temperature about 10 % has been estimated with both devices. Detection noise of side-of-fringe technique is limited by optical shot noise, forcing the optical power of the probe laser to high level (typ 100 μW), above the threshold (10 μW) of two-photon absorption. Therefore, homodyne balanced optical detection has been developed to enhance the signal to noise ratio at low probe laser power. The systematic errors associated to fibred homodyne balanced optical detection have been identified. Spurious interferences in optical fibres generate an amplitude modulation of the calibration tone. The simplest solution being to move as possible to free space optics. The amplification of the probe laser beam after its reflection by the optomechanical resonator has also been tested with success: a mechanical spectrum has been recorded with only 500 nW of probe laser power.

As a conclusion the objective 3 was partially achieved. The following systematic effect had to be solved before attempting to use quantum correlation for quantum primary thermometry: optical bistability caused by optical absorption and self-heating but also the residual amplitude modulation caused by the electrooptical phase modulator and analysed by the birefringent optical fibres. The photonic devices were metrologically characterised (repeatability, sensitivity, and stability). The optomechanical devices were only characterised in the noise thermometry read-out protocol.

Objective 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. The target uncertainties on temperature measurement are below 1 mK for photonic sensors and below 1 K for optomechanical sensors in quantum regime (below 10 K).

Specific thermostats covering the temperature range from 5 °C to 95 °C have been designed and fabricated for photonic thermometry. As silicon ring resonators has been coupled to the probe laser via a micrometre air gap and coupling gratings, the thermostat was based on a temperature-controlled platform connected to a conventional water thermostat. Another thermostat platform was connected to the optical fibres positioning units to avoid their misalignment while the temperature of the photonic ring resonator was varied. With this set-up, a coupling stability of 1 % has been achieved over the full temperature range. Calibrated Pt100 probes ensured traceability to the kelvin unit. The uncertainty of the temperature reading using photonic ring resonator in such thermostat remained below 15 mK. The major uncertainty components were the calibration of the wavelength (8 mK) and the calibration of the Pt100 (8 mK).

Two specific thermostats have also been fabricated to ensure traceability to the kelvin of the optomechanical noise thermometry technique. One thermostat was a constant flow ^{4}He cryostat with operating range from 4 K to 300 K. Temperature gradient and stability (6 hours) stand below 100 mK over the whole temperature range, assuming thermal equilibrium between the optomechanical resonator and the Cernox calibrated probes. The second thermostat was a cryogenic vacuum chamber (no ^{4}He flow) operating in a similar temperature range (1.5 K to 270 K). It was also equipped with Cernox calibrated probes, with 100 mK uncertainty. The self-heating of the “2D” membrane optomechanical resonator studied remained ten times smaller (self-heating ΔT = 0.2 K at temperature T= 5 K for a laser power about 70 μW) in comparison to “1D” nanobeam optomechanical resonator studied (self-heating ΔT = 2 K at temperature T= 100 K for a laser power about 100 μW). This was explained by a much higher value of optical power per unit surface within the 1D nanobeam in comparison to the 2D membrane, which drives two-photon absorption converted into heat. The more dramatic self-heating effect in case of 1D geometry is also due to the geometry of the thermal boundaries assuming better heat dissipation from the sensor into the substrate in the case of 2D membrane in comparison to 1D nanobeam.

As a conclusion, the objective 4 was mainly achieved in terms of the developed methods for ITS-90 traceable calibration of the new sensors. The photonic thermometry and optomechanical noise thermometry have been demonstrated but their attached uncertainty values around room temperature with 12 mK uncertainty, above the uncertainty target of the project (1 mK). The optomechanical noise thermometry has been demonstrated with an uncertainty above 10 K from 4K to 300 K, above the uncertainty target.

Impact

The project results have been presented at 16 European and international conferences (e.g. CPEM 2018, EQTC 2019, TEMPMEKO 2019, SMSI 2020, Graphene & 2D Materials Industrial Forum 2021, GSELOP2021) and at EURAMET TCT meetings (May 2018, April 2019, September 2020). The project partners are involved in the task group of the Comité consultatif de thermométrie (Emerging technologies). Four meetings of the stakeholder committee have been held on the occasions of preparation of 1st report in Madrid in February 2019, 2nd report in Delft in November 2019, 3rd report (online meeting) in December 2020 and final report in Berlin (hybrid meeting) in November 2021. Based on the activities presented by the partners during the reporting meetings, newsletters have been prepared and distributed within the stakeholder committee and other interested parties. Also, an online International Workshop has been organised at the end of the project in order to exchange knowledge and introduce the project results to the international scientific community involved in this field (external researchers from USA and China have also presented their research). The consortium produced 14 peer reviewed articles / proceedings, out of which are 12 published thus far. A final summary with the project results has been published in MPDI Optics 2022: "Photonic and Optomechanical Thermometry" https://www.mdpi.com/2673-3269/3/2/17/pdf. The project information and links to the publications and the presentations can be found on the project website (https://projectsites.vtt.fi/sites/photoquant/publications.html).

Impact on industrial and other user communities

The photonic sensors developed in this project (objective 4) shall provide a solution to *in-situ* temperature measurement in harsh environments such as high energy particles, nuclear irradiation, chemical species) and high resolution. The optomechanical noise thermometry has been demonstrated whereas the temperature uncertainty (few K) was still limited by some systematic effects for industrial applications. Nevertheless, technical solutions to the systematic effects have been identified, for their test in near future.

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 was the first European attempt to develop a quantum standard for temperature metrology. The developed optomechanical sensors provide first primary temperature sensors of easy access to end users. This project also paved 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.

The metrological characterisation of photo-elastic material properties and mechanical loss investigations on silicon, silicon nitride and diamond shall have a strong impact on scientific community as it provides a physical model and a material database for designing the process of high-performance ring resonators sensors.

Impact on relevant standards

The performance and reliability of the new type of sensors developed in this project and their potential in terms of robustness (compared to Standard Platinum Resistance Thermometers) in the realisation of a practical temperature scale have been discussed on CCT Task Group for Emerging Technologies (CCT-TG-CTh-ET) in October 2020. The viability of optomechanical sensors as new primary thermometers and their inclusion in the mise-en-pratique for the definition of the kelvin has been also discussed.

Longer-term economic, social and environmental impacts

A wider impact of the sensors developed within this project 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. Nowadays, the uncertainty attached to photonic and optomechanical sensors is still limiting their impact on temperature metrology. Photonic sensors could also 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.

Developed photonic devices can be used for temperature control in harsh environment for microprocessor production process, high power transistors, telecommunications. Optomechanical sensors shall be competitive at cryogenic temperature for absolute temperature determination: below 1K, the magnitude of thermal noise becomes comparable to quantum noise floor. Thus, the performance of optomechanical sensors in quantum entering quantum regime should be enhanced towards absolute zero kelvin.

List of publications

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This list is also available here: https://www.euramet.org/repository/research-publications-repository-link

Project start date and duration:	1st June 2018, 42 months	
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Internal Funded Partners: 1 CNAM, France 2 CEM, Spain 3 LNE, France 4 PTB, Germany 5 VSL, Netherlands 6 VTT, Finland	External Funded Partners: 7 CNRS, France 8 CSIC, Spain 9 IHP GmbH, Germany 10 SU, France 11 TU Delft, Netherlands 12 TUBS, Germany	Unfunded Partners: -
Linked Third Parties: 13 UPD, France (linked to CNRS)		
RMG: -		