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
The overall objective of the project is 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 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 Mach–Zehnder interferometer and membrane resonators with high optical (photonic sensors: $Q_0 > 10^5$; optomechanical sensors: $Q_o > 10^9$) and mechanical quality factors ($Q > 10^4$). A high f-Q product ($fQ > 10^{12}$ 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 uncertainty 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**

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 are being 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.

The designed and fabricated Zipper optomechnical resonator exhibit a mechanical Q.f product (quality factor times resonant frequency) above $10^{13}$ Hz, at telecom wavelength (C-band). A very efficient phononic shield which provides a very high mechanical Q factor (Q=10^7) above state-of-the-art published level.

**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: $Q_o > 10^9$) and mechanical quality factors ($Q > 10^4$). A high f-Q product ($fQ > 10^{12}$ 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 is designing and constructing photonic and optomechanical sensors with optical quality factors beyond the state of the art (photonic sensors: $Q_0 > 10^5$; optomechanical sensors: $Q_0 > 10^8$). Within this project, photonic silicon resonators are being 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 ($Q_0 \sim 10^5$) provides sharp optical resonance (\(\sim 10\) pm) required for high temperature resolution measurements thanks to the resonator optical refractive index (\(\sim 74\) pm/K). The photonic resonators exhibit also a near perfect Notch optical filter with a residual transmission below 5 % level. These high-quality resonators will ensure 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 show 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 and are currently under test.

The optomechanical sensors fabricated for this project are 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 100K.

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 (\(f \sim 3\) GHz) but moderate quality factor (\(Q \sim 2 \times 10^3\)) for keeping the mechanical oscillator closer to its ground state whereas TUD has developed a low frequency (\(f \sim 1\) MHz) but ultimate quality ($Q \sim 10^8$) 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.

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 studies the photoelastic parameters of the used samples, thus including effects of its geometry, of the mechanical stress applied to the membrane. These parameters are being 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 has 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.

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 being 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. 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 ($Q=1.6 \times 10^5$) of the fabricated optical resonators together with a high contrast of the notch filter (-12 dB). The temperature sensitivity is about 72 pm.K$^{-1}$, quite linear from 25$^\circ$ C to 40 $^\circ$C with a good repeatability (about 1 pm). The reproducibility is being enhanced with active feedback loops for laser power and frequency stabilisation.

In addition to photonic thermometry, quantum thermometry is realised using high quality optomechanical resonators. In this primary thermometer, the quantum reference is provided by the phase noise of the probe laser. A quantum correlation is created between its amplitude and phase noise by the optomechanical coupling process (i.e. light pressure reaction on the mechanical resonator). As the optomechanical resonator transduces the mechanical thermal noise into optical phase noise, the quantum correlation is used to determine the temperature of this device. Whereas quantum component of the laser phase noise remains small compared to thermal contribution, the quantum correlation technique provides a high detectivity.

At high temperature for which thermal noise strongly dominates quantum noise, the quantum correlation reading becomes limited by signal to noise ratio. Thus, the thermodynamic temperature of the device may be extrapolated from low temperature quantum correlation technique using optical phase noise thermometer whose optical phase noise power scales linearly with thermodynamic temperature. This optical noise thermometry technique requires rigorous calibration of the mechanical susceptibility of the device which may be realised with a calibrated frequency tone.

First temperature measurements with optomechanical noise thermometry technique have started at TUD at room temperature using a medium frequency (MHz) ultra high quality ($Q=10^6$) Zipper type optomechanical resonator operating at telecom wavelength (1550nm). Homodyne detection and optomechanical transduction are being calibrated with a dedicated technique using a reference frequency modulation of the laser power spectrum which is equivalent to a mechanical displacement thanks to optomechanical transduction process. Facing difficult optical coupling of a 1064 nm laser beam into a very high quality factor ($Q\sim10^3$) nanobeam optomechanical resonator, SU has decided to switch to another 1D nanobeam device working at telecom wavelength (1550nm) but having a high mechanical frequency (3 GHz) and a high $Q.f =10^{12}$ Hz product but also a lower optical quality factor. The read-out setup has then been adapted to this telecom optical wavelength and the first optical measurement of the resonant mechanical mode (3 GHz) has been performed with a side of the fringe read-out protocol. Pound Drever Hall and homodyne detection are under investigation for improved reading technical phase noise floor.

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

Traceability to the kelvin has yet to be demonstrated for existing photonic thermometers. Their systematic effects are 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 \((k_B T = \hbar f)\), optomechanical devices with different mechanical resonance frequencies \(f\) have been fabricated to maximise accuracy of a large number of temperature ranges (product \(fQ > 10^{12}\) Hz with \(Q\) mechanical quality factor). One thermostat is a constant flow ⁴He cryostat with operating range from 4 K to 300 K. Temperature gradient and stability (6 hours) are kept below 0.1 K over the whole temperature range, assuming there is a thermal equilibrium of the optomechanical resonator as required by this project for the validation of this sensor. The second thermostat uses two stages Peltier element to cool down the optomechanical device at approximately 170 K.

Various thermostats have been designed for the validation of photonic resonators based on different approaches. Some use water from high stability bathes for temperature-control while some use a chamber inside a temperature-controlled cabin. Preliminary tests have shown temperature homogeneity and stability at the mK level around room temperature. The fabrication of these thermostats is in progress and should be finished soon. The thermostats are characterised and modified in parallel to allow either fibre coupling or free space coupling of the probe laser to the photonic resonator.

**Impact**

The project and its latest results have been presented at several conferences (e.g. CPEM 2018, EQTC 2019, TEMPMEKO 2019, SMSI 2020) 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). A website dedicated to the project, containing news, documents and links, has been created. Three meetings of the stakeholder committee have been held, on the occasion of 1st interim report in Madrid in February 2019, at 2nd report in Delft in November 2019 and at 3rd report (online meeting) in December 2020. 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. They are also available on the project web page. Photonic and thermal modelling of microring photonic resonators fabricated with different materials (Silicon, Diamond and GaN) have been compared for temperature sensing and results published in 2020.

**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 (objective 4) 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 paves 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 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.

This project will provide high reliability robust miniature temperature sensors from cryogenics up to room temperature. Developed photonic devices can be used for temperature control in harsh environment for microprocessor production process, high power transistors, telecommunications. Optomechanical sensors will be competitive at cryogenic temperature for absolute temperature determination. They will provide state of the art quantum sensors at room temperature.

List of publications


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

<table>
<thead>
<tr>
<th>Project start date and duration:</th>
<th>1st June 2018, 42 months</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coordinator:</td>
<td></td>
</tr>
<tr>
<td>Stéphan Briaudeau, CNAM</td>
<td>Tel: +33 158 80 89 27</td>
</tr>
<tr>
<td>Project website address:</td>
<td><a href="https://www.vtt.fi/sites/photoquant/">https://www.vtt.fi/sites/photoquant/</a></td>
</tr>
<tr>
<td>Internal Funded Partners:</td>
<td>External Funded Partners:</td>
</tr>
<tr>
<td>1 CNAM, France</td>
<td>7 CNRS, France</td>
</tr>
<tr>
<td>2 CEM, Spain</td>
<td>8 CSIC, Spain</td>
</tr>
<tr>
<td>3 LNE, France</td>
<td>9 IHP GmbH, Germany</td>
</tr>
<tr>
<td>4 PTB, Germany</td>
<td>10 SU, France</td>
</tr>
<tr>
<td>5 VSL, Netherlands</td>
<td>11 TU Delft, Netherlands</td>
</tr>
<tr>
<td>6 VTT, Finland</td>
<td>12 TUBS, Germany</td>
</tr>
<tr>
<td>Linked Third Parties:</td>
<td></td>
</tr>
<tr>
<td>13 UPD, France (linked to CNRS)</td>
<td></td>
</tr>
<tr>
<td>RMG: -</td>
<td></td>
</tr>
<tr>
<td>Unfunded Partners:</td>
<td></td>
</tr>
<tr>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>