



Publishable Summary for 23FUN01 PhoQuS-T Photonic and quantum sensors for practical integrated primary thermometry

Overview

Temperature is one of the most frequently and widely used measurements and it influences almost every physical, chemical, and biological process. This project aims to take advantage of the kelvin redefinition by developing novel small-scale optical based primary thermometry approaches for the dissemination of thermodynamic temperature to industries such as semiconductor, micro- and nanotechnology, aerospace and naval, green energy and quantum technologies. It will significantly progress the state of the art by a) combining complementary photonic thermometry techniques (quantum opto-mechanics, optical phase noise, and photothermal effect) for the first time, b) investigating several sensor geometries (1D, 2D) and materials (e.g., Si, SiN, GaP, InP) of micro- and nano-sensing structures and c) extending the operating temperature range from 4 K to 500 K. In addition, the project will demonstrate practical quantum applications of the developed temperature sensors for ion trap monitoring and in quantum-based pressure standard.

Need

The kelvin redefinition has stimulated new and disruptive approaches to delivering temperature traceability, namely practical primary thermometry at the point of measurement. Such approaches better meet user needs by providing lifetime on-demand reliable traceable temperatures. The most innovative ways to provide such traceability are the photonic/quantum-based approaches investigated in this project. Whilst in their infancy these approaches have the potential to radically change the practice of thermometry through provision of in situ traceability without the need for sensor removal for recalibration (thanks to the high chipset integration capacity and the possibility of a “self-calibration”). Beside purely “metrological” need for a practical primary wide-range thermometer for the realisation and dissemination of the thermodynamic temperature according to the *mise-en-pratique* for the definition of the kelvin, multiple users would benefit from such an approach: from quantum technologies community to cryogenics, photonic/semiconductor, aerospace, transportation and energy (hydrogen) sectors. The sensors developed in this project are adapted to these applications where usual temperature sensors are unsuitable: self-calibrated optomechanical resonators as well as photonic resonators could provide robust, small-scale and wide-temperature range sensors, immune to electrical noise and easy to integrate.

This project will develop integrated optical practical primary thermometry from 4 K to 500 K to enable in-situ traceability in further practical applications. This will be reached through a combination of different technical approaches. With the optomechanical sensors (1D (nanobeam) or 2D (membrane)) the optical noise thermometry will be developed from 4 K to 300 K and the quantum thermometry will be tested below 10 K in order to provide a quantum reference for the optical noise thermometry (Objective 1). The operating temperature range will be extended from 80 K to 500 K with high-resolution photonic sensors based on passive and novel active photonic integrated circuits of micro- and nano-resonators. These photonic chip-based sensors need to be designed, manufactured and characterised and enhanced read-out techniques need to be developed and tested (Objective 2). For further practical applications, the integrated packaging for optomechanical and photonic sensors need to be developed as well as robust fibre to chip coupling over the temperature range from 4 K to 500 K needs to be developed by investigating different technologies for direct fibre coupling (laser welding, gluing, mechanical support) (Objective 3). Finally, the developed sensors need to be metrologically evaluated by establishing the corresponding uncertainty budgets for optomechanical and

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photonic sensors in their respective operating ranges and their application in ion trap monitoring and quantum-based pressure standard will be demonstrated (Objective 4).

Objectives

The overall objective of the project is to develop integrated optical practical primary thermometry with a combination of different approaches: with the optomechanical sensor, the quantum thermometry below 10 K will provide a quantum reference for the optical noise thermometry (operating in the range 4 K to 300 K), whilst using the high resolution photonic (ring-resonator) sensor the temperature range will be extended from 80 K to 500 K.

The specific objectives of the project are:

1. To develop optical noise thermometry from 4 K to 300 K with a target temperature uncertainty of 0.1 K, by using 1D (nanobeam) or 2D (membrane) optomechanical sensors and to test quantum thermometry below 10 K, in order to provide a quantum reference for noise thermometry. In addition, to design, fabricate and characterise sensors using different mathematical models. (WP1)
2. To extend the range for photonic thermometry from 80 K to 500 K, based on passive and novel active photonic integrated circuits of micro- and nano-resonators. To design, simulate, manufacture, and characterise (thermally and optically) the unpackaged photonic chip-based sensors, with a target Q factor of 10^7 . In addition, to develop and test enhanced read-out techniques, including reliable experimental set-ups and theoretical modelling. (WP2)
3. To develop integrated packaging (below cm^3) for optomechanical and photonic sensors and to develop robust fibre to chip coupling over the temperature range from 4 K to 500 K by investigating different technologies for direct fibre coupling (laser welding, gluing, mechanical support) to minimise the optical loss and achieve negligible strain effects over this temperature range. (WP3)
4. To validate the fabricated primary optomechanical sensors from Objective 1 and to calibrate the interpolating sensors from Objective 1 and 2 traceable to the international temperature scale (ITS-90). Then to evaluate the corresponding uncertainty budgets for optomechanical and photonic sensors in their respective operating ranges (target uncertainties for optomechanical sensors are 0.1 K from 4 K to 300 K and for passive photonic sensors are 25 mK from 80 K to 500 K and 5 mK from 283 K to 363 K.) In addition, to demonstrate the application of the calibrated photonic sensors in relevant quantum applications, such as in ion trap monitoring and quantum-based pressure standard. (WP4)
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (photonic and optomechanical temperature sensors, accredited laboratories, instrument manufacturers), research organisations, standards developing organisations (CIPM Consultative Committee for Thermometry (CCT), EURAMET and other RMO TC-Ts) and end users (academia, national metrology institutes, industrial R&D laboratories. (WP5)

Progress beyond the state of the art and results

This project aims at a paradigm shift in temperature measurement not only by producing a practical primary thermometer (in-situ traceability at point of measurement), but also by adopting a photon-based approach with a sub- μm scale spatial resolution.

Within this ambitious objective, significant advance will be made building on the achievements of the EMPIR JRP 17FUN05 PhotOQuanT, where the state-of-the-art optomechanical and photonic resonators were fabricated demonstrating optomechanical noise thermometry (at cryogenic temperatures) and photonic thermometry (around room temperature). State of the art will be advanced through using integrating photonic technologies which will combine different techniques onto a single device for a first practical quantum primary thermometer from cryogenics to 500 K. Quantum thermometry will provide a quantum reference for the optical noise thermometry operating in 4 - 300 K range, while sub mK resolution and wide operational range to 500 K are provided through photonic thermometry. In this project, for the first time such a practical primary temperature sensor will be developed, validated and its quantum applications demonstrated. For this breakthrough, all scientific/technical work in the JRP requires significant progress beyond state of the art.

Objective 1: Development of optical noise thermometry from 4 K to 300 K and quantum thermometry below 10 K

In the EMPIR JRP 17FUN05 PhotOQuanT, optomechanical noise thermometry was demonstrated over 4 - 300 K with 1D-structures suffering from self-heating. New 1D/2D geometries (to reduce the self-heating by a factor of 10) and arrays of resonators (to reduce uncertainty over a large temperature range) will be developed.

Quantum correlation thermometry facilitates integrated, nanoscale, magnetic-field insensitive primary thermometry as demonstrated at NIST (2017). Here, advantage will be taken of this technique at cryogenic temperatures (below 10 K) to provide a quantum reference for a high-performance noise thermometry on the same optomechanical structure operating in 4 - 300 K range (with target uncertainty 0.1 K).

Objective 2: Advanced photonic thermometry from 80 K to 500 K

Photonic thermometry is based on the thermo-optic effect and offers very high sensitivity (70 pm/K) and sub mK resolution (shown in EMPIR JRP 17FUN05 PhotOQuanT project). This project will go beyond the state of art, firstly, by exploring enhanced read-out techniques and by improving the device design to extend the operation range (80 K - 500 K) exploring Si and SiN; and secondly, by developing a non-Si based novel active thermometry approach (combining laser source and photonic sensor) as a step towards the fully integrated device.

Objective 3: Robust fibre to chip coupling packaging solutions over 4 - 500 K temperature range

The free-space coupling drastically limits the practical application of the optical sensors. This project will go beyond the state of the art by developing different approaches (gluing, welding, mechanical) for packaging and robust fibre-to-chip coupling over a large temperature range (4 K - 500 K) to mitigate for thermal expansion mismatch between fibre, chip and adhesive material over temperature range while catering to the requirements of optomechanical and photonic sensors.

Objective 4: Metrological validation and applications

Photonic thermometry and optomechanical thermometry are both recent emerging technologies. Nowadays, NIST demonstrated a proof of principle of the quantum correlation technique to calibrate thermal noise versus quantum noise in an optomechanical resonator. The first results of EMPIR JRP 17FUN05 PhotOQuanT project on optomechanical noise thermometry were mainly limited by a strong self-heating effect and the photonic thermometry has been demonstrated around room temperature with a standard deviation about 10 mK. Recently, uncertainties of 10 mK could be demonstrated by the Canadian NMI. The progress introduced in this project (2D optomechanical resonator with self-heating divided by at least 10, advanced photonic resonators enabling a broad temperature range, from 80 K to 500 K) should allow the consortium to improve the state of the art with these emerging technologies. Within this project, the metrological validation will be performed establishing traceability to ITS-90 over their full temperature range together with computation of the respective uncertainty budgets (with target uncertainties for optomechanical sensors of 0.1 K from 4 K to 300 K and for passive photonic sensors of 25 mK from 80 K to 500 K and 5 mK from 283 K to 363 K).

In addition, in this project, the application of these sensors to measure the temperature drift of ion traps, without interference with their operation will be explored. The application of the photonic thermometry for the temperature assignment in the photon-based approach for pressure measurements will open the way towards an all-optical quantum-based pressure standard.

Outcomes and impact

This research project focuses on the development of integrated optically based practical primary thermometry from 4 K to 500 K standard.

Outcomes for industrial and other user communities

The lack of practical primary thermometers constitutes a barrier for the dissemination of the redefined kelvin by the mise-en-pratique for the definition of the kelvin (MeP-K-19) i.e. for addressing industry issues. As a result, the practical primary thermometers developed here are expected to have high impact in industry.

This project will provide a technological breakthrough for integrated circuit temperature sensing issues, and also for other related temperature measurement needs e.g. those requiring reliable in-situ long time scale measurements such as space, aircraft, submarine or naval, where sensor retrieval (and hence recalibration)

is not feasible. Also, the wide-range primary sensor developed in this project, covering the cryogenic temperature range, is of particular interest for rapidly growing sectors such as Hydrogen (liquid H₂ storage) and Quantum Technologies, where temperature-controlled cryostats is crucial. The use of the new sensors developed in this project will enable accurate, zero drift, temperature sensing in the extended operating range (4 K to 500 K) having the capability to be embedded into a chipset or other integrated technologies – a technological breakthrough.

Outcomes for the metrology and scientific communities

The recommendations of the Consultative Committee for Thermometry (CCT) for the mise-en-pratique for the definition of the kelvin (MeP-K-19), specifies that a primary thermometry method must fulfil particular criteria in order to be endorsed for provision of temperature traceability. This project targets these requirements and aims to develop the first on chip practical primary thermometer from 4 K to 500 K, the impact of this on practical primary thermometry practice is potentially very high as the practical optical thermometers developed will open the way to a new metrology traceability scheme, which will have to be agreed by the international metrology community.

In addition to the benefits to the temperature metrology community from this project's outputs, the wider scientific community will be able to take advantage of the new sensors (e.g lab-on-a-chip application or in-situ measurement at the sub- μm scale) and will benefit from the technological developments (e.g. robust coupling fibre-chip, integrated optical components) associated with the large operational temperature range.

Outcomes for relevant standards

The practical primary thermometry approach developed will provide a new and more straightforward way to deliver SI traceability direct to where the user needs it most at the point of application. This is a paradigm shift in the way traceability is delivered (currently through an unbroken chain of measurements) and will require validation from the CCT to be accepted and will require some form of a standardisation recommendation before full implementation can be realised. More generally, and within a shorter timeframe, this project will produce technical data and documents for the CCT, via close cooperation with its working groups and task groups.

The relevant committees will be kept informed of the progress and outcomes of the project: annual reports to the CCT and RMO TC-Ts. The project consortium will raise awareness of these developments, concerning the quantum sensors and their needs for standardisation, within CEN-CLC Joint Technical Committee 22 "Quantum Technologies".

Longer-term economic, social and environmental impacts

Temperature is probably the most frequently and widely used measurement, and it influences almost every physical, chemical, and biological process. Consequently, any change to the fundamentals of thermometry, its measurement and traceability will have far-reaching impacts in all areas of human endeavour.

A practical primary thermometer available at the point of use introduces a paradigm change in the traceability scheme to the kelvin: calibration against standards held by a national metrology standard may no longer be required. A simple stable in-situ temperature reference is sufficient to estimate the statistical component of the uncertainty of the primary thermometer. This significantly reduces the complexity of the traceability process as well as its cost. Industry will be more efficient and productive as thermometers will no longer require calibration meaning that optimum energy is used, minimising emissions and waste.

The research will have a significant impact at the European level because it enhances the European laboratory network for quantum and nano-scaled temperature metrology (established during EMPIR JRP 17FUN05 PhotOQuant) and opens new opportunities for the first commercialisation of photonic temperature sensors in Europe. Many industries such as semiconductor, micro- and nanotechnology, aerospace and naval, green energy and quantum technologies, will benefit from the project's output and this should strengthen European industrial infrastructure for the development of new services and products. The project will improve collaboration between European NMIs, academia and technological institutions enabling the EU to take a leading role in the future in this important emerging technology area.

List of publications

n/a

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

Project start date and duration:		1 September 2024, 36 months	
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Internal Beneficiaries:	External Beneficiaries:	Unfunded Beneficiaries:	
1. LNE, France	8. CNRS, France		
2. CEM, Spain	9. IHP GmbH, Germany		
3. CNAM, France	10. LUH, Germany		
4. INRIM, Italy	11. SU, France		
5. PTB, Germany	12. TU Delft, Netherlands		
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