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 optomecanical 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

The optomechanical resonators form the basis for the integrated primary thermometry methods explored in this project. This project explores optomechanical noise thermometry (which could be used as a relative primary tehchnique) and quantum correlation thermometry (which could be used as a primary absolute technique to provide a quantum reference for optomechanical noise thermometry).

The design of the optomechanical system has been improved through the fabrication of a functional silicon-on-insulator (SOI) waveguides chip integrating one-dimensional optomechanical crystals. Each of the 30 available waveguides addresses 4 optomechanical resonators which are slightly detuned in wavelength with respect to each other to meet the maximum of the optical transmission given by grating coupler at each end of waveguide.

For these optomechanical crystals, different readout protocol for optical and optomechanical thermometry has been developed. Firstly, the possibility to implement photonic thermometry on an optomechanical crystal by monitoring the frequency shift of the optical resonance was validated. Secondly, a demonstration of optomechanical noise thermometry has been performed over a large temperature range (from few K to 300 K) with, for now, very large uncertainty (± 8K). The improvements in the optical setup and in the detection are ongoing in order to eliminate systematic effects (e.g. polarization dependence) and to reduce measurements uncertainty. The next step is to develop the quantum protocol. For this quantum-correlation-thermometry, a heterodyne detection has been implemented and is currently being tested. The acquisition chain has been updated and now integrates a high-frequency IQ-mixer and a high-speed digitizer. First tests at room temperature have been launched.

Another approach that allows the combination of optomechanical and photonic systems, has been explored. For this purpose, a system combining a ring resonator on a 2D-membrane optomechanical sensors was designed and array of these types of devices were fabricated. Currently, the mechanical and optical performance of these sensors (using the integrated waveguides and grating couplers) is evaluated. The design and machining of the holders to attach fiber arrays attached to the chips is ongoing. The next step is to prepare the test setups and protocols to test these sensors.

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

Photonic integrated circuits (PICs) form the basis of highly sensitive and precise photonic thermometry. This project explores enhanced read-out techniques and improved device designs. Firstly, the first generation of silicon (Si) and silicon nitride (SiN) based photonic integrated circuits (PICs) has been designed, simulated and manufactured with the aim of extending the operating range with an unambiguous signal between 80 K and 500 K. The Si PICs are based on a special 3 µm thick silicon-on-insulator platform. They feature multiple resonator designs in both single and Vernier configurations; the latter enhances the sensor's free spectral range. These chips can be used with both edge coupling and out-of-plane coupling, which utilises broad-band up-reflecting mirrors to direct light vertically. The SiN PICs incorporate ring resonators with very narrow resonances for precise readout, as well as in-plane reflection gratings with a low order to achieve unambiguous signals. Characterisation of PICs from both manufacturing runs is currently underway. In parallel, an experimental and theoretical study was carried out using chips from previous work and wafer-scale measurements to support the optimisation of design parameters for the planned second generation PICs. A method was developed to calculate the optimal parameters from only a few realised variations.

Secondly, a novel active thermometry approach was developed that combines a laser source and a photonic resonator. This is a step towards a fully integrated device. Designs and simulations have been finalised, and wafers have been manufactured in parallel using metalorganic vapour-phase epitaxy. The first structures are currently being fabricated using electron-beam lithography and dry etching schemes.

Thirdly, the setups used to characterise the PICs (based on tunable lasers and temperature-controlled chip platforms) have been updated and are currently being validated. For example, using a low-viscosity oil instead of water as the circulating liquid has increased the operating range of a free-space, temperature-controlled platform to 400 K. Another system features a vacuum chamber housed within a climate chamber. A combination of a heat exchanger and Peltier elements enables precision temperature control over a wide range of between -85 °C and +250 °C, with stability on the order of 10 mK. The vacuum environment minimises convective heat transfer during validation, enabling a more precise comparison of reference temperature and

PIC. These setups will be used to characterise the optical and thermal properties of unpackaged advanced passive and active PICs, e.g. quality factor, sensitivity and free spectral range. Enhanced readout techniques for precise, unambiguous temperature signals will be tested and will later be used in packaged sensor applications (Objectives 3 and 4).

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 optical sensors. This project will go beyond the state of the art by developing various packaging and fibre-to-chip coupling approaches, such as gluing, welding and mechanical coupling over a wide temperature range (4 K … 500 K). These techniques will mitigate the effects of thermal expansion mismatch between fibre, chip and adhesive material over the temperature range, while meeting the requirements of optomechanical and photonic sensors. To achieve this objective, chip packaging of photonic chips will be developed for operation at 80 K to 500 K, and for optomechanical chips for operation at 4 K to 300 K. First round of SOI and optomechanical resonator chips are fabricated and ready for packaging. Packaging solutions were tested on dummy chips, and the uncertainty they add to the final temperature measurements was studied and the results published. To further improve the understanding of the impact of packaging on the measurements, a full characterization will be carried out once the project chips have been fabricated and packaged.

Objective 4: Metrological validation and applications

Within this project, the metrological validation of the developed sensors will be achieved by establishing their traceability to the International Temperature Scale (ITS-90) across their entire temperature range and determining the corresponding uncertainty budgets. Several project partners are currently developing dedicated experimental setups for the metrological thermal characterisation of the photonic and optomechanical sensors within their respective temperature ranges. This includes characterising the systems in terms of stability, temperature gradients, and operational temperature ranges, installing ITS-90-traceable sensors, and providing optical and fibre access. This will also include experiments exploring the feasibility of replacing standard platinum resistance thermometers with photonic temperature sensors in a future temperature scale.

Additionally, this project will demonstrate the use of calibrated photonic sensors in relevant quantum applications, focusing on the monitoring of ion traps in optical clocks and quantum-based pressure standards. The sensors will demonstrate photonic temperature measurement that is directly integrated into the ion trap of an optical clock. Knowledge gained from the design of SiN photonic structures has been used to develop photonic temperature sensors, which will be integrated into the Al_2O_3 photonic platform of the HORIZON-CL4-2023 QU-PIC project.

In another application, photonic thermometry is used for optical temperature measurement, which is necessary for the optical approach to pressure measurement. The Fabry-Perot refractometer developed in the EPM JRP 22IEM04 “MQB-Pascal” project has been prepared for the integration of photonic sensors. The necessary modifications were implemented while maintaining the mechanical integrity and thermal stability required for high-precision refractometric measurements. These modifications included the design and manufacture of a new Invar cavity with enlarged openings to accommodate the photonic temperature sensors This enables the evaluation of integrated photonic sensing solutions within an established metrological platform.

Outcomes and impact

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

Key dissemination and communication activities

The dissemination and communication activities are carried out through communication via the project website and periodic newsletters; direct engagement with the Stakeholder Committee; dissemination through the individual stakeholder and different networks (metrology, quantum technologies, optomechanics) of the project participants; and through publications and conference presentations.

The project results were published in six peer-reviewed papers (https://www.mdpi.com/2304-6732/12/3/234, https://doi.org/10.3390/metrology5030044, https://doi.org/10.1016/j.measen.2024.101775, https://doi.org/10.1038/s42005-025-02456-9, https://doi.org/10.1098/rsta.2024.0457 , https://doi.org/10.1098/rsta.2024.0459). A popular article on photon-based thermometry was published in InstMC Precision journal, promoting photonic thermometry to a broader industrial audience.

Project achievements were presented in April 2025, at the Measuring by Light conference (multidisciplinary conference for industry and academics on the application of optical measurement techniques), with three oral presentations covering the project objectives and approaches, optomechanical measurements, and photonic chip fabrication.

Five presentations were delivered in October 2025 at the *TEMPMEKO* conference (most important international scientific events for thermometry community held every three years), addressing the project objectives and approaches, optomechanical measurements, photonic measurements, and active photonic approaches. Achievements related to the optomechanical approach were also presented at the "Mechanical Systems in the Quantum Regime" Gordon Research Conference in January 18 - 23, 2026, Barga, Italy.

First project results were presented through three talks - covering the optomechanical approach, photonic ring resonators and fibre-to-chip coupling, and active photonic approaches - at the workshop A Royal Society Theo Murphy Discussion meeting: The Redefined Kelvin: Progress and Prospects (24–25 February 2025, Glasgow, UK). Further results related to the optomechanical approach were presented at the Gordon Research Seminar (17-18 January 2026, Barga, Italy).

The project poster was presented at the special event celebrating the 150th anniversary of the BIPM.

<u>Outcomes for industrial and other user communities</u>

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.

<u>Outcomes for the metrology and scientific communities</u>

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.

<u>Outcomes for relevant standards</u>

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”.

<u>Longer-term economic, social and environmental impacts</u>

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

1. Schmid, D. et al, “Wafer-Scale Experimental Determination of Coupling and Loss for Photonic Integrated Circuit Design Optimisation”, *Photonics* **12(3)**, 234. Available at https://www.mdpi.com/2304-6732/12/3/234
2. Kozlova, O et al, “European Partnership in Metrology Project: Photonic and Quantum Sensors for Practical Integrated Primary Thermometry (PhoQuS-T)”, *Metrology* ***5*(3)**, 44. Available at https://www.mdpi.com/2673-8244/5/3/44
3. Erdogan, R.T., et al, “Amorphous silicon-carbide photonics for ultrasound imaging“, *Commun Phys* **9**, 25 (2026). Available at https://doi.org/10.1038/s42005-025-02456-9

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

<table>
<tr><td colspan="2">Project start date and duration:</td><td>1 September 2024, 36 months</td></tr>
<tr><td colspan="3">Coordinator: Olga Kozlova, LNE Tel: +33(0)158808901 E-mail: olga.kozlova@lne.fr
Project website address: https://phoqus-t.com/</td></tr>
<tr><td>Internal Beneficiaries:
1. LNE, France
2. CEM, Spain
3. CNAM, France
4. INRIM, Italy
5. PTB, Germany
6. RISE, Sweden
7. VTT, Finland</td><td>External Beneficiaries:
8. CNRS, France
9. IHP GmbH, Germany
10. LUH, Germany
11. SU, France
12. TU Delft, Netherlands
13. TUB, Germany</td><td>Unfunded Beneficiaries:</td></tr>
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15. NPL, United Kingdom
16. UofG, United Kingdom</td></tr>
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