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Project Report

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Abstract

Current temperature sensors require regular recalibration to maintain reliable temperature measurement. Photonic/quantum-based approaches have the potential to radically change the practice of thermometry through provision of in situ traceability, potentially through practical primary thermometry, without the need for sensor recalibration. This article gives an overview of the European Partnership in Metrology (EPM) project: Photonic and quantum sensors for practical integrated primary thermometry (PhoQuS-T), which aims to develop sensors based on photonic ring resonators and optomechanical resonators for robust, small-scale, integrated, and wide-range temperature measurement. The different phases of the project will be presented. The development of the integrated optical practical primary thermometer operating from 4 K to 500 K will be reached by a combination of different sensing techniques: with the optomechanical sensor, 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 to be extended from 80 K to 500 K. The important issues of robust fibre-to-chip coupling will be addressed, and application case studies of the developed sensors in ion-trap monitoring and quantum-based pressure standards will be discussed.

Keywords: photonic and quantum sensors; optical metrology; temperature measurements; traceability and calibration in metrology

1. Introduction

Temperature is the most frequently and widely used measurement quantity and it influences almost every physical, chemical, and biological process. Current temperature sensors (thermocouples, electrical resistors), which are used in industries and for scientific applications, require regular recalibration to maintain reliable temperature measurement [1,2].

The redefinition of kelvin in May 2019 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, and traceable temperatures. Among 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 recalibration. Besides the purely "metrological" need for a practical primary wide-range thermometer for the realisation and dissemination of thermodynamic temperature according to the *mise-en-pratique* for the definition of the kelvin (*MeP*-K-19D) [3], multiple users would benefit from such an approach. These range from the quantum technologies community to cryogenics, photonic/semiconductor, aerospace, transportation, and energy (hydrogen) sectors.

The PhoQuS-T [4] project will advance the work begun in the previous PhotOQuanT project [5,6] by developing small-scale, optically based primary thermometry approaches operating from a few K up to 500 K. Such sensors are adapted to applications where usual temperature sensors are unsuitable: by providing a self-calibrated optomechanical resonator as well as photonic resonator-based thermometers that could provide a robust, small-scale (sub-µm scale) and wide temperature range which are immune to electrical noise and easy to integrate.

The overall aim of the project is to develop integrated, optical, and practical primary thermometry from 4 K to 500 K to enable in situ traceability in practical applications. This will be obtained through a combination of different technical approaches. With the optomechanical sensors (1D (nanobeam) or 2D (membrane)), optical noise thermometry will be developed from 4 K to 300 K whilst quantum thermometry (The term quantum thermometry designates that the quantum approaches are used in order to measure the thermodynamic temperature. The term quantum thermometry should not be misread as quantum temperature or the temperature of the quantum objects. In this project, for the temperatures below 10K, we focused on the quantum correlation technique, which is briefly described in Section 2.3) will be realised below 10 K in order to provide a quantum (absolute) reference for optical noise thermometry (Objective 1). The operating temperature range will be extended from 80 K to 500 K through integration with high-resolution photonic sensors based on passive and novel active photonic integrated circuits of micro- and nano-ring resonators. These photonic chip-based sensors will be designed, manufactured, and characterised (Objective 2). For further practical applications, the integrated packaging for optomechanical and photonic sensors needs to be developed, as well as robust fibre-to-chip coupling for the temperature range from 4 K to 500 K by investigating different technologies for direct fibre coupling (laser welding, glueing, mechanical support) (Objective 3). Finally, the developed sensors will be metrologically evaluated by establishing the corresponding uncertainty budgets for optomechanical and photonic sensors in their respective operating ranges, and their application in ion-trap monitoring and quantum-based pressure standard will be demonstrated (Objective 4).

In the next sections, we give an overview of the different approaches that will be explored in the project. The current state-of-the-art and the planned progress beyond it for each of these four technical objectives will be presented. The expected results as well as the project impact will be discussed.

2. Methods

In the past decades, new types of temperature sensors have emerged [7]: noise thermometry [8], Doppler broadening thermometry [9,10], phosphor thermometry [11], Nitrogen-Vacancy diamond thermometry [12], fibre-optics thermometry [13,14], on-chip photonic [15] and optomechanical techniques [16,17], etc. Based on different physical principles, they have a potential to overcome the drawbacks of "conventional" temperature sensors and could offer fit-for-purpose and cost-effective measurement solutions. Among these emerging technologies, on-chip photonic and optomechanical sensors have an advantage to be easily integrated on a chipset, which makes them suitable for practical in situ applications.

In this project, we will explore different on-chip photonic and optomechanical techniques to move towards optically based, practical primary thermometry. The principles of these techniques are described in this section. These different techniques can be classified as absolute, relative, or interpolation techniques according to the definitions as formulated in "*Mise en pratique for the definition of the kelvin in the SI*" [3]:

- Absolute primary thermometry allows the measurement of thermodynamic temperature directly in terms of the definition of the base unit kelvin, i.e., the defined numerical value of the Boltzmann constant k. No reference is made to any temperature fixed point ($n = 0$, n = number of points) and all other parameters specified in the equation of state are measured or otherwise determined.
- Relative primary thermometry allows the measurement of thermodynamic temperature indirectly using a specified equation of state, with one or more key parameter values determined from temperature fixed points ($n > 0$), for which values of the thermodynamic temperature T and their uncertainties are known a priori from previous absolute or relative primary thermometry.

The interpolation technique allows for an interpolation of the temperature between the calibration points with a defined interpolation equation.

In this project, the combination of these different absolute, relative, and interpolation techniques will establish wide-temperature operation and a self-calibrated sensing approach as shown in Figure 1.

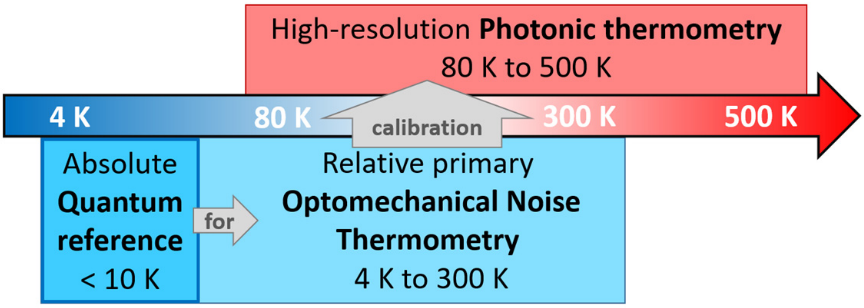

Figure 1. Combination of different thermometry techniques over the temperature scale.

2.1. Photonic Thermometry

Photonic thermometry is based on the measurement of the displacement of the optical resonance with temperature due to the thermo-optic effect. In this project, this technique will be implemented by the measurement of the wavelength shift in the optical resonances in the on-chip structures: photonic crystal structures or ring resonators.

The displacement of the resonance wavelength λ with temperature is governed by the thermo-optic effect ($n_{eff}(T, \lambda)$) and by thermal expansion ($L_{eff}(T)$):

$$\lambda = n_{eff}(T, \lambda) \cdot L_{eff}(T), \quad (1)$$

Note that the thermo-optic effect is predominant, as the thermo-optic coefficient of the materials used in this project is a factor of ten larger than the thermal expansion coefficient effect.

Photonic-based thermometry is an interpolation technique, which allows for interpolation between several calibration points. For such interpolation, at least a polynomial of the second degree is needed [18], which means that at least 3 calibration points are required. In practice, the polynomial fits of higher degrees (3rd [19], 4th [20]) are used.

2.2. Optomechanical Noise Thermometry

Optomechanical noise thermometry is based on the optical detection of the mechanical motion of a resonator. Such thermomechanical noise is the noise caused by the Brownian thermal motion of particles at a given temperature T, associated with an average kinetic energy E_k per degree of freedom equal to

$$E_k = k \cdot T/2, \quad (2)$$

For optomechanical resonators, it results in mechanical excitations that generate microscopic fluctuations within the resonator itself, which are directly related to its temperature. The variance of these mechanical displacements $\langle x^2 \rangle$ can be calculated as an integral of power spectral density noise of the resonators' thermal fluctuations around the mechanical resonance. These are proportional to the resonators' thermodynamic temperature [21]:

$$x^2 = (k \cdot T)/\left(\omega^2 \cdot m_{eff}\right), \quad (3)$$

where m_{eff} is the effective mass of the resonator and ω is the frequency of the mechanical resonance. In contrast to the absolute value of the resonance frequency, an absolute value of the effective mass of the resonator is difficult to obtain. This means that the optomechanical noise thermometry is a relative primary technique but having linear dependence needs only one calibration point. This calibration point can be obtained through linkage to the quantum correlation technique.

2.3. Quantum Correlation Thermometry

Quantum correlation thermometry is an absolute primary technique, which can be used as a reference for other techniques, allowing for in situ traceability at the point of measurement. First demonstrated by T. Purdy et al. [17], this technique uses the optical quantum force fluctuations (optical quantum backaction due to the radiation pressure) as a standard reference scale for measuring thermal force fluctuations. Except for very low temperatures (below 1 K), quantum backaction is difficult to observe as the optical quantum intensity fluctuations are orders of magnitude smaller than the thermal fluctuations. The cross-correlation technique demonstrated in [17] allows for retrieval of the optically driven motion (quantum correlations) from the thermally driven motion (thermal correlations). These quantum correlations (which are determined by fundamental constants) are used to scale the thermal motion, allowing for absolute temperature measurements.

3. Progress Beyond the State-of-the-Art

The current state-of-the-art-for practical temperature measurement is through resistance thermometers, thermocouples, and non-contact (infra-red) thermometers. None of these approaches are primary and require calibration to establish traceability to the kelvin and require regular recalibration to ensure that traceability is maintained.

By a combination of different techniques described in the previous section, this project aims to provide the means to affect a paradigm shift in thermometry by developing optically based, practical (i.e., deployable), primary thermometry approaches that can deliver traceability to the kelvin at the point of measurement.

Within this ambitious objective, significant advancements will be made, building on the achievements of the PhotOQuanT project, 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) [6]. In the PhoQuS-T project, the state-of-the-art will be advanced through using integrated photonic technologies that will combine different techniques onto a single device for the 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. To achieve this objective, the project will need to advance (Figure 2) significantly beyond the current state-of-the-art.

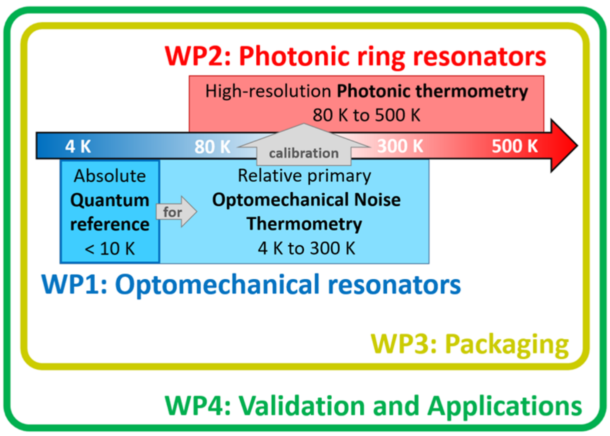

Figure 2. Technical workpackages structure of the PhoQuS-T project.

3.1. Workpackage 1: Development of Optical Noise Thermometry from 4 K to 300 K and Quantum Thermometry Below 10 K

3.1.1. State-of-the-Art for Optomechanical Thermometry

The first demonstration of primary quantum thermometry using optomechanical quantum correlation up to room temperature was demonstrated by T. Purdy et al. [17]. The technique uses a laser probe whose phase noise furnishes a quantum standard used to scale the Brownian motion of an optomechanical resonator. The difficulty of this measurement is that the quantum phase noise is very low compared to its thermal counterpart. Thus, the statistical uncertainty attached to the optical measurements becomes dominant in the uncertainty budget. Two complementary strategies may be implemented for reducing this statistical component (since quantum-based thermometry is most accurate near cryogenic temperatures where the thermal energy equals the quantum zero point energy: (1) increasing the frequency f of the mechanical resonance to keep the oscillator as close as possible to the ground level (quantum zero point energy); (2) enhancing the signal-to-noise ratio through the use of ultra-high Q factor (~10^7) mechanical resonators at the cost of longer integration times.

From 10 K to 300 K, thermomechanical optical noise thermometry with optomechanical devices can provide lower uncertainty compared to quantum correlation thermometry. The principle of optomechanical noise thermometry has some similarities to Johnson noise thermometry (JNT); but here, the Brownian motion of a mechanical oscillator is probed through an optical phase measurement. This leads to significant advantages over JNT, such as faster measurement times and frequency-based measurement. As the measurement is optically based, it is immune to electrical noise.

3.1.2. Progress Beyond the State-of-the-Art for Optomechanical Thermometry

In workpackage 1, significant progress beyond the state-of-the-art will be through the development of the optomechanical thermometry (target uncertainty 0.1 K), with an intrinsic quantum reference below 10 K for a high-performance optomechanical noise thermometry in a wide range from cryogenic (4 K) up to room temperature (300 K) and even above (450 K).

This will be achieved through the following: (a) design and fabrication of new 1D/2D geometry, high-mechanical-frequency, high-Q factor, optomechanical resonators to reduce the main systematic effect (self-heating) by at least a factor of 10; (b) the read-out protocol for primary quantum thermometry will be established; (c) novel multi-physics measurement on the 2D optomechanical membrane (exploring the optical and mechanical degrees of freedom) will be implemented for a temperature measurement with overlapping range (photonic thermometry from 50 K to room temperature, optomechanical noise thermometry from cryogenic to room temperature); (d) an array of optomechanical sensors will be implemented to reduce the corresponding uncertainty when measuring over a wide temperature range.

In addition, and innovatively, this project plans to combine photonic ring resonators with resonant membranes. This will be achieved by positioning a ring resonator on top of a membrane for simultaneous measurement [22]. Two read-out techniques will use the following: (a) photonic read-out, based on the position of the optical resonance corresponding to a dip in the transmission; (b) noise in the amplitude approach, which is caused by the effect of thermomechanical motion on the diameter and stress of the ring waveguide. By employing both techniques in the same device, a bridge between objectives 1 and 2 will be established, allowing for the first time a direct comparison of the two approaches. This also brings a significant advance, as it allows direct comparison of the two approaches as well as benefits from the complementarity and synergy between the approaches, with thermomechanical thermometry having the advantage of offering easy single-point calibration by providing an intrinsic linear relation between the noise power and temperature, while photonic thermometry offers higher resolution.

3.2. Workpackage 2: Advanced Photonic Thermometry from 80 K to 500 K

3.2.1. State-of-the-Art of On-Chip Photonic Thermometry

Photonic thermometry offers high sensitivity (70 pm/K) and sub-mK resolution [6,15]. Within the PhotOQuanT project [6], state-of-the-art, silicon-based photonic resonators were micro-fabricated with Q factors up to 10^5 and tested in the 270–350 K range. These first results were encouraging. featuring high-contrast notch resonances, high temperature sensitivity, and a noise equivalent temperature resolution of about 10 mK at room temperature. Furthermore, the material study in the PhotOQuanT project showed the potential of SiN for photonic thermometers. Note that in both cases, one potential drawback in the deployment of such sensors is that the laser and detector are both outside of the chip-based resonator; this issue is being addressed in this project.

Besides the PhotOQuanT project results, work on photonic thermometry with ring resonators was reported by other groups. After the pioneering work by Klimov et al. [15] in 2018, a recent practical ring resonator thermometer with an uncertainty of 10 mK was demonstrated with Si ring resonators by S. Dedyulin et al. [19] in 2023 and a 3-mK-resolution ring resonator thermometer was demonstrated by J. Wang et al. [23] in 2022.

3.2.2. Progress Beyond the State-of-the-Art for Photonics Thermometry

This project will go beyond the state-of-the-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 a fully integrated device (see Section 3.2.3).

In workpackage 2, we will go beyond state-of-the-art through enhancing the photonic sensor functionality by achieving a high optical Q factor of up to 10^7 in a broad operating temperature range of 80 K–500 K, leveraging the low propagation losses (~0.1 dB/cm) in Si waveguides on thick silicon on insulator (SOI). The approach of integrating the Si ring resonator on a thick SOI platform not only increases the sensitivity of the method but also the resonance Q factor; it also importantly accommodates relaxed fabrication tolerances. The platform's attributes include strong light confinement within thick Si waveguides and ring resonators, with a combination of ultra-low propagation losses, minimal polarisation dependency, and ultra-broadband operation wavelength (1.2–4 μm).

The design of the micro resonators will also be developed beyond the state-of-the-art. With standard ring resonators, the resonance peaks are repeated at a wavelength distance corresponding to a temperature change of less than 150 K (e.g., Free Spectral Range = 10 nm, $d\lambda/dT$ = 75 pm/K). Advanced resonator designs with a unique spectrum over a wide temperature range will be developed.

This project will also advance the state-of-the-art by working with not only with the established Si technology, but also SiN photonic integrated circuits—a technology selected for its ability to directly integrate with optomechanical sensors.

3.2.3. Active Photonic Thermometry (State-of-the-Art and Progress Beyond)

A step change in the state-of-the-art will explore a new active approach to ring resonator thermometry, which, whilst at a lower technical maturity level, offers a potentially disruptive advantage in the field of photonic thermometry. The passive photonic integrated chip (PIC) devices themselves can be highly miniaturised, but the external tuneable laser source, optical fibre connections, and spectrometer system add significantly to the scale and complexity of the system. More cost-effective approaches are preferable for practical implementation [24]. In contrast to Si, III–V-based semiconductors (e.g., InP PICs operating at 1300–1600 nm) allow for active photonic structures (i.e., including the activator laser source) to be directly fabricated on the same chip as the ring resonators. The use of III–V alloys also offers the potential to tailor the temperature sensitivities and operating temperature ranges, since key parameters, such as the band gap and Debye temperature, can be varied through alloying. The potential for active photonic thermometry has been explored theoretically by the University of Glasgow and NPL [25]. This new approach will be explored experimentally for the first time within the project with the aim of demonstrating the first ever active photonic thermometer acting as a testbed for future fully integrated chip-based devices.

3.3. Workpackage 3: Robust Fibre-to-Chip Coupling Packaging Solutions over 4–500 K Temperature Range

3.3.1. State-of-the-Art for Robust Fibre-to-Chip Coupling

For practical applications, low-loss, robust fibre-to-chip coupling is crucial for effective and accurate operation of photonic (Si-based) and optomechanical sensors. This objective focuses on an integrated packaging solution that serves both photonic and optomechanical sensors and enables reliable operation in the 4 K–500 K temperature range. The current conventional coupling methods are widely used in telecom/data communications, but their applicability is limited for this application due to the thermal strains, which result from the use of heterogeneous materials whose thermal expansion is mismatched. In the PhotOQuanT project, only free-space-coupled devices with an active alignment requirement were developed, which drastically limited their practical application.

3.3.2. Progress Beyond the State-of-the-Art for Robust Fibre-to-Chip Coupling

This project will go beyond the state-of-the-art by developing new approaches to mitigating thermal expansion mismatch between fibre, chip, and adhesive material over a wide temperature range while catering to the distinct requirements of optomechanical and photonic sensors. Three distinct packaging techniques will be developed.

The first technique is to use fast curable epoxies as adhesive materials and benefits from low thermal expansion mismatch glue for fibre-to-chip coupling with minimum thermal strain in contact with sensors. The second technique is based on adhesive-free laser welding for coupling fused silica fibres to SiO_2 coated chips. Laser welding is particularly suited for enabling direct fibre coupling to grating couplers. Eliminating the glue in the optical coupling interfaces potentially increases the durability of such optical sensors for thermometry. In the third technique, a glass slide will be integrated on top of the chip to provide a mechanical support for the optical fibres, thereby reducing any drift and strain over the entire operation temperature range.

The evolution of these packaging solutions will be closely coordinated with workpackages 1 and 2, which encompass the fabrication aspects of photonic and optomechanical sensor chips. These solutions are applicable to both single-fibre and fibre array-to-chip couplings. These complementary techniques will allow us to address multiple systems, simultaneously opening new avenues for packaging of nano-devices and robust interrogation of the thermometers.

3.4. Workpackage 4: Metrological Validation and Applications

3.4.1. State-of-the-Art for Metrological Validation

Photonic thermometry and optomechanical thermometry are both recent emerging technologies. Up until now, the paper by T. Purdy et al. [17] is the only publication on thermometry using the quantum correlation technique to calibrate thermal noise versus quantum noise in an optomechanical resonator. That paper demonstrated a proof of principle with a standard deviation about 6 K for 1 min integration time at 40 K (about 15%). The participants involved in the PhotOQuanT project demonstrated noise thermometry using optomechanical resonators, but time constraints meant that we were unable to demonstrate the quantum correlation thermometry technique. In addition, the first results of the PhotOQuanT project on optomechanical noise thermometry has issues related to systematic optical polarisation effects in optical fibres but also by the strong self-heating caused by the large photon number imposed by the optical detectivity of the experimental set-up. In the same project, photonic thermometry was demonstrated at around room temperature with a standard deviation about 10 mK [6]. Recently, uncertainties of 10 mK have been demonstrated by S. Dedyulin et al. [19].

3.4.2. Progress Beyond the State-of-the-Art for Metrological Validation

The progress anticipated in this project (2D optomechanical resonator with self-heating reduced by at least a factor of 10, advanced photonic resonators enabling a broad temperature range from 80 K to 500 K) should allow the consortium to significantly progress the state-of-the-art with these emerging technologies. Within this project, the metrological validation will be performed, establishing traceability to the current temperature scale in use (the International Temperature Scale of 1990 (ITS-90) [26]) over their full temperature range together with an additional evaluation of their respective uncertainty budgets. The uncertainty targets are as follows: optomechanical sensor 10% (<10 K) and 0.1 K (4 K–300 K), photonic sensor 25 mK from 80 K to 500 K as well as 5 mK from 283 K to 363 K, and an active photonic sensor 250 mK (80 K to 500 K). In addition, the first in situ calibration of photonic sensors with quantum optomechanical thermometry will be demonstrated via optomechanical noise thermometry in the 80 K–300 K range. Finally, a demonstration of the potential impact of the developed sensors will be undertaken by demonstration applications in ion-trap monitoring, the quantum pascal, and as evaluation as future standard thermometers (see description below).

3.4.3. Quantum Application Demonstrations

For quantum sensors based on atom spectroscopy and, in particular, for frequency measurements, the black body radiation shift is still a major contribution to the uncertainty budget [27,28]. This shift is induced by the thermal radiation of the environment and depends on the static differential polarisability of the ion. For a precise estimate of this shift, the temperature of the surrounding, particularly the ion-trap chips, has to be precisely known, typically at the kelvin level. A Paul ion-trap traps a single ion or multiple ions with radiofrequency fields and static electric fields. The ions can be stored in a trap and precisely controlled and manipulated using laser or microwave radiation. Such ion-traps are now being produced with chip-integrated photonics [29–31]. Ion-traps are used in quantum metrology, quantum sensing, quantum simulation, and quantum computing. For micrometre-scale ion-traps, fabricated on a monolithic chip with an integrated photonic layer, chip-integrated temperature sensors on the same scale are desirable. For some quantum metrology applications, the temperature of the ion-trap chip at room temperature needs to be monitored in situ. The same holds for future quantum-sensing applications in field use.

Another relevant quantum application is the realisation of the SI unit of pressure spearheaded by the so-called Fabry–Pérot refractometers in which the refractivity of a known gas can be measured with unprecedented accuracy [32]. It is suggested that in the future, such standards could be miniaturised, providing faster and calibration-free pressure measurements for industries at a fraction of the present cost. However, it is critical for such realisations that the temperature of the gas can be measured accurately. While primary photonic thermometers might not yet necessarily increase the absolute accuracy of the temperature measurement, they can potentially be operated with the same laser systems and equipment. Thus, this project will investigate the potential of cost and complexity reduction in the Fabry–Pérot refractometers. At the same time, the Fabry–Pérot refractometers will provide a mature testbed for novel photonic thermometers.

Both applications [33,34] described above are addressed in this project.

4. Discussion: Expected Project Results and Impact

The redefinition of the SI with regard to the kelvin opens up new possibilities for realising and disseminating thermodynamic temperature, especially through the development of long-term practical primary thermometry approaches. Some of the most innovative ways to provide such traceability are based on photonic/optomechanical technologies, i.e., those described in this paper. Delivering temperature traceability based on photonic/quantum-based practical primary thermometry at the point of measurement has the potential to radically change the practice of thermometry through provision of in situ traceability without the need for sensor recalibration.

This project is a step towards this ambitious goal as the photonic/optomechanical temperature sensors can offer micrometre spatial resolution, large temperature range (from few K up to room temperature), and can additionally be self-calibrated with noise thermometry and even provide a path towards primary temperature standards using quantum measurements.

4.1. Expected Project Results

This research project focuses on the development of integrated optically based practical primary thermometry from 4 K to 500 K. As per the expected results, we aim to develop new facilities and demonstrate the following:

- New device fabrication capabilities for photonic ring resonators, active photonic devices, and optomechanical resonators important for embedded sensor technologies.
- New sensor packaging capabilities via laser welding, glueing, or mechanical supports aiding implementation.
- Special calibration facilities traceable to ITS-90 for photonic and optomechanical sensors from 80 K to 500 K and 4 K to 300 K, respectively, to facilitate implementation.
- Demonstration of the self-calibration of photonic techniques with a quantum reference.
- Demonstration of the application of the developed photonic sensor for quantum applications (ion-trap, pressure standard).

4.2. Expected Project Impacts

The lack of practical primary thermometers constitutes a barrier for the dissemination of the redefined kelvin by the *MeP*-K-19D-recommended approaches, e.g., for addressing industry issues. As a result, the practical primary thermometers developed here are expected to have high impact in industry. 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.

As an example, this project will have an impact on integrated circuit temperature-sensing issues, as well as on 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 H_2 storage) and Quantum Technologies, where temperature-controlled cryostats are 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), with the capability to be embedded into a chipset or other integrated technologies.

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Abbreviations

The following abbreviations are used in this manuscript:

EPM	European Partnership in Metrology
ITS-90	International Temperature Scale of 1990
JNT	Johnson noise thermometry
MeP-K-19D	*Mise-en-pratique* for the definition of the kelvin
PIC	Photonic Integrated Chips
SOI	Silicon On Insulator

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