European Partnership on Metrology
Call 2023 –Fundamental Metrology, Industry, Normative and Research Potential

Selected Research Topic number: **SRT-f05**
Version: 1.0

Title: Photonic and quantum sensors for practical integrated primary thermometry

Abstract

The redefinition of the international system of units in terms of fundamental constants enables novel approaches for the practical primary thermometry realisation and dissemination of thermodynamic temperature. Proposals addressing this SRT should focus on the processes development for temperature dissemination, through the use of fibre coupled integrated optical sensors over the temperature range between 4 K and 500 K, as well as with the use of complementary photonic thermometry techniques, such as quantum opto-mechanics, optical phase noise and photothermal effect. Several geometries (1D, 2D) and materials (e.g., Si, SiN, GaP) of micro- and nano-sensing structures should also be investigated over this temperature range.

Keywords

Practical primary thermometry, Quantum optomechanics, Photonic thermometry, optical resonator, Noise thermometry

Background to the Metrological Challenges

In the post-kelvin redefinition era, temperature traceability is governed by the CCT-approved mechanism of *mise-en-pratique* for the definition of the kelvin (MeP-K-19). The development of a new generation of optically based primary thermometry approaches that could in the long term be used directly in-situ, would address the need for recalibration of sensors as currently required. At the same time, recent developments in quantum technologies require very well controlled in-situ thermometry (integrated directly into the quantum chip set) to be measured directly where the quantum measurements take place. In the EMPIR JRP 17FUN05 PhotOQuant project, state of the art opto-mechanical and photonic resonators have been fabricated and SI traceable temperature measurements have been implemented for accurate metrological validation of these new temperature sensors. The practical phase noise thermometry using opto-mechanical sensors was demonstrated over a large temperature range: from 4 K to 300 K. However, an array of opto-mechanical sensors is required to reduce the corresponding uncertainty when measuring over a large (above 300 K) temperature range. At cryogenic temperatures (below 10 K), quantum opto-mechanical technology enables accurate primary thermometry (uncertainty < 0.2 K). Quantum correlation thermometry as an alternative primary thermometry technology is integrated at the nanoscale and it is insensitive to magnetic fields. In addition to primary thermometry, photonic thermometers are required for high precision and resolution. Photonic thermometry is a chip scale technology based on the thermo-optic effect, the temperature dependence of the refractive index of an optical waveguide, that determines temperature from the resonance frequency of an optical resonator, resulting in very high temperature resolution (sub mK). The minimum operating temperature is imposed by the thermo-optic effect of the optical waveguide, which becomes very small for silicon below 80 K. Photonic thermometry has a very high sensitivity (about 70 pm/K for silicon), but it requires calibration using one of the other types of thermometry developed here because it is a non-primary thermometry technique. For practical applications (cryogenics temperatures), an optical coupling is required to the chip set via optical fibre. This can be realised by fixing the chip set on the fibre itself, but to ensure the reproducibility of the joining technique and compatibility of the materials used, the approach will need to be tested over a large temperature range. Standard coupling methods based on glue joining could be considered for this purpose. However, their use is limited due to the thermal stress of the glue at cryogenics temperatures. As an alternative, the laser welding approach has already been proposed to couple fused silica fibres to borosilicate glass substrates with integrated micro-optics. Stress compensation techniques and novel optical designs need to be developed to facilitate a wide temperature range optics platform. Last, photonic thermometry can also provide a non-invasive and accurate way to measure the temperature drifts of ion traps, without interfering with their operation.

Objectives

Proposers should address the objectives stated below, which are based on the PRT submissions. Proposers may identify amendments to the objectives or choose to address a subset of them in order to maximise the overall impact, or address budgetary or scientific / technical constraints, but the reasons for this should be clearly stated in the protocol.

The JRP shall focus on the traceable measurement and characterisation of photonic and quantum sensors for practical integrated primary thermometry.

The specific objectives are

1. To develop optical noise thermometry from 4 K to 300 K with target temperature uncertainty of 0.1 K, by using 1D (nanobeam) or 2D (membrane) opto-mechanical sensors. To test quantum thermometry below 10 K, and to provide a quantum reference for noise thermometry. To design, fabricate and characterise sensors by using different mathematical models.
2. To extend the range for photonic thermometry from 80 K to 500 K, based on photonic integrated circuits of micro- and nano-resonators. To design, simulate, manufacture and characterise (thermally and optically) the chip-based sensors. To develop and test enhanced read-out techniques, including reliable experimental set-ups and theoretical modelling.
3. To develop integrated packaging of the sensors (few cm^3) and to address the challenge of robust fibre to chip coupling over the temperature range between 4 K and 500 K. To explore different technologies for direct fibre coupling (laser welding, gluing, etc.) to minimise the optical loss and achieve negligible strain effects over this temperature range.
4. To validate the fabricated primary sensors and to calibrate the interpolating sensors (traceable to the international temperature scale (ITS-90)). To evaluate the corresponding uncertainty budgets. To demonstrate the application of the calibrated sensors in quantum applications, such as in ion traps monitoring and quantum dots.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (photonic and opto-mechanical 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).

These objectives will require large-scale approaches that are beyond the capabilities of single National Metrology Institutes and Designated Institutes. Proposers shall give priority to work that aims at excellent science exploring new techniques or methods for metrology and novel primary measurement standards, and brings together the best scientists in Europe and beyond, including other European Partnerships, whilst exploiting the unique capabilities of the National Metrology Institutes and Designated Institutes.

Proposers should establish the current state of the art and explain how their proposed project goes beyond this. In particular, proposers should outline the achievements of the EMPIR project 17FUN05 PhotOQuant and how their proposal will build on those.

EURAMET expects the average EU Contribution for the selected JRPs in this TP to be 2.0 M€ and has defined an upper limit of 2.5 M€ for this project.

EURAMET also expects the EU Contribution to the external funded beneficiaries to not exceed 40 % of the total EU Contribution across all selected projects in this TP.

Any industrial beneficiaries that will receive significant benefit from the results of the proposed project are expected to be beneficiaries without receiving funding or associated partners.

Potential Impact

Proposals must demonstrate adequate and appropriate participation/links to the ’end user’ community, describing how the project partners will engage with relevant communities during the project to facilitate knowledge transfer and accelerate the uptake of project outputs. Evidence of support from the “end user” community (e.g. letters of support) is also encouraged.

You should detail how your JRP results are going to:

- Address the SRT objectives and deliver solutions to the documented needs,
- Feed into the development of urgent documentary standards through appropriate standards bodies,
- Facilitate improved industrial capability or improved quality of life for European citizens in terms of personal health, protection of the environment and the climate, or energy security,
- Transfer knowledge to the optical thermometry sector.

You should detail other impacts of your proposed JRP as specified in the document “Guide 4: Writing Joint Research Projects (JRPs)”

You should also detail how your approach to realising the objectives will further the aim of the Partnership to develop a coherent approach at the European level in the field of metrology and include the best available contributions from across the metrology community. Specifically, the opportunities for:

- improvement of the efficiency of use of available resources to better meet metrological needs and to assure the traceability of national standards
- the metrology capacity of EURAMET Member States whose metrology programmes are at an early stage of development to be increased
- organisations other than NMIs and DIs to be involved in the work.

Time-scale

The project should be of up to 3 years duration.