



Photonic and Quantum Sensors for Practical Integrated Primary Thermometry

Needs

Metrology

Need for a practical primary thermometer with a wide range (4 K to 500 K) for the realisation and dissemination of the thermodynamic temperature according to the *mise-en-pratique* for the definition of the kelvin.

- Practical Quantum Standard
- SPRT Replacement

Industry

Need: integrated, in-situ, self-calibrated, wide-range temperature sensors

Applications

- Photonics/Semiconductors
- Quantum (computing, metrology)
- Cryogenics
- Aerospace
- Hydrogen energy
- Lab-on-a-chip
- Smart sensing

Overall objective

Our ambition is to change paradigm of temperature traceability with a novel small-scale embedded in-situ primary temperature standard.

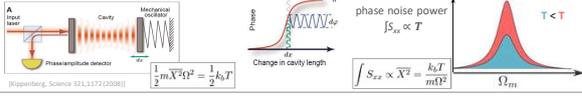
The goal of the project is to develop integrated photonic and optomechanical quantum-based practical primary thermometry from 4 K to 500 K, validated and traceable to best temperature standards.

Integrated photonic and quantum temperature sensors

- Broad T range:** from cryogenics to 500 K
- High accuracy:** 0.05 K uncertainty
- In situ:** chipset technology
- No drift:** primary sensor
- Insensitive to EM field:** photonic sensor

Optomechanical resonator

Optomechanical noise thermometry



Absolute quantum reference

Radiation pressure noise induces correlations between the field's quadratures in the resonator

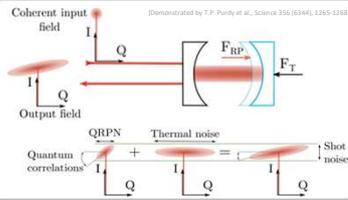
$$\delta X_I \rightarrow \delta X_I$$

$$\delta X_Q \rightarrow \delta X_Q + \alpha \delta F_{1a} + \beta \delta X_I$$

This correlation will serve as an absolute scale to calibrate the thermal noise:

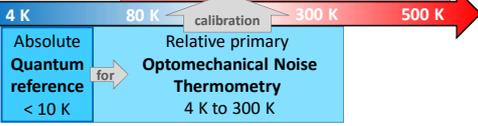
Thermal correlations $\propto \frac{k_B T}{m \Omega_m}$

Quantum correlations $\propto \frac{k_B T}{m \Omega_m}$



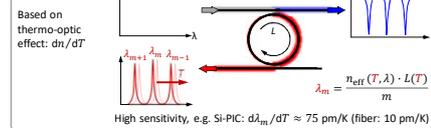
High-resolution Photonic thermometry

80 K to 500 K

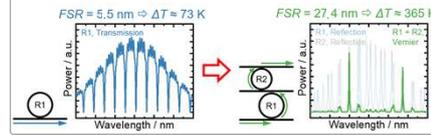


High Q factor Photonic Ring Resonator

Basic concept



Enhanced temperature range



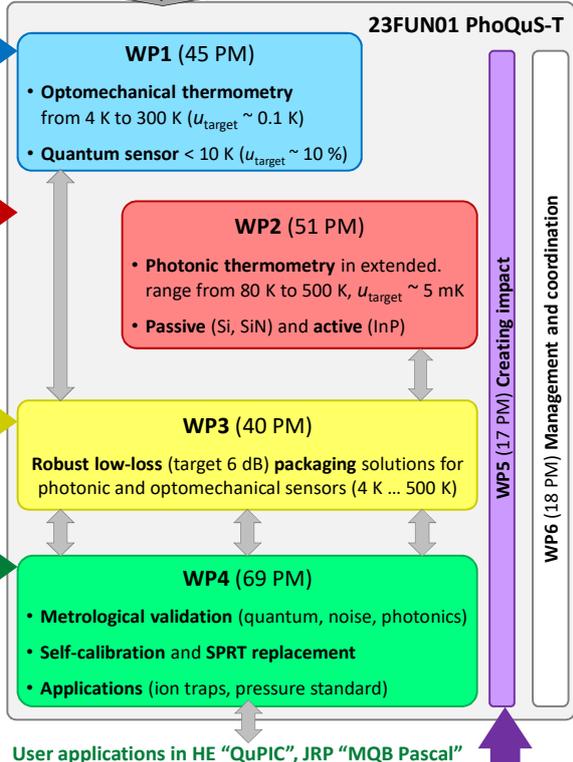
Excellence

Based on the outputs of the JRP 17FUN05 "PhotOQuant", 4 technical objectives progressing beyond the state of the art:

✓ "PhotOQuant" outputs	□ State of the art	➤ PhoQuS-T progress
1) Optomechanical noise thermometry (4 K to 300 K) and quantum thermometry (< 10 K) <ul style="list-style-type: none"> ✓ High Q factor optomechanical resonators (SiN, GaP) fabricated and tested ✓ Noise thermometry protocols developed and tested 	<ul style="list-style-type: none"> □ Self-heating is main systematic effect □ Noise thermometry is relative technique □ Only one demonstration of quantum correlation thermometry by NIST in 2017 	<ul style="list-style-type: none"> ➤ Absolute quantum thermometry below 10 K ➤ Combined relative & absolute thermometry (optics/photonics & optomechanics) ➤ Reduced self-heating with new design ➤ Array of sensors for wide T range operation
2) Advanced photonic thermometry (80 K to 500 K) <ul style="list-style-type: none"> ✓ Si ring resonators (RR) fabricated ($Q \approx 10^5$) and tested around room temperature ✓ High sensitivity: 75 pm/K, resolution: 10 mK ✓ Theoretical study: SiN high potential for RR (transparent in visible range, no two-photon absorption (TPA)) 	<ul style="list-style-type: none"> □ Restricted operational range (150 K) due to the free spectral range of single RR □ Self-heating due to the two photon absorption in Si □ Active photonic thermometry (combining laser + RR on a chip) explored theoretically 	<ul style="list-style-type: none"> ➤ Broad operational range from 80 K to 500 K with advanced design (e.g. coupled RR) ➤ Reduced self-heating for RR <ul style="list-style-type: none"> • Thick SOI platform for Si for high $Q \approx 10^7$, low propagation losses ($\approx 0.1 \text{ dB/cm}$) • New material SiN (no TPA, VIS and IR) ➤ Active photonic thermometer demonstrated (towards fully integrated chip-based devices)
3) Robust fibre-to-chip coupling packaging solutions (4 K to 500 K) <ul style="list-style-type: none"> ✓ Free-space coupled devices with active alignment systems were developed. 	<ul style="list-style-type: none"> □ Low-loss robust fibre-to-chip coupling is needed for further practical applications. □ Fibre-to-chip coupling solutions exist, but are not tested over temperature range from 4 K to 500 K. 	<ul style="list-style-type: none"> ➤ Low-loss robust fibre-to-chip coupling for practical applications from 4 K to 500 K (gluing, welding or mechanical support) ➤ Co-packaged solution for optomechanical and photonic sensors
4) Metrological validation and applications <ul style="list-style-type: none"> ✓ Optomechanical noise thermometry demonstrated over 4 K to 300 K range ✓ Photonics thermometry demonstrated from 300 K to 360 K ($u_{\text{stddev}} = 10 \text{ mK}$) 	<ul style="list-style-type: none"> □ Optomechanics: NIST (2017) demonstration for quantum correlations thermometry ($u = 1 \text{ K}$ at 40 K, $u = 30 \text{ K}$ at 300 K) □ Photonics: NIST (2018) demonstration with $u = 175 \text{ mK}$ and recent study at NRC (2023) with $u = 10 \text{ mK}$ (296 K to 353 K) □ No practical application demonstrated 	<ul style="list-style-type: none"> ➤ Metrological validation <ul style="list-style-type: none"> • Quantum thermometry (< 10 K): $u_{\text{target}} 10 \%$ • Noise thermometry (4 K ... 300 K): $u_{\text{target}} 0.1 \text{ K}$ • Photonics (80 K ... 500 K): $u_{\text{target}} 5 \text{ mK}$ at 300 K ➤ Self-calibration demonstration ➤ SPRT replacement possibility test ➤ Practical applications demonstration (ion trap and pressure standard)

JRP 17FUN05 "PhotOQuant" outputs

Implementation



User applications in HE "QuPIC", JRP "MQB Pascal"

Impact

Target groups

- Int. and EU TC in thermometry: CIPM (CCT), EURAMET, RMO TC-Ts
- NMIs/DIs: temperature metrology
- Scientific community: field of quantum and photonic technologies
- Start-ups, SMEs: quantum and photonic technologies
- Industries using embedded T sensors: semiconductors, aerospace, cryogenics, QT, H₂ energy

- Open access papers
- Conf. presentations
- Activities in networks
- Training / univ. lectures
- Website, newsletters
- Workshops, Staff exchange

Outputs

Outcomes

Impact

- ✓ New device fabrication capabilities for photonic ring resonators, active photonic devices and optomechanical resonators
- ✓ New capabilities for packaging sensors by laser welding, gluing, or mechanical support
- ✓ Special calibration facilities traceable to ITS-90 for photonic sensors (80 K to 500 K) and optomechanical sensors (4 K to 300 K)
- ✓ Demonstration of self-calibration of combined optomech. and photonic sensor
- ✓ Usability of the sensors in the demonstrated applications (ion trap, pressure standard)

- For CCT/TC-T and NMIs/DIs:
 - Potential inclusion of photonic/optomech. primary thermometry within CCT MeP-K.
 - Strategic recommendations beyond 2030
 - Stimulating greater NMI activity in photonic/quantum thermometry to support the emerging EU metrology infrastructure.
- For scientific community and industry:
 - Sensors embedded in chipsets for accurate, drift-free measurements from 4 K to 500 K
 - Adoption of primary thermometry reduces reliance on ITS-90 traceability over time.

- Direct in-situ calibration will enhance traceability efficiency, resulting in economic and environmental advantages (energy optimization, emission reduction).
- Enhancing collaboration amongst European NMIs, academia, and research institutions in quantum, photonics, and nano-scaled technologies will strengthen EU industry in these key technologies.
- The new chip-scale in-situ primary temperature standard has potential uses in quantum, semiconductor, aerospace, and hydrogen technology, contributing to Europe's leadership in these fields.

Consortium



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