EMPIR Call 2020 – Fundamental, Industry and Normative

Selected Research Topic number: **SRT-f04**
Version: 1.0

Title: Next generation ultrastable lasers: reducing thermal noise limit and overcoming technical limitations with new materials and technologies

Abstract

Ultrastable lasers are basic building blocks of optical clocks and provide short term frequency stability for numerous scientific and technological applications, including quantum technologies. Brownian motion of the constituents of the reference optical cavity now limits their stability to 10^{-17}. New technologies promise substantial reduction of this fundamental limit, such as, novel materials for mirror coatings like microstructures or crystalline Bragg reflectors, spacer materials like single crystals, vibration isolation techniques and technologies to operate reliably at cryogenic temperatures of a few kelvin and below. For the future generation of ultrastable lasers, these technologies need to be investigated and brought into operation in a coordinated approach. Proposals addressing this SRT should focus on opening the route to the next generation of ultrastable lasers at fractional frequency instabilities of 10^{-17} and below, tackling thermal noise and technical limitations with new materials and technologies.

Keywords

Ultrastable lasers, optical cavities, mirrors, optical clocks, spectral hole burning, frequency standards, frequency comparison, frequency combs, timescales, SI second

Background to the Metrological Challenges

Ultrastable lasers are key enablers of measurement capability in optical frequency metrology, which is driving the progress in many fields where precise measurements are needed (e.g. pressure, voltage, or geodesy). The measurement capability of optical clocks is basically set by the level of stability performance of the laser used to interrogate the atomic clock transition. In optical lattice clocks, the ultimate instability due to quantum projection noise from several thousand atoms is so low that their current instability is usually limited by laser frequency noise through the Dick effect. In the best single ion clocks, quantum projection noise (QPN) is limiting the stability. Here, the only way to improve the stability is by increasing the interrogation time, which is again limited by the laser coherence time.

New materials need to be investigated to enable the next steps in lasers frequency stability by reducing the so far limiting effects of thermal Brownian noise of the reference optical cavity. Novel approaches have been developed for mitigation to be used in the next generation of detectors, such as: new low thermal noise mirror coatings based on crystalline Bragg reflectors, and nanostructured surfaces, as well as vibration free cryostats. So far, low thermal noise mirror designs using modified dielectric coatings show high optical performance, but still relatively high thermal noise, while the current generation of crystalline mirrors, show lower thermal noise but their optical performance is not yet at the level of the dielectric counterparts. Their optical performance needs to be characterised to verify their suitability for ultrastable optical reference cavities. The mechanical quality factor of the components needs to be measured and its dependence on fabrication processes needs to be understood. Highly dispersive cavities to reduce noise sensitivity, and materials with high specific stiffness to reduce sensitivity to vibrations also need to be considered. Furthermore, as a possible alternative to optical cavities, novel frequency references based on spectral hole burning (SHB) in rare-earth doped ion crystals should be investigated, as the fundamental limit of such systems is still unknown

Also, vibration control and reduction must be addressed, since they are one of the main sources of technical noise - both for cavities and spectral hole burning - preventing ultrastable lasers from reaching the fundamental thermal noise limit. The present generation of commercial active vibration isolation systems can be significantly improved in their performance at low frequency, by using state-of-the-art seismometers, tiltmeters and interferometric levelling systems.

Integrating the novel optical reference cavities and SHB to closed cycle cryocooler technology needs to be able to meet strict requirements in terms of vibrations, and temperature stability, combined with continuous and reliable operation. Novel approaches need to be investigated to more efficiently decouple the vibrations of the closed cycle operation, from the optical cavity and the SHB setup, making use of passive and active isolation strategies. Approaches to reduce the transmission of temperature fluctuations from the cryocooler to the optical cavity have to be investigated also.

Furthermore, there is a need to deliver ultra-stable test systems with the potential to enable a new level of performance for optical clocks. Their improved stability at $10^{-17}/\sqrt{\tau}$ fractional frequency instability will significantly speed up the measurement time for the characterisation of systematic effects, and ultimately lead to a higher level of confidence in clock accuracy for the redefinition of the SI second based on optical standards.

The effective exploitation of ultra-stable lasers in optical clocks needs noiseless spectral purity transfer between the wavelengths of interest using optical frequency combs, which requires the full understanding of fundamental degradation effects in the frequency transfer from the cavity to the clocks via fibres and frequency combs, to be able to develop designs and strategies to minimise these effects.

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 opening the route to the next generation of ultrastable lasers at fractional frequency instabilities of 10^{-17} and below, tackling thermal noise and technical limitations with new materials and technologies.

The specific objectives are

1. To investigate (i) new mirror coating materials such as single crystalline Bragg reflectors, micro-structured surfaces or optimised dielectric coatings, and cavity spacers to realise the next generation of ultrastable optical cavities, and (ii) novel frequency references based on spectral hole burning (SHB) in rare-earth doped ion crystals (and associated mechanisms that can perturb the frequency stability of the spectral holes) as an alternative for the realization of ultrastable lasers.
2. To demonstrate improved vibration isolation systems at low frequency, by using state-of-the-art seismometers, tiltmeters and interferometric levelling systems, involving new materials, multi-degree of freedom servo control, and suspension systems. Their performance needs to be optimised for the frequency of interest of ultrastable lasers (≈ 1 mHz – 100 Hz). To develop vibration isolation strategies with targeted residual acceleration noise level below 10^{-6} $ms^{-2}/Hz^{1/2}$.
3. To integrate closed cycle cooling for continuous cryogenic operation of SHB and optical cavities at 124 K, 4 K and even below. Novel approaches need to be investigated to more efficiently decouple from the optical cavity or the SHB setup temperature fluctuations and vibrations intrinsic of the closed cycle operation.
4. To investigate noise sources occurring in the ultrastable laser synthesis process when translating from the reference cavity wavelength to that of interest for optical clock operation, and to identify fundamentally limiting noise processes. Local and remote cavity-vs-atom and cavity-vs-cavity frequency data should be correlated to perform new tests of fundamental physics like fine structure constant variations or gravitational waves detection.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (NMIs, research laboratories), and possible end users (e.g. geodesy, quantum technologies).

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, 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.

EURAMET expects the average EU Contribution for the selected JRPs in this TP to be 1.5 M€, and has defined an upper limit of 1.8 M€ for this project.

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

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,
- Transfer knowledge to the European time and frequency metrology community as well as the quantum technologies 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 EMPIR 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.