

## Publishable Summary for 20FUN08 NEXTLASERS

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

#### Overview

Quantum technologies are of utmost importance for the European community to create practical applications in many different fields, from computing and communications to health, finance, transport, and national security and defence. This critical technology will generate a multi-billion Euro market in new technological solutions for business and citizens. For exploitation of quantum effects in sensing, computing and communication, coherence is the most important parameter, and highly coherent laser sources are required both for the development of more advanced devices and for the widespread applications of quantum sensors outside specialist laboratories. This project aims at opening the route to the next generation of ultrastable lasers, realising optical fractional frequency instabilities of  $10^{-17}$  and below, corresponding to millihertz linewidth and tens of seconds coherence time.

#### Need

The EURAMET European Metrology Network for Quantum Technologies (EMN-Q) has formulated common metrology strategies and a roadmap for Quantum clocks and atomic sensors. There, ultrastable lasers, and low perturbation cryogenic systems were identified as essential enabling technology and their laser noise characterisation as important metrological validation. They are also described as central enabling technology for quantum sensors in the fields of spacetime references, geodetic references, navigation, deep-space tracking/positioning, monitoring of key variables for climate, geoscience, monitoring of underground resources, defence, and health. The research in this project on an ultrastable cavity design optimised for low frequency gravitational wave (GW) detection may also lead to future applications in these fields.

As one of the most advanced quantum sensors, optical clocks will immediately benefit from improved ultrastable lasers that interrogate atomic transition, as this fundamentally limits the measurement resolution that can be reached in finite measurement times. High resolution optical clock comparisons are necessary for the evaluation of their accuracy towards a redefinition of the SI second in terms of optical transitions. The improved ultrastable lasers developed in this project will also further enable clocks to become effective tools for tests of fundamental physics, chronometric geodesy, gravitational waves, and dark matter detection.

Ultrastable frequencies are needed for many high-tech industrial applications: Optical telecommunication, bistatic radar, long distance fibre links, synchronisation of telecommunication networks, satellite navigation and communication systems, and optical sensing. Here, the uptake of the project results by laser producers will make ultrastable frequency sources available to these communities, leading to improved quality and performance in these applications.

#### Objectives

This project will address the current limitations of ultrastable lasers, aiming to set the ground for the next generation of these devices with frequency instabilities at and below  $1 \times 10^{-17}$ .

The specific objectives of the project are:

1. To apply novel low thermal noise designs. New high-reflectivity low thermal noise mirror coatings such as single crystalline Bragg reflectors, micro-structured surfaces or dielectric coatings optimised for higher mechanical quality factor will be investigated. Furthermore, highly dispersive cavities based on the slow light effect aim at further reducing the thermal noise sensitivity. Spacer materials with high specific stiffness and thus lower sensitivity to vibrations will be addressed for the next generation of ultrastable cavities. Frequency references based on spectral hole burning (SHB) in rare-earth ion doped crystals as a promising alternative for frequency stabilisation of ultrastable lasers will also be investigated.

Mechanisms (temperature, pressure, vibration, etc.) that can perturb the frequency stability of the spectral holes will be studied to understand the fundamental limits of such systems.

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 will be optimised for the frequency of interest of ultrastable lasers ( $\approx 1 \text{ mHz} - 100 \text{ Hz}$ ).
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 will be investigated to more efficiently decouple temperature fluctuations and vibrations intrinsic of the closed cycle operation, from the optical cavity or the SHB setup.
4. To make the ultrahigh stability available to optical clocks. As the ultrastable lasers operate at wavelengths optimised for stability of the references (spectral holes in crystals or low-noise mirrors) different from the wavelengths needed to interrogate clock transitions in atoms or ions, the stability must be transferred to other wavelengths. The noise sources in this spectral transfer will be investigated and fundamentally limiting noise processes will be identified, amongst other techniques by using advanced digital signal processing.
5. To apply tests of fundamental physics. Local and remote cavity-vs-atom and cavity-vs-cavity frequency data will be correlated to perform new tests of fundamental physics such as fine structure constant variations. The prospects of specially designed optical cavities for future low-frequency gravitational waves detection will be analysed.
6. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (NMIs, research laboratories), and potential end users (e.g. geodesy, quantum technologies). The developments will enable robust, reliable ultrastable frequency sources with a large range of applications that will likely lead to commercial products.

### Progress beyond the state of the art

The frequency stability of today's most stable lasers is based on the length stability of well-isolated Fabry Perot Cavities (FPCs), e.g., a 50 cm long cavity with ultralow expansion glass spacer, reaching  $6 \times 10^{-17}$  fractional frequency stability, or a 21 cm cavity with silicon spacer at 124 K with  $4 \times 10^{-17}$  stability, limited by the fundamental Brownian thermal fluctuations of the cavity. Novel cavity designs based on e.g., metamaterial mirrors, are being developed to reduce the instability due to Brownian thermal noise by a factor of 5 to around  $1 \times 10^{-17}$ . There have been many activities to improve ultrastable lasers and make them commercially available. However, despite worldwide efforts during the recent 27 months, the instability could not be improved beyond  $4 \times 10^{-17}$ . Alternative references based on spectral hole burning that are less sensitive to thermal noise and environmental fluctuations are expected to reduce the current instability level by at least an order of magnitude to a few  $10^{-17}$  or below.

Using dedicated sensors and multiple-in multiple-out servo loops pioneered for Gravitational Waves (GW) detectors, the vibrations acting on the frequency references will be reduced below the level of currently available commercial systems to the micro g level also at lower frequencies.

The project will set up and investigate dedicated cryostats down to sub-kelvin temperatures that allows reliable low noise operation of ultrastable lasers with fractional frequency instability in the  $10^{-18}$  decade. The target is to identify and mitigate the limits in the transfer of frequency stability from the ultrastable lasers to the target wavelengths via optical frequency combs, which mainly originate from detection and uncontrolled path length fluctuations in wavelength conversion modules.

As a proof of the improvements obtained, ultrastable lasers from this project will be applied for tests of fundamental physics, where lower present bounds will be produced e.g. on potential violation of Lorentz invariance.

So far, NEXTLASERS could show, how to implement these ideas for future improvements of ultrastable lasers. On the other hand, also technological problems were identified, that will require further work beyond the duration of the project, to finally demonstrate an operational laser with frequency stability around  $1 \times 10^{-17}$ .

## Results

### *Novel low-thermal noise cavity designs (Objective 1):*

Microstructured metamirrors based on silicon nano-grating structures on fused silica substrates with plane phase profile were combined with dielectric coatings on the rear side of the substrate to form highly reflecting “meta etalons”. Optical ring-down measurements show overall reflectivities of 99.97% [Dickmann 2023]. These results are very promising for setting up high finesse ultra-stable cavities. Focusing metamirrors with curved phase profile on planar substrates were designed with the help of deep-learning algorithms. Fabrication and first tests to optically contact these structures to cavities have started.

Investigations on crystalline low-Brownian mirrors based on GaAs/AlGaAs Bragg reflectors at 124 K indicate excess noise above the Brownian noise. These results were published recently. So far, the physical noise mechanism is not understood and further investigations on its temperature dependence and spatial correlations are in progress.

Large mode diameters also reduce the influence of thermal Brownian mirror noise. A simulation code for systematic studies of cavity geometries and mirror configurations was developed, and configurations, that both provide large mode sizes on the mirrors and are largely insensitive to manufacturing tolerances, have been identified and their production being discussed with several optics’ suppliers.

As an alternative to optical cavities, spectral hole burning in europium-doped crystals is being investigated. A flexure samples of the crystal has yielded  $10^{-3}$  down to  $10^{-4}$  mechanical loss at cryogenic temperatures, depending on the choice of the mechanical mode of resonance. In a single pass geometry, excitation and simultaneous interrogation by up to 9 separate modes was implemented to reduce the sensing noise, and a dedicated FPGA system is used to reduce the loop delay and increase the locking bandwidth. Another crystal has been fabricated, characterised, and is being prepared to realise a slow-light cavity. The crystal surface was machined to create a constant optical thickness independent of local variations of refractive index.

### *Improved vibration isolation systems at low frequency (Objective 2):*

Acceleration and tilt sensors at low frequencies (1 mHz – 100 Hz) suitable for integration with the room-temperature vibration-isolation systems were identified. With these sensors, suppression of the low-frequency vibrations below 2 Hz in the vertical direction by about one order of magnitude could be achieved.

The frequency-dependent response of the cavity resonance frequency on accelerations was measured on several systems. This information was used to predict the actual vibration-induced frequency fluctuations in real-time. To strongly suppress their influence, the predicted fluctuations were subtracted from the laser frequency in a feed-forward scheme, using specially developed frequency agile frequency sources. Alternatively, the feed-forward coefficients were optimized by minimizing observed frequency variations, when the cavity accelerated on purpose. Both methods provide different coefficients, to understand the reason further measurements are now under way.

Microcontroller and FPGA based systems are now available in the consortium for further optimization. First realizations of a frequency feed-forward prove a tenfold reduction of the vibration sensitivity up to 10 Hz. This makes them an ideal complement for active acceleration feedback to overcome its current limitations above 2 Hz.

### *Integration of closed-cycle cooling for continuous cryogenic operation of SHB and optical cavities at 124 K, 4 K and below (Objective 3):*

For a 124 K silicon cavity, a cold He-gas circulation system with a closed-cycle heat exchanger was designed and is now installed. Vibrations will be decoupled from the cavity by flexible hoses that are damped at intermediate positions.

With a closed-cycle dilution cryostat for a sub 1-K silicon cavity a minimum temperature of 15 mK was reached and stabilised operation at 20 mK was achieved. A single-crystal silicon cavity has been setup by optically contacting high-reflectivity crystalline mirror coatings. A room-temperature finesse of 220 000 is obtained, and the cavity is mounted in the cryostats for tests at cryogenic temperatures. Similarly sub 2-K cryostats for the spectral-hole burning setups have been installed for first tests. Temperatures of 1.5 K and 80 mK have been achieved. Temperature fluctuations amplitudes of 30  $\mu$ K have been observed at 100 mK. With a 1 Hz/K temperature sensitivity of the crystal, this translates to a  $6 \cdot 10^{-22}$  fractional frequency instability. Next, vibrational levels and temperature stability will be investigated, and the mechanical decoupling optimized to enable stable optical references from cavities and spectral holes at the  $10^{-17}$  level.

#### *Making ultrahigh stability available to clocks (Objective 4):*

The use of ultrastable lasers very often requires the transfer of stability to other wavelengths, using optical frequency combs with low added noise. The electronics and digital signal processing chains to generate low-noise signals from optical frequency combs were designed. Concepts for fully digital signal processing using Field Programmable Gate Arrays (FPGAs) were developed between the partners.

By electrically gating the detected beat notes of stable continuous-wave (cw) lasers with a femtosecond comb the signal-to-noise ratio could be improved by 12 dB, improving the stability for frequency transfer at short averaging times by the same amount.

Digital control systems were also developed showing the capability for phase-locking up to 6 slave lasers to the same master laser, with high level of customization, instability  $< 3 \times 10^{-18}$  and low latency. Different laser technologies, focusing on those used in the optical clocks community, were used as slave lasers for the tests. In all cases, servo bandwidth  $> 200$  kHz could be achieved, which avoids the need for pre-stabilization and meet the targeted requirements. Activity will progress with the comparison to commercial solutions. Making use of these devices and having addressed other sources of technical noise (uncompensated free-space paths, fiber-delivery systems etc), partners will assess the ultimate instability of spectral transfer at a level of  $10^{-17}$  and below.

#### *Application for tests of fundamental physics (Objective 5):*

A three-dimensional data analysis method has been developed for correlating data from multiple clocks that takes into account geometrical configuration of the clocks to investigate dark-matter coupling to the fine-structure constant from observations of three clocks and distinguish it from technical noise. A correlation analysis of join data of local comparisons between cavities and atomic clock transitions from up to 7 systems distributed between USA, Europe and Asia is ongoing and a publication is being prepared

The response of a cavity made of two mirrors connected by a solid elastic spacer to measure gravitational waves was analysed theoretically. The theory for Weber-bar mechanical resonators was applied to optical resonators. It indicates that for spacers made of typical materials like ULE or fused silica, with mechanical resonances in the kHz range, a sensitivity competitive to already existing mechanical detectors can be achieved. The result was recently published [Narožnik 2023].

### **Impact**

In the first 27 months of the project, project partners engaged in a number of key communication and dissemination activities. 27 contributed oral presentations and 10 invited oral presentations were given, and 20 posters were presented at conferences such as Integrated Optics - Sensors, Sensing Structures and Methods (IOS 2022), IEEE EFTF-IFCS 2021, 2022 and 2023, the International Symposium on Novel Materials and Quantum Technologies (ISNTT 2021), the 8th Congress of the French Optical Society (OPTIQUE Dijon 2021), and the 760. WE-Heraeus-Seminar. 14 training courses were delivered outside the consortium, seven at universities, one at an international conference on subjects pertaining to the development and applications of ultrastable lasers and six at the European Frequency and Time Seminars 2022 and 2023. So far 12 peer reviewed papers have been published. A dedicated project website acts to communicate information on the project to a broader audience and serve as a platform for information and document exchange.

#### *Impact on industrial and other user communities*

This project will open the path for the next generation improved laser oscillators that – with the help of femtosecond combs – can provide ultrastable frequencies from radio frequency up to the visible and UV spectral region. These techniques can be transferred to companies that feed the supply chain for science and application and improved measurement capabilities, e.g., in the fields of optical telecommunication, radar systems, long distance fibre links, synchronisation of telecommunication networks, satellite navigation and communication systems, and optical sensing. Also, all quantum technologies that are limited by decoherence effects from their local oscillators, e.g., in quantum simulation, quantum computing or coherent quantum-communication, will benefit from improved and readily available ultrastable oscillator. Interest from two companies has appeared on taking up the developments on ultrastable laser, especially concerning continuous closed cycle cooling (objective 3) and converting them into commercial products. In one case a cooperation agreement is in preparation.

The observation of so far unexpected noise in AlGaAs coatings has attracted much attention from the



gravitational wave community, leading to an invitation to a workshop organized by LIGO on mirrors for the next generation of gravitational wave detectors and a connected publication. Informal regular online meetings have been established between LIGO members, the manufacturer and users to exchange ideas.

#### *Impact on the metrology and scientific communities*

The instability of the interrogation laser is one of the main limitations for the stability of optical clocks, which in turn limits their efficient evaluation and corresponding improvement, because excessive averaging times are required to detect small frequency shifts. Therefore, the novel ultrastable laser sources at the required wavelength for optical clocks from this project will immediately improve both the stability and the accuracy of all current optical clocks. This will improve timekeeping, accelerate a redefinition of the second and enable applications of optical clocks for geodesy, where  $10^{-18}$  relativistic frequency shifts need to be resolved to achieve a 1 cm height resolution. Reliable ultrastable lasers as flywheels with instability below that of currently employed masers can bridge downtimes of optical clocks, and thus contribute to an improved realisation of International Atomic Time (TAI) by optical standards.

The European comparison campaigns of optical clocks within the EMPIR project ROCIT “Robust optical clocks for international timescales” benefitted already from improved ultrastable lasers. E.g. the Yb<sup>+</sup> ion clock and the Sr lattice clock at PTB that were participating in the ROCIT comparisons, could increase their interrogation time and thus improve the stability and reliability by using an ultrastable reference laser pre-stabilized to a cryogenic Si cavity that is investigated in NEXTLASERS. Similarly, in the Yb lattice clock at INRIM link could benefit from improved cavity stability (see publication Clivati et al., 2022).

Concerning the future change in the definition and realisation of the SI unit of time, the route to impact will be through the EURAMET Technical Committee on Time and Frequency. The consortium is well represented in this body, where information on the project progress and outputs will be disseminated through tailored presentations and written reports.

The highest resolution in radio-astronomical observations is achieved using Very Long Baseline Interferometry (VLBI). Significant improvements of the VLBI performance at mm wavelengths can be expected by replacing H-masers with more stable lasers developed in this project. Providing better frequency and timing stability to e.g. VLBI geodetic observatories (“core station”) of the Global Geodetic Observing System (GGOS) of the International Association of Geodesy (IAG) will enable the identification and removal of systematic measurement biases for co-located geodetic instrumentation and calibration of space geodetic measurements. Improved VLBI is also of interest to the Time and Frequency metrology community, as it is used to monitor the rotation of the Earth with respect to TAI.

#### *Impact on relevant standards*

As a project is addressing fundamental aspects, no immediate impact on standards beyond the early-stage interaction with metrology bodies is expected. Nevertheless, because of the impact of ultrastable lasers for optical clocks, representatives of the project partners were taking part in the CCTF meetings and activities on frequency standards comparisons.

#### *Longer-term economic, social and environmental impacts*

Europe has a long tradition of excellence in quantum research and retaining its globally strong position in this field is of great strategic importance. In the EU “Quantum Manifesto” laser sources were identified as fundamental to building quantum devices, as well as to numerous spin-off applications. The ESA Quantum Technologies in Space strategic report defines ultrastable lasers as one of the main enabling tools for such goals as Time and Frequency Services, Earth Sensing and Observation, and Fundamental Physics. The next generation of ultrastable lasers that will be developed in this project will support this target.

Furthermore, quantum sensors for monitoring the environment in Earth sensing and observation can be improved or made suitable for practical use in the first place using readily available ultrastable frequency sources. Lastly, quantum devices relying on ultrastable sources can impact society by improving telecommunication, navigation, quantum cryptography and quantum computing.

Long-term impact on the multi-billion wireless telecommunication market from improved ultrastable sources is also expected. Mobile telecommunications will require synchronised clocks at every physical layer and currently sub-ns synchronisation is envisioned for the highest layer of clocks. Even higher performance at the 10 ps level will be required for monitoring the performance of the highest production level. Ultrastable lasers in combination with frequency combs as optical frequency dividers can provide superior RF-signals for

monitoring the performance and correct operation of even the highest level of accuracy.

The annual market revenues in Global Navigation Satellite Systems from both devices and services are expected to grow to €325 billion in 2029. The European GNSS industry accounts for more than a quarter of the global market share. However, there is a growing concern about the over-reliance of critical infrastructure since GNSS radio signals are greatly affected by the weather, unencrypted, and easily jammed, and no back up system is available. With the ability to provide superior RF-signals using ultrastable lasers located at ground stations of the GNSS, it will be possible to monitor GNSS functionality and to detect jamming attempts of this critical infrastructure.

At the current stage of the project, contacts to industry have been established to transfer the newly developed technology to commercially available devices.

### List of Publications:

Clivati, C. et al (2022) 'Coherent Optical-Fiber Link Across Italy and France', *Physical Review Applied* 18(5). Available at <https://doi.org/10.1103/PhysRevApplied.18.054009>

Cole, G. D. et al (2023) 'Substrate-transferred GaAs/AlGaAs crystalline coatings for gravitational-wave detectors', *Applied Physics Letters* 122(11) p. 110502. Available at <https://doi.org/10.1063/5.0140663>

Dickmann, J. et al (2023) 'Experimental realization of a 12,000-finesse laser cavity based on a low-noise microstructured mirror', *Communications Physics* 6(1). Available at <https://doi.org/10.1038/s42005-023-01131-1>

Dickmann, J. et al (2023) 'Levitating the noise performance of ultra-stable laser cavities assisted by a deep neural network: the non-intuitive role of the mirrors', *Optics Express* 31(10) p. 15953. Available at <https://doi.org/10.1364/OE.483550>

Donadello, S. et al (2023) 'Embedded Digital Phase Noise Analyzer for Optical Frequency Metrology', *IEEE Transactions on Instrumentation and Measurement* 72 p. 1-12. Available at [Checks do not identify a good link - revision to checks needed!](#)

Goti, Irene et al (2023) 'Absolute frequency measurement of a Yb optical clock at the limit of the Cs fountain', *Metrologia* 60(3) p. 035002. Available at <https://doi.org/10.1088/1681-7575/acbc5>

Herbers, S. et al (2022) 'Transportable clock laser system with an instability of  $1.6 \times 10^{-16}$ ', *Optics Letters* 47(20) p. 5441. Available at <https://doi.org/10.1364/OL.470984>

Kedar, D. et al (2023) 'Frequency stability of cryogenic silicon cavities with semiconductor crystalline coatings', *Optica* 10(4) p. 464-470. Available at <https://doi.org/10.1364/OPTICA.479462>

Le Targat, R. et al (2023) 'First-order thermal insensitivity of the frequency of a narrow spectral hole in a crystal', *Physical Review A* 107(1). Available at <https://doi.org/10.1103/PhysRevA.107.013518>

Narožnik, M., Bober, M., Zawada, M. (2023) 'Ultra-stable optical clock cavities as resonant mass gravitational wave detectors in search for new physics', *Physics Letters B* 846 p. 138260. Available at <https://doi.org/10.1016/j.physletb.2023.138260>

Risaro, M. et al (2022) 'Improving the Resolution of Comb-Based Frequency Measurements Using a Track-And-Hold Amplifier', *Physical Review Applied* 18(6) p. 064010. Available at <https://doi.org/10.1103/PhysRevApplied.18.064010>

Shelling Neto, L., Dickmann, J., Kroker, S. (2022) 'Deep learning assisted design of high reflectivity metamirrors', *Optics Express* 30(2) p. 986. Available at <https://doi.org/10.1364/OE.446442>

Yu, J. et al (2023) 'Excess Noise and Photoinduced Effects in Highly Reflective Crystalline Mirror Coatings', *Physical Review X* 13(4) p. 041002. Available at <https://doi.org/10.1103/PhysRevX.13.041002>

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

Project start date and duration:		01 June 2021, 36 months
Coordinator: Uwe Sterr, PTB		Tel: +49 531 592 4310
Project website address: <a href="https://www.ptb.de/empir2021/nextlasers/home/">https://www.ptb.de/empir2021/nextlasers/home/</a>		E-mail: uwe.sterr@ptb.de
Internal Funded Partners:	External Funded Partners:	Unfunded Partners:
1. PTB, Germany	7. CNRS, France	
2. INRIM, Italy	8. HHUD, Germany	
3. LNE, France	9. LINKS, Italy	
4. OBSPARIS, France	10. LUND, Sweden	
5. RISE, Sweden	11. TUBS, Germany	
6. VTT, Finland	12. UMK, Poland	
Linked Third Parties: 13. CNRS, France (linked to OBSPARIS), 14. ENSMM, France (linked to CNRS)		
RMG: PTB, Germany (Employing organisation); VTT, Finland (Guestworking organisation)		