

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 1×10^{-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 in order 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 (≈ 1 mHz – 100 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 6×10^{-17} fractional frequency stability, or a 21 cm cavity with silicon spacer at 124 K with 4×10^{-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 1×10^{-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.

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 characterised by optical ring-down measurements, showing reflectivities of 99.97%. 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. So far, the noise mechanism is not understood and further investigations on its temperature and spatial correlations are in progress.

Large mode diameters reduce the influence of thermal Brownian mirror noise. A simulation code for systematic studies of cavity geometries and mirror configurations was developed. The search for configurations, that both provide large mode sizes on the mirrors and are largely insensitive to manufacturing tolerances has started.

As an alternative to optical cavities, spectral hole burning in europium-doped crystals is being investigated. Samples of the crystals were prepared for mechanical loss measurements. In a single pass geometry, excitation and simultaneous interrogation by up to 9 separate modes was implemented to reduce the noise. Another crystal has been fabricated, characterised, and is being prepared to realise a slow-light cavity.

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. This information will be used to predict the actual vibration-induced frequency fluctuations in real-time. To strongly suppress their influence, the predicted fluctuations will be subtracted from the laser frequency in a feed-forward scheme, using frequency agile frequency sources that are currently developed.

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 preparations have started for its realisation. 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. Similarly sub 2-K cryostats for the spectral-hole burning setups are being installed for first tests. 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 design of electronics and digital signal processing chains to generate low-noise signals from optical frequency combs has started. Concepts for fully digital signal processing using Field Programmable Gate Arrays (FPGAs) were developed between the partners.

The electrically gated detection of beat notes of stable cw lasers with a comb showed very promising results, significantly improving the signal-to-noise ratio that typically limits the stability at short averaging times.

Next the FPGA hardware and the gated detection will be further characterized to demonstrate a frequency transfer with added electronic and detection noise well below the targeted laser instability of 10^{-17} for averaging times down to at least 1 s. To identify the fundamental noise limits of the spectral transfer by femtosecond frequency combs, the noise added by nonlinear processes in the spectral broadening will be investigated. The partners are improving their comb setups to enable systematic studies, e.g., by adding additional amplitude modulation, 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.

The response of a cavity made of two mirrors connected by a solid elastic spacer to perturbances by gravitational waves was analysed theoretically. Preliminary results, adopting the theory invented for Weber-bar mechanical resonators, show the existence of some resonances for spacers made of typical materials like ULE or fused silica in the kHz range with a sensitivity competitive to already existing mechanical detectors

Impact

In the first nine months of the project, project partners engaged in a number of key communication and dissemination activities. Six presentations and two invited oral presentations were given, and three posters were presented at conferences such as Integrated Optics - Sensors, Sensing Structures and Methods (IOS 2022), IEEE EFTF-IFCS 2022, the International Symposium on Novel Materials and Quantum Technologies (ISNTT 2021), the 8th Congress of the French Optical Society (OPTIQUE Dijon 2021), and 760. WE-Hereaus-Seminar. Three training courses were delivered, two at universities, on subjects pertaining to the development and applications of ultrastable lasers. A dedicated project website was set up to communicate information on the project to a broader audience and serve as a platform for information and document exchange. The website is accessible at www.ptb.de/empir2021/nextlasers/home/.

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 oscillators.

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.

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.

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.

List of Publications:

L. S. Neto, J. Dickmann and S. Kroker, *Deep learning assisted design of high reflectivity metamirrors* Opt. Express **30**, 986-994 (2022), <https://doi.org/10.1364/OE.446442>

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

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| Project start date and duration: | | 01 June 2021, 36 months |
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| Project website address: https://www.ptb.de/empir2021/nextlasers/home/ | | 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) | | |