Publishable Summary for 17FUN03 USOQS
Ultra-stable optical oscillators from quantum coherent and entangled systems

Overview

Optical clocks require more stable optical oscillators to accelerate the redefinition of the SI second, bring excellent fundamental science to metrology and enable applications for innovative sensors in clock-based geodesy. The overall objective of this project is to realise a new generation of ultra-stable optical oscillators which take advantage of quantum technologies. This implies a knowledge transfer in theoretical and experimental quantum manipulation from quantum optics and quantum computing, to the optical frequency metrology field. While the application of quantum measurement strategies in atomic clocks and sensors via multi-particle and light-matter interactions is at the proof-of-principle stage, this project will implement and further develop state-of-the-art quantum measurement strategies on optical clocks of metrological relevance. It will impact on metrology and sensing with cold atomic systems and optical devices, as well as in those techniques used in scalable quantum information processing and simulation.

Need

Optical clocks based on ultra-stable laser radiation are nowadays of prominent importance both in scientific and industrial activities. They are already the pillar of primary frequency metrology and are foreseen to become in the near future pillars of ICT industry, navigation and sensing, progressively replacing microwave clocks becoming a key enabling technology at all effects. Optical fiber links will disseminate stable frequency standards for accuracy studies and comparisons on a continental scale, as well as allowing tests of fundamental physical laws. At the same time, ultra-low-noise synthesis of RF and microwave oscillators by means of optical frequency combs will impact aero-space navigation, very long baseline interferometry (VLBI) and telecommunication. Frequency stabilisation techniques based on a classical measurement approach and passive optical resonators seem now to be close to their maximum potential of exploitation. In current state-of-the art optical clocks (laser plus stabilisation cavity), the frequency stability is limited by two main causes: the first limitation is the thermal noise of the mirror coating and of the reference cavity itself, which affects the stability of the clock through the Dick effect (aliasing of laser frequency noise in the clock sequence). The second, more fundamental limitation is the standard quantum projection noise (QPN) of the quantum absorber, which is proportional to the inverse square root of the number of particles contributing to the signal.

The application of quantum techniques based on the creation of and measurements on correlated atomic quantum states and quantum engineered light-matter interaction have been envisaged to overcome these two limitations. In particular, multi-particle entangled states may exhibit a reduced sensitivity to quantum phase fluctuations, thus reducing the imprinted noise into the stabilised oscillator, as well as a fundamental limit beyond the QPN, with a frequency instability scaling like the inverse of the number of atoms (the "Heisenberg limit"). On the other hand, collective excitation and interaction of atoms with quantised modes of the electromagnetic field, for instance in an optical cavity, may generate coherent optical radiation with a phase noise beyond the current limit of optical resonators. The entanglement of different states can be used to design an optimised sensor with intrinsic cancellation of unwanted field sensitivities and enhanced sensitivity to the field to be measured.

Objectives

The overall objective is to implement, study and characterise both established and brand-new methods to develop quantum-enhanced optical oscillators toward 10^{-17} instability at one second integration time. This will enable the operation of optical clocks and atomic sensors at their projected accuracy limits of 10^{-18} with practical measurement times ranging from minutes to less than an hour. Non-classical techniques will be introduced to overcome technical obstacles and the QPN limit, to approach the Heisenberg noise limit.

The specific objectives of the project are:

1. To demonstrate entanglement-enhanced spectroscopy in optical lattice-based and ion-based clocks. In particular, to design and study spin-squeezing via quantum non-demolition methods to go beyond the quantum projection noise (QPN) at the 10^{-16} instability level at 1 s and study entanglement techniques in ion-based clocks to overcome the single-ion QPN limit.
2. To stabilise an optical oscillator at the QPN limit in the collective atom-cavity strong coupling regime, identifying suitable strategies to surpass the QPN limit with intrinsic field-shift compensation.
3. To develop an active frequency standard based on optically-trapped ultra-cold atoms with engineered lattice topologies to supersede thermal-noise limited optical cavities.
4. To demonstrate elementary scaling-of-entanglement operations with ion strings across multiple trapping segments towards increased sensitivity of measurement beyond classical limits.
5. To disseminate the results among the quantum optics and cold atoms community in order to advance fundamental research in metrology and enable further applications for innovative sensors in clock-based relativistic geodesy.

Progress beyond the state of the art

This project is designed to account for the need of merging quantum coherent measurement and quantum state engineering techniques with optical oscillators based on ultra-cold atoms and ions at the state-of-the-art level and beyond. It represents the natural continuation and exploitation of the achievements of the EMRP project EXL01 QESOCAS. This project will represent the first step towards quantum-enhanced frequency metrology targeting the ambitious goals of:

1) an optical oscillator with mHz linewidth (LO instability below 10^{-16} at 1 s).
2) demonstration of an entanglement enhanced atomic sensor scalable to larger number of ions.
3) Demonstration of optical clocks with S/N ratio below the shot noise limit.
4) Impact the quantum optics and cold atoms communities for atom-based sensors, atom interferometry, and the areas of quantum information processing and simulation.

Results

Creation of quantum engineered states in neutral and ion optical clocks (objectives 1, 2 and 4)

Quantum engineered systems are studied both to better understand subtle predictions of quantum mechanics and as tools to realise quantum computer prototypes, and exotic states of matter and light, whose statistical behaviour strongly diverges from the classical one. This project aims to apply for the first time to optical clocks a series of tools, derived from quantum engineered states, like collective atomic spin-squeezing, superradiant emission, strong atom-cavity coupling, which have not yet fully been demonstrated in the optical domain.

Theoretical studies on entanglement protocols are an essential part of the project, aiming to identify the most adequate and effective approaches to be used in the optical domain. Methods to better describe non Gaussian quantum states have been investigated.

Realisation of sub QPN detection in optical clocks (objective 2)

The EMRP project EXL01 QESOCAS showed that quantum enhanced sensors are becoming practical devices to improve the sensitivity of metrology sensors, with signal-to-noise ratios deep in the quantum regime. This project will further exploit those achievements and adapt novel quantum engineered states to overcome the QPN limit in optical clocks at the 10^{-16} instability level at 1 s. The latter includes systems such as the collective atom-cavity strong coupling regime.

This project has further investigated these techniques and demonstrated that non-destructive measurement can be effectively implemented in optical lattice clocks, paving the way for the realization of spin squeezing in the optical domain. Also, the design of a high finesse cavity to achieve atomic entanglement has been finalized and the experimental apparatus is now under construction.

Realisation of an active optical oscillator (objective 3)

State-of-the-art optical atomic clocks rely heavily on narrow lasers obtained with the aid of ultra-stable cavities. This project will explore new methods based on collective quantum effects and nonlinear optical response of atomic quantum states based on ultra-narrow optical transitions in alkali-earth atoms inside an optical cavity. New methods will be studied and tested to generate or stabilise a local oscillator with short-term stability of 10^{-17}, outperforming that of state-of-the-art passive optical resonators. Removal of delicate high-finesse cavities from the optical clock systems would be a huge milestone towards miniaturising and simplifying their set-up, and in consequence providing reliable and commercially available optical atomic clocks.

By realizing strong collective coupling between a sample of thermal strontium atoms and an optical cavity, superradiant lasing pulses on the narrow intercombination line of strontium-88 was demonstrated. Pulsed superradiance represents an important step towards a continuous active frequency standard. In addition, different schemes are being investigated to achieve continuous super-radiant emission.

Engineered scaling-of-entanglement and trap geometries of ion string operations (objective 4)

Previous EMRP project EXL01 QESOCAS developed technologies for entanglement in scalable micro-fabricated ion traps. This project will explore the advantages and limitations of entanglement in trapped ion systems directly from a metrological perspective beyond the proof-of-principle stage. In particular, this project will address systematic effects potentially detrimental to accurate measurements, develop and test an alternative approach to scalable entanglement, explore the scalable approach geared towards state-of-the-art application in quantum metrology in its platform technology. The demonstration of scalability will offer a firm perspective on the true potential of trapped-ion systems with non-classical techniques in metrology.

First entanglement gates for the in-phase axial mode (low heating rate, 10 phonons/s) have successfully been run and yield a fidelity of 85 %. This fidelity is too low to continue directly to demonstrate uncertainties below the QPN. Therefore, we currently focus on increasing the gate-fidelity, by diagnosing the limiting factor(s), to achieve targeted fidelity of 90%. Technical noises prevented up to now 2-ion entanglement in ion microtraps. Demonstration of 2-ion entanglement remains a fundamental goal of this activity toward the demonstration of scalability.

Impact

The impact objective of this project is to disseminate the results among the quantum optics and cold atoms community in order to advance fundamental research in metrology and enable further applications for innovative sensors in clock-based geodesy.

It is widely recognised (see e.g. the JRPs 15SIB03 OC18 and 15SIB05 OFTEN) that optical clocks are presently limited in their ultimate performances by their short-term stability (single ion QPN and local oscillator Dick effect). This is exploring the potential of non-classical measurement technologies in metrology for a step change in optical clocks and quantum-enhanced sensor systems. The implementation of non-classical techniques in such systems will greatly reduce short term instabilities and consequently the averaging time needed for accuracy evaluation. Simplification of the realisation of ultra-stable laser and cavity systems enables robustness and reliability gains. Designed entangled systems enable practical high-resolution sensing in noisy environments. Each of these results will have major impact on fundamental research, opening at the same time realistic perspectives for industrial applications and commercialisations of state-of-the-art, reliable and robust clocks and sensor systems.

The scientific results obtained so far are indicating that super-radiant emission on one side and dynamic decoupling on the other side are powerful technique in principle capable of reducing the Dicke effect limits of local oscillators. Further investigation is needed to allow practical exploitation in clock design.

So far to date, the project has published 7 peer reviewed publications in journals. 39 presentations at scientific conferences were done (10 national and 29 international/European). The project website has now been established. Training activities for the scientific community and graduates were held, with 100 people attending. 15 other dissemination activities were organised in 6 different countries targeted on the general public, broader scientific attendance and industrial end users. Ion icrotraps were exhibited at the UK National Quantum Technologies Showcase and collaboration with industrial stakeholders (such as Teledyne e2v, Toptica, NKT Photonics, Acktar, Chronos, British Telecomunications) has commenced in cross-correlation with the H2020 FETFlag program. In addition, two training lectures have been given by members of the consortium: by LUH at PIER Graduate Week in October 2018 and by NPL at UCL's Centre for Doctoral Training in Delivering Quantum Technologies in January 2019. Two master thesis and two PhD thesis were published within the USOQS project.

Impact on industrial and other user communities

Ultra-stable oscillators are used in many technological fields like telecommunications, radar systems, interferometry etc. The development of new, more compact and robust optical oscillators will represent an important technological breakthrough in all these fields. Such oscillators also have applications in geodesy (monitoring environmental changes or volcanic processes), geological exploration (energy and mining), astronomy (VLBI timing), space exploration (gravity and field sensing, deep space navigation), defence (autonomous navigation and timing) and in the telecommunications industry (frequency standards and timing, secure communications). The techniques developed here will advance knowledge in the field of quantum computing, with applications e.g. in quantum cryptography, but also in the field of quantum simulations of complex chemical processes in pharmaceutical R&D, which could yield a disruptive effect through time and cost reduction for bringing new products to the market. Contacts are undertaken with some selected laser industries to have them contributing in the development of specialized laser sources.

Impact on the metrology and scientific communities

This project will push forward the use of quantum techniques that can improve the stability of optical oscillators and linked devices beyond their current limitations. In particular, the realisation of collective spin-squeezing of a multi-particle system may be tremendously beneficial for optical clocks and atomic sensors based on a few-particle system, such as present ion traps. The use of a large ensemble of quantum entangled ultra-cold atoms as an active device may supersede the use of macroscopic optical resonators affected by thermal noise. Improved atomic clocks at the NMIs are also critical for high-profile science, such as the European VLBI Service, for whom the availability of precise frequency standards enables synchronisation of large arrays of radio telescopes, giving astronomers images with unprecedented resolution and at shorter wavelengths not previously available.

Two important results were already achieved in this direction: 1) pulsed superradiant emission as a first step toward continuous superradiant lasing, 2) innovative laser phase reconstruction technique to allow very long interrogation times beyond the intrinsic laser coherence time. These results were the subject of scientific publications and will be published next in international scientific conferences proceedings.

Impact on relevant standards

Although not directly aimed at the realisation of new frequency standards, the most direct impact of this project will be on future realisations of the SI second. Approaching 10^{-17} instability at 1 s will impact accuracy studies on optical frequency standards, accelerating the process for the redefinition of the SI second. The atoms/ions studied in this project are already included in the list of secondary representations of the second. Improved stability and reduced uncertainty will represent a benefit in the realisation of TAI.

Longer-term economic, social and environmental impacts

The importance of quantum technology was recognised by the European Commission in the "Quantum Manifesto" to formulate a common strategy for Europe to lead the second Quantum Revolution. The engagement in the new field of quantum technologies will help to keep Europe at the forefront of state of the art capabilities. It will support and enable the development of new world-leading industries in instrumentation (clocks, sensors, quantum computers and simulators, associated electronic and optical hardware, defence systems) and services (communication, computing, timing and navigation, security). Development of these technologies will stimulate the growth of a highly-skilled work-force in the advanced manufacturing sector of the European economy. Benefits to defence and civilian security, as well as autonomous navigation systems, will have significant impact on the way of life.

List of publications

[1] Y Zhang, L Shalm, J Bienfang, M Stevens, M Mazurek, S Nam, C Abellán, W Amaya, M Mitchell, H Fu, C Miller, A Mink, and E Knill, Experimental Low-Latency Device-Independent Quantum Randomness, Phys. Rev. Lett. 124, 010505, DOI: https://doi.org/10.1103/PhysRevLett.124.010505

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[3] V Prakash, L Bianchet, M Cuairan, P Gomez, N Bruno, and M Mitchell, Narrowband photon pairs with independent frequency tuning for quantum light-matter interactions, Vol. 27, Issue 26, pp. 38463-38478 (2019), https://doi.org/10.1364/OE.382474

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[5] N Bruno, L Bianchet, V Prakash, N Li, N Alves, and M Mitchell, Maltese cross coupling to individual cold atoms in free space, Vol. 27, Issue 21, pp. 31042-31052 (2019), DOI: https://doi.org/10.1364/OE.27.031042

[6] M Gabbrielli L Lepori L. Pezzè, , , Multipartite-entanglement tomography of a quantum simulator, New Journal of Physics, Volume 21, March 2019 https://iopscience.iop.org/article/10.1088/1367-2630/aafb8c/meta

[7] G Sorelli, M Gessner, A Smerzi and L Pezze, 2018, Fast and optimal generation of entanglement in bosonic Josephson junctions, Phys. Rev. A, 99, 022329 https://arxiv.org/pdf/1511.01835.pdf

<table>
<tr><td colspan="2">Project start date and duration:</td><td>01 June 2018, 36 months</td></tr>
<tr><td colspan="3">Coordinator:
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Project website address: http://empir.npl.co.uk/usoqs/</td></tr>
<tr><td>Internal Funded Partners:
1 INRIM, Italy
2 NPL, United Kingdom
3 OBSPARIS, France
4 PTB, Germany</td><td>External Funded Partners:
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