Publishable Summary for 20FUN05 SEQUME
Single- and entangled photon sources for quantum metrology

Overview

Quantum technologies (QT) are one of the most relevant contributors to innovation and advanced technologies. However, there is an important range of quantum-enhanced measurements that are not yet exploited by national metrology institutes (NMIs) because single-photon and entangled-photon sources with the required performance parameters (e.g. purity for single-photon sources and sub-shot noise quantification for entangled sources), are not readily available. Major advancements have been made in engineering these sources, but if they are to be used in metrological applications, significant further development is necessary. This project will develop high brightness, high-efficiency entangled photon sources (based on semiconductor quantum dots (QDs)) and it will exploit high-purity single-photon sources (based on ion implantation in diamond and on single molecules), to demonstrate the quantum advantage achieved when using these sources for specific measurements.

Need

Several international, European and national quantum programmes are currently under way, e.g. the European "Quantum-Flagship", Quant-ERA, ITN Networks, the German QT initiatives, the UK Quantum Technologies programme (which was recently re-launched), as well as programmes in Australia, Austria, Canada, China, Japan, Russia, Switzerland, and in the US. However, these initiatives do not yet comprehensively address the metrological challenges related to QT, such as traceability, standardisation and optimisation of quantum enhanced measurements. A robust European metrology infrastructure is required that enables the traceable characterisation of entangled-photon and single-photon sources.

The Strategic Research Agenda for Metrology in Europe has identified a need for further work in quantum metrology, to ensure Europe keeps at the leading edge of QT development worldwide. Noise limits must be overcome and the invasiveness of measurements (i.e. disturbance on the tested objects) must be minimised, both of which can be achieved using novel quantum-enhanced approaches. For this, single-photon sources and entangled-photon sources used in traceable quantum-enhanced measurements must be assessed and their performance parameters specified. Additionally, novel validated methods should be developed for the fabrication of single-photon sources and to optimise the sources for highest purity and indistinguishability.

Objectives

The overall objective of the project is to develop bright entangled photon sources based on different application-oriented platforms and to exploit high-purity single-photon sources to demonstrate the quantum advantage achievable using these sources for specific measurements.

The specific objectives of the project are:

1. To assess single-photon sources and entangled-photon sources in traceable quantum-enhanced measurements (e.g. quantum calibration at the single-photon level, sub-shot noise measurements, quantum imaging, sub-diffraction imaging and quantum illumination), to overcome classical measurement limits (e.g. noise);
2. To specify the performance parameters of single-photon and entangled-photon sources required to carry out different quantum-enhanced measurements;
3. To develop novel validated methods for the fabrication of single-photon sources and to optimise the sources for highest purity ($g^{(2)}(t = 0)$ close to 0), brightness (photon rate > 5×10^6 photons per second) and indistinguishability (Hong-Ou-Mandel visibility > 95 %), according to the performance parameters specified in Objective 2;

4. To develop the European metrology infrastructure required for the traceable characterisation of entangled-photon and single-photon sources, i.e. detectors (including photon-number resolving detectors), amplifiers, as well as standardised quantum-optical setups for characterisation (in particular entanglement tomography);
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the EMN Quantum, measurement supply chain, standards developing organisations (e.g. CEN and ISO) and end users (in the fields of quantum technology and nano-photonics).

Progress beyond the state of the art

This project will partially build on previous achievements of EMRP EXL02 SIQUTE and EMPIR 17FUN06 SIQUIST projects, and will go beyond the state of the art by developing optimised single- and entangled-photon sources for quantum metrological application and by demonstrating the quantum advantage achieved by using these sources.

Assessment of single-photon sources and entangled-photon sources in traceable quantum-enhanced measurements (objective 1)

This project will investigate new fields of quantum metrology and quantum-enhanced measurements, which have not been investigated thus far. Much progress has been made on developing highly efficient and highly pure single-photon sources and entangled-photon sources with high indistinguishability in terms of high Hong-Ou-Mandel (HOM) visibility. The necessary and straightforward next step is to use these sources in optical quantum-enhanced metrology. In particular, the project will carry out a metrological assessment of single-photon sources and entangled-photon sources in traceable, quantum-enhanced measurements, e.g. quantum calibration at the single-photon level, sub-shot noise measurements, quantum imaging, sub-diffraction imaging and quantum illumination, to overcome classical measurement limits (e.g. noise); to date these measurements have never been performed by NMIs. To achieve these measurements, the project will design, develop and implement high performance single-photon and entangled-photon light sources for applications in enhanced quantum imaging with the target of beating the quantum noise limit. New paradigms of quantum measurements, such as weak values (i.e., the amount of correlation between measured and measuring system) and correlated measurements in Hong-Ou-Mandel (HOM) configurations will be explored as a tool for enhancing the resolution and sensitivity of microscopes and spectroscopic tools. Furthermore, the NMIs will address the completely new aspect of traceability in quantum enhanced measurements.

Performance parameters of single-photon and entangled-photon sources (objective 2)

This project will improve the performance parameters (e.g., purity and sub-shot noise quantification) for quantum light sources, which will significantly advance their application readiness. The main thrust of this project, however, is to explicitly determine the performance parameters, which are necessary for different quantum-enhanced measurements. This will be achieved by identifying both consolidated and recently proposed tools and physical observables, suitable for characterising the relevant “quantumness” properties, such as e.g., entanglement verification, sub-shot noise quantification, squeezing measurements for entangled sources; and purity, Glauber correlation functions, and photon flux variance measurements for single-photon sources.

Development of novel validated methods for the fabrication of single-photon sources and optimisation of the sources (objective 3)

Within this project, the partners will advance methods for the fabrication of single-photon sources and optimise the development of sources with the highest purity ($g^{(2)}(t = 0)$ close to 0 (i.e. target value < 0.001 in the context of this project), brightness (photon rate $> 5 \times 10^6$ photons per second) and indistinguishability (Hong-Ou-Mandel visibility > 95 %). This will include fabrication of i) single-photon sources based on single defects in bulk diamond and on single molecules, and ii) single and entangled photon sources based on InGaAs/GaAs quantum dots (QDs).

Development of a European metrology infrastructure for the traceable characterisation of entangled-photon and single-photon sources (objective 4)

To meet the accelerating range of demands with respect to the upcoming new challenges in quantum technology, the metrological infrastructure in Europe needs to be continuously improved. This project will address the traceable characterisation of single-photon sources and especially of entangled-photon sources with respect to quantum technological applications, which has not yet been achieved. To carry out this traceable characterisation, low-photon flux detectors and corresponding amplifiers, photon-number resolving detectors will be developed, which will go beyond the state-of-the-art in terms of detection noise, measurement uncertainty and stability.

Results

Assessment of single-photon sources and entangled-photon sources in traceable quantum-enhanced measurements (objective 1)

So far, measurements of the single photon purity of telecom QDs under three different excitation schemes were performed and evaluated, and a Franson interferometer has been developed and is operational to carry out the planned work. Also, a Hong-Ou-Mandel setup as basis for the planned experiments has been developed. It will be extended for cascaded HOM measurements to prepare the N00N states in the course of the project.

Performance parameters of single-photon and entangled-photon sources (objective 2)

So far, the groundwork for the development of the theoretical model for the emission dynamics of a solid state single-photon source has been done for pulsed and continuous wave (CW) emission. The investigation in the properties and features of $g^{(n)}$ and $\Theta^{(n)}$ parameters for sources assessment has started. Preliminary investigations were performed to exploit a combination of both parameters for source mode reconstruction. Using the techniques of quantum information theory, an analysis was carried out to evaluate how detrimental effects affect the performance of quantum illumination. The quantum channel capacity may be one of the performance indicators. As this method is general, it has a potential to be applied on other processes involving quantum states.

The respective experimental key parameters of entangled photon sources that need to be measured to assess their non-classicality performances were collected. Among them are intrinsic parameters (generation probability / rate of two-photon state, decay times of biexciton and exciton, entanglement fidelity, fine-structure splitting, spin precession of biexcitonic/excitonic states, and background luminescence) as well as external parameters with noticeable impact on measurement results (photon-extraction efficiency of DUT, temporal resolution and efficiency of detectors, and dark counts / noise of detection system). The setup for quantum state tomography including two-photon resonant excitation is ready to use.

Development of novel validated methods for the fabrication of single-photon sources and optimisation of the sources (objective 3)

So far, a sample containing single SnV centres was produced and tested. Single SnV centres were identified and tested: pure single photon emission was detected to be $g^2(0) < 0.1$, deviation from zero is entirely due to detector dark counts (noise limit $g^2(0) = 0.093$). The emitters are almost strain-free, showing ideal ground state splitting and narrow resonance lines. The charge transition cycle of the SnV was identified and used to devise a method for charge state stabilization, i.e., illumination with a laser in the blue spectral range. Charge state can be initialized and results in very narrow photoluminescence excitation (PLE) lines over 1 hour of experiment, i.e., the cumulative linewidth is 33 MHz at a Fourier-limit of 25 MHz). A Hong-Ou-Mandel interferometer for determining the single photon indistinguishability was set up with classical visibility of > 99.5 %. Under off-resonant excitation single photons from SnV centres show HOM visibilities of > 40% limited by the timing jitter due to off-resonant excitation and spectral diffusion induced by the large off-resonant pump power.

Single-mesa quantum dot structures and easy circular Bragg grating (CBG-) structures of high structural quality are fabricated that provide up to 450 kcounts/s on a charge-coupled device (CCD) detector under CW excitation. The accompanying assessment of single-photon purity and visibility of indistinguishable photons provides reasonable results, too. Development and fabrication of samples will go on continuously.

Development of a European metrology infrastructure for the traceable characterisation of entangled-photon and single-photon sources (objective 4)

So far, the cryo-optic facility for the transition edge sensor (TES) has been set up successfully, including vacuum fibre feedthrough and magnetic shielding box and holder for TES-modules, both built in-house. Temperatures < 100 mK were observed, as well as temperature-stabilized operation at 100 mK. Optical simulations have shown the possibility to reduce the TES reflectance losses embedding the TES in an optical cavity with an antireflection coating. Other solution, like plasmonic structures are under study. The fabrication of aluminium/titanium bilayer film and TES in order to obtain devices with critical temperature close to 1 K to reduce the response time of the detector was started.

Impact

The project webpage was created (https://sequme.cmi.cz/) and had more than 1000 views so far. In the first 9 months of the project, 10 presentations were given at conferences, seminars and workshops. Additionally, 9 papers have been published in open access peer-reviewed journals. The consortium has further delivered one external training activity for the participants of the QuDot-Tech Summer School 2.

Impact on industrial and other user communities

This project will trigger and accelerate progress in the field of quantum technologies, due to the development of high-end, highly innovative quantum devices for use and application in science, quantum communication and quantum metrology. More specifically, the entangled and single-photon sources will impact the development of the associated measurement infrastructure for quantum enhanced metrology and for low-flux measurements, i.e. new and better amplifiers, new optical single photon excitation sources, which e.g. can be used in different fields where low optical fluxes need to be measured. The developed sources have the potential to become a commercial product useful for companies active in the field of quantum technology. They will also be very useful for educational purposes, both in academia and schools. This will be achieved through academic partners, and demonstrations at universities and schools. Furthermore, the lack of useful entangled and single-photon sources hinders the development of quantum technology fields such as quantum cryptography and quantum metrology; the developments within this project with respect to higher single photon flux rates, photon indistinguishability and entanglement, will remove these roadblocks. To support knowledge transfer to the industrial community, a workshop on the newly developed devices will be organised and held to which representatives of industry (both manufacturers of and users of photon sources) will be invited.

Impact on the metrology and scientific communities

This project will have high impact on the metrology and scientific communities through the development of entangled and single-photons sources, based on single emitters. Specifically, the knowledge about entangled photon sources and their use at NMIs are scarce and therefore opportunities for applications with quantum light sources have not been exploited so far. It is anticipated that this project will create rather fast, new prospects and applications for quantum enhanced metrology, e.g. sub-shot noise metrology, quantum imaging of biological systems and quantum illumination. In addition, the project will further accelerate the development of a characterisation infrastructure for low flux measurements, e.g. in new amplifiers, as well as in practical fibre-coupled single-photon sources, where low optical fluxes need to be measured.

The project partners are members of the EMN Quantum and will present the project and its results at the meetings of this network and its corresponding network project. Also, an annual report is issued, in which all QT-related projects are listed. The results of this project will be disseminated to the scientific community predominantly via high impact publications on sources of single, indistinguishable and entangled photons, low flux and single-photon radiometry, low-noise amplifiers and excitation sources, therefore paving the way new and unforeseen research fields. To further support knowledge transfer, representatives of academic organisations and NMIs will be invited to a workshop that the project will organise.

Impact on relevant standards

New documentary standards based on the results of this project in the field of low-flux radiometry are expected, as a result of input to different standardisation bodies. The current *mise en pratique* for the candela allows the photon-number-based (and thus quantum-based) realisation of photometric and radiometric units. Furthermore, in the long term, a photon-based definition of the SI base quantity candela might be envisaged. Members of the consortium are active in the European Telecommunications Standards Institute (ETSI) and in CEN-CENELEC with respect to standardisation in (quantum) communication and in quantum technology, respectively. Results from this project will be implemented in documentary standards generated by these standards developing organisations.

Longer-term economic, social and environmental impacts

The project has the potential to have a significant economic impact on the European market, because it will strengthen Europe’s position in the field of quantum technologies. The sources and metrological infrastructure developed within the project may lead to their implementation in commercial products and the development of highly innovative commercial devices, respectively, and thus stimulate new high-tech jobs in Europe. This project may also have a long-term impact on the field of data safety, guaranteed by secure quantum communication, for which single-photon sources can be exploited.

List of publications

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Coordinator: Stefan Kück, PTB Tel: +49 531 592 4010 E-mail: stefan.kueck@ptb.de Project website address: https://sequme.cmi.cz/		
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