Publishable Summary for 17FUN06 SIQUST
Single-photon sources as new quantum standards

Overview

The aim of this project is to develop new absolute standard radiation sources, which exploit the discrete and quantum nature of photons, and the necessary metrological infrastructure. These sources will be based on single-photon emitters with a calculable photon emission rate and high purity, i.e. with a very low multiple photon emission probability. Such sources hold promise as new quantum standards which will have a large number of applications, e.g. for use in the calibration of single-photon detectors, for the realisation of the SI base unit candela, for quantum random-number generation, for quantum key distribution, for sub-shot noise metrology, for quantum-enhanced metrology, and for photon-based quantum computation.

Need

The need for this project arises from the fact that single-photon sources will be necessary for applications in the field of quantum technologies (e.g. quantum computing, quantum communications, quantum metrology, quantum-enhanced imaging and sensing), which are among the most relevant topics with respect to innovation and high technology in Europe and worldwide (Objectives 1 and 2). The use of single-photon sources in quantum computing will lead to much needed increases in computational power, which cannot be achieved by classical computers, and this will enable problems to be solved in physics, biology, chemistry and material science. However, the use of quantum computing will mean that the currently safe cryptographic protocols and procedures that are used in communication and data storage will become obsolete. Hence quantum cryptography, quantum key distribution and quantum communication will also be needed to maintain data safety and secure communication. Quantum metrology is needed to enable the classical shot-noise limit to be undercut and this will result in more precise measurements becoming possible. In addition, quantum imaging and quantum sensing need to be developed to enable high resolution measurements, as well as the possibility of carrying out imaging without the direct detection of photons, which hit the intended target (Objective 3). There is therefore a need to be prepared for when these new challenges, possibilities and technological innovations happen. The importance of this can also be seen from the European 1 billion € "Quantum-Flagship" programme that will start in 2018. This was triggered by the "Quantum Manifesto" and related European and national programmes, see e.g. the German "QUTEGA" initiative, the UK Quantum Technologies programme ("Quantum Hub") Quant-ERA and the expected follow-on programmes. This project is in line with the aforementioned programmes and it will strengthen the metrological basis for the innovations and developments to come in the field of quantum technologies, i.e. it will enable the National Metrology Institutes to meet future requirements. It will also perfectly complement and benefit the objectives of the quantum technology roadmap outlined in the context of the European Flagship initiative, by fulfilling the necessary metrology needs.

An ideal single-photon source emits one photon on demand, at a time chosen by the user with the emitted photons being indistinguishable from one another and having an adjustable repetition rate. Such a photon source would represent a new quantum standard with an extensive range of widely needed applications: for the calibration of single photon counter devices, for the realisation of the SI base unit candela, for quantum random number generation, for quantum key distribution, for photon based quantum computation and sub-shot noise metrology (Objectives 1, 2 and 3).

Furthermore, the characteristics of the single-photon sources need to be measured with traceability to national standards, therefore the necessary measurement infrastructure needs to be developed. This supporting measurement infrastructure for single photon metrology, i.e. new and better amplifiers and attenuators for the measurement of low optical fluxes, is needed in many fields of application (e.g. biology, chemistry, astronomy, etc.) and not just in the field of single photon metrology (Objective 4).

Also, this project's results will lead to commercial products and to new standards, which need to be promoted (Objective 5).

Significant progress was made, in the previous EMRP JRP EXL02 SIQUTE, where e.g. for the first time a single-photon source was absolutely characterised metrologically. This was an important step towards the realisation of a photon standard-source. However, the photon fluxes of state-of-the-art technologies are too low (($< 1 \times 10^6$ photons per second) and the emission bandwidths are too broad (> 100 nm) for practical use. Therefore, single-photon sources are still far from being completely predictable, deterministic and indistinguishable. More development is needed to bring close-to-ideal single-photon sources into the NMIs to form the basis for future work in the field of quantum-enhanced metrology (Objectives 1, 2 and 3).

Objectives

This project focuses on the development of single-photon sources as new quantum standards. The specific objectives are:

1. To develop single-photon sources as new quantum standards in the visible, near-infrared and telecom wavelength range, based on optically and electrically-driven impurity centres in nano- and bulk diamonds, quantum dots in semiconductor structures and molecules having, simultaneously, photon rates $> 1 \times 10^6$ photons per second, emission bandwidths < 2 nm and high purity emission indicated by $g^{(2)}(t = 0)$ values < 0.05.
2. To assess new materials and concepts for single-photon sources, such as 2D materials (e.g. hexagonal boron nitride and thin transition-metal dichalcogenides) and coupling designs to optimise the collection efficiency (e.g. micro-resonators, waveguides, optical antennas). To assess the impact of excitation schemes on the quantum optical properties of single-photon sources.
3. To establish sources of indistinguishable and entangled photons based on near infrared (< 1 µm) quantum dot single-photon sources with a visibility > 90 % and novel sensing and measurement techniques based on these sources.
4. To develop metrology infrastructure for traceable single-photon source characterisation, i.e. detectors, amplifiers, single-photon spectroradiometers.
5. To promote the results, to trigger commercialisation of products, and to deliver input to standardisation organisations.

Progress beyond the state of the art

In recent years, there has been significant progress in the field of single-photon sources and their use in metrology. This also includes the progress made by the previous EMRP JRP EXL02 SIQUTE. In this previous project, leading European research institutes and NMIs worked closely together to bring quantum technology at the single-photon level into the NMIs. Within EMRP JRP EXL02 SIQUTE, the first single-photon source absolutely calibrated with respect to its total optical radiant flux and spectral power distribution, traceable to the corresponding national standards via an unbroken traceability chain, was realised along with the pump laser providing optical excitation for the single-photon sources at varying repetition rates. The total photon flux rates were between 190 000 photons per second and 260 000 photons per second, respectively and the single-photon emission purity was indicated by a $g^{(2)}(0)$-value, which was between 0.10 and 0.23, depending on the excitation power. Although this might be considered as a huge step towards the realisation of a new photon standard source, the photon fluxes are still too low ($< 1 \times 10^6$ photons per second), the emission bandwidth is too broad (> 100 nm) and the purity is still insufficient ($g^{(2)}(t = 0) > 0.1$) for real practical use.

Photonic structures are required in order to enhance the photon collection efficiencies. Typical collection efficiencies from solid-state materials (diamond, quantum dots) using high numerical aperture objectives are within the few percent range due to the high material refractive index and the resulting large fraction of light captured by total internal reflection. Photonic structures typically employed for enhancing the photon collection efficiency are solid immersion lenses and waveguiding structures (e.g. nano-pillars), resulting in typically 30 % collection efficiency. Even larger efficiencies (50 % - 100 %) are expected for schemes based on coupling to micro-resonators or planar optical antenna and microlens structures where the latter combines high extraction efficiency and ease of use in NMI applications.

Results

1. *To develop single photon sources as new quantum standards in the visible, near infrared and telecom wavelength range, based on optically and electrically driven impurity centres in nano and bulk diamonds, quantum dots in semiconductor structures and molecules having, simultaneously, photon rates > 1×10^6 photons per second, emission bandwidths < 2 nm and high purity emission indicated by $g^{(2)}(t = 0)$ values < 0.05.*

Single photon sources as new quantum standards in the visible, near infrared and telecom wavelength range will be developed. They will be based on optically and electrically driven impurity centres in nano and bulk diamonds, quantum dots in semiconductor structures and molecules having, simultaneously, photon rates > 1×10^6 photons per second, emission bandwidths < 2 nm and high purity emission indicated by $g^{(2)}$(t = 0) values < 0.05.

2. *To assess new materials and concepts for single-photon sources, such as 2D materials (e.g. hexagonal boron nitride and thin transition-metal dichalcogenides) and coupling designs to optimise the collection efficiency (e.g. micro-resonators, waveguides, optical antennas). To assess the impact of excitation schemes on the quantum optical properties of single-photon sources.*

New materials and concepts for single-photon sources, such as 2D materials (e.g. hexagonal boron nitride and thin transition-metal dichalcogenides) and coupling designs to optimise the collection efficiency (e.g. micro-resonators, waveguides, optical antennas) will be assessed. Furthermore, the impact of excitation schemes on the quantum optical properties of single-photon sources will be assessed.

3. *To establish sources of indistinguishable and entangled photons based on near infrared (< 1 µm) quantum dot single-photon sources with a visibility > 90 % and novel sensing and measurement techniques based on these sources.*

Sources of indistinguishable and entangled photons based on near infrared (< 1 µm) quantum dot single-photon sources with a visibility > 90 % and novel sensing and measurement techniques based on these sources will be established.

4. *To develop metrology infrastructure for traceable single-photon source characterisation, i.e. detectors, amplifiers, single-photon spectroradiometers.*

Metrology infrastructure for traceable single-photon source characterisation, i.e. detectors, amplifiers, single-photon spectroradiometers will be developed.

5. *To promote the results, to trigger commercialisation of products, and to deliver input to standardisation organisations.*

The results of this project will be promoted, the commercialisation of products in quantum photonics will be triggered, and input will be given to standardisation organisations.

Impact

This project will create impact for end-users (e.g. manufacturers of quantum communication systems) by giving them access to new and improved single-photon sources. High-technology companies working in the field of quantum technologies will be able to accelerate innovation. National Metrology Institutes will use these as new standard sources for radiometry and photometry, enabling them to provide the measurements required to certify new quantum technologies based on the discrete and quantum properties of photons. Schools and academia will benefit from the development of easy-to-use and affordable devices for education in quantum technologies.

Impact on industrial and other user communities

The technological developments within this project will trigger and speed-up innovation 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 single-photon sources and the supporting measurement infrastructure will impact on the development of measurement infrastructure for low-flux measurements, i.e. new and better amplifiers and attenuators, new optical single photon excitation sources, which will be used in different fields where low optical fluxes need to be measured, e.g. quantum communication, but also in medicine, biology, astronomy and research in general. The developed (standard) single-photon sources have the potential to become a commercial product useful for companies active in the fields of quantum technology, e.g. the telecommunication industry, metrology equipment companies, and academic spin-off companies. They will also be very useful for educational purposes, both in academia and schools, as cheap and easy-to-handle single-photon sources will be available. Furthermore, the lack of useful single-photon sources hinders the development of quantum technology fields such as quantum cryptography and quantum metrology. The development of single-photon sources with higher flux rates and indistinguishability, will lead to the removal of these road blocks.

Impact on the metrology and scientific communities

The development of new standard sources based on single-photon emitters will create impact for the realisation of optical radiant flux scales in the low-photon-flux region and it will be the basis for the definition of the optical radiant flux in terms of photon rate, i.e. the countable number of photons over time, with selectable emission rates. As this field develops, it is foreseen that quantum standards, based on counting photons, will also enter the metrological area of radiometry and photometry. The results will therefore impact on metrology committees like the Consultative Committee for Photometry and Radiometry (CCPR) or the technical committees of the regional metrology organisations (EURAMET, COOMET), where the partners are active. The SI base unit for luminous intensity, covering the areas of photometry and radiometry, is the candela, which is currently realised in purely classical ways, i.e. by incandescent standard lamps carrying and maintaining the luminous intensity scale or by photometers, which are radiometrically calibrated in a way which is traceable to the primary standard for optical radiant flux. However, in the current *mise en pratique* for the candela, the possibility for a photon-number-based realisation is explicitly formulated. Therefore, there will be a direct impact on the *mise en pratique* and thus on the metrology community in general. Furthermore, these sources would be ideal for the calibration of single-photon detectors, especially if a multiple-wavelength source is available. Also, the sources developed and characterised in this project can emit entangled photons, thus opening new fields in quantum metrology. The scientific results of this project will lead to high impact publications, which will act as further multipliers for research fields which are not even anticipated yet.

Impact on relevant standards

The development of a standard single-photon source will impact the National Metrology Institutes by giving them access to photon sources that are useful for a variety of applications, as mentioned above. Furthermore, new documentary standards based on the results of this project in the field of low-flux radiometry are expected, such as ETSI standards on quantum communication and quantum key distribution, and the *mise en pratique* for the candela. As mentioned above, the current *mise en pratique* for the candela allows the photon-number-based (and thus quantum-based) realisation of photometric and radiometric units.

Longer-term economic, social and environmental impacts

This project will have a significant economic impact on the European market, because it will strengthen the European position in the field of quantum technologies. The sources and metrological infrastructure developed within the project may give rise to commercialisation and thus lead to employment in high-technology areas, due to the development of highly innovative devices for commercialisation by companies followed by their implementation in commercial products. Another aspect to be considered is the field of data safety, guaranteed by secure quantum communication, for which single-photon sources can be exploited. So, in the longer-term perspective, end-users from the fields stated above will benefit from the outcomes of this project.

List of publications

None at this time.

Project start date and duration:		01 June 2018, 36 months
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Internal Funded Partners: 1 PTB, Germany 2 Aalto, Finland 3 CMI, Czech Republic 4 INRIM, Italy 5 Metrosert, Estonia 6 NPL, United Kingdom 7 VTT, Finland	External Funded Partners: 8 CNR, Italy 9 CSIC, Spain 10 FAU, Germany 11 INFN, Italy 12 TUB, Germany 13 UdS, Germany 14 UNITO, Italy 15 USTUTT, Germany	Unfunded Partners: