Final Publishable JRP Summary for EXL02 SIQUTE
Single-photon sources for quantum technologies

Overview

Photons are mass-less elementary particles which have the potential to be used for quantum communication, computing and metrology applications. In order to meet the scientific criteria of these applications, single photons, which will have unique characteristics, are required. This project developed compact and efficient single-photon sources, and suitable measurement techniques for the characterisation of these sources.

Need for the project

It is increasingly important to be able to transmit data securely. At present this is done using encryption, but it is possible to intercept these communications and break the encryption. Quantum communication and computing have the potential to be the next generation of encryption technology and offer secure transmissions. Using photon signals means that any interruption of a signal can be detected and it is not possible to copy a transmission.

Quantum communication and computing rely on transmitting a single photon with a specific characteristic. Whilst there are several different technologies being developed for quantum computation and quantum information processing in general, photons are particularly attractive as they can travel at the speed of light, interact weakly with their surroundings and can be manipulated with linear optics. The transmission is dependent on a single particle, which means it cannot be intercepted without the knowledge of the sender and receiver.

The development of a single photon source would be a key step for radiometry, the measurement of radiation. Single-photon sources with an adjustable photon rate would establish the necessary and robust link to the well-developed classical radiometry, because setups comparing analogue detectors, traced to a primary standard, and single-photon detectors can easily be established. Finally, single-photon sources are needed for quantum enhanced measurements exploiting quantum techniques such as entanglement.

This project arose from the fact that up to now no single-photon-source existed that fulfils all the requirements needed for quantum communication and computing, quantum metrology and quantum-based radiometry and there was no metrological infrastructure for single photon detectors.

Scientific and technical objectives

Photons can be generated from vacancy centres within nanocrystals, in this case nitrogen vacancies in diamonds. This relies on artificially producing a diamond and irradiating it to produce a single vacancy centre. Then irradiating the vacancy with a laser pulse to cause it to emit a photon. To be useful the direction of this photon needs to be controlled, so methods of improving collection efficiency are also required.

Single photon sources can also be emitted from quantum dots, in this case indium arsenide (InAs) quantum dots within a gallium arsenide (GaAs) structure. These have the potential to emit photons by electrical excitation, which should make the process easier, but they do need very low temperatures 12-20 K.

Photon entanglement occurs when two photons have a relationship or correlation, so that knowing characteristics of one will give you information about the other. This is a fragile phenomenon, which makes it

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difficult to measure but means that it has the potential to measure small forces and absorptions that cannot be done in any other method.

Studying photon sources has to be done in parallel with the development of detectors. Currently no NMI can calibrate a single photon detector in a proven way. Therefore this project aimed to set up calibration and characterisation services.

The following four objectives were identified to achieve the overall goal of developing efficient single-photon sources and their underpinning metrological infrastructure. Objective 1 dealt with the development of bright, compact efficient single-photon sources based on quantum dots and vacancies in nanodiamonds. Objective 2 looked at controlling the excitation, and thus the production of photons, by adjusting the frequency. Objective 3 characterised the sources with appropriate metrics such as wavelength, bandwidth, photon statistics, anti-bunching and indistinguishability. Finally, in objective 4, the possibility and potential of using single-photon sources and entanglement for quantum enhanced measurements were explored.

The objectives were:

- The development of bright, compact and near-unity collection efficiency single-photon sources with a photon flux of up to 10^7 photon/s based on quantum dots, vacancies in nanodiamonds and photonic waveguide technologies;
- The development of an excitation scheme with adjustable frequency allowing for traceable photon flux measurements at high photon rate to be utilised in the calibration of very low photon rates;
- the characterisation of these single-photon sources by appropriate metrics in terms of wavelength, bandwidth, photon statistics, anti-bunching, and indistinguishability;
- The demonstration of the suitability of these sources for different entanglement enhanced measurements based on those metrics.

Results

Development of bright, compact and near-unity collection efficiency single-photon sources with a photon flux of up to 10^7 photon/s based on quantum dots, vacancies in nanodiamonds and photonic waveguide technologies

Within this project, different types of single-photon sources have been researched [1, 7, 9, 10, 18-20, 22, 25, 27-29]. One approach was based on impurity centres in diamond, namely Nitrogen-vacancy centres (NV-centres) and Silicon-vacancy centres (SiV-centres). Although impurity doped nanodiamonds are established bases for single-photon sources, they typically lack high efficiencies due to poor collection efficiency for the emitting photons.

A major step towards the realisation of efficient single-photon sources was the design of appropriate structures, into which the impurity doped nanodiamonds can be incorporated. The design of such structures led to so-called dielectric antenna structures, which imply a specific emission characteristic with high collection efficiency, i.e. a high coupling of the emission into the collecting optics, typically a microscope objective with high numerical aperture.

At the end of the project, an NV-centre- and a SiV-centre-based single-photon source were developed [27, 28]. In addition, a metallo-dielectric antenna was designed and realised, which collected more than 99% of the emitted photons from single colloidal quantum dots [7].

For the realisation of highly efficient semiconductor based single-photon sources, the optimisation of the semiconductor structures design was carried out. Based on these designs, different types of semiconductor based single-photon sources were produced by molecular beam epitaxy growth, e-beam lithography and reactive ion etching. Quantum dot based nanowire single-photon sources and GaAs photonic trumpet structures were produced [18, 19]. Finally, a nanowire structure with electrical injection was manufactured and delivered.

Single-photon sources for the infrared spectral range are scarce and are rather inefficient. Therefore, within this project, the idea of using a heralded single-photon source based on spontaneous parametric down conversion was implemented, with photon emission at the most relevant wavelengths for optical telecommunication. Efficiency of 64 % was demonstrated [29].

In conclusion, this objective was only partially met. For the photonic waveguide based sources, the targeted photon levels were achieved. For the vacancies in nanodiamonds, the obtained photon rate is about an order of magnitude lower than targeted (i,e., 10^7 photon/s), however, a high purity source was realised, which is a significant achievement. For the quantum dot based sources, the designed structures could not be manufactured in an appropriate manner, so that the target photon flux could be reached. However, single-photon sources are now established at European NMI project partners.

Development of an excitation scheme with adjustable frequency allowing for traceable photon flux measurements at high photon rate to be utilised in the calibration of very low photon rates
A sub-ns pulse diode laser driving electronics for the excitation of the single-photon sources with high repetition rate [28], a tunnel-type multi-element trap detector as beam attenuator and a detector-based transfer standard for very low photon fluxes were designed and manufactured within this project [24]. Based on these developments, the first comparison for the detection efficiency of a single photon detector using a direct optical flux measurement by a conventional Si-photodiode at such low power levels [24]. This objective was fully achieved.

Characterisation of these single-photon sources by appropriate metrics in terms of wavelength, bandwidth, photon statistics, anti-bunching, and indistinguishability
As described in the first objective the project fabricated different types of single-photon sources, which have been metrologically characterised. In the participating NMIs, setups for the traceable measurement of wavelength, bandwidth, photon statistics, anti-bunching, and indistinguishability were established. An absolute single-photon source based on a single nitrogen-vacancy (NV) center in a nanodiamond at room temperature was experimentally realised, i.e. its absolute spectral photon flux was determined and its purity with respect to photon emission properties, i.e. its anti-bunching behaviour, was measured [27]. The indistinguishability (or purity) of a waveguide based single-photon source was determined by a Hong-Ou-Mandel (HOM) interference experiment [29].

This objective was fully competed and a single photon source can now be characterised by an appropriate metrics in terms of wavelength, bandwidth, photon statistics, anti-bunching, and indistinguishability in the European NMI project partners, which was not possible before.

Demonstration of the suitability of these sources for different entanglement enhanced measurements based on those metrics
This objective was on the research of quantum enhanced measurements. The enhancement in spatial resolution in confocal fluorescence microscopy was realised. This was achieved by exploiting the non-classical photon statistics of single nitrogen-vacancy colour centres in diamond. By developing a general model of super-resolution based on the direct sampling of the high-order autocorrelation function of the photoluminescence signal, it was shown that it is possible to resolve arbitrarily close single-photon emitters [6].

A source of wavelength-degenerate (1584 nm) polarisation-entangled photon pairs has been realised by the project. Measurements have been successfully performed to demonstrate the indistinguishability of the component states and measurement of a Bell parameter was carried out to prove the entanglement of the photon pairs. Furthermore, the photon source can be systematically perturbed in order to evaluate the sensitivities when used for specific applications.

Correlation and entanglement-enhanced measurements were demonstrated within this objective, however, they were only partially carried out. .

Actual and potential impact

This project developed compact and efficient single-photon sources, and suitable measurement techniques for the characterisation of these sources.

Actual impact

The results achieved within the project will support the development of better and easier-to-use single-photon sources. The sub-ns pulse diode laser driving electronics with adjustable frequency for excitation of single-photon sources developed in the second objective of the project will be useful for further investigation of different types of single-photon sources, because it allows a scaling up of the photon flux by increasing the repetition rate instead of by increasing the excitation power. Antenna designs for simplification of photon collection were also developed and characterised by the project, as well as the high efficient waveguide-based single-photon source.

The absolute single-photon source realised within objective 3 of this project will be further developed and has the potential to enter the market as new standard source for detector calibration. A calibration service for Silicon Single-Photon Detectors (Si-SPAD) is planned in some of the NMI project partners, and is due to be established after the completion of an international comparison for detection efficiency determination.

The switched integrator amplifier, developed for the characterisation of single-photon sources in terms of wavelength, bandwidth, photon statistics, anti-bunching, and indistinguishability, i.e. for the direct measurement of single-photon fluxes in the fW-power regime with standard (analogue) Si-photodiodes, is already used in several NMIs. The amplifier allows the NMIs to measure small photon fluxes directly with standard (analogue) silicon phodiodes.

Dissemination of results

The results of this project have been reported in 28 peer-reviewed publications and activities have been presented in 72 talks or posters at scientific conferences. Furthermore, guidelines dealing with the calibration and the alignment of Silicon-based single-photon avalanche detectors were uploaded to the SIQUTE project website [17] located at: www.ptb.de/emrp/siqute.html.

Potential impact

These outcomes will be beneficial for the scientific and metrology communities working in the corresponding fields of quantum metrology, quantum cryptography and quantum radiometry, i.e. for universities, NMIs, and companies. The results obtained will also inspire continuing work on the further development of single-photon sources and their characterisation. In the medium to long term the sources developed within this project will be further optimised in terms of higher stability and robustness, which will lead to a higher acceptance of these sources not only in the academic field, but also in an industrial environment. *S*ingle-photon sources will be used in a variety of fields such as quantum communication, radiometry, bio-photonic and medicine, medical diagnostics as well as sub-shot noise metrology, microscopy, spectrometry and interferometry. Single-photon sources will also become more "normal" or "standard" components, like lasers or LEDs to be used in highly technological applications like quantum communication, quantum computation and quantum imaging. The sources will be the basis for cheap, robust and reliable room temperature single-photon sources for use by academics and eventually schools, thus reducing the mystery and reservation surrounding "quantum technologies".

List of publications

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JRP-Coordinator: Dr Stefan Kück, PTB Tel: +49 531 592 4500 E-mail: stefan.kueck@ptb.de JRP website address: www.ptb.de/emrp/siqute.html	
JRP-Partners: JRP-Partner 1 PTB, Germany JRP-Partner 2 CMI, Czech Republik JRP-Partner 3 INRIM, Italy JRP-Partner 4 Metrosert, Estonia	JRP-Partner 5 MIKES, Finland JRP-Partner 6NPL, United Kingdom JRP-Partner 7 USMF, USA
REG1-Researcher (associated Home Organisation):	Julien Claudon CEA, France
REG2-Researcher (associated Home Organisation):	Niels Gregersen DTU, Denmark
REG3-Researcher (associated Home Organisation):	Stephan Götzinger FAU, Germany
REG4-Researcher (associated Home Organisation):	Christoph Becher UdS, Germany
REG5-Researcher (associated Home Organisation):	Jesper Mørk DTU, Denmark

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