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

Background

In recent years, a lot of research has been expended in the development of single-photon sources for different kinds of applications. In this project NV- and SiV-doped nanodiamonds will be embedded into metallo-dielectric structures. This will allow room temperature, near unity collection efficiency operation of diamond based single-photon sources with a photon rate of up to one order of magnitude higher (~ 10^7 photons per second) than the current one. Furthermore, an adjustable excitation scheme from 100 kHz to 100 MHz will be developed to extend the operation range of nanodiamond based SPS from to less than 1 fW to high single-photon photon fluxes (3 pW). Furthermore, electrically-pumped semiconductor based single-photon sources with close to unity collection efficiency will be developed. This will be achieved by structure optimization using theoretical modelling. Therefore, these sources will also be deterministic from the point of photon emission rate. Furthermore, single-photon sources in photonic waveguide devices for operation at the telecommunication wavelength of 1.55 µm will be developed with parameters and characteristics not currently available. The project will also deal with overcoming the limits of classical measurements, which is a major aim in quantum metrology. Quantum optical states exhibiting non-classical correlations have been proven to provide the possibility to go beyond the limits of classical measurements. Entanglement enhanced measurements will be performed based on the high quality sources developed within the project.

Need for the project

The need for the project arises from the fact that up to now no single-photon-source exists that fulfill all the requirements needed for the scientific and technological fields of quantum communication, quantum computing and quantum metrology. Such single-photon sources are needed by:

- Quantum key distribution and quantum cryptography: Currently, both are limited to weak laser pulses as pseudo single-photon sources. However such sources can have more than one photon per pulse leaving current systems vulnerable to attacks via photon number splitting or require strong attenuation of the laser pulses and the use of decoy states, thus leading to low key rates. This is not an issue if true single-photon sources with high photon rates (up to 10^7 photons/s, developed within this project) are used.
- Quantum computing: photon based quantum computation relies on close to perfect single-photon sources. Whilst there are a number of 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. Furthermore, the availability of single-photon sources enables implementation of quantum computation using only linear optical elements and photodetectors.
- Quantum enhanced measurements: Quantum enhanced optical measurements exploit quantum techniques such as entanglement or non-classical state correlation to yield sensitivity and accuracy better than purely classical approaches.
- Radiometry: The development of a new standard source for the low photon flux regime will provide a major step within the metrology for single-photon detectors. Furthermore, single-photon sources with an adjustable photon rate will establish the necessary and robust link to classical radiometry, because setups comparing analogue detectors, traced to a primary standard, and single-photon detectors can easily be established.

EMRP
European Metrology Research Programme
Programme of EURAMET
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Scientific and technical objectives

The aim of the JRP is to develop compact and efficient single-photon sources and to implement them in quantum optics and metrological applications in order to advance the measurement performance and facilitate new scientific discoveries in these fields. Therefore, the specific scientific and technical objectives are

- 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 (WP1, WP2);
- 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 (WP1);
- the characterisation of these single-photon sources by appropriate metrics in terms of wavelength, bandwidth, photon statistics, anti-bunching, and indistinguishability (WP1, WP2);
- the demonstration of the suitability of these sources for different entanglement enhanced measurements based on those metrics (WP3).

Expected results and potential impact

This project aims towards the realisation of new, highly efficient, reliable single-photon sources by exploiting the scientific and technological excellence of the project partners.

The highlights of the first 12 months of this project are:

- the development and formulations of designs and concepts for the single-photon sources. This included the design of optimized antenna structures for efficient single-photon collection, the design of a photonic trumpet for high mode matching and the construction of an initial eigenmode solver based on the Fourier modal method. These results are prerequisites for the further development of highly efficient single-photon sources based on defect centres in diamond and on quantum dots in semiconductor structures;
- the preparation of an optically pumped nanowire single-photon source. This sample was delivered to PTB for further characterization in terms of g^2-value, spectral distribution and photon rate. Furthermore, a GaAs photonic trumpet with an elliptical base which is compatible with polarization control was realized, see SEM image in Figure 1. The fabrication work includes the MBE growth of a sample, e-beam lithography and RIE etching. Two tilted observations by SEM reveal that the base of the trumpet is compatible with single mode emission as well as with polarized emission, because the diameters are 260 nm and 150 nm. The top diameter (2.3 µm) is compatible with a directive emission, completely intercepted by a numerical aperture of 0.8;
- a procedure for locating nanodiamonds with identified NV- and SiV-centres was established based on the usage of substrates with markers. By overlaying white light scans, fluorescence scans and SEM pictures, individual nanodiamonds containing single SiV centres can be registered with the markers;
- the preparation of the low-photon-flux measurements. Specifically, detector-based transfer standards for very low photon fluxes, sub-ns pulse diode laser driving electronics, a tunnel-type multi-element trap detector as beam attenuator (Figure 2) as well as a Switched-Integrator Amplifier (SIA) were designed and manufactured. The transmittance of the attenuator is $T = 5.48 \cdot 10^{-7} \pm 5$ %. The SIA has a conversion factor as high as 10^{12} and in conjunction with a small area, state of the art Si photodiode the noise level measured can be as low as 1 fW/Hz^{½} which corresponds to ≈4000 photons /Hz^{½} at wavelength of 750 nm;
- An experiment for the generation of single photons in the telecom band based on spontaneous parametric down-conversion was set-up (Figure 3). The process employed is based on the spontaneous decay of a pump photon at 710 nm into signal and idler photons at 1310 nm and 1550 nm. A tuning range of parametric fluorescence from 1295 nm – 1350 nm and 1510 nm – 1580 nm, thus covering the full telecom O- and C-bands were observed. By correlating the detection events of both detectors, the correlation between signal and idler photons was proven and at low pump power

(approx. 100 µW) the background count rate is very small leading to a high correlation-to-accidentals ratio (CAR) of 97;

- a project website with a password-protected area was established (www.ptb.de/emrp/siqute.html).

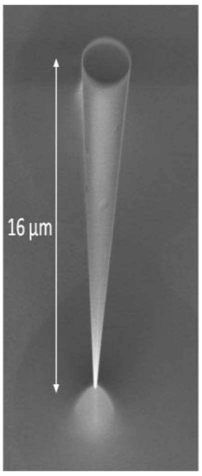

Figure 1. GaAs photonic trumpet with an elliptical base which is compatible with polarization control.

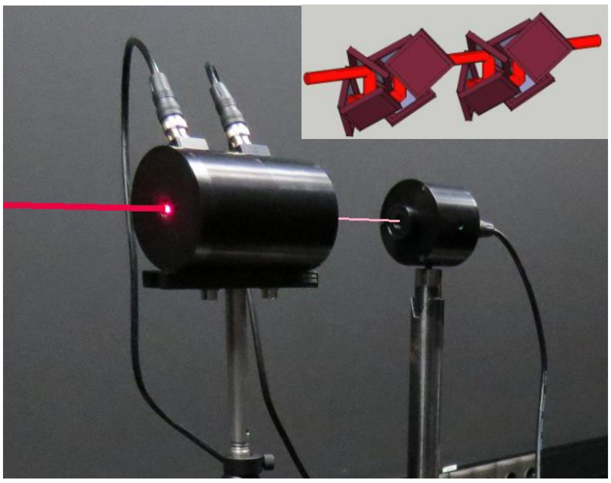

Figure 2. The high-attenuation tunnel-type detector for calibration of single-photon devices. The top inset shows an illustration of the 12-element attenuator for six decades beam attenuation.

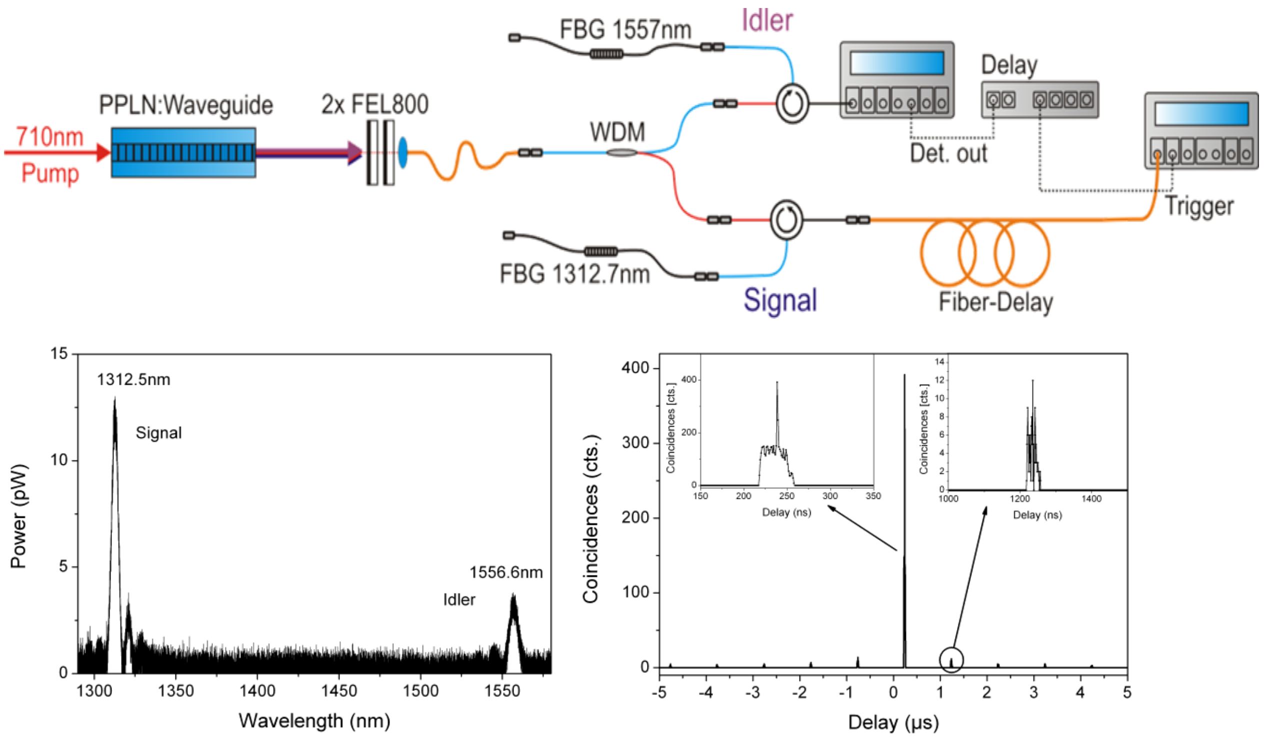

Figure 3: Experimental set-up (top), typical emission spectrum (bottom left) and correlation measurement results (bottom right).

The direct impact of this project will manifest itself by the development of single-photon sources to 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. The results achieved thus far within the project will impact the development of better and easier-to-use single-photon sources: antenna designs for simplification of photon collection, i.e. to be used with standard immersion oil objectives and solid immersion lenses as well as Si-V-doped nanodiamonds on specially taylored substrates for easier identification in repeated experiments. Furthermore, a detector-based transfer standard for the improvement of traceable very low photon flux measurements is under construction and implementation. These results will not only be beneficial for the project, but also for the scientific and metrology communities working on the corresponding fields.

The indirect impact of this project will manifest itself in the mid- and long-term. The sources developed within this project will be a breakthrough in the acceptance of single-photon sources not only in the academic field, but also in an industrial environment. Single-photon sources will become “normal” or “standard” components, like laser or LEDs to be used in highly technological applications like quantum communication, quantum computation and quantum imaging. With these sources, quantum communication will become realistic in a wider field, due to the excellent sources available after the end of the project. The sources will be the basis for cheap, robust and reliable room temperature single-photon sources for use by academics and schools. By this, the mystery and thus the reservation against “quantum stuff” will be diminished and brought into the students´ and engineers´ world.

JRP start date and duration:	01 June 2013, 36 months
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