14IND05 MIQC2
Optical metrology for quantum-enhanced secure telecommunication

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Co-ordinator
Ivo Pietro Degiovanni
INRIM

Workpackage 2

Metrology for commercial components for free-space QKD

Progress Report at November 2016

(18 Months)

Objectives

WP2: Metrology for commercial components for free-space QKD

The aim of this work package is to establish measurement and characterisation facilities within the consortium for components of free-space QKD devices, with the goal to contribute a significant part to a Joint Virtual European Metrology Centre for Quantum Photonics. This includes metrology for single-photon sources and detectors as well as relevant optical components. Within the scope of this project, we define visible-light QKD as the spectral range where silicon-based detectors are applicable, i.e. as the wavelength range between 400 nm and 950 nm.

Task 1: Measurement facilities for detectors for free-space QKD
The aim of this task is to establish measurement facilities - using different methods - addressing detectors, their detection efficiencies (DE) and corresponding uncertainties - relevant for free-space QKD (i.e. in the VIS-NIR).

Task 2.2: Measurement facilities for sources used in free-space QKD
The aim of this task is to establish measurement facilities among the partners addressing sources, and their corresponding measurands and uncertainties, relevant for open-space QKD.

Task 2.3: Measurement facilities for components used in free-space QKD
The aim of this task is to establish measurement facilities among the partners for components other than sources and detectors which are relevant for open-space QKD. Within this project, the focus is on polarisation controllers with respect to the degree of polarisation, intensity modulators with respect to modulation depth, attenuators with respect to transmission, and quantum random number generators.

Task 2.4: Validation of facilities by measuring two measurands (the detection efficiency of single-photon detectors and $g^{(2)}(0)$-value of sources) used in free-space QKD
The aim of this task is to validate the measurement facilities between the partners. Selected pilot studies and comparisons of the two most relevant measurands, i.e. the detection efficiency of single-photon detectors and the $g^{(2)}(0)$-value of sources used in free-space QKD, i.e. in the VIS-NIR spectral region, will be performed.

Task 2.5: Development of new few-photon detector and validation of measurement techniques for characterising components of free-space QKD systems
The aim of this task is to develop new components for QKD systems which have the potential to be implemented into QKD systems. A new radiometric standard based on an induced-junction photodiode will be developed and investigated, and efficient single-photon sources (SPSs) based on deterministic quantum dot micro-lenses will be developed and optimised with respect to their out-coupling efficiency and quantum optical features.

The main achievements to date

A 6-element thermally cooled miniature Si photodiode reflection trap for the measurement of the detection efficiency and linearity of free space single-photon detectors has been developed.

A 2-channel-TES-photon counter (TES: transition edge sensor) has been installed; the data acquisition components and pulse analysis software enable photon-number resolving measurements in the range of 1 to 15 photons / pulse. Quantum dot-based single- and two-photon sources as well as micro-lasers have been investigated and the reconstruction of the emitted photon number distributions have been demonstrated. First publications and presentations are in preparation.

The technical protocol for a pilot study on the detection efficiency of a silicon SPAD has been established.

The measurement of the detection efficiency of a commercial free-space single photon detector based on Si-SPAD by comparison against the few-photon detector based on PQED has been completed.

Quantum dot samples were grown and processed by means of in-situ electron beam lithography. A sample with 21 efficient single-quantum dot microlenses were provided to PTB Braunschweig.

Details

Task 2.1: Measurement facilities for detectors for free-space QKD

The development of a thermally cooled miniature Si photodiode reflection trap for the measurement of the detection efficiency and linearity of free space single-photon detectors is complete. It consists of six HPN-S1337-BQ SP (windowless) silicon photodiodes arranged in a polarisation-independent alignment. Temperature monitoring is implemented inside the detector. The theoretical field of view is approximately 12°, the trap can be used for collimated beam diameters of up to 2 mm.

The development of the double monochromator-based calibration facility for performing the spectral characterisation of the detection efficiency, the linearity and the spatial uniformity of free space silicon single-photon avalanche diodes is ongoing. The readout electronics have been produced, the trap detector cooler and the controller are ready. For the monochromator-based calibration facility, a suitable collimation beam has been achieved (divergence angle < 0.6 °).

The establishment of a laser-based calibration facility for the detection efficiency of single-photon detectors using in-situ calibrated neutral density filters as well as an attenuator based on Si-photodiodes in a trap configuration is on schedule. The design of the attenuator is in progress: eight Si-based photodiodes will be used; two can be adjusted to provide collinear input and output beams.

A 2-channel TES (transition edge sensor) photon counter has been installed; data acquisition components and pulse analysis software enable photon-number resolving measurements in the range of 1 to 15 photons / pulse. The fibre-optic beam splitter and attenuators necessary for system detection efficiency measurements are currently in calibration at PTB´s Photometry and Applied Radiometry department. Preliminary estimations of the system detection efficiency (DE) have been performed using a continuous wave laser and yielded a DE of approx. 84 % for both detector channels.

Task 2.2: Measurement facilities for sources used in free-space QKD

The setup for the measurement of the photon number distribution function using the photon-number resolving Transition Edge Sensor (TES) was completed. Classical light sources as well as two-photon sources were successfully measured.

The usability of the TES-photon counter for photon number resolving measurements at wavelengths of approx. 930 nm has been demonstrated. Quantum dot-based single- and two-photon sources as well as micro-lasers have been investigated and the reconstruction of the emitted photon number distributions have been demonstrated. First publications and presentations are in preparation.

The cavity for a high-resolution scanning Fabry-Perot spectrometer has been designed and component parameters calculated. A re-evaluation of potential single-photon emitters has indicated that operation over 600 – 950 nm is preferred, with performance up to 950 nm being mandatory for joint work with TUB. It was determined that it was not feasible to interchange the new cavity with the existing telecom wavelength cavity;therefore a separate system is being built with its own housing.

The development and the fabrication of SPSs is underway and samples of single-photon emitters can be provided upon request.

The measurement design and the experimental setup for the characterization of the spatial profile of the SPS by means of spatial-resolving detectors is completed. First measurements with the SPAD array have been performed. EMCCD characterisation at single-photon level, with each pixel operating in Geiger mode was carried out, and the results published [Optics Letters **41**, 1841 (2016), open access].

Task 2.3: Measurement facilities for components used in free-space QKD

The work on characterisation of free-space-QKD transmitter exploiting the polarization as encoding degree of freedom has been organised. One system for polarisation control based on passive optical components, such as (non-)polarising beam splitter and waveplates, has been designed, together with the measurement apparatus: a single-photon polarimeter operating in the NIR-VIS. The realisation of the experiment, and the measurement facilities for the characterization the intensity modulator and the attenuator, are ongoing.

The model developed in EMRP 14IND05-MIQC to predict the effect of after-pulses on bit rate and entropy on a two-device QRNG has been numerically investigated to explore its sensitivity to different models of after-pulse behaviour, in advance of experimental measurements.

Task 2.4: Validation of facilities by measuring two measurands (the detection efficiency of single-photon detectors and $g^{(2)}(0)$-value of sources) used in free space QKD

The technical protocol of the pilot comparison is written and the time schedule has been fixed. Measurements have been performed at PTB, the comparison artefacts (Excelitas SPCM-AQH) are currently at NPL.

Task 2.5: Development of new few-photon detector and validation of measurement techniques for characterising components of free-space QKD systems

A “few photon detector” based on a temperature-stabilised induced-junction photodiode has been set up. Currently, it uses a built in, temperature controlled current-to-voltage amplification stage.

A low-noise photocurrent amplifier for biased photodiodes, suitable for the measurement of photon fluxes of about 1 Million photons per second is under development. First tests confirm that the SIA works with biased detector at 3.7 V. The noise performance evaluation with photodiodes from the qu-Candela project (Euramet, Project N. T1.J2.3) is under way.

The Metrology Light Source were used to measure the ratio of the photo-current to ring current of the few photon detector and the metrology light source. The photon flux was set to approximately 10^7 photons per second and 10^4 photons per second. Additional linearity measurements for photocurrents between 5×10^{-8} A and 1×10^{-4} A were performed at 850 nm using laser radiation. These measurements showed that a sample photodiode of the same type as used in the few photon detector is linear between photocurrents of 5×10^{-8} A and 1×10^{-5} A, when no voltage is applied to the detector. The most common source of non-linearity at 850 nm is the saturation of recombination channels by the radiation inducing a so-called supra-linearity. This type of non-linearity has not been observed during the measurements of the witness photodiode.

The measurement of the detection efficiency of a commercial free-space single photon detector based on Si-SPAD by comparison against the few-photon detector based on PQED is completed.

Quantum dot samples were grown and processed by means of in-situ electron beam lithography. A sample with 21 efficient single-quantum dot microlenses were provided to PTB Braunschweig. Epitaxial growth for further enhanced outcoupling efficiency beyond 50 % will be performed, and a second batch of efficient single-photon sources will be processed and delivered to the partners.

The development of efficient free-space (photon extraction efficiency > 50 %) and fibre-coupled (photon extraction efficiency > 20 %) single-photon sources based on deterministic quantum dot-microlenses is ongoing. Numerical modelling for optimised outcoupling efficiency promises values of 48 % and 18 % for free-space and fibre-coupled single-photon sources (with backside gold mirror), respectively. Ongoing simulations target still higher values. Sample growth using these optimum designs is in progress and will be followed by deterministic processing of single-QD microlenses. In parallel, the fibre-coupling of single QD-microlenses is being developed with expert support. Microlenses with backside gold mirrors have been fabricated that show a 29X enhancement as compared to planar samples (no mirror, no lens).

A flip-chip process for a back-side Au mirror and anti-reflection coating to enhance the photon outcoupling efficiency beyond 50 % has been started.