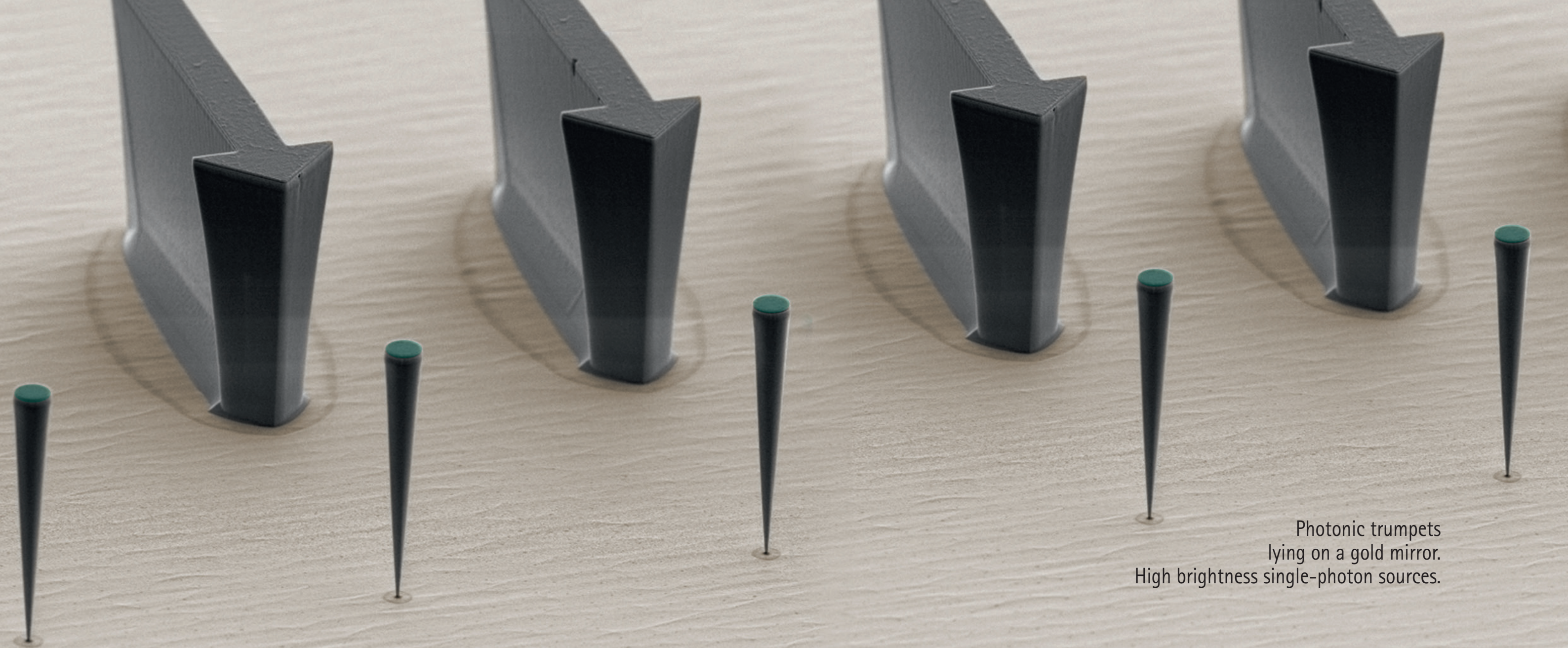


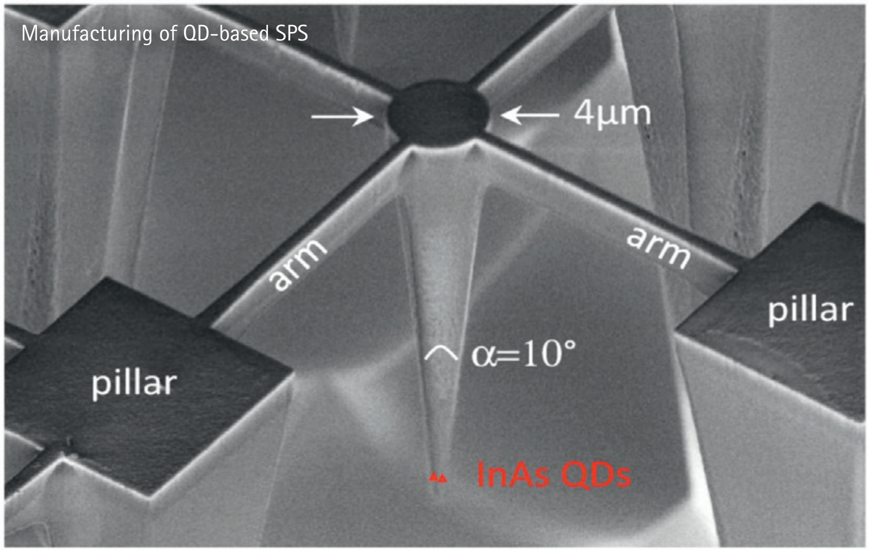
Photonic trumpets
lying on a gold mirror.
High brightness single-photon sources.

Security with single photons

The development of compact and efficient single-photon sources is central to a number of technical fields, including quantum computing, quantum cryptography and radiometry. **Professor Stefan Kück** tells us about the SIQUTE project's work in developing single-photon sources, research which could have a significant impact in both the academic and commercial sectors

A type of massless elementary particle, photons are well-suited to a range of quantum communication, computing and metrology applications. However, currently no single-photon source is available that meets the scientific and technical criteria of these applications, an issue that lies at the core of the SIQUTE project. “In this project we are mainly focusing on the production of single photons, meaning the development of single-photon sources,” says Professor Stefan Kück, the project’s coordinator. This is central to the development of a number of quantum applications, including quantum cryptography, which could greatly enhance internet security. “If you want to enhance security by having just one photon in a specific time period, then first you really need to have a single-photon source. This is very important,” stresses Professor Kück. “The reason is that if you want to establish secure quantum communication, then in principle you can do this by transmitting single photons with a specific characteristic. If, however, you transmit two photons where this characteristic is identical, then an eavesdropper can take one and read your secure data.”

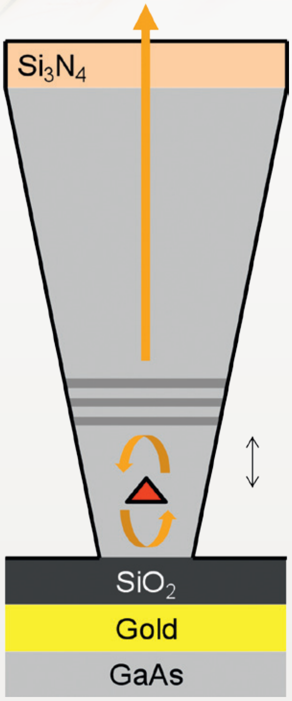
The concept of quantum communication is built on the knowledge that it is not possible to copy a photon and produce another with identical characteristics. In order to copy a photon you first need to measure it, and when you measure it you change its quantum state, which has significant implications in terms of information security. “When you change the quantum state of a photon, this change can be detected. When the recipient of a secure message detects that the photon has changed they know not to use the key, because somebody has intercepted it. This is the idea of quantum communication,” explains Professor Kück. The development of pure single-photon sources would be a huge step forward in these terms, helping meet the needs of cutting-edge quantum optical technologies. “We are aiming at quantum communication in this project. Our goal is to develop more accurate and more efficient single photon sources,” says Professor Kück.



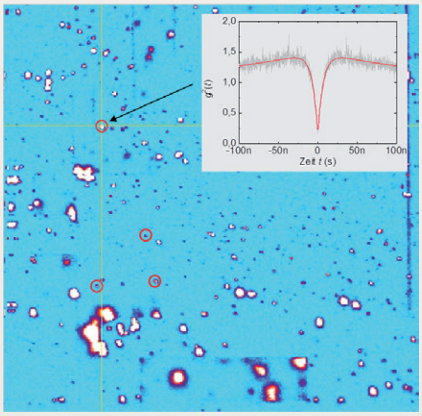
Single photon sources

Researchers are investigating two main single photon sources, the first of which are vacancy centres within nanocrystals. Professor Kück and his colleagues are investigating single photon sources based on impurity centres within diamond. "Nitrogen vacancy centres are present in natural diamonds. But, for it to be a single photon source, you need there to be just one of these nitrogen vacancy centres in a specific volume of the crystal. So if you have two or more of these nitrogen vacancy centres, then you don't have a single-photon source, you need there to be just one," he explains. This can be achieved by artificially producing these diamonds, for example by shooting nitrogen or silicon atoms into these nano-diamonds. "By this method you're producing silicon and nitrogen centres in very clean diamond. The trick is to have a rather low irradiation of these ions, so that you have a really low concentration of this nitrogen or silicon in your crystal."

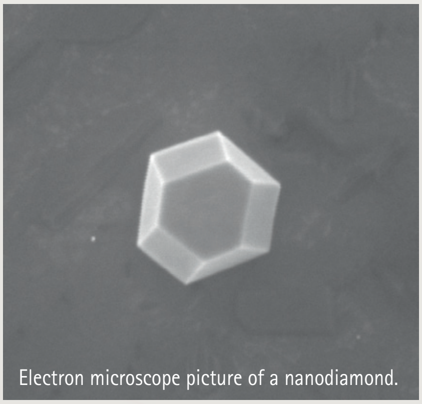
The nitrogen vacancy centre can be irradiated with a laser pulse; it will then go into an excited state, and emits a photon by spontaneous emission. However, this photon is not emitted in a specific direction, which Professor Kück says is an important consideration in terms of the project's overall goals. "It's very difficult to collect photons from a source which emits in all directions. But if you put this nano-diamond into a specific structure, then you will guide this emission into a specific direction," he outlines. Researchers are implementing defect centre doped nanocrystals into metallo-dielectric structures, which will allow for near unity in collection efficiency. "By putting this nano-diamond into a specific structure, then we can guide this photon emission in a specific direction. If we can do this effectively, then we can go up to a very high collection efficiency, approaching 100 percent," says Professor Kück. "We haven't achieved that yet, but in principle the photon collection efficiency should be very high with this approach."



Optically pumped design for indistinguishable photon emission. Design of a photonic NW SPS trumpet structure implementing a weak cavity effect.



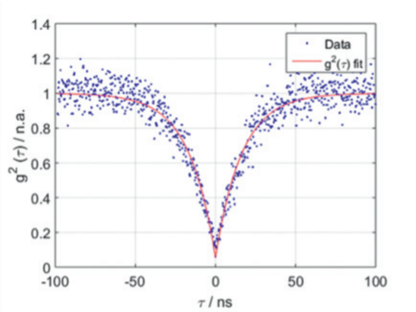
Map of Diamond Nanocrystals. The inset shows the $g^{(2)}$-function for the encircled nanodiamond.



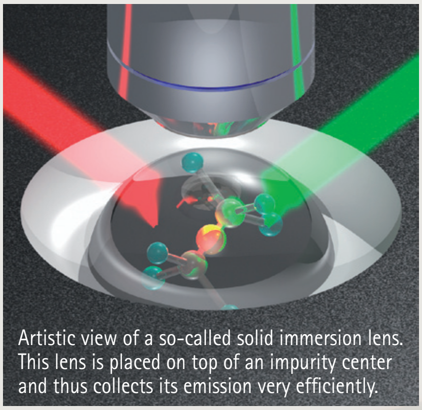
Electron microscope picture of a nanodiamond.

The second type of single photon source the project is investigating are quantum dots, a type of semi-conductor device which is relevant to several areas of research. The project's work in this area centres on the fabrication of Indium Arsenide (InAs) quantum dots, which are placed within Gallium Arsenide (GaAs) structures. "Quantum dots are semi-conductor materials, and we place them in slightly different semi-conductor materials. One major advantage of this approach is that, in principle, you can access semi-conductors electrically. That means single photons can be emitted by electrical excitation," says Professor Kück. These single-photon sources should be easier to handle; however, Professor Kück says that there are also disadvantages with these semi-conductor quantum dots. "They have to be operated at very low temperatures. So typically at say 12-20 Kelvins, so you need to strongly cool them," he explains.

This is a significant obstacle in terms of the practical application of quantum dots, but it is relatively insignificant when it comes to the project's work, with the project consortium bringing together six National Metrology Institutes and several research laboratories with advanced facilities. This enables researchers to investigate fundamental questions around photons; the third workpackage in the project is centred on measuring entanglement. "We say that two photons are entangled when a measurement on one photon exhibits a certain relationship, or correlation, to a measurement on the other photon. It means that if you measure one then you know the characteristics of the other, even though they may be quite a long way from each other," says Professor Kück. This gives



The measurement of the $g^{(2)}$-function, the 2nd order correlation function, is the proof for single-photon emission. The dip in the middle, which almost goes down to zero, indicates that almost all photons arrive as single photons at the detector.



Artistic view of a so-called solid immersion lens. This lens is placed on top of an impurity center and thus collects its emission very efficiently.

researchers the chance to observe photons indirectly. “You can send a photon beam in one direction, and these photons will interact in a scene, with other particles in that scene. We can observe what is going on by looking at the entangled photons in a different location,” continues Professor Kück.

A key point to note here is that entanglement between two photons is by nature fragile and liable to disruption. While on the one hand this fragility is a problem, seemingly limiting the applicability of the feature, on the other it means that it can act as a highly sensitive sensor. “You can really see very small interactions between light and matter, and these interactions will have an impact on the entanglement that you can measure. You can measure small forces and small absorptions. So you can see some things which you cannot see if you observe it classically,” outlines Professor Kück. Researchers can get more detail on photon interactions, and measure them more accurately, part of the wider goal of carrying out precise measurements beyond classical limits; Professor Kück says this work holds wide relevance. “The potential of quantum communication is widely recognised, while we’re also working on the calibration of single-photon detectors,” he outlines.

> If you want to establish **secure quantum communication**, then in principle you can do this by **transmitting single photons** with a **specific characteristic**. If, however, you transmit **two photons** where this characteristic is **identical**, then an **eavesdropper** can take one and read your secure data

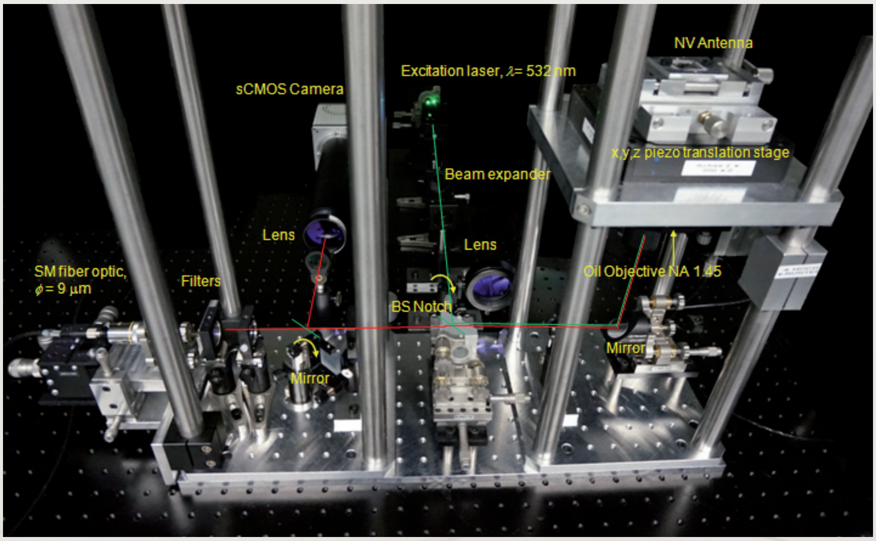
Single-photon detectors

This is central to the detection of weak signals, which occur in many fields beyond quantum communication, including medicine, biology and astronomy. Many national metrology institutes have worked on the calibration of detection devices, but Professor Kück says existing techniques have some clear limitations. “Currently there is no national metrology institute capable of calibrating single-photon detectors in a proven way. This is one area in which our research will have a major impact,” he says. This work will form an important part of the future research agenda. “One future research direction will be to set up calibration services, characterisation services, for devices, which means detectors and sources. This will be done at different National Metrology Institutes,” continues Professor Kück. “A follow-up project will work on quantum communication, aiming to address the main problems in the field.”

This is a complex task, and there are many issues to consider when it comes to information security.

While in principle totally secure communication should be possible, in reality Professor Kück says it will be difficult to guarantee it. “There is a long way to go before we can achieve absolute security,” he acknowledges.

The confocal microscope setup for excitation and detection. Such a setup is typical for excitation of single impurity centres in nanodiamonds and the detection of their emission.



At a glance

Full Project Title

Single-photon sources for quantum technologies (SIQUTE)

Project Objectives

The aim of the SIQUTE project 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.

Project Partners

Funded Partners (all are national metrology institutes): CMI, Cesky Metrologicky Institut, **Czech Republic** • INRIM, Istituto Nazionale di Ricerca Metrologica, **Italy** • Metrosert, AS Metrosert, **Estonia** • MIKES, Mittatekniikan Keskus, **Finland** • NPL, NPL Management Limited, **United Kingdom** • PTB, Physikalisch-Technische Bundesanstalt, **Germany**
Unfunded Partners: USMF, The University System of Maryland Foundation, Inc., **United States** • Funded Universities and Academia: Commissariat à l’énergie atomique et aux énergies alternatives, **France** • Danmarks Tekniske Universitet, **Denmark** • Friedrich-Alexander-Universität Erlangen - Nürnberg, **Germany** • Universitaet des Saarlandes, **Germany**

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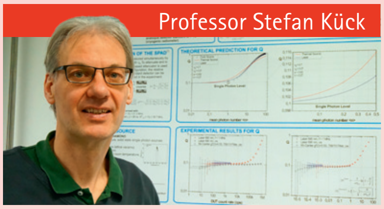
Professor Stefan Kück



Professor Stefan Kück started his academic career in 1990, when he began his PhD work on Cr^{4+} doped laser materials, which he finished 1994. He completed his habilitation on tunable laser materials in 2001. He then switched topics towards metrology, especially laser radiometry, photometry and single photon metrology. Currently he leads the Department of Photometry and Applied Radiometry at the Physikalisch-Technische Bundesanstalt, the German national metrology institute. Since 2013, he coordinated the joint research project “Single-photon sources for quantum technologies” (SIQUTE).

SIQUTE