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Chapter 1

Introduction

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quantum candela as redefinition of classical candela requires extremely well-calibrated detectors to make sense super calibration requires single photon sources

ideal for calibration are narrow linewidth emitters at various wavelengths in this thesis we investigate SiV centers and find a distribution of wavelengths SiV centers can be selected according to wavelenghts and deployed as calibration tools

single photon sources should have sufficient Intensity

normal light sources emit many photons at once quasi single photon sources have non-zero probability to emit more than one photon single photon sources are ideal for calibration

heralded single photon sources give single photon sources with almost perfect certainty at the cost of lower intensities [?] SiV centers deliver high certainty and extreme intensities SiV centers can be coupled to antennas to even further increase intensities thus SiV centers are great for calibration purposes

SiV centers can be deployed as hybrid integrated single photon sources in conjuction with VCLS that are convenient to handle and operate they do not require sophisticated setups and operate at room temperature

ideal for calibration are stable emitters that do not bleach SiV centers in low strain bulk are stable SiV centers in nanodiamonds can exhibit blinking, i.e. fluorescence light intermittence however, the use of nanodiamonds has advantages increased collection efficiency high mobility, nanodiamonds can be moved by pick-and-place high mobility enables special applications such as coupling with antennas

in this thesis we: produces SiV centers hosted in synthetic nanodiamonds investigate SiV centers in nanodiamonds as single photon sources at room temperature explore luminescence properties with regards to potential applications in quantum metrology explore the possibilities of using SiV centers with antennas

1.2 applications of single photon sources

metrology applications

1. reliable single photon sources can be used to calibrate detectors since their photon output is known exactly [?]. Detectors have different sensitivities for different wavelengths. Narrow band emmitters such as SiV centers allow to work with a specific wavelength, i.e. a well-defined and clean detector response [?]. Narrow-band single photon sources with a variety of different wavelength are ideal for calibration. This is possible, see distribution.

2. redefinition and of classical SI candala based on single photon sources to achieve a high precision definition [?].

single photon sources emit single photons. Highly calibrated detectors can detect them faithfully and thus a definition of candela in terms of photon counts makes sense.

1.3 Introduction

The International System of Units (SI, abbreviated from the French SystÃÍme international (d'unitÃľs)) emerged in the late 18^{th} century as a coherent metric system of measurement with rationally related units and simple rules for combining them [?]. Since its inception it was improved and augmented continously as an effort to accomodate continuued scientific and technological progress. The current SI system is comprised of seven base units: The kilogram (kg), the second (s), the Ampere (A), the Kelvin (K), the mole (mol) and the candela (cd). Currently a redefinition of four of base units (kilogram, mole, Kelvin, Ampere) in terms of fundamental constants is under way [?, ?, ?]. The proposed change will provide more universally realizable definitions of these base units, particularily for the measurement of electrical quantities [?]. It will also do away with the last base unit definition relying on a historic material artefact, the international prototype of the kilogram. As a result all base units will for the first time follow from one or more fundamental constants of nature.

At the same time similar discussions regarding the SI base unit for luminous intensity, the candela, have emerged. It has been suggested that it can be improved by leveraging recent advances in classical radiometry and photometry as well as the development of novel quantum devices and techniques [?].

Traditional applications relying on accurate photometric and radiometric measurements are light design, manufacturing and use of optical sources, detectors, optical components, couloured materials and optical radiation measuring equipment [?]. In the classical regime of optical radiation high flux levels dominate. Here primary optical radiation scales for sources and detectors are generally based on cryogenic radiometry establishing a link to the SI units of electricity [?]. Other calculabe sources such as synchrotrons and blackbody radiators can serve as primary source scales in the ultraviolet and deep-UV regions by establishing tracability to SI units of thermometry, electricty and length [?, ?].

Scaling down to the quantum world of radiometry is associated with a loss of measurment accuracy. In this regime dedicated photon counting techniques are required to deal with the challenge of low flux levels. Since they rely on counting photons directly, the can provide efficient and traceable measurements and improved uncertainties. For high-accuracy absolute radiometry in this regime predictable single or quasi-single-photon sources and photon detectors are called for.

The recent advances being made in managing and counting individual photons and producing single-photon sources show tremendous promise of producing within a few years a radiant flux with a well-established number of photons per second with an unprecedented precision and accuracy beyond the standard quantum limit [7,8]. Moreover, the ability to reliably manipulate individual photons will foster the development of new types of instruments that will require, in turn, advances in metrology to create new quantum-based calibration methods and standards. For these reasons, a reformulation of the candela has been proposed in terms of photon units. This reformulation is considered to be a small, but useful step in the future direction of photometry, radiometry and the âĂŸcandelaâĂŹ in the quantum world. For instance, the emerging fields of nanotechnology and quantum communication are promising new technologies. While their immediate challenges are for new metrological approaches for reliable characterization of properties at the nanoscale, it is foreseen that to advance the progress of these technologies in building verifiable large-scale systems, they will need accurate measurements traceable to the SI using quantum- based radiometric units.

A key requirement for the progress of quantum information technology is the development of sources that deterministically produce single photons upon request (on-demand source). Recently, single-photon sources and entangled-photon sources have become available, where the key issue is the non-Poisson generation of single photons. A laser beam can be described by a single-mode coherent state with Poissonian photon-number distribution, p(n) = (Îijn /n!)eâĹŠÎij , where Îij is a mean photon number in the beam. Thus, a highly attenuated laser pulse with very small Îij approximates quite well a single-photon Fock state with the probability ratio of multiple photons to a single photon going to 0 as Îij âĘŠ 0. Unfortunately, the fraction of vacuum states then increases dramatically. Moreover, the mean photon number cannot be made arbitrarily low because of detector dark counts.

Quasi-single-photon states can be prepared more efficiently by using signal and idler photon pairs generated by spontaneous parametric down-conversion (SPDC) [111]. SPDC is a deterministic single-photon source (see also section 5.2), where the number of photons in one mode is thermally distributed and the total number in all modes is Poissonian distributed. The key feature is a strong time correlation between photons in the pair. Ideally, if a photon counter detects one photon in the idler path then, for an extremely short time interval, of the order of hundreds of femtoseconds, the other photon in the pair is in the signal path. However, losses in the signal beam and dark counts of the trigger detector can result in no photon in the signal beam even if the trigger detector has clicked. SPDC photons can be satisfactorily used as a heralded single-photon source, albeit random, and provide a useful approximation capable of demonstrating single photon-ness. In general, the probability of having multi-photon states is rather low, mainly because the efficiency of the overall SPDC conversion is very poor. Eventually, these states can be effectively eliminated by using techniques available in the literature [112, 113]. In conclusion, a SPDC quasi-single-photon source is characterized by a substantial reduction in the portion of vacuum contributions, i.e. empty signals, compared with an attenuated laser. Colour centres in synthetic diamond with a substitutional nitrogen atom and a vacancy at any adjacent lattice position represent an interesting single-photon source with strong anti-bunching and a spectral width about 1nm at room temperature [114].

In quantum dots, i.e. semiconductor nanostructures characterized by a two- or more-level electronic system, the photon is emitted by recombination of an electronâĂŞhole pair that can be created by optical pumping or by an electric current [115]. The chosen material determines the wavelength of the emitted beam while the spectral width is a function of the number of excited energy levels and the average number of created electronâĂŞhole pairs. Single-photon-like states can also be generated by radiative transitions between electronic levels of a single atom (ion) or molecule caught in a trap and placed inside (or sent into) an optical cavity, interacting both with the excitation laser beam and the vacuum field of the cavity [116]. These single- photon sources have desirable properties such as a narrow spectrum and high collection efficiency due to the presence of the cavity. However, the practical feasibility of such sources is still low because of their technological complexity (among others, high vacuum is needed). Furthermore, semiconductor quantum dots and colour centres face the problems of spectral dephasing and inhomogeneity, which make it difficult to find independent emitters that generate indistinguishable photons for applications, such as quantum computing.

Organic molecules in a crystalline host matrix offer another candidate as a practical scalable single-photon source [117]. At low temperatures, some molecular transitions become lifetime limited and offer almost unity quantum yield. Recently, two independent Fourier-limited solid-state single- photon sources have been demonstrated [118]. The solid-state arrangement of this approach enables very long measurement times using the same emitter, practical frequency tunability of individual molecules, and a straightforward method for scaling and miniaturization.

As a consequence of the number of technologies being pursued to develop single-photon emitters with different source properties, a number of new metrics are needed to assess these sources. Suitable metrics include the methods and measurement facilities that have been developed for quantitative characterization of statistical properties of light and non-classical signature of single- photon sources, such as their anti-bunching behaviour, purity, degree of indistinguishability and ability to be used for entanglement [113, 119]. Capabilities for quantifying the classical and quantum characteristics of photons have also been demonstrated in the measurement of single photon/correlated photons with Hanbury-BrownâĂŞTwiss, two- photon and Michelson interferometers [120, 121]. The present challenge is to improve the accuracy of these measurements and enable them to characterize sources under varying conditions of pumping, temperature, geometry and wavelength. As an example, a good measure of the quality of a single-photon source is its second-order autocorrelation function, i.e. the correlation measured in a Hanbury-BrownâĂŞ Twiss-type experiment. The signature of true (ideal) single- photon emission is an absence of any coincidences at zero time difference between the two detectors.

The evolution of photometry, radiometry and the candela has been reviewed in terms of needs and developments in both the classical and the quantum world. The metrological basis of these physical quantities and associated SI base unit is linked to the important biological process of human vision, which is generally described in terms of photon interactions. For several decades, the advances in this field of metrology have been spurred by research and development of new and improved source-based and detector-based primary methods. The current state-of-the-art uncertainties of these measurements largely meet the diverse community of users in the classical world of lighting, manufacturing, commerce and health and safety applications. However, there have been recent developments in producing novel single-photon sources and single-photon detectors. The measurement challenges in characterizing these new âĂŸphoton on demandâĂŹ sources and PNR detectors have been identified. The growth and potential of new quantum-based tools that exploit these new sources and detectors are largely limited by the lack of traceablequantumopticalmetrologytoolsandtechniques. The definition and practical realization of the candela and the other photometric and radiometric units are regularly reviewed by the Consultative Committee for Photometry and Radiometry (CCPR) to ensure that they reflect current best measurement practices and meet the existing and emerging needs of its user community. The possibility of a reformulation of the candela has been discussed here in terms of expanding its scope of application from meeting existing and future needs in classical photometry and radiometry to including future needs in quantum radiometry. This would build on the existing official definition in terms of radiant intensity by providing an explanatory note in terms of fundamental photon units. This reformulation is considered by members of the photon counting community to be a small, but useful step in the future direction of photometry, radiometry and the âĂŸcandelaâĂŹ in the quantum world. In addition to addressing the metrological needs of emerging quantum-based optical technologies and applications, this reformulation would also be in harmony with the proposed redefinitions of four of the seven SI base unitsâĂŤthe kilogram, ampere, kelvin and moleâĂŤin terms of fundamental constants in a quantum-based SI system.

1.4 psu

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