Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 contents

light are particles named photons single photons are useful applications include quantum information here we focus on quantum metrology quantum metrology applications

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 in an ongoing 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 improve the definitions of these base units to make them easier to realize experiemntally, particularily for the measurement of electrical quantities [?]. It will also eliminate the last remaining base unit definition which relies on a historic material artefact, the international prototype of the kilogram. As a result all base units will, for the first time, be tied to one or more fundamental constants of nature.

As these developments are put into motion, 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 [?].

At the time of writing the definition of the candela read:

> The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} Hz and that has a radiant intensity in that direction of 638^{-1}W sr^{-1}.

Traditional applications relying on this definition in conjunction with accurate photometric and radiometric measurements are light design, manufacturing and use of optical sources, detectors, optical components, colored 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 as well as associated new quantum-based callibration methods and standards are called for. To promote the development of such technologies a reformulation of the candela has been proposed in terms of *countable* photon units [?, ?, ?, ?, ?]. Here we emphasize the distinction between *countable* and *calculabe* sources of photons. The latter being available as blackbodies or synchrotron radiators.

A straightforward quantum-based reformulation has been suggested based on [?, ?]:

$$P = nh\nu, \tag{1.1}$$

where the radiant intensity per steradian $P = 638^{-1}\,\mathrm{W\,sr^{-1}}$ in a given direction and the photon frequency $\nu = 540 \times 10^{12}\,\mathrm{Hz}$ are assumed to be exact with their numerical values inherited from the present definition of the candela. The anticipated proposed changes to the SI system will define Planck's constant $h = 6.626\,070\,15 \times 10^{-34}\,\mathrm{J\,s}$ as an exact numerical constant [?]. As a consequence the number of photons per second per steradian in a candela n becomes a constant defined as:

$$n = \frac{P}{h\nu} \approx 4.091\,942\,9 \times 10^{15}\,\mathrm{counts\,s^{-1}\,sr^{-1}}. \tag{1.2}$$

Given this definition of the radiant intensity of a candela in terms of countable photons, a possible formulation of the quantum candela could read:

> The candela is the luminous intensity, in a given direction, of a source that emits photons of frequency $540 \times 10^{12}\,\mathrm{Hz}$ at a rate of $4.091\,942\,9 \times 10^{15}$ photons per second per steradian in that direction.

This definition would incur a change of 0.0014 % from the current value of the candela, an acceptable change, taking into account the fact that current experimental realizations of the candela are limited to uncertainties of 0.02 % [?]. Proposals such as this are regularly reviewed by the Consultative Committee for Photometry and Radiometry ensuring that the current best measurement practices and existing as well as emerging needs of the user community of the candela are met [?].

While a proposed formulation of a quantum-candela can be considered a small change to the SI system, a shift towards quantum based radiometic SI units it likely to become a critical enabler driving the development of accurate and traceable measuerment methods on the single-photon level. In order for the definition of the quantum-candela to have practical meaning, photon counting detectors are required. To ensure proper calibration of such devices, reliable deterministic single photon sources are required. As novel instruments and associated calibartion standards emerge, our ability to work with individual photons in a wide range of applications will improve [?, ?, ?, ?]. The quest for single photon sources is supported by large research projects such as “Single-Photon Sources for Quantum Technology" funded by European Metrology Research Program.

Advances in radiometry are particularily important for fields like quantum communication and quantum computing. They are heavily reliant on deterministic reliable single-photon sources and well-calibrated detectors capable of resolving single photons. As such they have acted as major driving forces in their development [?, ?]. Amongst others, some well known applications include quantum key distribution [?, ?, ?] or transmission in a quantum network [?, ?, ?].

At present several candidates for on-demand single-photon sources are available: One consists of a laser beam attenuated such that the mean number of photons in the beam becomes close to one [?, ?, ?]. However, the mean photon number cannot be controlled perfectly and a non-zero probability remains that multiple photons are present.

Quasi-single photon states can be realized more efficiently using photon-pairs, consisting of a signal and an idler photon. Pairs are created when a photon interacts with a non-linear optical medium in a process called spontaneous parametric down-conversion (SPDC) [?, ?, ?, ?, ?, ?]. The deciding feature of the process is the strong time-correlation between the signal and idler photons. If both photons are injected into individual signal paths, an detection event in one of the paths heralds the existence of a photon in the other path. SPDC pairs can thus be used to construct single-photon sources. Unfortunately, due to the poor efficiency of the SPDC process, the probability of generating pairs is unfavorable [?, ?]. Thus efforts have been undertaken to improve the effeciency [?, ?, ?].

Quantum dots emit photons by recombination of electron-hole pairs created by optical excitation or via an electric current [?, ?, ?]. The choice of semiconducting material determines the electronic structure of the system and thus the characteristics of the emitter. Similarily single-photons can be obtained as a result of radiative transitions between energy levels of single atoms or molecules trapped in an optical cavity [?]. While these sources have desirable properties such as high-collection efficiency, the practical usefulness is limited due to their technilogical requirements, amongst others a high vaccuum is needed to operate these sources [?].

For a wide range of single photon sources, significant progress has been made towards improving purity, indistinguishability and collection efficiency [?, ?, ?, ?, ?].

However, a single photon source suitable for the calibration of single-photon detectors is difficult to realize [?]. Ideally, a standard single photon source should be emmitting with a quantum efficiency of 100 % indicating that the entire exitation energy is transformed into radiation without losses. At the same time single photons should be emitted with a probability of one and subsequently collected with perfect efficiency.

Very recently, steps towards realizing an ideal deterministic single photon source have been taken. In particular it has been demonstrated that color centers in nanodiamonds involving silicon [?, ?] and nitrogen [?] are promising candidates for the realization of standard single photon sources [?, ?]. Single photon sources were absolutely calibrated by a classical detector and a calibrated spectormeter. Thus a unbroken traceability chain to the SI system has been achieved. The photon flux of the source can be controlled via the settings of the pump laser repetition rate. In this way a direct link between the high photon flux levels of the classical regime and low photon flux levels in the quantum world has been established. For the nitrogen vacancy center a photon flux rate of $\approx 1.4 \times 10^5$ photons per second was established.

In this thesis we focus on the silicon-vacancy center and its properties as a single photon source. In doing so we aim to add momentum to the application of single photon source as high accuracy calibration devices and subsequently, to the development of photon counting detectors and the adoption of the quantum-candela.

1.4 psu

Kontoinhaber: Effektboutique Bankname: Volksbank Esslingen IBAN: DE72611901100244357005 BIC: GENODES1ESS 229,00 âĆň Ihre Bestellnummer lautet: BE12813.