STABLE SOLID-STATE SOURCE OF SINGLE PHOTONS

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Abstract The controlled generation of single photons is mandatory for applications in quantum communication, in particular for secure quantum cryptography, and also for a number of fundamental problems in quantum optics. Here, we present a stable all solid-state source for single photons utilizing the fluorescence light from a single nitrogen–vacancy center (N–V center) in diamond.

1. INTRODUCTION

The generation of non-classical light and particularly of single photon states is one of the key experimental challenges in quantum communication and computation. The ideal single photon source emits light such that only one of two detectors behind a semitransparent beam splitter registers an event. A specially suited process for that is fluorescence of a single two-level quantum system.

Such two-level systems can be found with good approximation in atoms or ions and organic molecules. Experiments with single trapped atoms and ions [1] or with single quantum dots [2] require significant technical effort. Single organic dye molecules as the fluorescent emitter in solvents or polymers [3] degrade rapidly at room temperature – typically after about 10^9 emissions.

Here, we present an alternative candidate for generating single photons at room temperature. Single nitrogen–vacancy (N–V) centers in diamond combine the robustness against photo bleaching of single atoms with the simplicity of experiments with dye molecules.

2. NITROGEN–VACANCY (N–V) CENTERS

N–V centers are one of many well studied luminescent defects in diamond [4]. They are formed by a substitutional nitrogen atom with a vacancy trapped at an adjacent lattice position. We addressed single N–V centers in an untreated synthetic type Ib diamond sample ($500 \times 500 \times 200$ μm) in a confocal microscope setup shown in figure 1a.

The light of a diode pumped solid state (DPSS) laser with a wavelength of $\lambda = 532$ nm was focused into the diamond with relay optics and a standard microscope objective (M=60, NA=0.85). The fluorescence light coming from the illuminated N–V center was collected by the same microscope objective and focused into a single mode fiber. This defines the spatial mode for confocal detection and leads to a longitudinal resolution of 1.6 μm and a vertical resolution of 430 nm. The combination of a dichroic mirror and a color glass filter suppressed residual pump light for the fluorescence detection setup.

To position the focal spot within the diamond, a piezoelectric scanning unit (transverse position) and a motorized linear translation stage (longitudinal position) were used. The fluorescence light from the single N–V center was analyzed either by a Hanbury-Brown–Twiss configuration or a grating spectrometer. We finally detected the fluorescence light with passively quenched silicon avalanche photodiodes (APD) with a dark count rate of ≈ 250 counts per second [5].

N–V centers are identified by spectral analysis (figure 2a) of their zero phonon line at 637 nm. Additional phonon contributions result in the characteristic spectral shape with an overall width of about 120 nm [4]. The observed fluorescence light shows a clear saturation behaviour with a saturation intensity of $I_{\mathrm{sat}} = 3.6 \times 10^9$ Wm^{-2} ($P_{\mathrm{sat}} = 1.3$ mW)(figure2b).

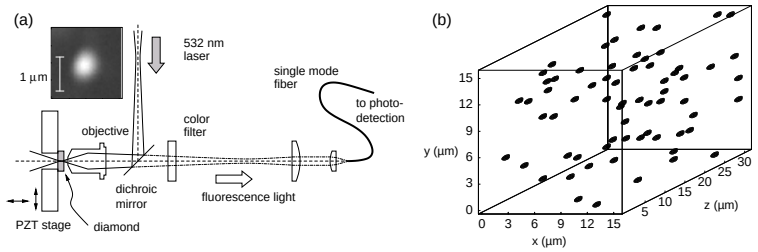

Figure 1 (a) Experimental setup: A frequency doubled DPSS laser (532 nm) is focused into a type Ib diamond crystal. Fluorescence light is collected with a confocal microscope into a single mode optical fiber, and detected with silicon APDs. The inset shows the fluorescence image of a single N–V center. (b) Distribution of N–V centers resulting in a density of 5×10^9 cm^{-3}.

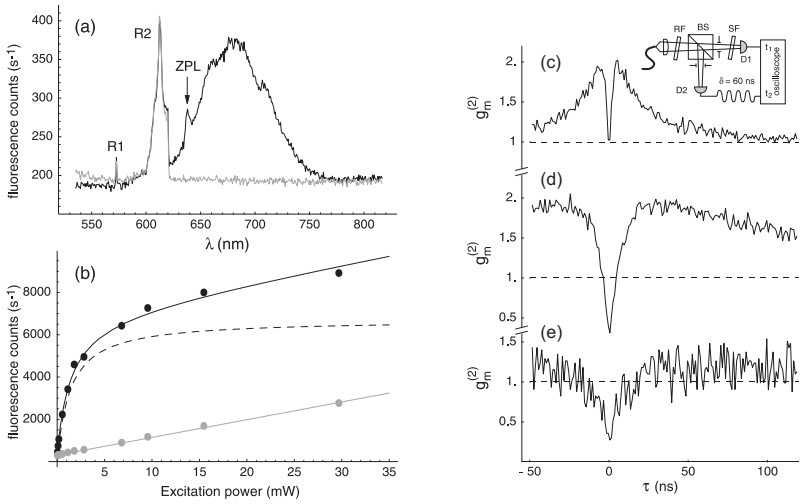

Figure 2 (a) Fluorescence spectrum of a single N–V center (black) and reference spectrum in type Ib diamond (gray). Besides the zero phonon line (ZPL) at $\lambda = 637$ nm and the vibrationally broadened spectrum of the N–V center, we find single- (R1) and two-phonon Raman scattering (R2) from bulk diamond. (b) Fluorescence as a function of the excitation power from a single N–V center (black) and from bulk diamond (grey). (c) Measured pair correlation function $g_m^{(2)}(\tau)$ for excitation powers of 30 $P_{\rm sat}$, (d) 1.6 $P_{\rm sat}$ and (e) 0.16 $P_{\rm sat}$: The fluorescence light is detected by two photodiodes D1, D2 behind a beam splitter BS and two filters RF, SF. A clear signature of photon antibunching is seen in $g_m^{(2)}(\tau)$ around $\tau = 0$.

We analyzed the photon statistics of the fluorescence light of our single photon source in a Hanbury–Brown–Twiss configuration. Figures 2c-e exemplarily show $g_m^{(2)}(\tau)$ for different excitation powers. Most prominently, the minimum at zero delay clearly proves the single photon character of the emitted fluorescence [5].

3. OTHER DEFECTS

One of the few drawbacks using N–V centers as single photon sources is the broad spectral emission. To increase the spectral yield in narrow wavelength bands, microcavities have been considered [6].

Alternatively, the narrow emission spectrum of other luminescence centers could be used. Particularly, we observed defects emitting at 695 nm (figure 3a) and at 800 nm (figure 3b). These systems exhibit saturation behaviour but seem to suffer from photo bleaching after a few hours. Up to now, we could not observe antibunching from these centers.

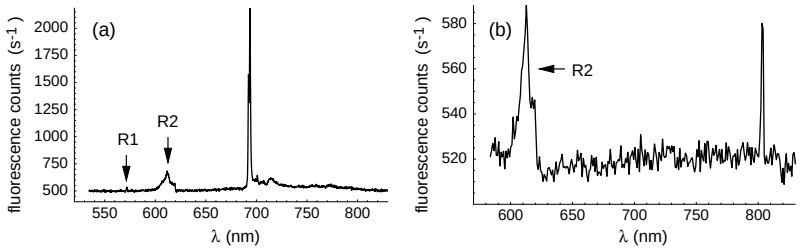

Figure 3 (a) Spectra of other color centers emitting light at 695 nm and (b) 800 nm with Raman background (R1, R2).

4. SUMMARY

We have shown that fluorescence of N–V centers in synthetic Ib diamond shows photon antibunching. The emission spectrum lies in the conveniently detectable red to near infrared region, decay times are short, and the radiative quantum efficiency is close to one. The robustness against photo bleaching and the simplicity of the all-solid state setup distinguishes N–V centers from other fluorescing quantum systems. The potential for miniaturizing the setup and the superior stability makes N–V centers very attractive as practical single photon sources for quantum communication.

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