NV-Centers in Nanodiamonds as Single-Photon Source

L. Liebermeister, LMU München, Faculty of Physics, München, Germany (February 2014)

Application Note

Introduction

A single-photon source is a quantum system which emits photons, but with vanishing probability to emit two or more photons at the same time. Single photons are useful in quantum key distribution but also in fundamental quantum research. Such a quantum system, capable of emitting single photons can be realized with a single trapped atom, a quantum dot, a single dye molecule or a single defect center in a crystal. We are using the nitrogen-vacancy center, a common color center in a diamond. This system acts as an artificial molecule with an optical transition within the diamond band gap. Due to its embedding in the diamond crystal lattice, such color centers are very stable and easy to handle.

To make use of the single photons in experiments it is necessary to efficiently collect the emitted photons into a single optical mode. As already shown, good collection can be achieved using microscope objectives combined with a solid immersion lens. As we focus on efficiency as well as on robustness, reliability and ability to miniaturize, we investigate other techniques. Our photon-collection is based on the evanescent coupling of the single quantum emitter to the guided mode of an optical nanofiber which is then translated adiabatically to a standard optical fiber.

In our experiment, a diamond nanocrystal hosting a single nitrogen vacancy (NV) center is optically selected with our confocal scanning microscope and positioned deterministically onto the sub wavelength-diameter waist of a tapered optical fiber (TOF) with the help of an atomic force microscope.

The hybrid microscope

For the analysis and assembly of the single-photon source we use a home-built confocal microscope combined with an commercial AFM. The AFM is used to perform nano manipulation of individual diamond nanocrystals which can be monitored with the confocal microscope. Additionally the confocal microscope is used to optically characterize the NV-center before and after the assembly.

Using polarizers, wave plates and two liquid crystal retarders, the green excitation laser light (532nm) can be intensity-controlled and the angle of its linear polarization can be rotated. A dichroic mirror reflects the excitation light onto a voice-coil mirror which can be tilted computer-controlled. Two lenses image the voice-coil mirror onto the entrance aperture of a microscope objective. This objective lens focuses the excitation onto the nanodiamond sample but also collects its fluorescent emission. The collected fluorescence is guided in reverse through the setup. The light is transmitted by the dichroic mirror and coupled into an optical fiber. This fiber can be either plugged into two single photon detectors in HBT (Hanbury Brown and Twiss)-configuration or into our home-built spectrometer.

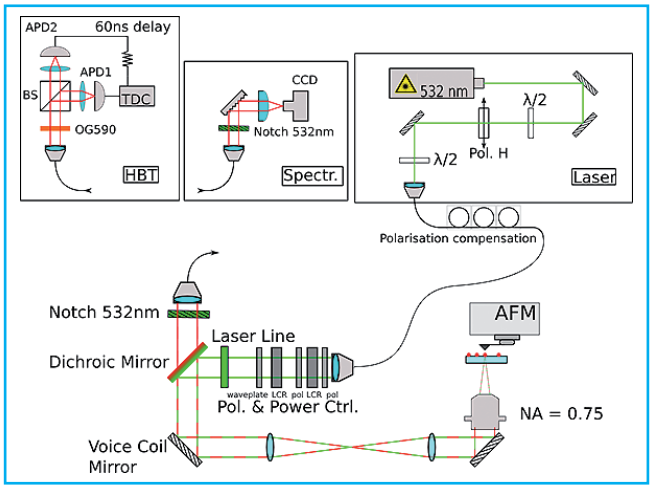

Figure 1: The setup: the confocal microscope with the AFM (lower part), the excitation laser (upper right), the single photon detectors in HBT-interferometer arrangement (upper left) and the home-built spectrometer (upper middle).

Characterization of single NV-centers

The nanodiamonds, shipped as polishing grain in water suspension, are spin-coated on a glass substrate. This substrate is then placed in our confocal microscope. The NV-centers can be excited with a green laser through the objective. The fluorescence emission of the NV-center is then collected by the same objective and guided to our analysis setups, a HBT interferometer with two single photon detectors and a spectrometer.

The focal spot of the confocal microscope can be moved over the glass substrate using a voice coil mirror. Recording the combined count-rate of the two detectors in the HBT setup at the same time enables us to plot fluorescence maps of the sample, indicating the position of the fluorescing emitters. The spectrometer is then used to spectrally analyze the fluorescence

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emission of selected emitters to identify the NV-centers on the sample. With the HBT-setup we can record the autocorrelation function of the emission, obtaining information about the photon statistics and the number of single emitters contributing to the signal. Additionally, we can rotate the excitation polarization while recording the combined count-rate at both detectors. From this measurement we can extract the projection of the dipole-plane of the NV-center onto our image plane.

We assemble our single photon source by picking up an optically preselected nanodiamond with an AFM-tip and place it onto a tapered optical fiber (TOF). If we excite the nanodiamond on the TOF through the confocal microscope we collect free-space fluorescence emission with the microscope, but there is also emission coupled into the guided mode of the TOF. We can connect the ends of the TOF to the spectrometer and compare the spectrum of the emission coupled into the TOF with the emission spectrum collected by the confocal microscope. This gives access to the wavelength-dependence of the coupling.

Properties of the NV-emission and resulting demands to the spectrometer and the CCD

In our experiment, the NV-center is excited off-resonantly by a frequency-doubled Nd:YAG laser at 532nm. In a few picoseconds the NV-center relaxes to its excited state while emitting phonons. The intrinsic lifetime of the excited state is of the order of 20ns. There is a direct optical transition to the ground state but also an additional non-radiative decay channel including a long-lived metastable state which limits the quantum efficiency of the system. We collect photons from the optical transition with our confocal microscope. Including the emission rate and the collection efficiency of the confocal microscope of few percent the resulting count rate at our detectors is in the order of a few thousand counts per second.

NV-centers are known to couple strongly to phonons which results in a broad emission spectrum (about 100nm at room temperature). To reduce the measurement time we want the whole spectrum to be recorded at once. The broad spectrum also reduces the signal per pixel as the signal is distributed over many pixels.

To get a good signal to noise ratio with our spectrometer at such low intensities the CCD has to have a high quantum efficiency to let as many photons contribute to the signal as possible but also a low background to allow us to benefit from longer integration times.

Realization of the spectrometer

We use a simple, home-built spectrometer which consists of a fiber collimator, a diffraction grating and a lens to image the spectrum onto the CCD (Andor iDus DU401A-BVF). We chose this CCD due to its high cooling performance resulting in a low background but features high quantum efficiencies in the visible red.

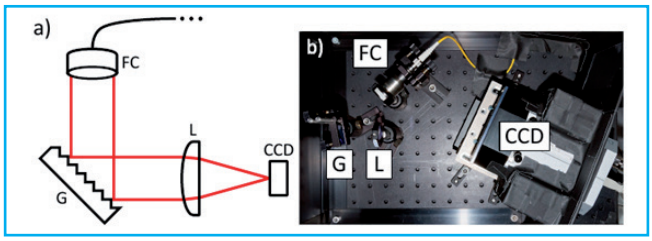

Figure 2: a) Schematic and b) a photography of the spectrometer with a fiber coupler (FC), a diffraction grating (G), a lens (L) and the detector Andor iDus DU401A-BVF (CCD)

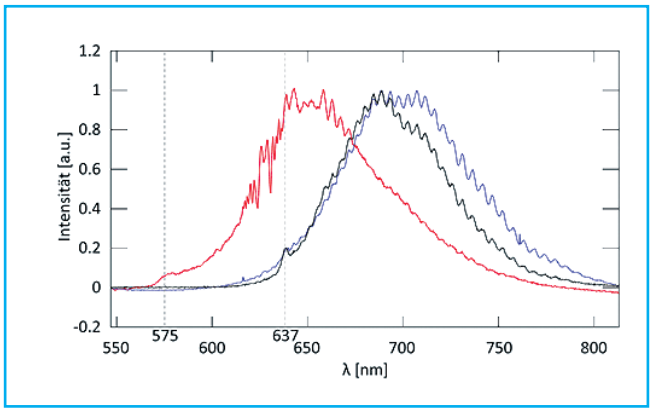

Figure 3: Three different spectra taken with our home-built spectrometer showing in red and blue the fluorescence of two different nanodiamonds hosting a low number of NV-centers, and in black the fluorescence of NV-centers in a diamond bulk sample. The waviness on all three spectra is probably due to some interference in the fiber or the spectrometer.

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Conclusion
With the Andor iDus DU401A-BVF we are able to identify and characterize NV-centers in our confocal microscope within a few minutes even for single emitters.

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