Todo list

Extra long title which spans serveral lines and therefore has to be split manually and the vertical spacing has to be adjusted

My Name

My university

(Diploma/doctoral...) Thesis

Supervisor:

Prof. Dr. Supervisor

Supervisor's Department, University of ...

March 2013

Abstract

A novel method... It is based on...

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Acknowledgements

First of all, I want to thank my supervisor...

I am very grateful for the guiding help of...

I am grateful to...

Chapter 1

Introduction

"Every competent physicist can 'do' quantum mechanics, but the stories we tell ourselves about what we are doing are as various as the tales of Sheherazade, and almost as implausible." - David J. Griffiths

Quantum optics is the sciences of light which deals with single light particles, namely photons. Within the last few years the topic of quantum technologies has witnessed a large progress in fields like quantum cryptography, quantum computation and quantum metrology. Requirements for these technologies are ideally single photons which are produced "on demand" i.e. deterministically and have well defined properties. For instance, quantum computing places restraints on the photon sources, called the diVincenzo criteria (). The progress of these technologies calls for measurement standards to make the individual measurements comparable???

enter di-Vincenzo criteria

The candela is the SI (système internationale) unit for optical radiation [?] and is the only unit which is linked to physiological processes, namely the varying sensitivity of the human eye to radiation of different frequencies. It is a photometric quantity, meaning that a physical measurement of the light in terms of luminous intensity represents the visual sensation experienced by a human observer exposed to the same source of light. It is one of the base units since the system was first introduced. In the latest definition, the candela is linked to the unit watt. The current definition of the candela (cd) is the following: "The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} hertz and that has a radiant intensity in that direction of $1/683$ watt per steradian."[?] Advances in the quantum technologies which operate in the photon-counting regime would profit from a redefinition of the candela in terms of photon number, named "quantum candela".

The term "quantum candela" is used to describe a reformulation of the candela by defining it via a countable number of photons. This new definition would be of a form that converts the current definition into

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

where

$$
\begin{aligned}
P &= \text{power} = 1/683\,\mathrm{W} \text{ exactly} \\
n &= \text{number of photons per second} \\
h &= \text{Planck's constant} = 6.626\,069\,3(110000000) \times 10^{-34}\,\mathrm{J\,s} \\
\nu &= \text{photon frequency} = 540 \times 10^{12}\,\mathrm{Hz} \text{ exactly}
\end{aligned}
$$

which yields [?]

$$n = 4.091\,942\,9(70000000) \times 10^{15}\,\mathrm{s}^{-1}$$

The number of photons of all wavelengths emitted or contained in a given beam of light is given by [?]:

$$N_P = \int \frac{E_\nu}{h\nu}\,\mathrm{d}\nu = \int \frac{\lambda E_\lambda}{hc}\,\mathrm{d}\lambda \tag{1.2}$$

From this equation, the minimal number of photons to illuminate a scene can be calculated. However, in nature most light sources emit continuous light, therefore not the absolute number of photons, but the number of photons emitted per unit time, i.e. the photon flux Φ_P is of interest:

$$\Phi_P = \frac{\mathrm{d}N_P}{\mathrm{d}t} \tag{1.3}$$

For high-accuracy absolute radiometry at the quantum level, predictable or quasi-single-photon sources and photon detectors are needed. 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). Colour centres in synthetic diamond represent an interesting single-photon source with strong anti-bunching and a spectral width about 1nm at room temperature [?]. Being a solid state system, they are easy to handle and neither cooling nor vacuum is required. Diamond has the advantage, that it is a homogeneous host material, therefore the color center can be treated as a single atom. Additionally, it has a large band gap of 5.5 eV [?] Why nanodiamond? higher extraction efficiency of fluorescence light easy positioning using pick-and-place technique easy to obtain isolated color centers Why silicon-vacancy center? bright single photon source (count rates up to Mcps) narrow linewidth of zero-phonon line (down to 0.7 nm at room temperature) For the application of silicon vacancy color centers as absolute single-photon sources a fully characterized state of the emitted light is imperative.

Chapter 2

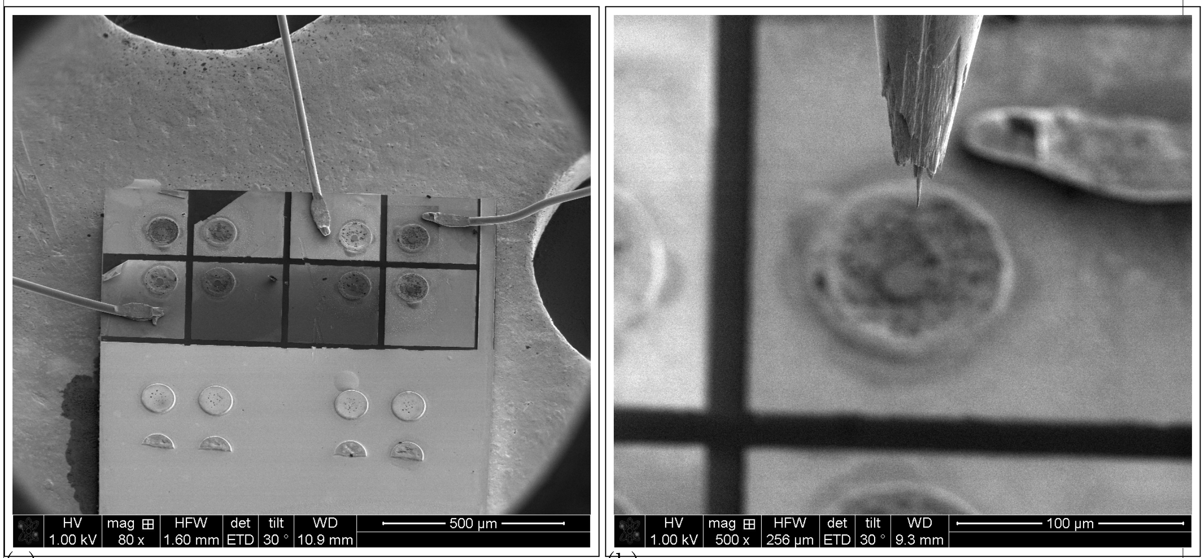
Coupling Nanodiamonds to Photonic Structures

Abstract: Kopplung von SiVs an optische Strukturen: Antennen + Vcsel Motivation zusaetzliche experimentelle Details - Marker schreiben - erster Versuch zur Identifikation von NDs mit guten SiVs mittels Weisslichtlaserscan - NDs mit AFM transferieren -Nanomanipulator Probleme mit Spitze - Abloesen von Diamanten (BASD + CVD) von Substrat im Ultraschallbad kann dazu fuehren, dass Substrat mitabgeloest wird) -> in Kalilauge aufloesen LII, S96 - warum nicht einfach neue CVD-Diamanten herstellen, wie die, die am Anfang meiner Diss so gut funktioniert haben -> Dichte am Substrat zu hoch zum Aufpicken - warum nicht die implantierten HPHT Diamanten hernehmen (Groessen 20, 40, 80nm) -> nur die 40nm grossen Diamanten zeigen irgendein Signal , sind aber zu klein zum Aufpicken

Photo of Nanomanipulator

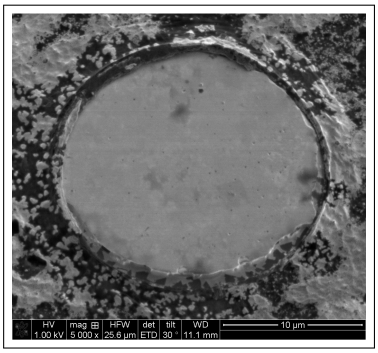
2.1 Coupling Nanodiamonds to Vertical-Cavity Surface Emitting Lasers

For metrology, the photon flux rate has to be high enough to be measured by a low optical flux detector [**?**].



(a) (b)

Figure 2.1: <caption>



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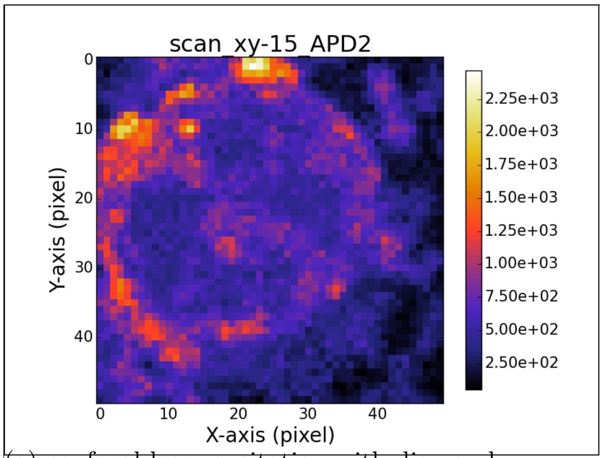
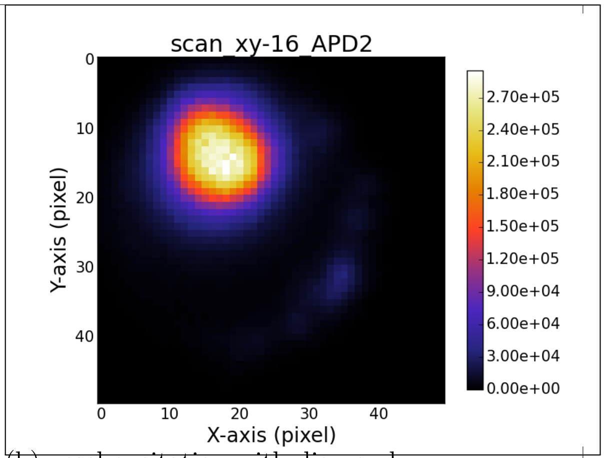
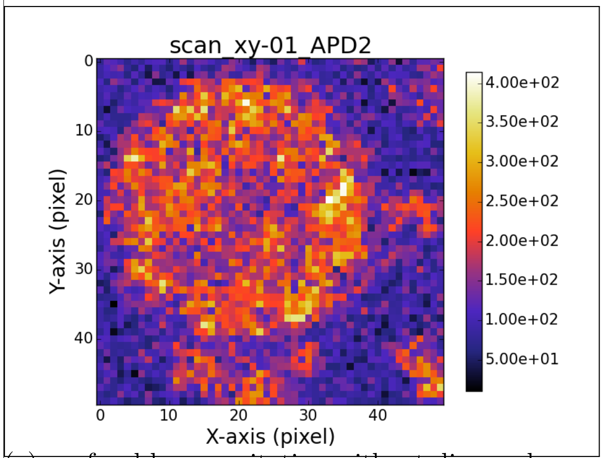


(a) confocal laser excitation with diamond

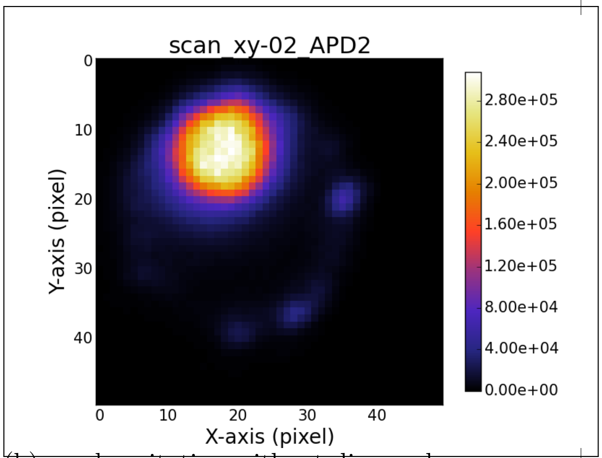


(b) vcsel excitation with diamond

Figure 2.3



(a) confocal laser excitation without diamond



(b) vcsel excitation without diamond

Figure 2.4: <caption>

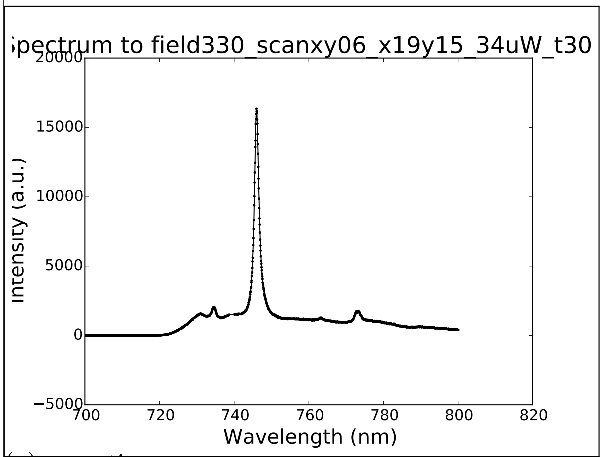
2.1.1 Pick-And-Place Process to Vertical-Cavity Surface Emitting Laser

2.1.2 Spectroscopic Measurements of Nanodiamond in Vertical-Cavity Surface Emitting Laser

2.2 Coupling Nanodiamonds to Double Bowtie Antenna Structures

2.2.1 Nanodiamond With Multiple SiV centers Coupled to Antenna

2.2.2 Nanodiamond With Single SiV center Coupled to Antenna



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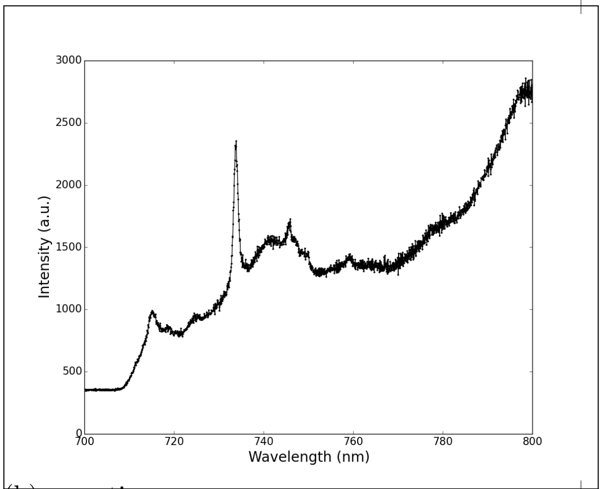

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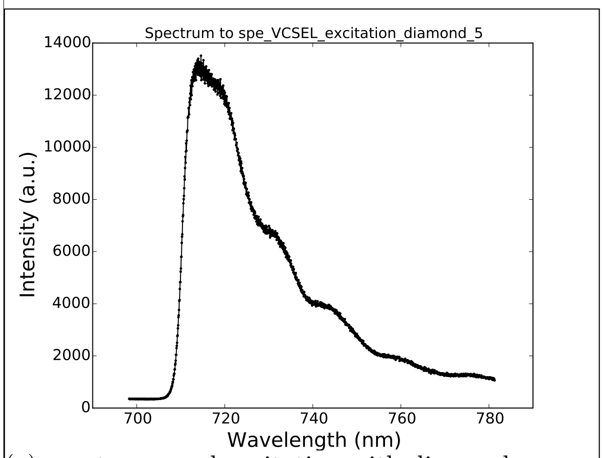
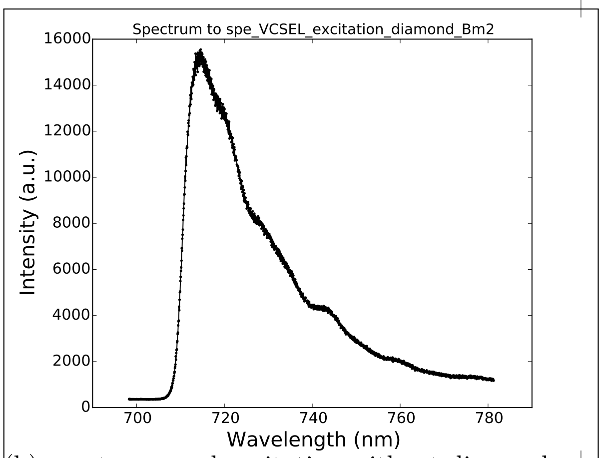
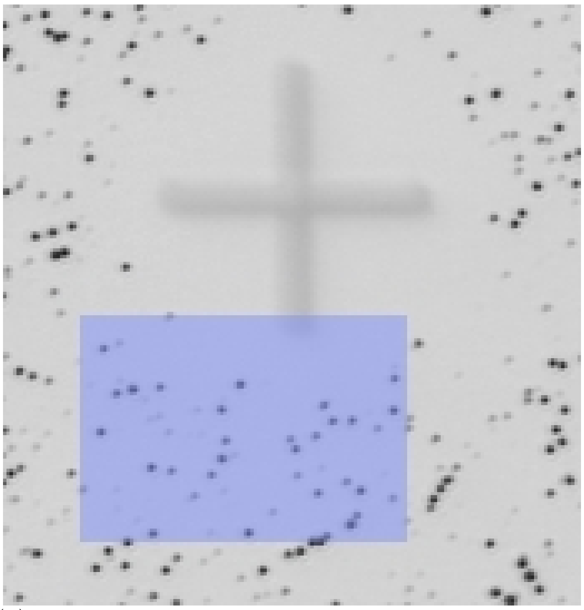


(a) spectrum vcsel excitation with diamond

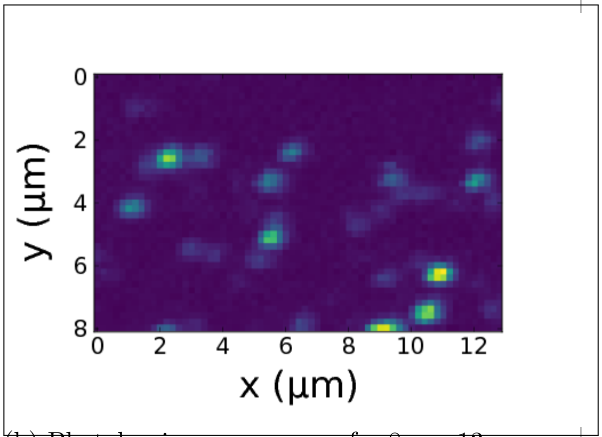


(b) spectrum vcsel excitation without diamond

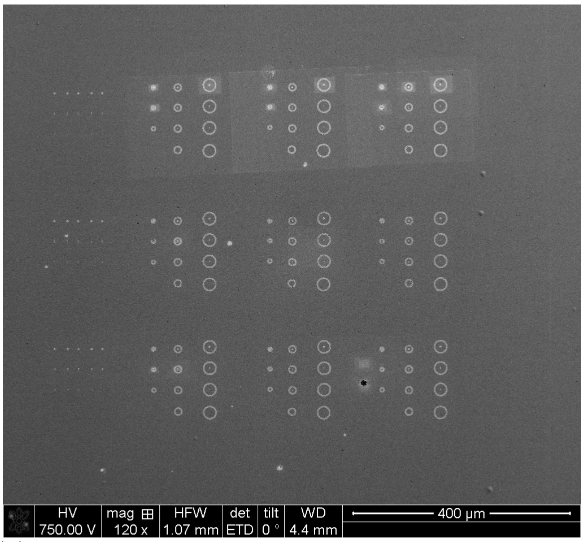
Figure 2.6: <caption>



(a) Picture recorded with a commercial high resolution laser scanning microscope. The area shaded in blue represents the photoluminescence scan in image b)



(b) Photoluminescence scan of a 8 µmx13 µm



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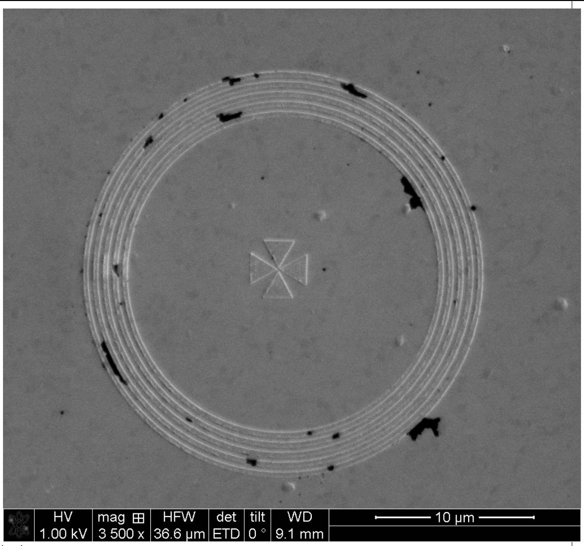

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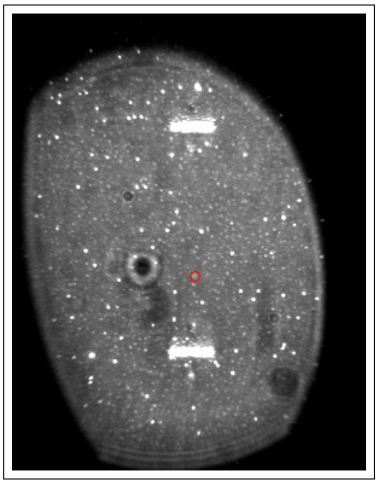
Figure 2.8: <caption>



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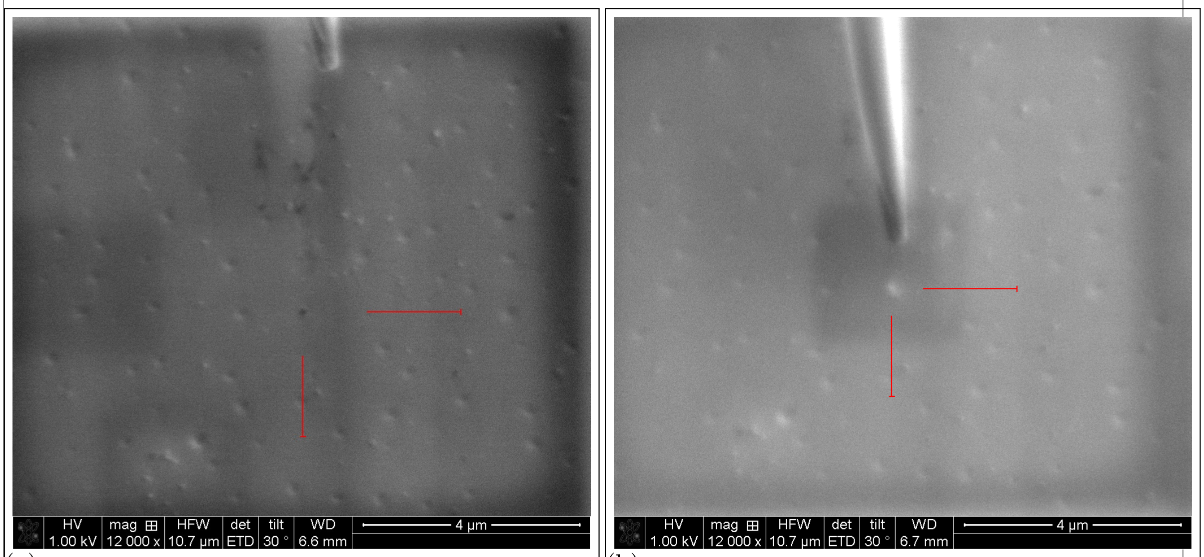
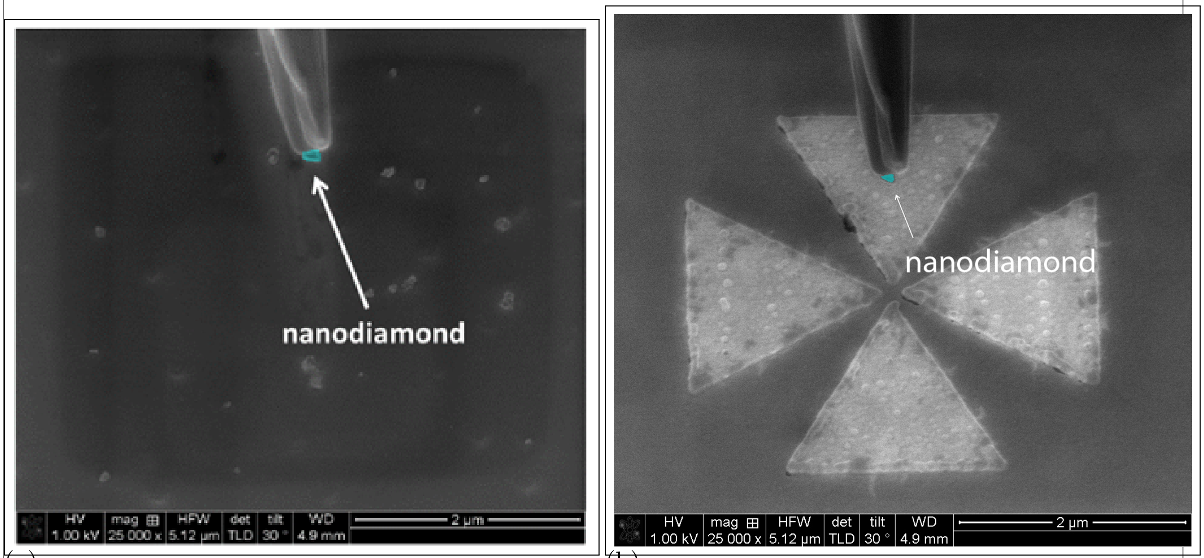


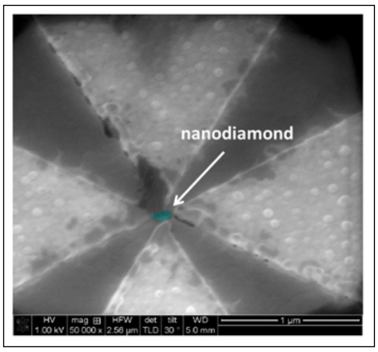
(a) (b)

Figure 2.10: caption



(a) (b)

Figure 2.11



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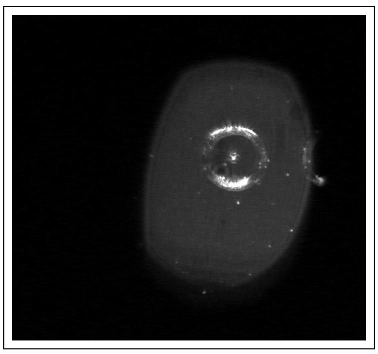

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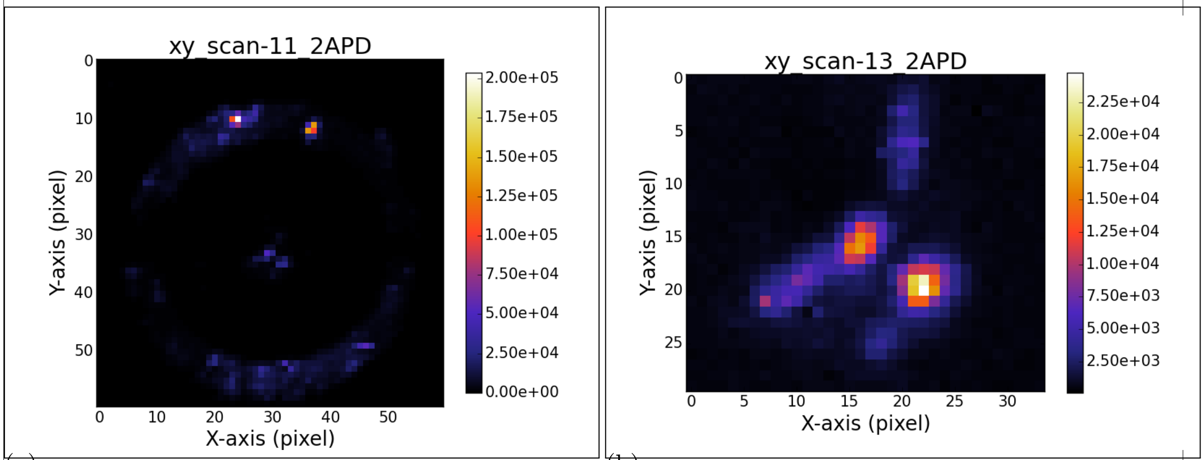

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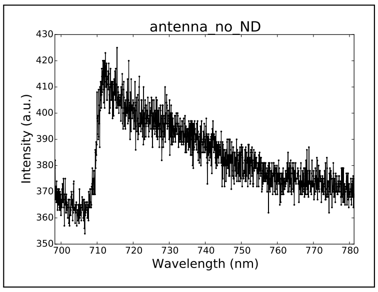

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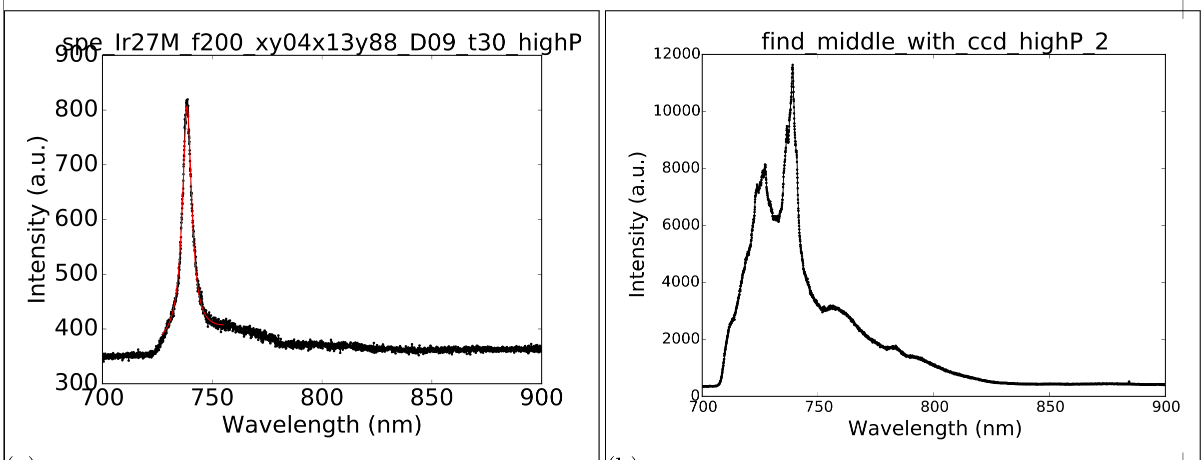

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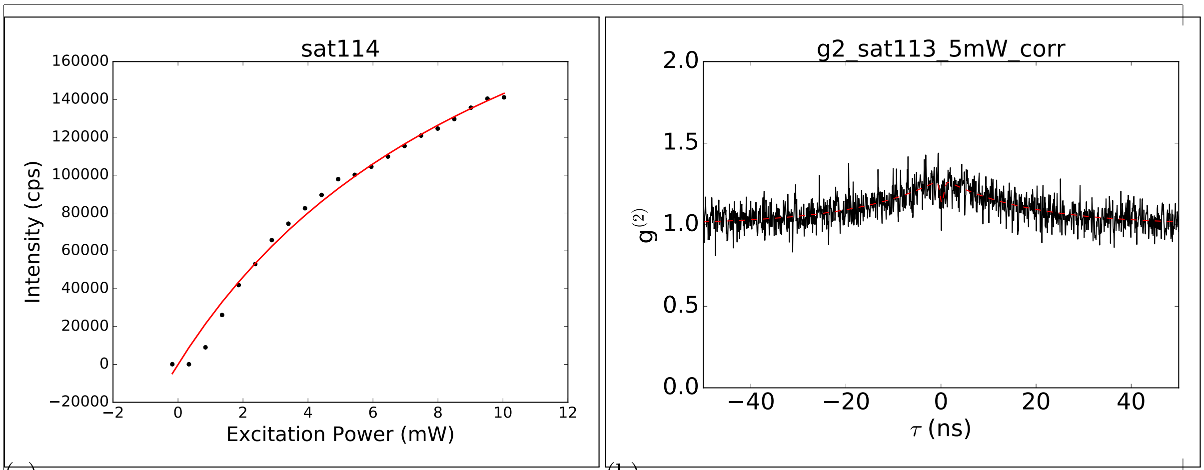

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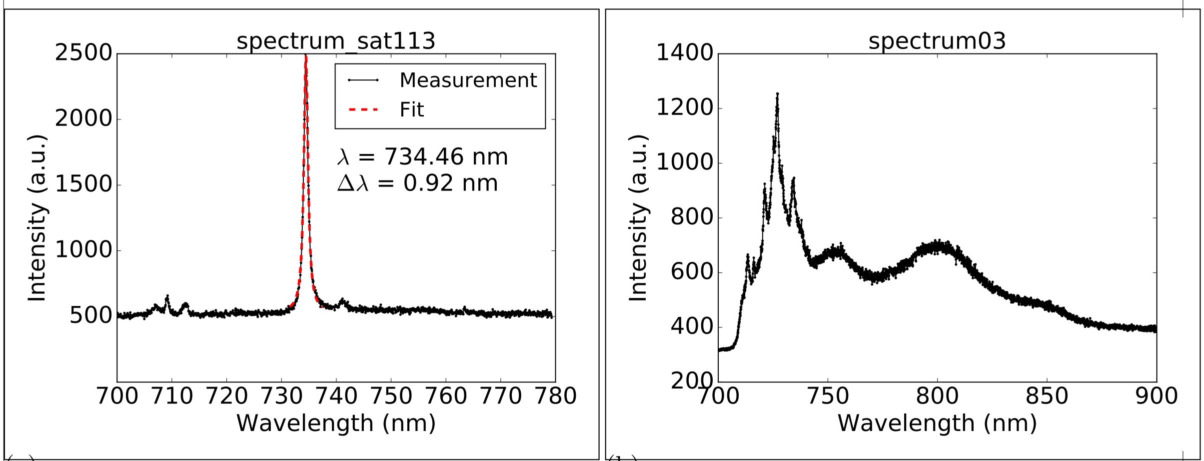

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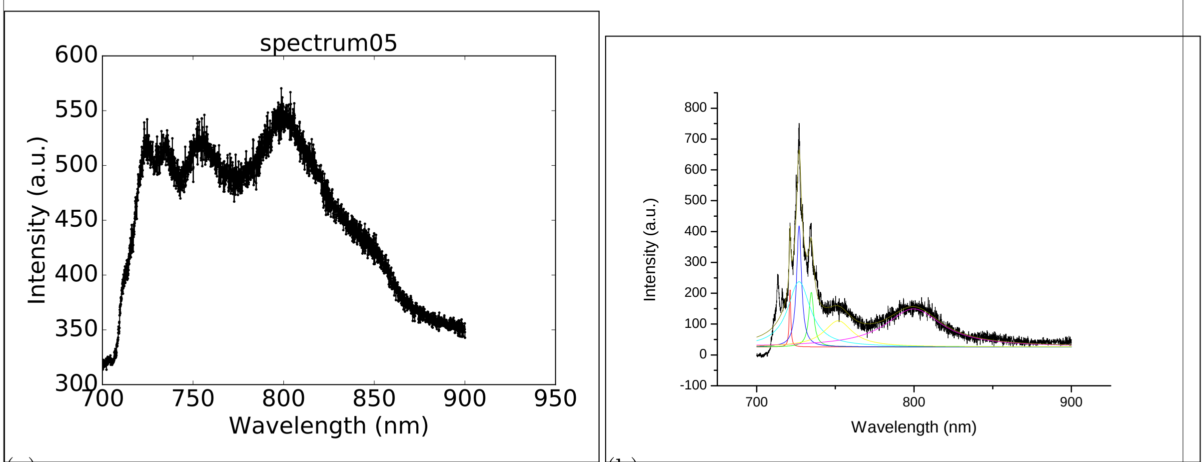

(a) (b)

Figure 2.19: <caption>

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