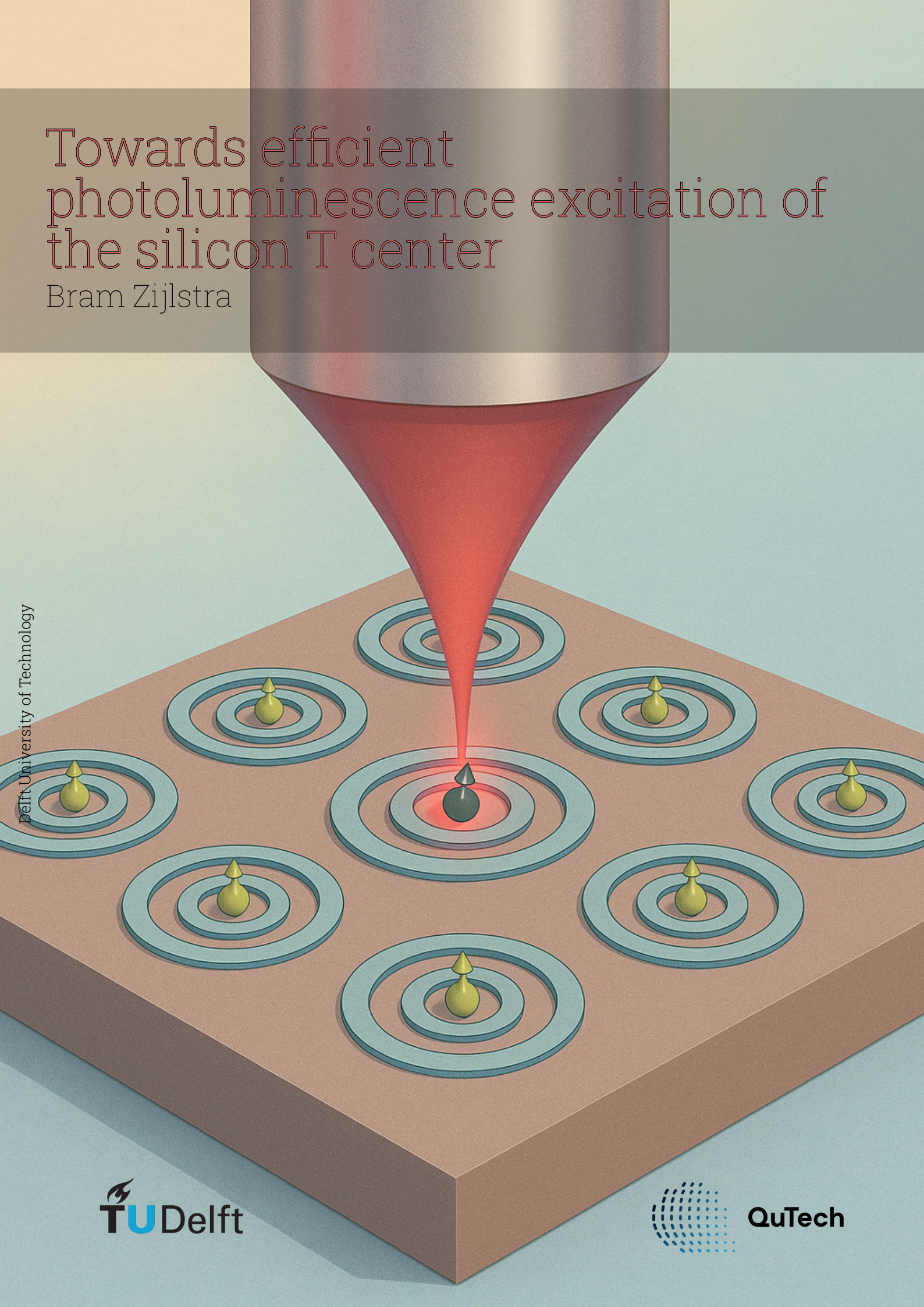


Towards efficient photoluminescence excitation of the silicon T center

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by

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Abstract

A quantum internet would enable capabilities that are provably impossible using only classical information. These applications include, but are not limited to, secure communication, quantum clock synchronization, and quantum sensor networks [2]. In a future quantum internet, there is a need for an interface between spin-encoded qubits in network nodes and the photonic communication between them. The silicon T center is a promising candidate for use in such a spin-photon interface [3] as it emits in the telecom O-band, has relatively long spin coherence in bulk ^{28}Si samples (2.1ms) [4], and is compatible with the silicon-on-insulator (SOI) platform for easy manufacturing and scalability. However, its relatively weak and slow emission makes characterization measurements time-consuming.

This thesis investigates how the T center count rate can be increased in confocal resonant excitation measurements. Two photonic structures are characterized: micropucks and bullseye cavities. Bullseyes are found to enhance zero-phonon line emission and are better suited for time-resolved measurements. Count rate estimates show that combining bullseye cavities with time-resolved interval photoluminescence excitation (TRIPLE) measurements can increase the signal-to-noise ratio by a factor of 2.4 compared to the conventional approach. The TRIPLE setup is built, and a fluorescence lifetime of 620ns is measured in a bullseye structure using off-resonant excitation. Single T center resonant excitation has not yet been achieved, but the setup provides a strong foundation for future measurements.

Acknowledgments

This thesis is the result of over seven months of hard work, learning, and collaboration, and I am grateful to everyone who supported me along the way.

First and foremost, I want to thank **Christian** for sharing so much of your knowledge with me. It always amazed me how you not only knew the answers to my many questions, but also explained them clearly and thoughtfully. Throughout the project, we worked together on everything from laying fibers in the basement to taking measurements on the bullseyes. For me, one of the highlights was our close collaboration, which made the work always enjoyable and rewarding.

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I am also grateful to **Matteo** for the insightful discussions about the T center transition dipole orientation, **Elena** for teaching me the art of fiber splicing, and **Jan** for your help throughout the project. To everyone else in the Carlos lab—**Lin, Arjan, Ernest, Francis, Hania, and Sofia**—thank you for your support and the fun times.

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Finally, I would like to thank my family and friends for their support throughout this process.

Bram Zijlstra
Delft, April 2026

Contributions

M. Pirro fabricated the samples used in this study. C. Primavera constructed the initial setup, with photoluminescence (PL) and Phonon sideband (PSB) photoluminescence excitation (PLE) capabilities, and performed simulations of the bullseye structures. B. Zijlstra carried out estimations of linewidth and measurement time, conducted measurements on both bullseye and micropuck structures, and performed count rate estimations for resonant excitation measurements. The analysis of these measurements was conducted jointly by B. Zijlstra and C. Primavera.

C. Primavera, Y. Hermann, and R. M. provided guidance during the development of the TRIPLE measurement setup, which B. Zijlstra built. B. Zijlstra further performed measurements related to pulse shape testing, as well as SNSPD latching and efficiency. C. Primavera conducted the off-resonant pulsed measurements and cross-polarized latching tests.

C. Primavera served as the daily supervisor, while C. Errando Herranz provided supervisory support and advice on the measurements. R. Hanson advised on the measurements. This work was partially funded by the Kavli Nanolab Delft.

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Introduction

1.1. Spin-photon interfaces for use in the quantum internet

A quantum internet would enable capabilities that are provably impossible using only classical information. These applications include, but are not limited to, secure communication, quantum clock synchronization, and quantum sensor networks [2]. Such a quantum internet will consist of network nodes and transmission channels connecting them. In this thesis, the focus will be on the use of photonic transmission channels and nodes with qubits encoded in spin states. The interface between flying qubits in the channels and stationary qubits is known as a spin-photon interface. A spin-photon interface uses a spin-selective interaction between the photon and a spin to generate entanglement between stationary and flying qubits. Example candidates for use as spin-photon interfaces in the quantum internet include color centers in diamond [5], silicon carbide [6], and silicon [3]. These color centers have shown promise as building blocks for quantum networks, as demonstrated by the realization of a multinode quantum network [5] and the demonstration of heralded entanglement on a metropolitan scale [7]. However, it remains uncertain which of these color centers possesses the most suitable properties for use in quantum networks, and many of their properties still require further investigation.

Several properties determine the suitability of color centers as spin-photon interfaces in quantum networks. One important criterion is the indistinguishability of the emitted photons, which is typically quantified by the optical linewidth. Additionally, compatibility with photonic integration is essential for scalability. The presence of additional spins that can function as quantum memories is another key requirement. Finally, the coherent emission fraction plays a central role in determining the performance of the spin-photon interface. The coherent emission fraction is influenced by factors such as emission into the zero-phonon line (ZPL), quantum efficiency, and the branching ratio (or cyclicity) of optical transitions.

1.2. The silicon T center as a spin-photon interface

A promising spin-photon interface is the silicon T center. This color center emits light in the telecom O-band, has relatively long spin coherence in bulk ^{28}Si samples (2.1ms) [4], and is compatible with the silicon-on-insulator (SOI) platform for easy manufacturing and scalability. In recent years, significant progress has been made in advancing the silicon T center as a spin-photon interface. This includes the characterization of its optical transitions [3]. T centers have also been integrated into waveguides and optical cavities to enhance emission [8, 9]. Furthermore, its linewidth has been reduced by a factor of 35 using a resonance-check scheme [10]. Finally, remote entanglement between two T centers has been demonstrated, showing their promise for use in quantum networks [11].

1.3. Challenges of the T center

Challenges still remain for the T center, such as its relatively slow and weak emission at the zero-phonon line compared to other color centers. This weak and slow emission is reflected in its lifetime of 940ns and its Debye–Waller factor of 0.23. As a consequence of this, measurement efficiency is reduced; as measurements at low count rates can take many hours to complete [3]. Furthermore, due to the T center’s sensitivity to electrical and magnetic noise, the optical coherence of integrated T centers is relatively poor compared to that of other color centers, such as the diamond SnV center. In photonic structures, T centers typically exhibit FWHM linewidths of 0.5–2.5 GHz [3], which are significantly larger than the lifetime-limited linewidth of 14 MHz in high-Purcell-enhancing cavities [11]; therefore, techniques to reduce or mitigate spectral diffusion are required for high entanglement rates.

1.4. Objectives

Explorations of color centers for use in quantum networks require efficient measurement of their properties. For silicon T centers, a bottleneck in such measurements is their relatively slow and low emission rate. The objective of this thesis is therefore to accelerate the characterization of silicon T center properties using resonant excitation measurements in the context of quantum network applications. Specifically, this work aims to (i) determine the conditions required for efficient resonant excitation of the T center; (ii) analyze the impact of photonic structures on the count rate in photoluminescence excitation; (iii) identify the most efficient configuration for confocal measurements of T centers; and (iv) design and implement an optimized confocal measurement setup.

Theoretical background

In order to analyze efficient photoluminescence excitation of the T center, background information on the silicon T center, measurement techniques and photonic structures is required.

2.1. The T center

2.1.1. Atomic structure

Figure 2.1 (a) shows the atomic structure of a T center defect in a silicon lattice. The T center consists of two carbon atoms, one hydrogen atom, and an unpaired electron.

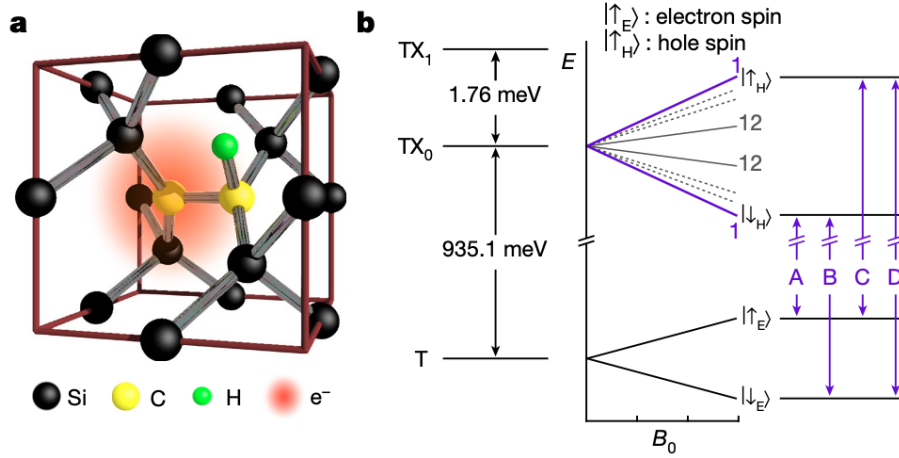


Figure 2.1: (a) The atomic structure of the silicon T center. (b) The energy levels with and without the presence of a magnetic field and the transitions between the T and the TX_0 states. Image reproduced from [3].

Figure 2.1b shows the three lowest energy levels of the T center.

The ground state is known as the T state. The optical excitation of this state is known as TX ; in this state, a bound exciton (electron-hole pair) is created. The two electrons in this state form a spin singlet. The hole in the exciton has total angular momentum $j = 3/2$, which, due to the imperfect symmetry of the defect, splits into two spin doublets known as TX_0 and TX_1 . The atomic structure of the defect has monoclinic (I) C_{1h} symmetry. There are 24 distinct orientations, forming 12 inversion-symmetric pairs.

2.1.2. Spin properties

Spins in the T center

The ground state T has an unpaired electron spin and a hyperfine-coupled nuclear spin from the hydrogen atom. Both spins are relatively long-lived in isotopically purified silicon-28, with coherence times in bulk silicon greater than 2.1 ms and 1.1 s, respectively [4, 12]. Additional nuclear spins are present when one or both carbon atoms in the T center are the carbon-13 isotope.

Spin splitting

In the presence of an external magnetic field, the energy levels of the T and $TX0$ states split according to the Zeeman effect. This splitting is illustrated on the right-hand side of Figure 2.1 (b). The ground state electron Landé g -factor (g_E) is found to be $g_E \approx 2.005$ [13]. The splitting of the excited state $TX0$ is anisotropic and depends on the orientation of both the defect and the magnetic field; this gives rise to effective g -factors ranging from $g_H = 0.85$ to $g_H = 3.50$ [13, 14]. The relationship between the angle of an applied magnetic field and g_H for different orientations is shown in Figure 2.2.

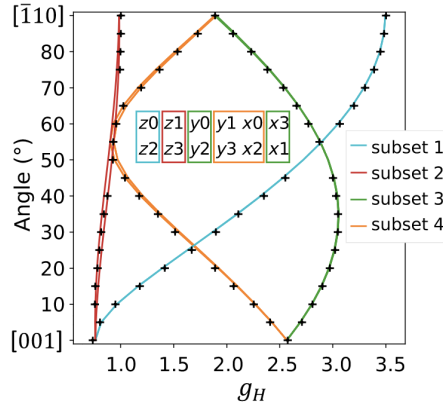


Figure 2.2: g_H factors for different orientation symmetry subsets in case of a varying magnetic field direction. Image reproduced from [14].

Under these conditions, the four spin-selective transitions A, B, C, and D, shown on the right-hand side of Figure 2.1 (b), are detuned from the original transition between the excited and ground states according to:

$$\Delta_{A,B,C,D} = \frac{1}{2} \mu_B |B_0| (\mp g_{E,i} \mp g_{H,i}) . \quad (2.1)$$

Spin relaxation time

An important property for the use of a T center as a spin-photon interface is the spin relaxation time (T_1). The spin relaxation time (T_1) for a color center is defined as the characteristic time required for the spin to reach equilibrium after random spin flips along the spin quantization axis [13]. The spin relaxation time (T_1) sets fundamental limit on the spin coherence time (T_2). The electron spin relaxation time is predominantly set by spin-lattice relaxation such as thermal relaxation and the emission or scattering of phonons in the crystal through the spin-orbit interaction [15]. Spin relaxation times for the T center have been measured to exceed 1s in bulk and to be approximately 1ms in micropuck optical structures [13, 3].

Spin coherence time

Another property of interest is the spin coherence time (T_2). It is characterized by two measures: T_2 , the homogeneous dephasing time (measured by Hahn echo) and T_2^* , the inhomogeneous dephasing time (measured by Ramsey interferometry) [15]. The T_2 time is set by fast noise processes. While the inhomogeneous dephasing (T_2^*) is set by fluctuations in the spin bath from experiment to experiment during averaging. An increase in the spin coherence time can be engineered by reducing the nuclear spin bath density through isotopic purification.

Spin cyclicity

A key property for evaluating the T center as a spin-photon interface is the electron spin cyclicity. Cyclicity is a measure of the average amount of spin-preserving transitions before a spin flip occurs. Based on the transitions as given in Fig. 2.1 (b), the cyclicity can be expressed as:

$$\text{Cyclicity}_{\downarrow} = \frac{\Gamma_A + \Gamma_B}{\Gamma_A}, \text{Cyclicity}_{\uparrow} = \frac{\Gamma_C + \Gamma_D}{\Gamma_D}, \quad (2.2)$$

where $\Gamma_A, \Gamma_B, \Gamma_C$ and Γ_D are the respective transition rates.

2.1.3. Optical properties

This section discusses relevant optical properties of the T center. Table 2.1 presents T center optical properties and compares them to common color centers.

Vacancy	ZPL Wavelength [nm]	Quantum Efficiency [%]	Debye-Waller Factor	Radiative Lifetime [ns]
Diamond SnV	620 [16]	~80 [17]	0.57 [18]	4.5 [16]
Diamond NV	637 [19]	>85 [20]	0.03 [21]	11 [21]
Silicon T Center	1326 [13]	>23.4 [9]	0.23 [13]	940 [13]

Table 2.1: Comparison of T center optical properties to common color center defects. Table adapted from [1]

Decay

Decay from the excited state can happen through different paths. The direct decay from the excited state (TX_0) to the ground state (T) is known as zero-phonon line (ZPL) emission. Emission can also occur with the assistance of phonons, producing lower-energy photons that form the so-called phonon sideband (PSB). Furthermore, the excited state may also relax through non-radiative channels. The rate of decay can thus be written as $\Gamma_0 = \gamma_{ZPL} + \gamma_{PSB} + \gamma_{nr}$ [9], where $\gamma_{ZPL} + \gamma_{PSB}$ represents the radiative emission rate.

$$\Gamma_0 = \gamma_{ZPL} + \gamma_{PSB} + \gamma_{nr} \quad (2.3)$$

Lifetime

In literature, the rate of emission is often expressed in terms of the excited state lifetime, which is defined as the inverse of the emission rate: $\tau = 1/\Gamma$, where τ is the lifetime and Γ is the rate of emission. For the T center, the excited state lifetime in bulk silicon-on-insulator (SOI) samples is 940ns [4]. This value is relatively high compared to other common defects (see Table 2.1). The lifetime of the T center has been reduced in photonic structures, for example, in micropucks it is found to be 802ns [3]. In photonic crystal cavities, the lifetime is further reduced to 136.4 ± 0.6 ns [9], and in some cases, to as low as 64.4ns [11]

ZPL transition wavelength

For the T center, the ZPL transition occurs at 935.1 meV, corresponding to approximately 1326nm which is in the telecommunications O-band [13]. This wavelength is useful in quantum networks, as it enables low-loss optical fiber transmission and integration with existing fiber infrastructure. The PSB emission occurs primarily at wavelengths between 1350 and 1600 nm [13].

Debye-Waller factor

The relative strength of ZPL to PSB emission is a characteristic property of color centers, given by the Debye-Waller factor (β_0). We define the Debye-Waller factor as [9]:

$$\beta_0 = \gamma_{ZPL}/(\gamma_{ZPL} + \gamma_{PSB}). \quad (2.4)$$

The DWF of the T center is 0.23, relatively low compared to the diamond SnV center, yet higher than that of the diamond NV center.

Quantum Efficiency

The quantum efficiency (η_{QE}) is defined as the fraction of radiative decay relative to the total decay rate: $\eta_{QE} = \frac{\gamma_{ZPL} + \gamma_{PSB}}{\Gamma_0}$ [9] In the T center it has a lower bound of $\eta_{QE} \geq 23.4\%$ [9].

Optical coherence

For a single emitter, the optical coherence is described by its full width at half maximum (FWHM) linewidth. The measured linewidth is referred to as the homogeneous linewidth of the emitter. The homogeneous linewidth can be compared with the “lifetime-limited” linewidth, defined as $\gamma_0 = \frac{1}{2\pi\tau}$ [15]. The increase in linewidth beyond the lifetime-limited value is referred to as homogeneous broadening. This broadening is dictated by phonon interactions, power broadening, fluctuations in local electric and magnetic fields, and temperature effects.

Spectral diffusion

Spectral diffusion refers to time-dependent fluctuations in the transition wavelength of a single emitter. A way to distinguish spectral diffusion is by the speed of the noise compared to the optical lifetime. Fast environmental noise leads to homogeneous broadening of the measured linewidth, while slow environmental noise, such as thermal drift, magnetic field fluctuations, and electrical noise, can cause shifts in the emission wavelength visible during measurements, referred to as spectral wandering. The use of purified silicon can reduce both spectral diffusion and the homogeneous linewidth of a color center by minimizing electric and magnetic field noise [22]. As mentioned in the introduction, the T center exhibits a relatively broad linewidth compared to other defects. In photonic structures, T centers typically exhibit FWHM linewidths of 0.5–2.5 GHz [3], which are significantly larger than the lifetime-limited linewidth of 14 MHz in high-Purcell-enhancing cavities [11]. Inversion-symmetric color centers, such as the SnV, do not suffer from this sensitivity and typically achieve linewidths much closer to the lifetime limit. For example, a linewidth of 32.0 ± 0.1 MHz is observed, compared to the lifetime-limited linewidth of 26.6 ± 0.3 MHz [23].

Inhomogeneous broadening

In samples containing multiple T centers, the linewidth may be broadened due to inhomogeneous broadening. Inhomogeneous broadening arises from variations between emitters in an ensemble and is caused by differences in local strain and electromagnetic fields. To distinguish single emitters from an inhomogeneous ensemble, the homogeneous linewidth for single emitters should be reduced sufficiently to prevent overlapping linewidths. For the T center this is done by cooling the defects to around 4K [4, 3, 9].

2.2. Measurement techniques

2.2.1. Off-resonant excitation measurements

In off-resonant excitation or photoluminescence (PL) measurements T centers are illuminated with an above bandgap light source, for example with a 515nm laser. This off-resonant light creates free carriers that bind to the defects and recombine emitting a photon. PL measurements allow for the rapid detection of T centers, however it can be hard to isolate single T centers due to the unselective nature of off-resonant excitation. Furthermore, PL measurements do not allow for spin-selective excitation or transitions, making this technique unsuitable for some property measurements.

2.2.2. Resonant excitation measurements

Resonant excitation measurements involve selectively exciting a specific transition in a color center. Such measurements are also known as photoluminescence excitation (PLE) measurements. In such measurements, the laser is tuned to match the resonant transition wavelength. As the laser has the same wavelength as the emitted fluorescence, the latter is often overwhelmed by residual laser light. To distinguish fluorescent photons from laser photons, a filtering method based on a separation of these based on a degree of freedom is required. In this thesis, we shall consider filtering based on wavelength and based on time.

PSB-resolved measurements

The first degree of freedom used for filtering is the wavelength of the emitted fluorescence. The ZPL emission has the same wavelength as the excitation laser, so it cannot be spectrally filtered. Instead, filtering is performed on the PSB photons, which have larger wavelengths. In this measurement technique, the T center is continuously excited using an infrared laser tuned near the ZPL wavelength. The collected light, consisting of both fluorescence and reflected laser light, is then filtered within the

PSB spectral range (1350–1600 nm), so that only fluorescence is detected. An advantage of this approach is that spectral filtering enables continuous excitation and collection. A limitation of this approach is that PSB emission does not significantly increase when the emitter is placed in a ZPL-resonant cavity. As a result, it can be difficult to obtain a strong signal from the T center. Another limitation is that PSB emission is not suitable for entanglement generation, rendering the collected photons unsuitable for use in a spin–photon interface.

Time-resolved measurements

Filtering can also be performed using the temporal degree of freedom of light, as fluorescent light is emitted after excitation. This approach is referred to as time-resolved interval photoluminescence excitation (TRIPLE).

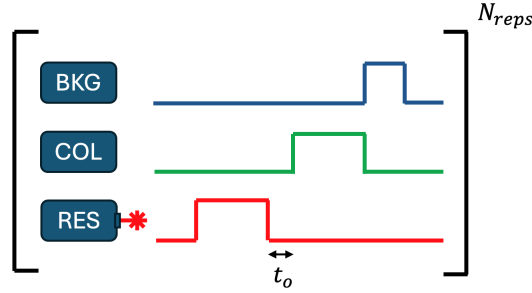


Figure 2.3: Pulse sequence of the time-resolved interval photoluminescence excitation measurement

In Figure 2.3, the measurement scheme for a TRIPLE measurement is shown. In this scheme, the laser is pulsed, and only photons detected after each pulse are registered as signal. The duration of the laser pulse is defined as the excitation window. The time window following the laser pulse during which photons are counted as T center emission is the collection window. After the collection window, an optional background window can be defined to measure background counts, which are then subtracted from the signal.

Between the excitation window and the collection window, there is typically a dead time (t_0), during which residual laser leakage is present. This dead time is influenced by the fall time of the laser pulse and the recovery time of the SNSPD following a detection event. A gating mechanism can be placed before the SNSPD to mitigate the SNSPD recovery time. The excitation window, deadtime, collection window, and background window together form a pulse sequence.

This pulse sequence is repeated many times to form a pulse train, enabling the accumulation of statistics on T center emission. This procedure is then repeated for different laser wavelengths to determine the excitation efficiency as a function of wavelength. The inverse of the pulse sequence duration defines the pulse repetition rate, which influences the measured count rate. For this measurement, a high extinction ratio between the laser on/off states is required to prevent leakage during the collection window. Furthermore, fast laser rise and fall times are required to accurately define the excitation, collection, and background windows. An advantage of this type of measurement is that it enables direct detection of ZPL photons, which can be enhanced by photonic structures. A disadvantage of this approach is that pulsed excitation does not allow continuous measurement, thereby introducing measurement overhead.

2.2.3. Spin Relaxation time measurement

An important property of the T center is the spin relaxation time (T_1). In this section, we describe a measurement technique for determining the spin relaxation time. This technique is based on a PSB-resolved photoluminescence excitation (PLE) measurement. This measurement technique is reproduced from [3].

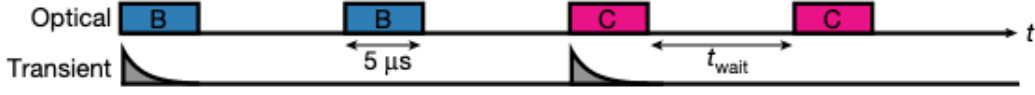


Figure 2.4: The pulse sequence for a spin relaxation time measurement. Image reproduced from [3]

A spin relaxation measurement can be performed using the pulse sequence shown in Figure 2.4. In this sequence, excitation pulses prepare the spin in either the up state (B pulse) or the down state (C pulse). For $t_{\text{wait}} \ll T_1$, pulses 1 and 3 pump the spin into the opposite spin state and produce a luminescence transient. This luminescence is due to optical decay from either the A or B transitions for a B-pulse initialization, or from the C or D transitions for a C-pulse initialization. This transient is proportional to the area difference between consecutive B or C pulses. As t_{wait} approaches and exceeds T_1 , the spin relaxes between pulses, and the transient signal vanishes. By plotting the transient as a function of t_{wait} and fitting the decay, the relaxation time T_1 can be extracted.

2.3. Photonic structures for use in confocal measurements

The use of photonic structures in combination with color centers serves two main functions: enhancing the emission of a color center in a specific spectral region via the Purcell effect, and funneling the emitted light into a mode that can be efficiently collected.

Purcell enhancement

First, we discuss the Purcell effect and its impact on emission from a color center in a photonic structure. For this, we assume the color center to be a dipole emitter and the cavity to be resonant with the emitter's ZPL. In this case, the total decay rate becomes:

$$\Gamma_{\text{cav}} = (F_P^{\text{ZPL}} + 1)\gamma_{\text{ZPL}} + \gamma_{\text{PSB}} + \gamma_{\text{nr}}, \quad (2.5)$$

with F_P^{ZPL} the ZPL Purcell factor [9]. This shows that the ZPL emission fraction is enhanced, thereby increasing the total radiative emission. The ZPL Purcell factor can be expressed in terms of the lifetime reduction and the Debye–Waller factor:

$$F_P^{\text{ZPL}} = \frac{1}{\beta_0 \eta_{\text{QE}}} \left(\frac{\tau_0}{\tau_{\text{cav}}} - 1 \right), \quad (2.6)$$

where β_0 is the Debye–Waller factor, η_{QE} the quantum efficiency, τ_{cav} the lifetime in the cavity and τ_0 the lifetime in bulk[1].

An alternative definition is the lifetime Purcell factor, given by:

$$F_P^\tau = \frac{\Gamma_{\text{cav}}}{\Gamma_0} = \frac{\tau_0}{\tau_{\text{cav}}} - 1. \quad (2.7)$$

The relationship between the two Purcell factors is given by [9]:

$$F_P^{\text{ZPL}} = \frac{F_P^\tau}{\beta_0 \eta_{\text{QE}}}. \quad (2.8)$$

Collection efficiency

Having discussed how the Purcell effect influences an emitter in a cavity, we now consider how such structures affect the collection efficiency. In a confocal setup, the numerical aperture (NA) of the objective determines the range of angles over which the system collects light. The photonic structure is designed to guide the emitted light into angles that the objective can efficiently collect. This guidance is achieved through effects arising from the wave nature of electromagnetic radiation. These effects become significant when the structure dimensions are comparable to or smaller than the wavelength of light. The electromagnetic behavior of light in such structures can be modeled using COMSOL. Using these simulations, the structure can be optimized for both collection efficiency and Purcell enhancement by engineering the mode volume and quality factor.

2.3.1. Micropucks

This section is based on findings in [3]. One type of photonic structure used in confocal measurements is the micropuck. Micropucks are micropillars etched into silicon-on-insulator (SOI) substrates, which influences both the collection efficiency and the photonic density of states. The integration of T centers into these structures alters the photon counts detected in measurements of the embedded color centers.

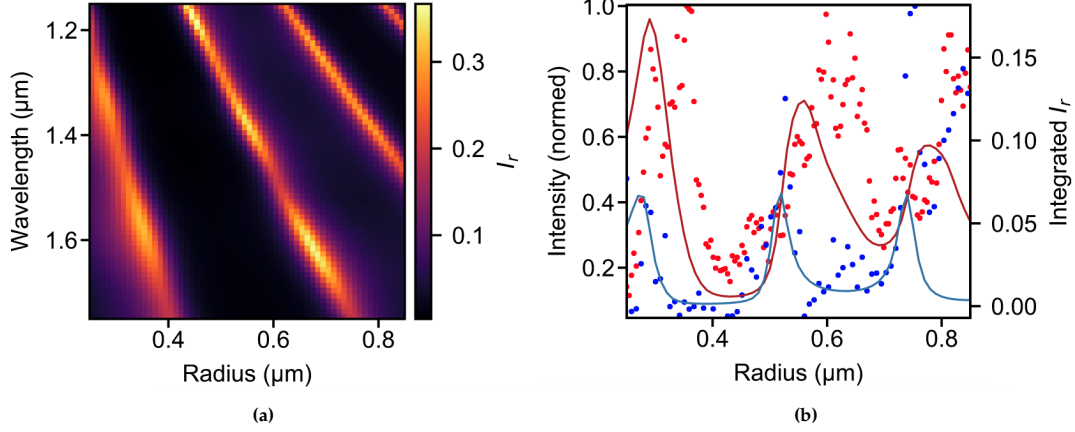


Figure 2.5: (a) Simulated relative intensity (color axis) collected by an NA = 0.7 microscope objective from a planar emitter at the micropuck center as a function of wavelength and micropuck radius. (b) Simulated (solid) vs measured (dots) intensity of the T ZPL area (blue) and the integrated sideband intensity (red) in PL as a function of micropuck radius. Simulated data are plotted as relative intensity in the objective (right axis), and measured data are peak values normalized (left axis). Figures reproduced from [3]

In Figure 2.5, it can be seen that micropuck optical structures exhibit different relative intensities in a confocal measurement setup for specific radii and wavelengths. The relative intensity is defined as the product of the light emitted and collected by the objective and the Purcell factor. For these structures, it is observed that the relative intensity increase due to micropuck size has varying shapes.

For diameters around 305 nm, the intensity peak spans a large portion of the phonon sideband of the T center emitter. Micropucks of this diameter are therefore well suited for PSB collection. In such structures, the lifetime of the T center has been measured at $\tau = 802\text{ns}$.

For diameters around 520 nm, the peak can be relatively high and narrow when centered on the ZPL emission line of the T center. Micropucks of this diameter are therefore well-suited for ZPL collection. At this radius, there is a 58-fold increase in ZPL intensity from a centered planar T center in the micropuck compared to a similarly positioned T center in unpatterned SOI.

An advantage of micropucks is that they are relatively easy to fabricate and possess only a single degree of freedom. A disadvantage is that they offer relatively little Purcell enhancement compared to other structures.

2.3.2. Bullseyes

Another type of photonic structure used in confocal measurements is the so-called bullseye cavity. Bullseye cavities consist of a micropuck surrounded by concentric rings. The addition of the rings enhances both the collection efficiency and the Purcell factor. The shape of bullseye cavities is characterized by three degrees of freedom. These are: the radius of the central puck (R), the filling factor of the rings (ff), and the distance between the center of the first ring and the outer edge of the second ring, known as the ring period (Δ). In Figure 2.6 (a), these dimensions are visualized.

Figure 2.6 (b) presents simulations of the optical performance of bullseye cavities. The simulations indicate a maximum 115-fold enhancement in emission compared to an unpatterned SOI substrate at specific wavelengths for an optimally coupled T center. At this maximum, the collection efficiency into a 0.85 NA objective is simulated to be $\eta_{cav} = 45\%$. The ZPL Purcell factor at this maximum is $F_p^{ZPL} = 34.5$, corresponding to an expected lifetime Purcell factor of $F_p^\tau = 1.8$.

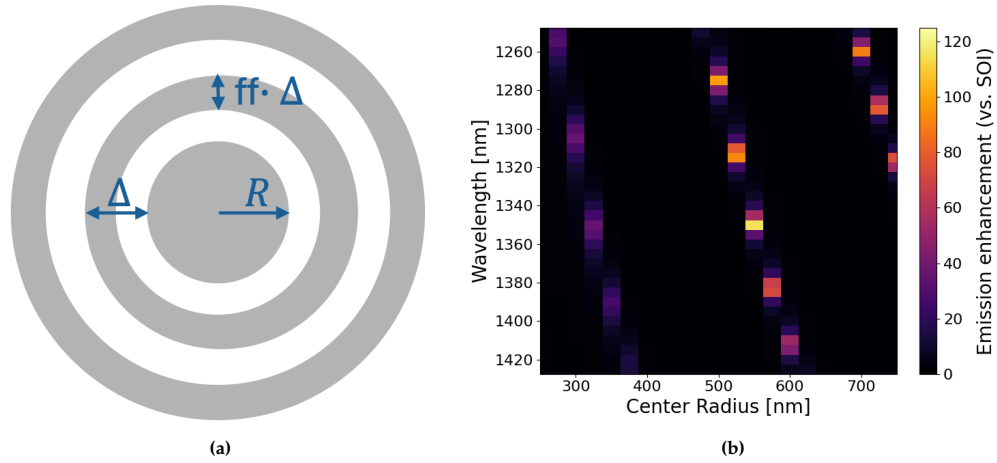


Figure 2.6: (a) Degrees of freedom for a bullseye. (b) Simulated emission enhancement compared to unpatterned SOI (color axis) collected by an $NA = 0.85$ microscope objective from a planar emitter at the bullseye center as a function of wavelength and bullseye center radius for $\Delta = 500\text{nm}$ and $ff = 80\%$

The simulated emission enhancement peaks are relatively narrow but can still be used without cavity tuning. However, they do not enhance the PSB, making bullseye cavities more suitable for ZPL collection than for PSB collection. A downside of using bullseyes is that they have more degrees of freedom than micropucks, which can make fabrication more difficult.

Conditions for effective resonant excitation measurements

This chapter investigates the conditions required for efficient resonant excitation measurements of T center properties such as spectral diffusion, spin relaxation, and spin cyclicity.

3.1. Linewidth, magnetic field and orientation

For characterizing properties such as the spin relaxation time or the spin cyclicity of the T center, transitions B and C must be resolvable in wavelength. This requirement is satisfied when the linewidth is smaller than the energy difference between these transitions. We will therefore investigate the factors that influence this energy difference and, with that, the spectral resolvability of the transitions. Based on the energies of each transition, as defined in equation 2.1, the energy difference between the B and C transitions can be expressed as:

$$\Delta E_{BC} = E_B - E_C = \mu_B |B_0| (g_E - g_H). \quad (3.1)$$

Equation 3.1 shows that this energy difference is mainly determined by the hole g-factor (g_H) and the magnetic field strength (B_0), since all other variables remain constant.

Magnetic field strength

A stronger magnetic field yields larger spin-splitting energies, thereby improving the ability to resolve spin-selective transitions optically. In literature, typical values for the magnetic field over the sample are reported as 300mT[9], 200mT[24], and 40-160mT[3]. Following this reasoning, the magnetic field should be chosen as large as possible. We note, however, that this is not always preferable, as a large spin-splitting energy can make microwave driving difficult. A magnetic field of 1T corresponds to a microwave driving frequency of 28GHz, which requires expensive equipment and complex operation.

Orientation

Equation 3.1 shows that the hole g-factor significantly affects the optical resolvability of the transitions. Figure 2.2 shows the variation in hole g-factors for different T center orientations and magnetic field directions. For some photonic structures, the T center orientations that couple efficiently can be derived, allowing the magnetic field direction to be chosen so as to optimize the hole g-factor for those orientations. Otherwise, the magnetic field orientation can be chosen to maximize the expected spin-splitting energy.

Linewidth

Another factor affecting the resolvability of spin-selective transitions is the emitter linewidth. This linewidth should be smaller than the energy difference defined in equation 3.1. To provide insight into the linewidths required for high resolvability, we estimate the spin-splitting energy for representative

conditions. As an example, for a magnetic field strength of $B_0 = 300\text{mT}$ applied along the [001] direction ($g_H \approx 2.6$ for x and y orientations and $g_H \approx 0.7$ for z orientations), the resulting energy difference is approximately 2.5GHz for x and y orientations and 5.4GHz for z orientations. The emitter linewidth must therefore be below these values to enable effective measurements involving spin-selective transitions.

3.2. Count rate

To measure T center properties efficiently, an important factor is the detected count rate from a single emitter, as this affects the measurement time in photoluminescence excitation experiments. This section investigates the effect of the count rate on the measurement time for spin relaxation measurements.

Spin relaxation measurement time

To estimate the measurement time required for spin relaxation experiments, we first define the signal count rate S and the background count rate R_{bg} . The signal count rate depends on the waiting time between measurements according to

$$S = S_0 e^{-t_{\text{wait}}/T_1},$$

where T_1 is the spin relaxation time. For a single measurement, the first excitation pulse yields an expected total count of

$$\bar{N}_1 = (S + R_{bg})t_{\text{pulse}},$$

while the second pulse yields

$$\bar{N}_2 = R_{bg}t_{\text{pulse}}.$$

A single datapoint can then be defined as the difference

$$d_i = \bar{N}_{1i} - \bar{N}_{2i},$$

with an associated uncertainty

$$\sigma_d = \sqrt{\bar{N}_1 + \bar{N}_2}.$$

To achieve a relative error below $\epsilon = 5\%$, the number of repetitions M must satisfy

$$\frac{\sqrt{\bar{N}_1 + \bar{N}_2}}{\bar{N}_1 - \bar{N}_2} \leq \epsilon.$$

The total measurement time is then given by

$$T_m = M \cdot (t_{\text{wait}} + t_{\text{measurement}} + t_{\text{overhead}}),$$

allowing the total time to be estimated for different initial conditions. These estimates are plotted in Figure 3.1.

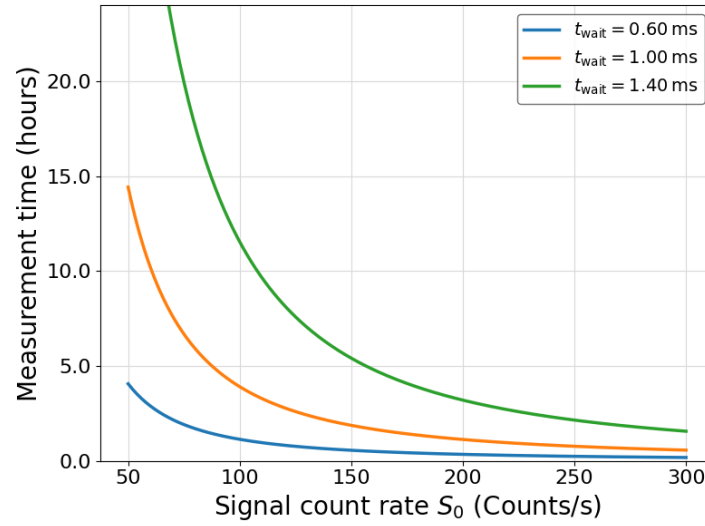


Figure 3.1: Measurement time for a spin relaxation measurement. For these estimates $R_{\text{bg}} = 100\text{cps}$, $t_{\text{pulse}} = 5\text{ms}$ and $T_1 = 1\text{ms}$.

Figure 3.1 shows that as the signal count rate decreases, the measurement time increases to non-practical durations. In addition to this, shorter measurement times are desirable, as they allow faster measurement iterations and reduce sensitivity to slow drifts in experimental parameters. Therefore, it is important to maximize the signal count rate, which ideally should exceed 100cps to enable efficient measurements.

Characterization of photonic structures

In Chapter 3, we found that the efficiency of resonant excitation measurements increases with the count rate. To this end, we analyzed the impact of photonic structures on the count rate using photoluminescence (PL) measurements on both micropuck and bullseye structures.

4.1. Micropucks

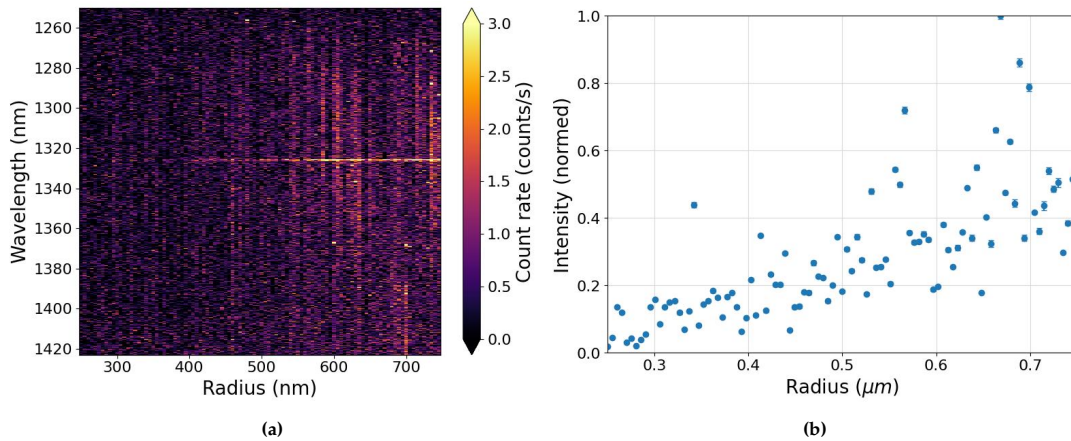


Figure 4.1: (a) Background corrected PL intensity (color axis) as a function of wavelength and micropuck radius for an excitation power of $10\mu\text{W}$, and integration time of 20second. Collected in multimode fiber. (b) Integrated sideband intensity (1350 – 1600nm) in PL as a function of micropuck radius as measured in the Delft setup. Data are peak-value normalized, and measurements were performed at an excitation power of $10\mu\text{W}$.

Spectrum

In Figure 4.1a, a PL spectrum of a range of micropucks with increasing radius per position is shown; the radii of the micropucks vary from 250nm to 745nm. For micropucks with larger radii, T-center photoluminescence is visible; however, for smaller micropucks, it is not. The expected count rate would be significantly higher if T centers were present in these micropucks, so it is likely that no T centers are present in these micropucks. When comparing this figure to Figure 2.5a, no intensity resonances are observed. An increase in count rate is observed with increasing micropuck radius. Possible reasons for the absence of resonances include measurement-related factors such as insufficient excitation power, inadequate integration time, and a measurement window covering too narrow a

wavelength range. Other contributing factors may include issues with the micropucks, such as a low T-center density, imprecise fabrication that prevents enhancement, or excessive background fluorescence. Further investigations are needed to determine the causes of the missing resonance peaks and the absence of T-center emission in small micropucks.

Integrated PSB intensity

In Figure 4.1b, it is evident that the pattern observed in Figure 2.5b was not reproduced with the Delft setup and samples. Instead, a gradual increase in PSB counts was observed with increasing micropuck radius. Possible reasons for the absence of the expected patterns include both measurement- and sample-related factors. Measurement-related limitations include insufficient integration time for PSB collection, low PSB collection efficiency, and incomplete emitter saturation. Sample-related issues include insufficient emitters, background fluorescence overwhelming T-center emission, and fabrication errors in the micropuck structures.

4.2. Bullseyes

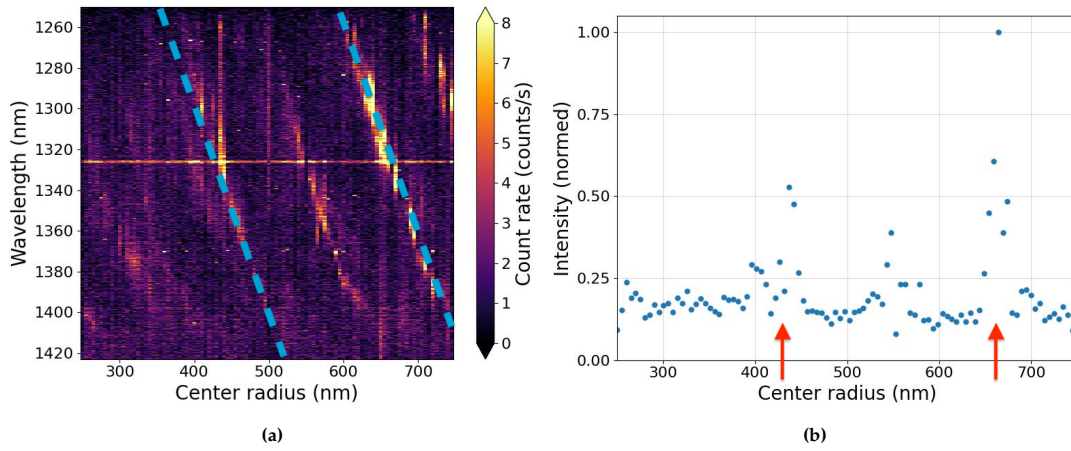


Figure 4.2: (a) Measured intensity (color axis) in PL for bullseye structures as a function of wavelength and bullseye center radius with $ff = 80\%$ and $\Delta = 500\text{nm}$ for na excitation power of $10\mu\text{W}$. Collected in a single-mode fiber. Whispering gallery modes are denoted in blue. (b) Integrated PL intensity around the T center ZPL wavelength (1325 – 1327nm) in bullseye cavities as a function of the center radius of the bullseye. Data is peak value normalized. The red arrows indicate whispering-gallery modes.

Intensity spectrum

In Figure 4.2a, intensity measurements of bullseye cavities are shown, matching the parameters of the simulations in Figure ???. The measurements reproduce the emission enhancement pattern observed in the simulations. However, additional modes are observed, which were absent in the simulations. Additional simulations confirmed that these modes correspond to whispering gallery modes. The T-center emission line at approximately 1326nm is observed for all center radii. These results indicate that T centers are present in all bullseye structures. Each bullseye likely contains more than one T center, as otherwise some bullseyes would not exhibit T-center emission. Further investigation of the T-center density is needed to determine the number of T centers in each bullseye.

Integrated ZPL intensity

In Figure 4.2b, ZPL counts are shown for different bullseye center wavelengths. The measurements indicate that the intensity is enhanced when the cavity is resonant with the T-center ZPL, confirming the simulations. However, it is hard to quantify the exact increase in emission based on these measurements, as there are likely many T centers in each cavity. The whispering-gallery modes exhibit the highest ZPL enhancement, which may result from a greater number of T centers coupling to them.

Count rate estimations for resonant excitation measurements

Using the available photonic structures and measurement techniques, we estimate the expected signal-to-noise ratios from a single emitter in resonant excitation measurements for two structure–technique combinations.

Noise

In the setup used, the noise level is dominated by the SNSPD’s dark count rate, measured at approximately 100 cps. This value is therefore used as the noise level in the estimations.

Collection efficiency

An important factor to consider is the system’s collection efficiency. It is given by the product of all component efficiencies in the setup. The system collection efficiency is $\eta_{sys} = \eta_{window}\eta_{path}\eta_{SNSPD}$ for confocal setups, and $\eta_{sys} = \eta_{GC}\eta_{path}\eta_{SNSPD}$ for fiber coupling with a grating coupler. Table 5.1 shows the system collection efficiencies for two literature setups, along with the efficiency of our setup.

Source	Higginbottom[3]	Johnston[9]	Delft setup
SNSPD, η_{SNSPD}	70.0%	70.0%	70.0%
Detection path, η_{path}	33.0%	78.6%	33.0%
Cryostat window, η_w	66.0%	N/A	95.0%
Grating coupler, η_{GC}	N/A	46.1%	N/A
System, η_{sys}	15.2%	25.3%	21.9%

Table 5.1: Photon collection efficiencies for different optical setups. In the Higginbottom setup, a confocal setup is used to measure micropuck structures; in the Johnston setup, a 1D photonic crystal cavity is coupled to a fiber using a grating coupler; and in the Delft setup, a confocal setup is used to measure Bullseye structures. The Delft setup values for SNSPD and the Detection path were based on the Higginbottom setup due to their similarity and the lack of better data; the Cryostat window efficiency was based on known values.

5.1. Count rate estimations for PSB PLE measurements on the micropucks

As sufficient data are not available to estimate the count rate in the Delft setup for PSB PLE on the micropucks, the estimation follows the approach of [3] up to the quantum efficiency.

Count rate in PSB PLE measurements

To estimate the expected number of counts in the PSB collection measurements, several factors must be considered. First, the saturation factor is taken to be 0.5. Additionally, the decay rate is governed by the emitter lifetime in unpatterned SOL. Next, the relative intensity, $I_r(\lambda)$, accounting for the Purcell enhancement and the objective collection efficiency (η_{obj}) as illustrated in Figure 2.5a. The area normalized PSB distribution in homogeneous media [13]. Finally, the quantum efficiency, η_{QE} , of the emitter must be taken into account. Multiplying all these factors yields the expected count rate for the setup.

PSB PLE measurements on micropuck structures

For the micropuck structures, the expected count rate was reported as 11.2 kcps in [3]. However, this estimation does not account for quantum efficiency, non-ideal cavity coupling arising from emitter position or orientation, single-mode fiber coupling, or incomplete saturation effects. To properly compare this count rate with that in TRIPLE measurements, we include the quantum efficiency, $\eta_{\text{QE}} = 23.4\%$, resulting in an expected count rate of 2620cps and a signal-to-noise ratio of approximately 26.

In [3], the measured count rate was 320 cps; this eightfold reduction is attributed to non-ideal cavity coupling, single-mode coupling, and incomplete saturation. These factors are also present in the Delft setup, so a comparable reduction can be expected in measurements using that setup.

This indicates that both the structures and the measurement setups should be optimized to maximize PSB collection efficiency, as low efficiencies can significantly limit the measurable count rate. Other methods to achieve this, in addition to the micropuck, include waveguides, PSB reflectors, or grating couplers optimized for the PSB.

5.2. Count rate estimations for TRIPLE measurements

Count rate in TRIPLE measurements

This estimation is based on the approach presented in [9].

To determine the expected number of counts for TRIPLE measurements, several factors must be considered. These include the saturation factor (0.5), the system collection efficiency at the ZPL (η_{sys}), and either the cavity collection efficiency at the ZPL wavelength (η_{cav}) for cavity systems or the objective collection efficiency (η_{obj}) for confocal setups. Additional factors are the probability of a T center decaying into the resonant cavity mode ($\beta = \frac{F_p^\tau}{F_p^\tau + 1}$), the probability of detecting a photon during the collection window ($e^{-t_0/\tau_{\text{exc}}} - e^{-t_1/\tau_{\text{exc}}}$), and the pulse repetition rate (R_{pulse}). The count rate is then expressed as

$$0.5\eta_{\text{sys}}\beta(e^{-t_0/\tau_{\text{exc}}} - e^{-t_1/\tau_{\text{exc}}})R_{\text{pulse}}, \quad (5.1)$$

where t_0 and t_1 define the start and end of the collection window relative to the end of the excitation pulse.

TRIPLE measurements on bullseye structures

Based on the bullseye simulations discussed in Chapter 4, the expected Purcell factor is $F_p^\tau = 1.8$, corresponding to an expected lifetime of 329ns. From this, the fraction of ZPL decay is derived to be $\beta = 0.64$. The system collection efficiency, as measured in the Delft setup, is $\eta_{\text{sys}} = 21.9\%$, while the cavity collection efficiency, based on the simulations presented in Chapter 4, is less than 45%. For the detector deadtime, a value of $t_0 = 170\text{ns}$ is used, similar to [9]. The collection window can be optimized in combination with the pulse repetition rate to achieve the highest count rate. Assuming a pulse consisting of a 900ns excitation window and a 1900ns collection window, the resulting decay probability within the collection window is approximately 59%, yielding a pulse repetition rate of 333kHz. Using these parameters, the expected count rate is estimated to be 6161 cps. This corresponds to an expected signal-to-noise ratio of 61.6, which is a factor of 2.4 higher than that obtained using PSB PLE measurements on micropuck structures.

If we also account for a factor of 8 reduction due to non-ideal cavity coupling, single-mode coupling, and incomplete saturation, we expect a count rate of around 770cps. Further increases in count rate can be achieved in multiple ways; a promising approach is to use even higher Purcell-factor cavities, which

would result in higher relative ZPL emission and enable a higher pulse repetition rate. The estimations also show that photon collection efficiency can be further improved by reducing the deadtime between excitation and collection. This effect becomes increasingly significant for cavities with higher Purcell factors and shorter lifetimes.

These estimations demonstrate that the TRIPLE measurement technique, when used with bullseye cavities, achieves higher count rates than the PSB PLE measurements on micropuck structures. Furthermore, implementing TRIPLE measurements represents an important step toward integrating T centers into higher-Purcell-factor photonic cavities.

6

Time-resolved interval photoluminescence excitation measurements

In Chapter 5, it was concluded that the installation of TRIPLE measurements allows for higher count rates in confocal measurements and is an important step towards integrating T centers in photonic cavities. This chapter presents the design and implementation of the TRIPLE measurement setup.

6.1. Experimental setup

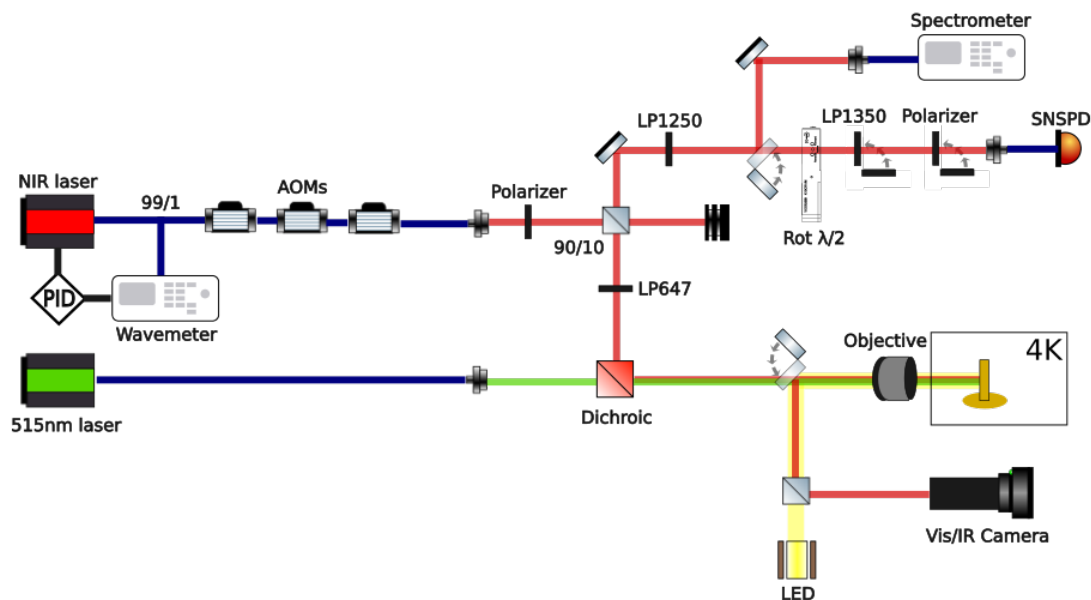


Figure 6.1: The optical setup

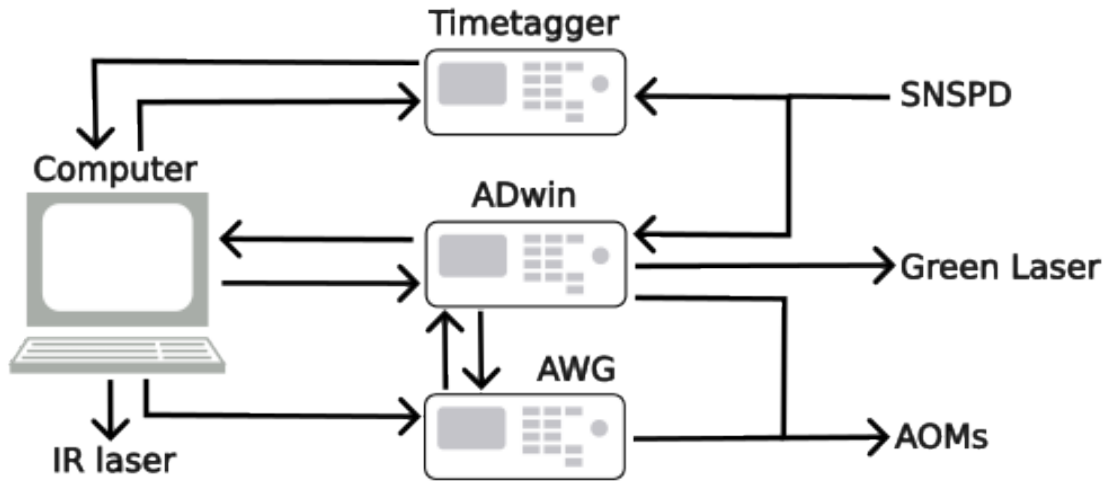


Figure 6.2: The control setup

6.1.1. Optical setup

Figure 6.1 shows the optical setup. In this setup, off-resonant light is provided by a Hübner Photonics Cobolt 06-MLD 515nm laser and is merged into the IR laser path using a dichroic mirror. This light is removed from the collection path using a 647nm long-pass filter. Resonant excitation is achieved with a Santec TSL-570A O-band laser, maintained at a constant frequency using a PID feedback loop and monitored with a Bristol Instruments 871B wavemeter. Optical pulses are generated using three AeroDiode fiber-coupled AOMs for 1310nm. Each AOM has a rise/fall time of 20ns and an extinction ratio of 60dB. A free-space linear polarizer ensures that the laser light is linearly polarized before entering a 90/10 beamsplitter. The sample is mounted in a cryostat, with an objective placed on a nanopositioning stage, allowing precise movement of the laser over the sample. For rapid sample scanning, a white LED and an IR camera are incorporated into the optical path.

In the collection path, a SpectraPro HRS-300 spectrometer equipped with a PyLonIR sensor module is employed for photoluminescence experiments. For more efficient PSB or ZPL collection, a PhotonSpot superconducting nanowire single-photon detector (SNSPD) is used. An optional polarizer, used in combination with a rotatable half-wave plate, allows rotation of the polarization of the collected light at the SNSPD or filtering of residual laser light. A 1350nm filter is inserted to remove ZPL light during PSB collection experiments.

6.1.2. Control setup

Figure 6.2 illustrates the control setup used for time-resolved resonant excitation measurements. The setup is controlled by a computer using the Python-based QMI software. Pulse sequences are generated using a Jäger ADwin Pro II microcontroller (time resolution: 1μs) and a Zurich Instruments HDAWG arbitrary waveform generator (sampling rate: 2.2GHz). For time-resolved photon detection, a Picoquant Multiharp 150 time tagger is used.

6.2. Pulses Shape tests

In Chapter 5, it was shown that increased deadtime between the excitation and collection windows reduces the count rate in TRIPLE measurements. Optical pulses with sharp edges reduce laser leakage after the excitation pulse, thereby enabling a shorter deadtime. This section, therefore, investigates the pulse shapes generated by the setup.

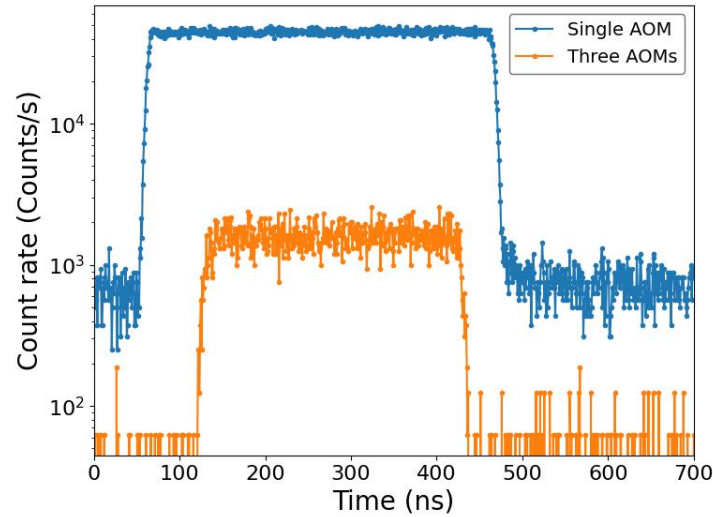


Figure 6.3: Measured optical pulse shapes for a 400ns electrical pulse by the AWG. Plotted are, in blue, the pulse shape for a single AOM in the optical path, and, in orange, for 3 AOMs in the optical path. In these measurements, the laser was attenuated and fed to an avalanche photodiode (APD). Note that for the measurement with the single AOM in the path, the lab lights were on.

Figure 6.3 shows the pulse shapes obtained using a single AOM and three AOMs in the optical path. In this experiment, highly attenuated optical pulses were measured using an avalanche photodetector (APD), as the SNSPD was unavailable at the time. For a single AOM, the optical pulse closely follows the shape of the AWG electrical input. The pulse exhibits sharp edges, and its width is approximately equal to the 400ns AWG input. For three AOMs in series, the optical pulse is attenuated due to additional insertion loss. This attenuation does not affect the measurements, as the power can be calibrated. Furthermore, the pulse width deviates from the 400ns AWG input and is approximately 100ns shorter. This is likely due to differences in AOM triggering times, resulting in a reduced pulse window during which all AOMs are simultaneously open. As a result, one or more AOMs may remain partially open, leading to laser leakage after the visible pulse. Future investigations should aim to quantify this leakage to optimize deadtime and minimize the residual laser signal after the pulse. Improvements in the optical pulse shape can be achieved by introducing custom delays for each AOM. These improvements can lead to reduced deadtime and, consequently, higher count rates.

6.3. Time-resolved off-resonant excitation

In this section, the AWG is connected to the off-resonant laser. This laser can be pulsed at sufficiently high attenuation and repetition rates without additional modification. These measurements allow testing of the software, measurement, and control systems, and enable extraction of the lifetime. Before collection, a bandpass filter centered at the T center emission wavelength is added to isolate the signal.

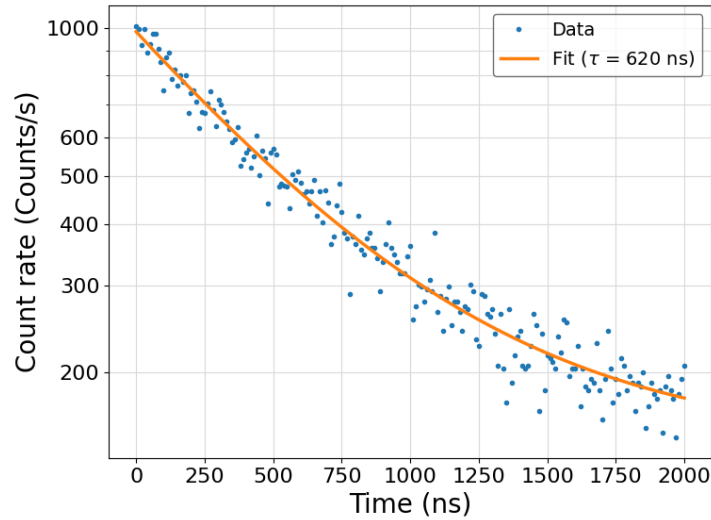


Figure 6.4: Measured count rate as a function of the time in the collection window for a pulse train containing 5×10^5 pulses. An exponential fit is shown in orange for a lifetime of 620ns.

In Figure 6.4, the count rate under off-resonant excitation is plotted as a function of time after a pulse. An exponential decay with an offset is fitted to the data, yielding a lifetime of 620ns, which is higher than the estimated 329ns reported in Chapter 5. Possible reasons for a lifetime higher than the simulated value for an emitter in a bullseye cavity include imperfect cavity fabrication and non-ideal emitter–cavity coupling. Since a single lifetime can be fitted, the fluorescence likely originates from either a single emitter or multiple emitters with similar lifetimes. Given that multiple emitters are expected in the sample, it is likely the second. Additional simulations of bullseye cavities should be performed to understand better the effects of fabrication errors and non-ideal emitter–cavity coupling. The ability of the setup to measure this lifetime demonstrates that the software, measurement, and control systems are functioning correctly.

6.4. SNSPD latching and efficiency

SNSPD latching

During attempts to perform resonant excitation measurements on the setup, it was observed that the SNSPD would occasionally “latch,” meaning it would become stuck in a resistive state after detecting many photons. To “delatch” the detector, the bias current must be reduced, then gradually increased back to its previous level. In the current setup, this delatching process can only be performed manually, meaning that measurements fail if a latching event occurs. Latching occurs more rapidly at higher bias currents in the SNSPD. However, the bias current cannot be reduced without compromising efficiency.

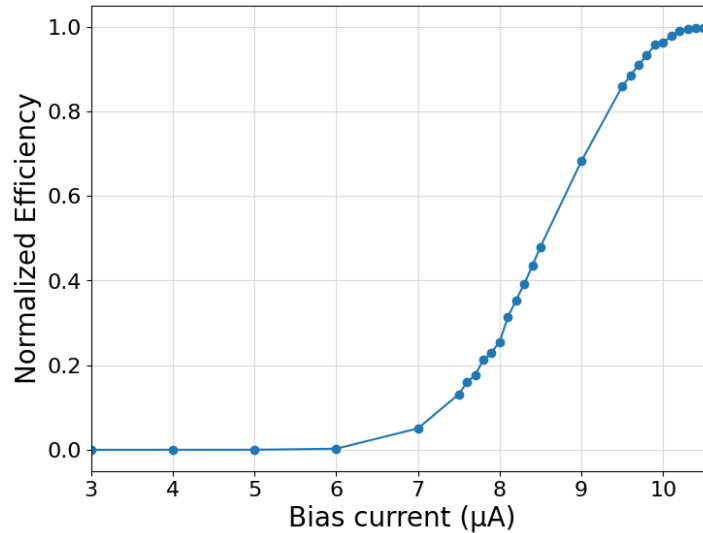


Figure 6.5: Normalized SNSPD efficiency as a function of bias current over the SNSPD

Figure 6.5 shows the normalized SNSPD efficiency as a function of the bias current applied to the detector. Ideally, the bias current would be set to approximately $9\mu\text{A}$, corresponding to about 70% of the maximum detector efficiency. For TRIPLE measurements, latching was observed at these bias currents. To prevent this, the bias current had to be reduced to approximately $8\mu\text{A}$. At this bias current, no latching occurred for a laser power of $0.7\mu\text{W}$, a pulse duration of 500ns , and a collection window of $2\mu\text{s}$. However, at this bias current, the SNSPD operates at only approximately 30% of its maximum efficiency. Other factors influencing latching behavior include the excitation window duration, pulse repetition rate, and laser power.

Latching solutions

Several solutions to SNSPD latching can be implemented, including SNSPD gating, cross-polarization of the excitation and collection paths, and automatic delatching electronics. In the setup, cross-polarization was implemented to suppress laser light before collection. This allowed the SNSPD bias current to be increased to $9.0\mu\text{A}$, corresponding to approximately 70% of its maximum efficiency. A limitation of this approach is that the excitation and collection polarizations must be carefully chosen to prevent the emitted signal from being suppressed by the collection-path polarizer. Additionally, the excitation laser polarization may reduce the saturation efficiency of the T center. The losses associated with these effects are difficult to quantify without a reference T center. If such a reference is available, its signal can be optimized by rotating the half-wave plate.

6.5. Time-resolved interval resonant excitation

When performing TRIPLE measurements on a promising bullseye emitter, several issues remained, and T center emission has not yet been measured. Future work should explore additional approaches to enable this measurement. Furthermore, the measurement has only been performed on a single bullseye and should be extended to multiple positions. A broader investigation should be conducted into the sizes of the excitation and collection windows, as well as the inclusion of an optional background window. In addition, the excitation power should be examined, along with the effect of cross polarization on the count rate.

7

Conclusions

This thesis contributes to the accelerated characterization of color centers in silicon by investigating and implementing methods for efficient photoluminescence excitation of the T center.

First, the conditions required for efficient resonant excitation of the T center were determined. It was found what combination of magnetic field, T center orientation and linewidth is needed to optically resolve the B and C transitions. It was also found that, for effective measurements of the spin relaxation time, the signal count rate should ideally be well above 100cps.

In the subsequent chapter, PL measurements were performed on photonic structures to assess their effect on the observed count rates. From these measurements, it was concluded that although T centers were present in some micropucks, no PSB enhancement could be observed. In the bullseye structures, it was clear that T centers were present and that these structures enhanced ZPL emission at their cavity resonances.

Then, using count rate estimations, the most effective structures and measurement techniques for confocal measurements were identified. It was found that TRIPLE measurements, in combination with bullseye structures, increased the S/N ratio by a factor of 2.4 compared to PSB PLE measurements on micropuck structures. Furthermore, TRIPLE measurements were better suited to ZPL-enhancing cavities.

Finally, the design and implementation of TRIPLE measurements were presented. The optical pulse shapes were characterized, and using off-resonant excitation pulsing, the setup was able to measure a lifetime of 620ns in a bullseye structure. Although single T centers have not yet been measured using this technique, it still shows promise for delivering higher count rates and enabling PLE measurements in ZPL resonant cavities.

The next steps will be to investigate excitation and collection parameters, along with their implementation across more structures, to enable single T center identification using the TRIPLE technique. This would open the door to measurements of many T center properties and to the exploration of other color centers in silicon. The application of this technique to T centers embedded in cavities allows for further quantum network experiments.

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