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Exciting and Resolving Quantum Dot Emission with Adiabatic Rapid Passage and Fabry Perot Interferometer



Master Thesis
to obtain the academic degree of
Diplom-Ingenieur
in the Master's Program
Technische Physik

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Abstract

This is a placeholder for the abstract. It summarizes the whole thesis to give a very short overview.
Usually, this the abstract is written when the whole thesis text is finished.

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Abstract

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1. Introduction

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1. Introduction

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2. Droplet etched gallium arsenide quantum dots

2.1. Fabrication and optical properties

Quantum dots (QD) are nanostructures which confine the motion of electrons and holes in all three-dimensional spatial dimensions. Confinement results in discrete energy levels, which is why quantum dots (QDs) are sometimes referred to as *artificial atoms*. Additionally, they provide potentially suitable implementations of qubits, the basic unit of quantum information. The discussion in this section is based on the PhD thesis of Huber [1].

Gallium arsenide quantum dots investigated within this master's thesis are grown by molecular beam epitaxy (MBE) with the self-assembled nanodrill technology described in the work of Wang et al. [2]. As displayed in figure 2.1(a) the aluminium (Al) forms droplets on AlGaAs after evaporation. The Al reacts with AlGaAs, which leads into nanoholes etched into the surface. Under optimal conditions, these nanoholes are highly symmetric as can be seen in figure 2.1(b). This results into QD with high in-plane symmetry. The next step is the annealing process in which gallium arsenide (GaAs) is deposited to fill the nanoholes. The QD is finalized by capping the layer with AlGaAs acting as top barrier.

Compared to the band gap of the host material $\text{Al}_{0.4}\text{Ga}_{0.6}\text{As}$ of 1.92 eV at room temperature, the core of the QD, GaAs, has a band gap of only 1.42 eV at room temperature. This energy difference between the band gaps and nanosized dimensions of the QD are responsible for the 3D confinement and the type-I band alignment depicted in figure 2.1(c). This thesis focuses on optical transitions between the first energy level in the conduction band (CB) and the valence band (VB), often called the s-shell. The carriers are electrons e^- and the holes left behind h^+ . These are fermions and can therefore only up to two of them can, in accordance with Pauli's exclusion principle, occupy a single energy state. Electrons and holes are strongly localized inside the QD and interact with each other by Coulomb

2. Droplet etched gallium arsenide quantum dots

interaction. This leads to multi-particle complexes with the most fundamental being the exciton (X), a bound state of an electron and a hole. A fully occupied s-shell, can be described by the quasiparticle called biexciton (XX).

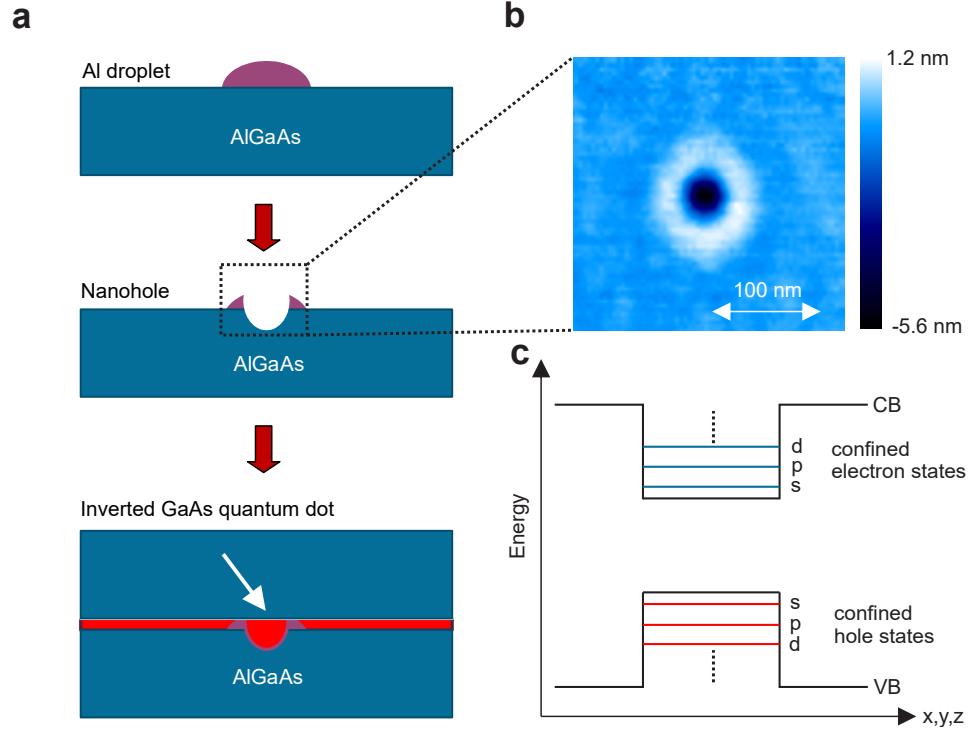


Figure 2.1.: (a) The growth process of a GaAs quantum dot by MBE.
 (b) Atomic force microscopy (AFM) image of the nanohole before it is filled with GaAs.
 (c) Conduction band (CB) and valence band (VB) of an optically active QD. [1]

In a QD polarization-entangled photon pairs can be generated via a biexciton-exciton cascade [3], illustrated in figure 2.2. $|XX\rangle$ forms a full shell, which means that the total angular momentum projection along the quantization axis of the XX complex sums up to $M = 0$. After exciting the QD into the $|XX\rangle$ state (e.g. by optical pumping) it decays by spontaneous recombination of an electron-hole-pair accompanied by the emission of a single photon into the $|X\rangle$ state. The two-dipole allowed radiative transitions lead to only two possible $|X\rangle$ states:

- $| -1 \rangle$ under emission of a right-circularly-polarized photon $|r\rangle$
- $| +1 \rangle$ under emission of a left-circularly-polarized photon $|l\rangle$

$| -1 \rangle$ and $| +1 \rangle$ are degenerate in energy and decay into the groundstate $|G\rangle$ under emission of $|l\rangle$ and $|r\rangle$, respectively.

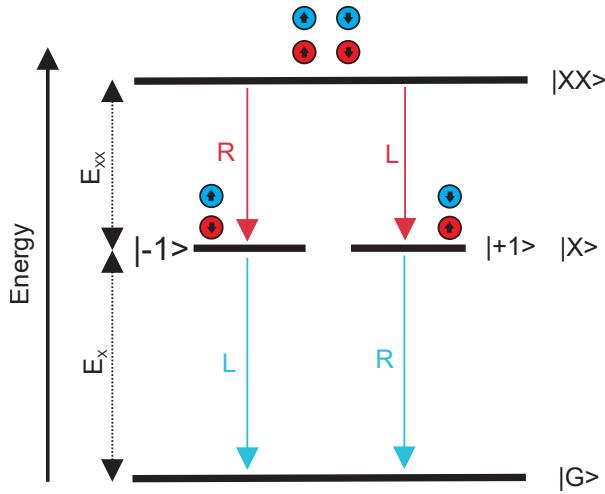


Figure 2.2.: Biexciton-esciton cascade in a QD. [1]

Figure 2.3 displays another perspective of GaAs QDs with a comparison of the order of magnitude of its height profile and wavefunction of the exciton.

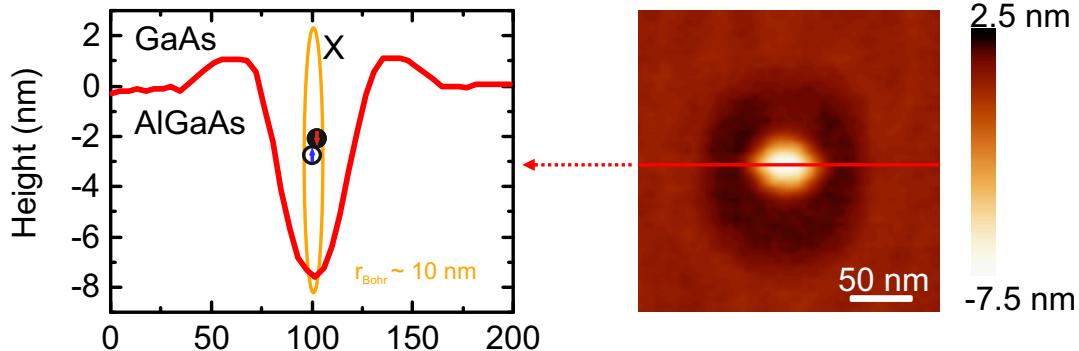
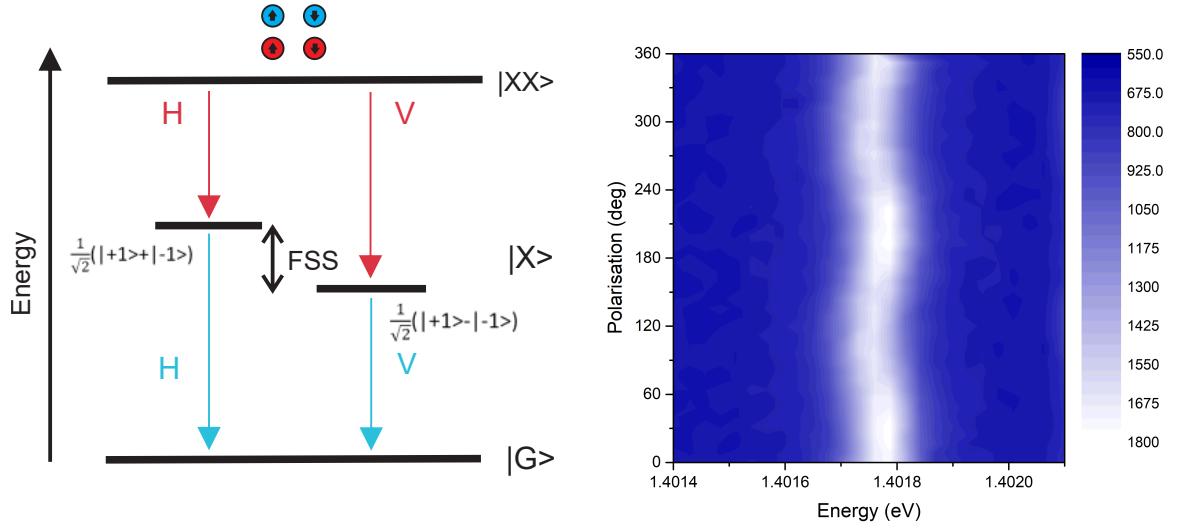


Figure 2.3.: Height profile (red) of a droplet-etched nanohole in an AlGaAs layer is shown in the left image. The orange line represents the wavefunction of the exciton which resembles the ground state of an hydrogen atom. Because of that the Bohr radius r_{Bohr} is denoted. The right image shows the atomic force microscopy picture of the nanohole. An GaAs quantum dot is obtained after filling the hole with GaAs and avergrowth with AlGaAs [4]

2.2. Fine structure splitting

Fine structure splitting (FSS) in a QD describes the energy splitting between the two possible bright $|X\rangle$ states. In GaAs it originates from the exchange interaction between electrons and holes. [5].

In figure 2.4a the $|XX\rangle$ decay path with splitted $|X\rangle$ eigenstates is shown. $|XX\rangle$ exhibit no splitting as the angular momentum of the electrons and holes add to zero and therefore no exchange interaction occurs. In figure 2.4b photoluminescence spectra recorded with a linear polarizer are shown.



(a) XX decay cascade without X degeneracy because of fine structure splitting. [1] (b) Photoluminescence spectra of X emission of a GaAs Qd plotted for different polarizer angles. In the image the effect of the linear polarization of the fine structure components is visible. [6]

Figure 2.4.: Fine structure splitting in a GaAs quantum dot.

2.3. Zero-phonon line and phonon sideband

The excitonic emission of GaAs QDs exhibit non-Lorentzian asymmetric broadening. As shown by Peter et al. [7] this side bands can be traced back to a coupling to acoustic phonons. The discussion of phonon side bands (PSBs) is based on Friedrich and Haarer [8] and Peter et al. [7].

Figure 2.5 displays a schematic representation of the zero phonon line (ZPL) and PSB absorption spectrum. The intensity distribution between the two components depends strongly on temperature.

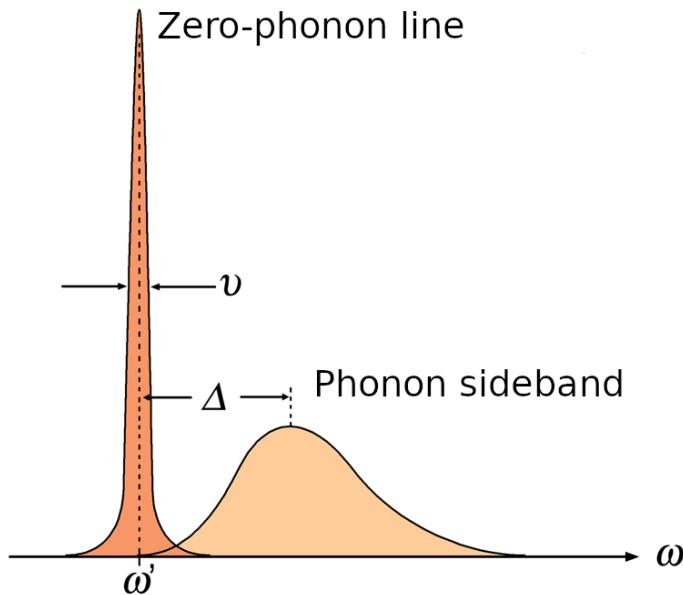
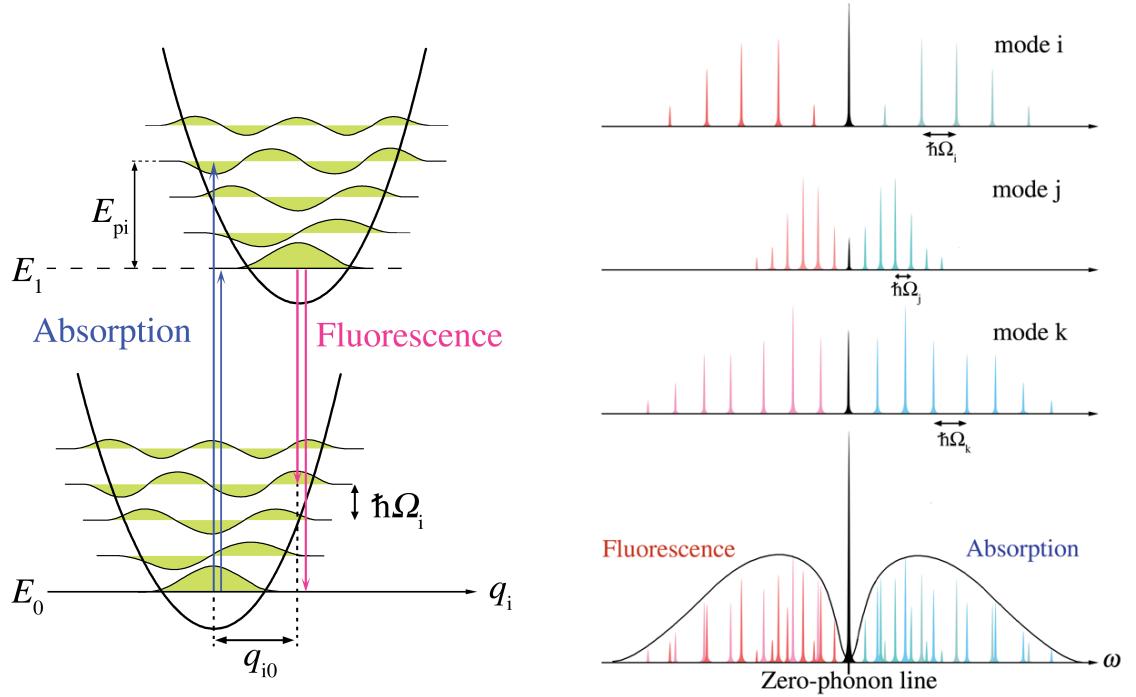


Figure 2.5.: Absorption line shape of an electronic excitation. The emission is mirrored at ω' .

To determine the frequency gap Δ the Franc-Condon principles are used. They state that electronic transition between ground and excited state is much faster than the motion in the lattice. Hence, there is no motion along the configurational coordinates q_i during the energy transitions as depicted in figure 2.6a. The transitions can be displayed as vertical arrows with the shorter arrow describing the ZPL and the longer one describing the PSB. According to the Franc-Condon principles, the more the wave functions of two vibrational energy levels overlap, the likelier is the electronic transition between these two. In the case of figure 2.6a this occurs when the photon energy equals to the energy difference $E_1 - E_0$ plus three quanta of vibrational energy $\hbar\Omega_i$. The emission follows the same principle.



(a) Energy spectrum of a two-level electronic system with phonon coupling. The arrows describe emission/absorption with and without phonons respectively.
(b) Three lattice normal modes (i, j, k) and the resulting emission/absorption spectrum.

Figure 2.6.: Zero-phonon line and phonon sideband. [9]

Figure 2.6a and 2.6b implicitly assume approximations in addition to the Franck-Condon principles. The lattice vibrational mode has to be well described by a quantum harmonic oscillator. Additionally, it is assumed that only the lowest lattice vibration is excited and that the harmonic oscillator potentials are equal in both states. These preconditions are visible in the equally parabolic shaped potential wells and equally spaced phonon energy levels in figure 2.6a.

The zero-phonon line is stronger than the phonon side band because of the superposition of the lattice modes. Each lattice mode m lead to a different energy difference $\hbar\Omega_m$ between phonons. That is why the transitions with phonons result in a energy distribution and the zero-phonon transition add at the electronic origin $E_1 - E_0$.

The theoretical limit of the spectral range of the zero-phonon line for a GaAs quantum dot can be calculated with the time-energy uncertainty relation

$$\Delta E \cdot \Delta t = \frac{\hbar}{2\pi} \quad (2.1)$$

This gives for typical lifetime of a GaAs quantum dot of $\Delta t = 250 \text{ ps}$

$$\Delta E = 2.64 \mu\text{eV}. \quad (2.2)$$

The frequency uncertainty can be obtained through

$$\Delta\nu = \frac{\Delta E}{h}. \quad (2.3)$$

The wavelength λ relates to ν with the Planck-Einstein relation

$$\lambda(\nu) = \frac{c}{\nu} \quad (2.4)$$

and the wavelength uncertainty $\Delta\lambda$ can be approximated with a Taylor series around ν_0

$$\Delta\lambda = -\lambda'(\nu_0) \cdot \Delta\nu. \quad (2.5)$$

With equation (2.3) and the center wavelength of the zero-phonon line λ_0 in table 2.1 this gives

$$\Delta\lambda = \frac{c}{\nu_0^2} \cdot \Delta\nu = \frac{\lambda_0^2}{c} \cdot \Delta\nu \quad (2.6)$$

$$\approx 1.0 \text{ pm} \quad (2.7)$$

Reorganize

Table 2.1.: Parameters of GaAs quantum dots used in the laboratory of semiconductor physics department in Linz. Zero-phonon line calculates from the theoretical limit according to the life time of the excitonic state (as can be seen in equation (2.7)) up to broader lines which are still valued enough to be measured. The phonon sideband resembles data taken from Schöll et al. [10].

Quantum dot emission	Center wavelength λ_0	Spectral range $\Delta\lambda$	Waveform
Zero-phonon line	(700 to 800) nm	(1.0 to 1.4) pm	Cauchy
Phonon sideband	~0.25 nm higher than zero-phonon line	500 pm	Gauss

The zero-phonon line is described with a Cauchy distribution

$$\Phi_{dot,zero}(\lambda) = \frac{1}{\pi \cdot \Delta\lambda_{zero} \cdot 0.5 \left[1 + \left(\frac{\lambda - \lambda_{0,zero}}{\Delta\lambda_{zero} \cdot 0.5} \right)^2 \right]} \quad (2.8)$$

with $\lambda_{0,zero}$ as the center wavelength and $\Delta\lambda_{zero}$ as the spectral range of the zero-phonon line.

The phonon side band is described with a Gauss distribution

$$\Phi_{dot,side}(\lambda) = \frac{1}{\sqrt{2 \cdot \pi \cdot \Delta\lambda_{side}^2}} \cdot \exp \left(-\frac{(\lambda - \lambda_{0,side})^2}{2 \cdot \Delta\lambda_{side}^2} \right) \quad (2.9)$$

2. Droplet etched gallium arsenide quantum dots

with $\lambda_{0,side}$ as the center wavelength and $\Delta\lambda_{side}$ as the spectral range of the phonon side band.

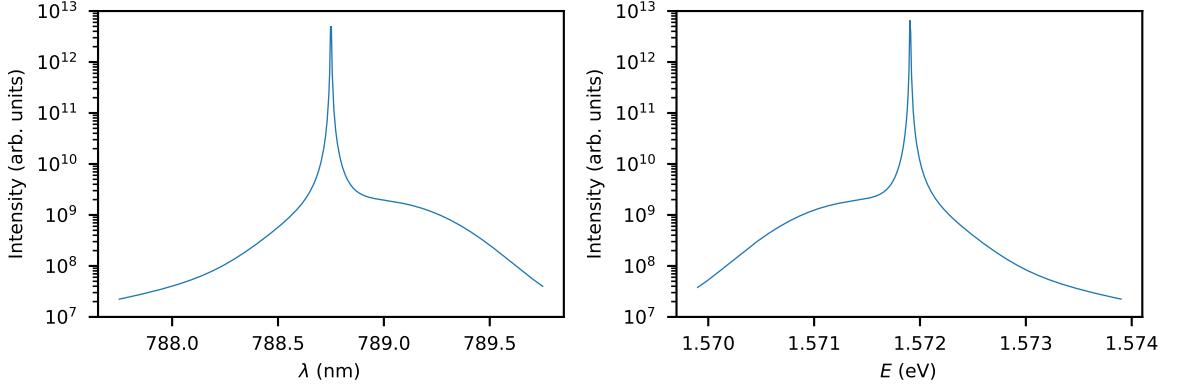


Figure 2.7.: Simulated exciton emission of a GaAs quantum dot plotted dependant on the wavelength λ and the Energy E . The parameters can be found in table 2.1.

2.4. Optical excitation of a quantum dot

In this section, the different ways of optically exciting QDs are discussed. It is based on the PhD thesis of Huber [1] and the master's thesis of Schimpf [6]. The excited state of a QD can be populated in various ways. A common way is the above-band excitation, depicted in figure 2.8(a). Electrons are optically excited by a laser with energies above the band gap of the QDs host material $\text{Al}_{0.4}\text{Ga}_{0.6}\text{As}$ with $E_g = 1.92 \text{ eV}$ at room temperature. Subsequently, the electrons are captured by the QDs and relax via phonon-scattering to the lowest energy level, the s-shell. However, above-band excitation is not favourable for entangled photon generation, because of pronounced recapture processes [11] and spin scattering processes [12]. Additionally, indistinguishability of the emitted photons is reduced because of carrier-relaxation-induced time-jitter and fluctuating electric fields. As this team is interested in extracting entangled X/XX photon pairs, above-band is more than often not the best exciting technique of GaAs QDs. Resonant excitation of electron-hole pairs provides an alternative without the disadvantages of above-band excitation. As shown in figure 2.8(b) this technique creates electron-hole-pairs directly in the s-shell.

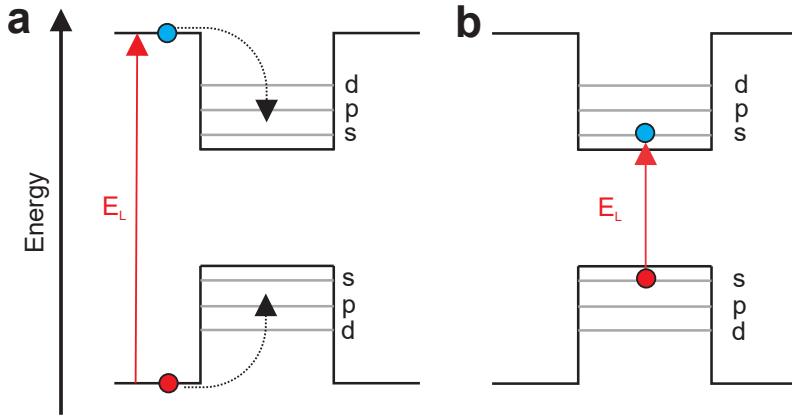


Figure 2.8.: Optical pumping of a QD by (a) above-band excitation and (b) resonant excitation [1]

Due to dipole-selection rules, resonant population of the $|XX\rangle$ state requires a two-photon-absorption process. Hereby, the energy of a femtosecond-pulse laser E_p is tuned to exactly the half of the XX energy with respect to the ground energy E_{XX} , as sketched in figure 2.9a. Because of coulomb interaction two times the X energy with respect to the ground energy $2 \cdot E_X$ is not equals E_{XX} but differs by the binding energy E_B . The laser is therefore tuned to

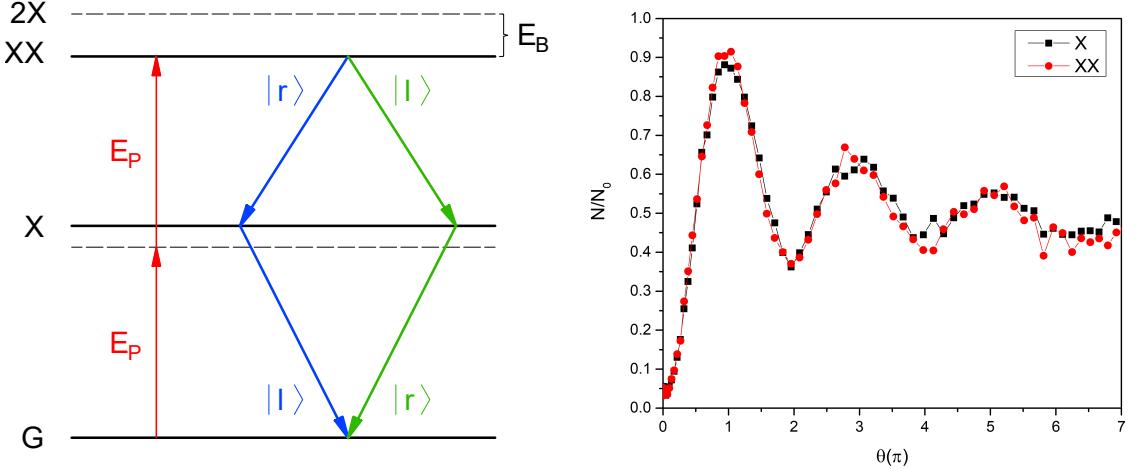
$$E_p = E_X - E_B/2 \quad (2.10)$$

Empirically $E_B \approx 3.78$ meV for GaAs QDs. Resonant two-photon absorption is a third-order non-linear effect which involves two photons and electrons at once. It depends on the third-order-susceptibility $\chi^{(3)}$ of GaAs and therefore requires relatively high laser power.

As this two-level system is driven in resonance its population exhibits Rabi oscillations. The final population of the XX can be described by

$$N_{XX} = \sin^2\left(\frac{\theta}{2}\right) \quad (2.11)$$

with θ as the pulse area in relation to the Rabi oscillations. θ is not the area of the excitation pulse, but depends on it in a non-trivial way [13]. Measured Rabi oscillations of X and XX are shown in figure 2.9b [14]. Theoretically, the curve should oscillate between occupancies N/N_0 of 0 and 1. However, as a consequence of phonon damping the occupancy converges to a purely probabilistic value of 0.5 [15].



(a) Resonant two photon excitation of XX. The laser is tuned to $E_P = E_{XX}/2$. (b) Rabi oscillations of X and XX as a function of the pulse area θ . N/N_0 is the occupancy and N_0 the maximum population.

Figure 2.9.: Resonant two photon excitation [6]

2.5. Single photon emission

The XX-X cascade shown in figure 2.9a results in a single photon pair per emission cycle. Single photons are necessary for quantum cryptography and quantum optics in general which motivates the following discussion of this topic based on the thesis of Huber [1]. The single photon purity of the $|XX\rangle$ to $|X\rangle$ and the $|X\rangle$ to $|G\rangle$ signals, respectively, can be determined by performing a Hanbury-Brown-Twiss (HBT) experiment. A HBT setup is shown in figure 2.10a and it allows to measure the second-order correlation function, which is defined as

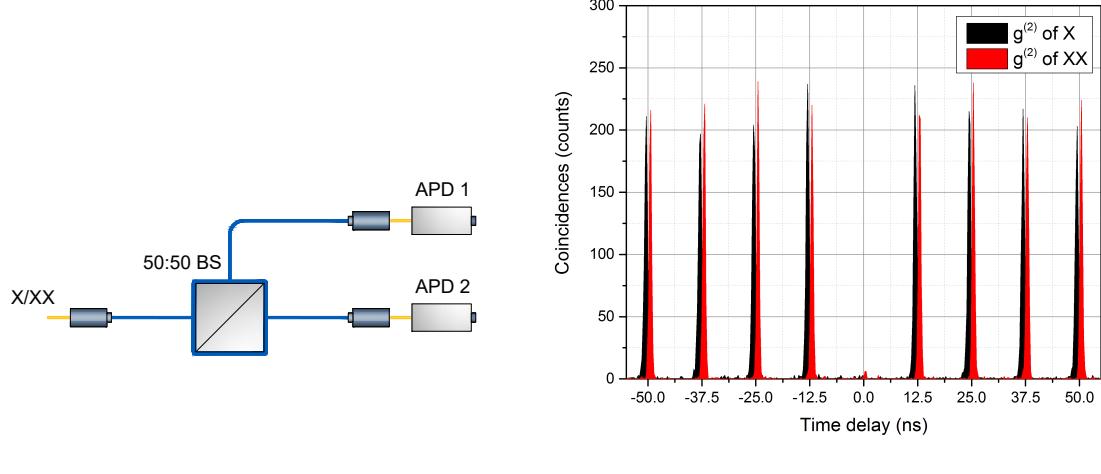
$$g^{(2)} = \frac{\langle I(t)I(t+\tau) \rangle}{\langle I(t) \rangle \langle I(t+\tau) \rangle} \quad (2.12)$$

with $I(t)$ as the light intensity and τ as the time delay. When a single photon enters the input of the beam splitter (BS) it can only be measured at one output, but never at both simultaneously. Assuming a perfect single photon emitter, a coincidence measurement between APD1 and APD2 will result in $g^{(2)}(\tau) = 0$ at zero time delay. Subsequently, side peaks are expected correlated to the repetition rate R of the laser by $\tau_s = z/R$ with $z \in \mathbb{Z} \setminus \{0\}$. The single photon purity can then be defined as

$$\kappa(b) = \frac{A_0(b)}{A_s(b)} \quad (2.13)$$

2.5. Single photon emission

with A_0 as the area under $g^{(2)}(\tau)$ around $\tau = 0$ and A_s as the average area under the side peaks at τ_s . The time bin b has to be chosen so that it includes a full side peak. If b would be chosen too small it would falsely increase κ , if chosen too high it includes unnecessary much noise.



(a) Setup to measure to measure the Hanbury-Brown-Twiss effect.

(b) Second-order auto-correlation function $g^{(2)}$ of X and XX.

Figure 2.10.: Hanbury-Brown-Twiss HBT experiment [6]

3. Entangled photon generation using adiabatic rapid passage with frequency-chirped pulses

3.1. Introduction and motivation

3.2. Chirp

A chirped signal is a signal which frequency changes over time. For example, in a linear-frequency chirp the frequency $f(t)$ would change over time as

$$f(t) = ct + f_0 \quad (3.1)$$

where f_0 is the starting frequency at $t = 0$ and c is the chirpiness. A linear chirped sinusoidal wave is depicted in figure 3.1.

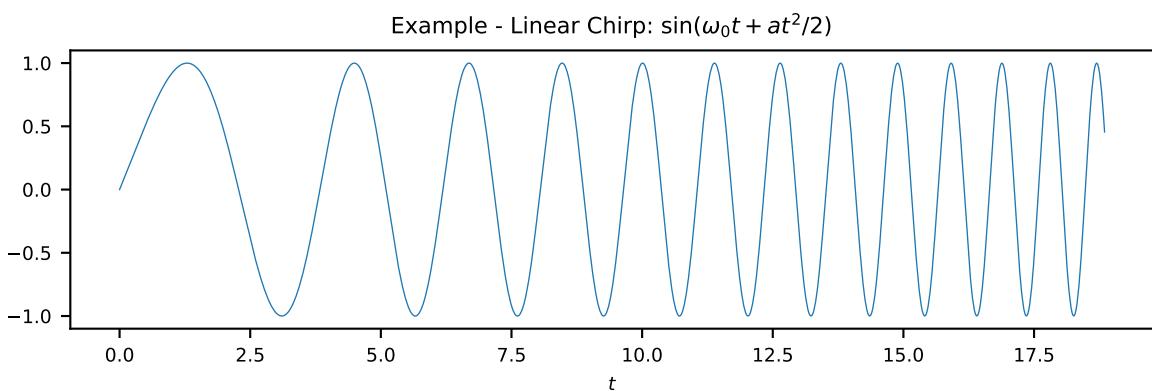


Figure 3.1.: A chirped sinusoidal wave which increases in frequency over time.

As this chapter is concentrated on exciting QDs with frequency-chirped pulses, the mathematical description of chirped laser pulses will now be discussed. The electric field of a laser $E(t)$ has the shape

$$E(t) \sim \text{Re} \left(f^{1/2}(t) \cdot \exp(-i\omega t - i\phi(t)) \right) \quad (3.2)$$

with the central frequency ω and the linear chirp $\phi(t)$.

Depending on the laser either a Gaussian or a hyperbolic secant describes the pulse shape more accurately [16, 17]

- Gaussian pulse:

- Pulse shape of

$$f_{gauss}(t) = \left(\frac{A_{gauss}}{\sqrt{2 \cdot \pi \cdot \tau_0 \cdot \tau}} \exp\left(-\frac{t^2}{2 \cdot \tau^2}\right) \right)^2$$

with the normalization constant A_{gauss} , the pulse duration τ_0 , the central frequency ω and the chirp coefficient α .

- Linear chirp of

$$\phi_{gauss}(t) = \frac{a_{gauss} t^2}{2}$$

- Secant pulse:

- Pulse shape of

$$f_{secant}(t) = A_{secant} \cdot \operatorname{sech}^2\left(\frac{t}{\tau_0}\right) = A_{secant} \cdot \left(\frac{2}{\exp(\frac{t}{\tau_0}) + \exp(-\frac{t}{\tau_0})} \right)^2$$

with the normalization constant A_{secant} , the pulse duration τ_0 , the central frequency ω and the chirp coefficient α .

- Linear chirp of

$$\phi_{secant}(t) = a_{secant} \left(\frac{t}{\tau_0} \right)^2$$

where $\tau = \sqrt{\alpha^2 / \tau_0^2 + \tau_0^2}$ characterizes the chirped pulse length and $a = \alpha / (\alpha^2 + \tau_0^4)$ is the frequency chirp rate.

3.3. Adiabatic rapid passage

One way to inverse the QD from the ground state to the biexciton state is by exciting it with a transform-limited laser pulse of constant center frequency, which is equals to half of the ground state

biexciton transition frequency. However, in order to ensure the inversion precise control of the field intensity is required [16]. Adiabatic rapid passage (ARP) with frequency chirped is an alternative to this Rabi-flopping scheme. Basically, the goal is to adiabatic state from ground state to biexciton state without energy-level crossing [18]. Schemes which provide that, are also stable with respect to intensity changes of the laser field.

In order to calculate the final biexciton occupation, Glässl et al. [16] assumed linearly-chirped Gaussian laser pulse as discussed in section 3.2. The simulation results are visible in figure 3.2.

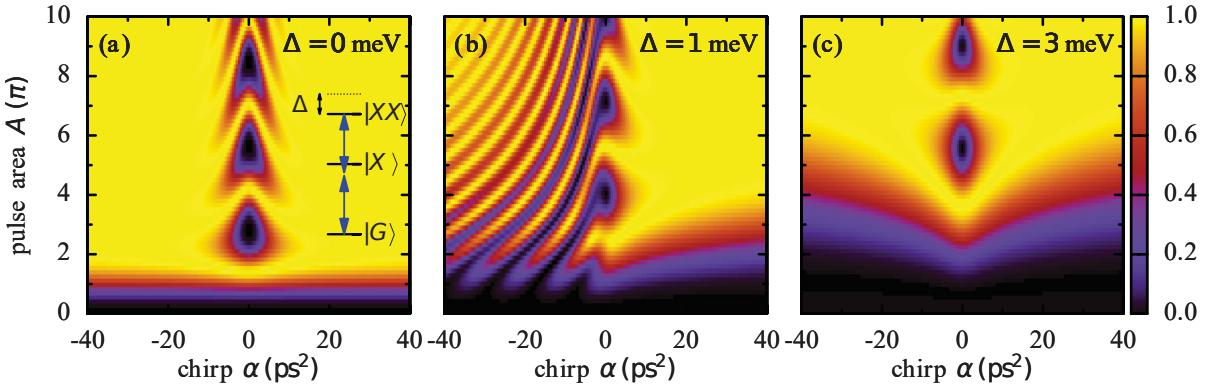


Figure 3.2.: Final biexciton occupation after chirped Gaussian pulse of pulse duration $\tau_0 = 2$ ps. It is plotted vertically as a function of the original pulse area A and vertically as a function of the chirp α for biexciton binding energies of (a) $\Delta = 0$, (b) 1, and (c) 3 meV [16].

The central frequency is chosen so that for $\alpha = 0$ it resonates to ground state biexciton transition, which is sketched in figure 3.2. For $\alpha = 0$ Rabi oscillations are visible and its period depends strongly on the biexciton binding energy Δ . However, for $\alpha \gg 0$ biexciton preparation becomes insensitive to small variations to the pulse area A as long it exceeds a certain threshold. For $\alpha < 0$ this fails for moderate values of Δ as can be seen in figure 3.2(b).

3. Entangled photon generation using adiabatic rapid passage with frequency-chirped pulses

3.4. Interferometric autocorrelation

3.5. Modified-spectrum autointerferometric correlation

3.6. Adiabatic rapid passage

3.7. Simulation

3.8. Measurements and discussion

4. Building up a scanning Fabry-Pérot interferometer from scratch

4.1. Introduction and motivation

The Fabry Pérot interferometer (FPI) is an optical resonator developed by Charles Fabry and Alfred Pérot. An incoming light beam will only be transmitted through the resonator consisting of two semi-transparent mirrors if it fulfils the resonance condition.[19]

Goal: Resolve
QD emission
line.

4.2. Transverse modes of electromagnetic radiation

4.2.1. Gaussian beam

In this subsection, light beams are described by the wave picture according to Meschede [20]. They fulfil the Maxwell equations and therefore their electric field $\mathbf{E}(\mathbf{r}, t)$ fulfils the wave equation

$$\left(\nabla^2 - \frac{1}{c^2} \frac{\partial}{\partial t^2} \right) \mathbf{E}(\mathbf{r}, t) = 0. \quad (4.1)$$

Along the propagation direction z a light beam behaves similarly to a plane wave with constant amplitude A_0 which is a known solution to the wave equation (4.1)

$$E(z, t) = A_0 e^{-i(\omega t - kz)}. \quad (4.2)$$

However, far from its source light is expected to behave like a spherical wave

$$E(\mathbf{r}, t) = A_0 \frac{e^{-i(\omega t - \mathbf{k}\mathbf{r})}}{|\mathbf{k}\mathbf{r}|}. \quad (4.3)$$

4. Building up a scanning Fabry-Pérot interferometer from scratch

To get a better understanding of the propagation of light, only paraxial (near the z-axis) parts of the spherical wave are considered. Additionally, the wave is split into its longitudinal (z-axis) part and its transversal part and beams with axial symmetry are assumed, which only depend on a transversal coordinate ρ . Under these circumstances \mathbf{kr} can be replaced with kr and because of $\rho \ll r, z$ the Fresnel approximation can be applied:

$$E(\mathbf{r}) = \frac{A(\mathbf{r})}{|\mathbf{kr}|} e^{i\mathbf{kr}} \simeq \frac{A(z, \rho)}{kz} \exp\left(i\frac{k\rho^2}{2z}\right) e^{ikz} \quad (4.4)$$

with $r = \sqrt{z^2 + \rho^2} \simeq z + \rho^2/2z$.

Equation (4.4) resembles the plain wave in equation (4.2), with the spacial phase transversally modulated by $\exp(ik\rho^2/2z)$. Another spherical wave solution can be obtained by applying the following replacement (z_0 is a real number)

$$z \rightarrow q(z) = z - iz_0. \quad (4.5)$$

Thereby, the fundamental (or TEM₀₀) Gaussian mode has been constructed

$$E(z, \rho) \simeq \frac{A_0}{kq(z)} \exp\left(i\frac{k\rho^2}{2q(z)}\right) e^{ikz}. \quad (4.6)$$

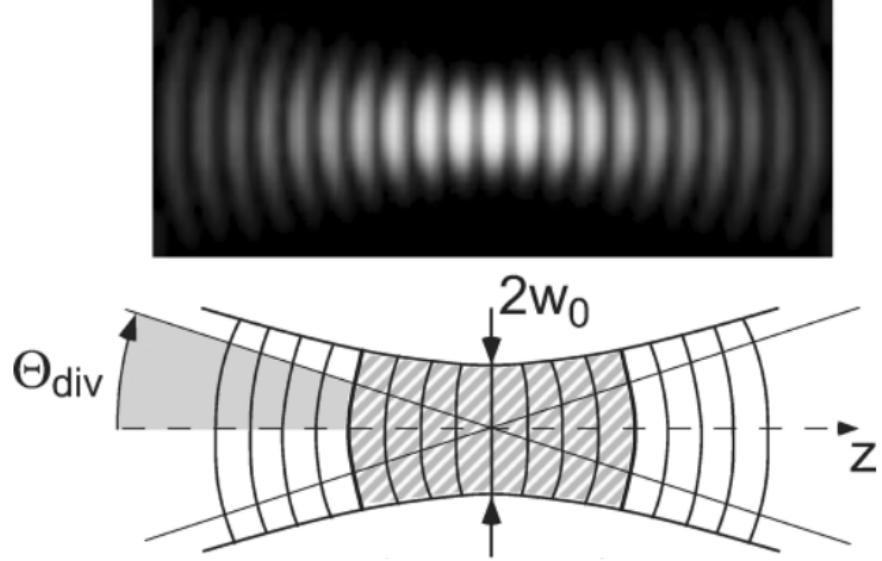


Figure 4.1.: A Gaussian beam near its beam waist. Near the center they resemble plan wave fronts, while outside they converge towards spherical wave fronts. Their Rayleighzone is shaded at the lower part of the figure.[20]

The electrical and magnetical fields of gauss modes are transversal to its propagation direction. These waveforms are called transversal elctrical and magnetic modes with indices (m, n) . Its fundamental solution is the TEM₀₀-Mode, which is the most important one and will therefore be examined in more detail in the rest of this subsection.

By executing the replacement $q(z) \rightarrow z - iz_0$ explicitly the equation (4.6) can be expressed as

$$\frac{1}{q(z)} = \frac{z + iz_0}{z^2 + z_0^2} = \frac{1}{R(z)} + i \frac{2}{k\omega^2(z)}, \quad (4.7)$$

with new variables z_0 , $R(z)$ and $\omega(z)$ being introduced. With the decomposition of the Fresnel factors into real and imaginary part, two factors can be identified: one complex phase factor, which describes the curvature of the wavefronts and a real factor, which describes the envelope of the beam. Therefore, the exponential in equation (4.6) becomes

$$\exp\left(i \frac{k\rho^2}{2q(z)}\right) \rightarrow \exp\left(i \frac{k\rho^2}{2R(z)}\right) \exp\left(-\left(\frac{\rho}{\omega(z)}\right)^2\right) \quad (4.8)$$

For the following description of gauss modes the following parameters have to be introduced

- **Evolving radius of curvature $R(z)$:**

$$R(z) = z(1 + (z_0/z)^2) \quad (4.9)$$

- **Beam waist $2\omega_0$:**

$$\omega_0^2 = \lambda z_0 / \pi \quad (4.10)$$

The beam waist $2\omega_0$ or beam radius ω_0 describe the smallest beam cross section at $z = 0$. If the wave propagates inside a medium with the refractive index n , λ has to be replaced with λ/n . The cross section of the beam waist is then $\omega_0^2 = \lambda z_0 / (\pi n)$.

A Gaussian beam can be completely characterized at every point z on the beam axis either with the parameter couple (ω_0, z_0) or alternatively with the real and imaginary part of $q(z)$. The parameters of the Gaussian beam are transformed by linear operations, which coefficients are identical to those from geometrical optics

$$q_{out} = \frac{Aq_{in} + B}{Cq_{in} + D} \quad (4.11)$$

with the parameters A, B, C, D determined by the optical element transforming the Gaussian beam described by q_{in} .

4.2.2. Higher Gauss modes

The wave equation (4.1) can be simplified, by only allowing monochromatic waves with harmonic time dependence

$$\mathbf{E}(\mathbf{r}, t) = \text{Re} \left(\mathbf{E}(\mathbf{r}) e^{-i\omega t} \right). \quad (4.12)$$

With $\omega^2 = c^2 \mathbf{k}^2$, the *Helmholtz equation* can be deduced, which only depends on the location \mathbf{r}

$$(\nabla^2 + \mathbf{k}^2) \mathbf{E}(\mathbf{r}) = 0. \quad (4.13)$$

In favour of a formal treatment of the Gaussian modes, the Helmholtz equation is splitted into its transversal and longitudinal contribution,

$$\nabla^2 + k^2 = \frac{\partial^2}{\partial z^2} + \nabla_T^2 + k^2 \quad \text{with} \quad \nabla_T^2 = \frac{\partial}{\partial x^2} + \frac{\partial}{\partial y^2}, \quad (4.14)$$

and apply it on the electric field of equation (4.4). It is assumed that the amplitude A only changes slowly in the order of the wavelength,

$$\frac{\partial}{\partial z} A = A' \ll kA, \quad (4.15)$$

which allows the approximation

$$\frac{\partial^2}{\partial z^2} A e^{ik\rho^2/(2z)} \frac{e^{ikz}}{kz} \simeq (2ikA' - k^2 A) e^{ik\rho^2/(2z)} \frac{e^{ikz}}{kz}, \quad (4.16)$$

and results in the *paraxial Helmholtz equation*,

$$\left(\nabla_T^2 + 2ik \frac{\partial}{\partial z} \right) A(\rho, z) = 0. \quad (4.17)$$

The fundamental solution is the TEM₀₀ mode in equation (4.6). Examples of higher modes can be found in figure 4.2.

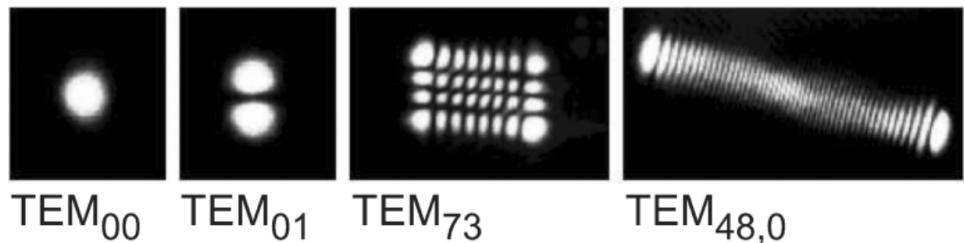


Figure 4.2.: Gaussian modes higher order of a simple Ti-sapphire laser. The asymmetry of the high modes are caused by technical inaccuracies of the resonator elements (mirrors, laser crystal).

4.3. Fundamentals of Fabry-Pérot interferometers

4.3.1. Resonator losses

For the following discussion of the FPI, a two-mirror-resonator with the reflecting surfaces facing each other and air as medium in between is assumed. The theoretical foundation is provided by the work of Ismail et al. [21].

The time the light needs for one roundtrip is given by

$$t_{RT} = \frac{2l}{c} \quad (4.18)$$

where l is the geometrical length of the resonator and c is the speed of light in air.

The photon-decay time τ_c of the interferometer is then given by

$$\frac{1}{\tau_c} = -\frac{\ln(R_1 \cdot R_2)}{t_{RT}} \quad (4.19)$$

where R_1 and R_2 are the corresponding intensity reflectivities of the mirrors.

The number of photons at frequency ν inside the resonator is described by the differential rate equation

$$\frac{d}{dt} \varphi(t) = -\frac{1}{\tau_c} \varphi(t). \quad (4.20)$$

With a number φ_s of photons at $t = 0$ the integration gives

$$\varphi(t) = \varphi_s e^{-t/\tau_c} \quad (4.21)$$

4.3.2. Resonance frequencies, free spectral range and spectral line shapes

The round-trip phase shift at frequency ν is given by

$$2\phi(\nu) = 2\pi\nu t_{RT} = 2\pi\nu \frac{2l}{c} \quad (4.22)$$

where $\phi(\nu)$ is the single-pass phase shift between the mirrors.

Resonances are visible for frequencies ν at which the light interferes constructively after one round trip. Two adjacent resonance frequencies differ in their round trip phase shift by 2π . Hence, the free

4. Building up a scanning Fabry-Pérot interferometer from scratch

spectral range $\Delta\nu_{FSR}$, the frequency difference between two adjacent resonance frequencies, can be calculated from equation (4.28)

$$2\Delta\phi_{FSR} = 2\pi \quad (4.23)$$

$$\Rightarrow 2\pi\Delta\nu_{FSR} \frac{2l}{c} = 2\pi \quad (4.24)$$

$$\Rightarrow \Delta\nu_{FSR} = \frac{c}{2l} \quad (4.25)$$

According to equation (4.21) the number of photons decay with the photon-decay time τ_c . With $E_{q,s}$ representing the initial amplitude, the electric field at ν_q can be given by

$$E_q(t) = \begin{cases} E_{q,s} \cdot e^{i2\pi\nu_q t} \cdot e^{-t/(2\tau_c)} & t \geq 0 \\ 0 & t < 0 \end{cases}. \quad (4.26)$$

The Fourier transformation of the electric field can be expressed as

$$\tilde{E}_q(\nu) = \int_{-\infty}^{\infty} E_q(t) e^{-i2\pi\nu t} dt = E_q(t) \int_0^{\infty} e^{[1/(2\tau_c) + i2\pi(\nu - \nu_q)]t} dt = E_{q,s} \frac{1}{(2\tau_c)^{-1} + i2\pi(\nu - \nu_q)}. \quad (4.27)$$

The normalized spectral line shape per unit frequency is then given by

$$\tilde{\gamma}_q(\nu) = \frac{1}{\tau_c} \left| \frac{\tilde{E}_q(\nu)}{E_{q,s}} \right|^2 = \frac{1}{\tau_c} \left| \frac{1}{(2\tau_c)^{-1} + i2\pi(\nu - \nu_q)} \right|^2 = \frac{1}{\tau_c} \frac{1}{(2\tau_c)^{-2} + 4\pi^2(\nu - \nu_q)^2} \quad (4.28)$$

$$= \frac{1}{\pi} \frac{1/(4\pi\tau_c)}{1/(4\pi\tau_c)^2 + (\nu - \nu_q)^2} \quad (4.29)$$

with $\int \tilde{\gamma}_q(\nu) d\nu = 1$. By defining the full-width-at-half-maximum linewidth (FWHM) $\Delta\nu_c$ we get

$$\Delta\nu_c = \frac{1}{2\pi\tau_c} \Rightarrow \tilde{\gamma}_q(\nu) = \frac{1}{\pi} \frac{\Delta\nu_c/2}{(\Delta\nu_c/2)^2 + (\nu - \nu_q)^2} \quad (4.30)$$

By normalizing the Lorentzian lines so that the peak is at unity we finally obtain

$$\gamma_{q,L}(\nu) = \frac{\pi}{2} \Delta\nu_c \tilde{\gamma}_q(\nu) = \frac{(\Delta\nu_c)^2}{(\Delta\nu_c)^2 + 4(\nu - \nu_q)^2} \quad (4.31)$$

with $\gamma_{q,L}(\nu_q) = 1$.

4.3.3. Airy distribution of Fabry-Pérot interferometers

The response of the FPI is calculated with the circulating-field approach [21], where a steady-state is assumed. E_{circ} is the result of E_{laun} interfering with E_{RT} . E_{laun} is the transmission of the incoming light

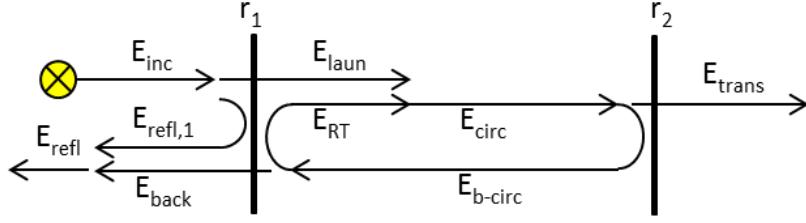


Figure 4.3.: FPI with electric field mirror reflectivities r_1 and r_2 . Indicated in this figure are the electric fields resulting from an incoming E_{inc} , the reflected field $E_{refl,1}$ and transmitted field E_{laun} . E_{circ} and $E_{circ,b}$ circulate inside the resonator, resulting in E_{RT} after one round-trip. E_{back} is the backwards transmitted field.[22]

E_{inc} and E_{RT} is E_{circ} after one round-trip in the resonator, i.e., after the outcoupling losses of mirror 1 and 2. Therefore, the field E_{circ} can be calculated from E_{laun} by

$$E_{circ} = E_{laun} + E_{RT} = E_{laun} + r_1 r_2 e^{-i2\phi} E_{circ} \Rightarrow \frac{E_{circ}}{E_{laun}} = \frac{1}{1 - r_1 r_2 e^{-i2\phi}} \quad (4.32)$$

where r_1 and r_2 are the electric-field reflectivities of mirror 1 and 2.

The generic Airy distribution considers only light inside the mirrors and is defined as

$$A_{circ} = \frac{I_{circ}}{I_{laun}} = \frac{|E_{circ}|^2}{|E_{laun}|^2} = \frac{1}{|1 - r_1 r_2 e^{-i2\phi}|^2} = \frac{1}{(1 - \sqrt{R_1 R_2})^2 + 4\sqrt{R_1 R_2} \sin^2(\phi)} \quad (4.33)$$

by using

$$\begin{aligned} |1 - r_1 r_2 e^{-i2\phi}|^2 &= |1 - r_1 r_2 \cos(2\phi) + ir_1 r_2 \sin(2\phi)|^2 = [1 - r_1 r_2 \cos(2\phi)]^2 + r_1^2 r_2^2 \sin^2(2\phi) \\ &= 1 + R_1 R_2 - 2\sqrt{R_1 R_2} \cos(2\phi) = (1 - \sqrt{R_1 R_2})^2 + 4\sqrt{R_1 R_2} \sin^2(\phi) \end{aligned}$$

and additionally $R_i = r_i^2$ and $\cos(2\phi) = 1 - 2\sin^2(\phi)$.

Commonly, light is sent through the FPI. Therefore the following sections will use the Airy distribution A'_{trans} .

$$A'_{trans} = \frac{I_{trans}}{I_{inc}} = \frac{I_{circ} \cdot (1 - R_2)}{I_{laun} / (1 - R_1)} = (1 - R_1)(1 - R_2) A_{circ} = \frac{(1 - R_1)(1 - R_2)}{(1 - \sqrt{R_1 R_2})^2 + 4\sqrt{R_1 R_2} \sin^2(\phi)} \quad (4.34)$$

A'_{trans} is displayed in figure 4.4 for $R_1 = R_2$. The peak value at one of its resonance frequencies calculates as follows

$$A'_{trans} = \frac{(1 - R_1)(1 - R_2)}{(1 - \sqrt{R_1 R_2})^2} \stackrel{R_1=R_2}{=} 1. \quad (4.35)$$

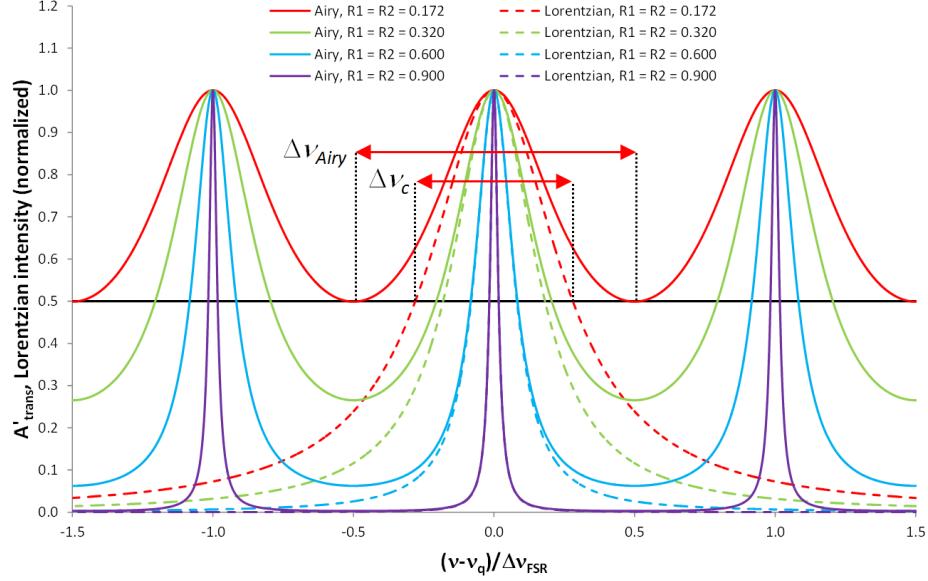


Figure 4.4.: Airy distribution A'_{trans} as described in equation (4.34) compared to the Lorentzian lines $\gamma_{q,L}$ as described in equation (4.31)

4.3.4. Airy linewidth and finesse

The airy linewidth is defined as the full width at half maximum (FWHM) of A'_{trans} . It can be set in relation with the free spectral range $\Delta\nu_{FSR}$ and the mirror reflectivities as follows.

A'_{trans} decreases to half of its peak value at $A'_{trans}(v_q)/2$ when the phase shift ϕ changes by the amount $\Delta\phi$ so that the denominator of A'_{trans} in equation (4.34) is twice as big

$$\left(1 - \sqrt{R_1 R_2}\right)^2 = 4\sqrt{R_1 R_2} \sin^2(\Delta\phi) \quad (4.36)$$

$$\Rightarrow \Delta\phi = \arcsin\left(\frac{1 - \sqrt{R_1 R_2}}{2\sqrt[4]{R_1 R_2}}\right) \quad (4.37)$$

With equation (4.22) and (4.25), the phase shift can be expressed as

$$\phi = \frac{\pi\nu}{\Delta\nu_{FSR}} \quad (4.38)$$

$$\Rightarrow \Delta\phi = \frac{\pi(\Delta\nu_{Airy}/2)}{\Delta\nu_{FSR}}. \quad (4.39)$$

Therefore, with equation (4.37) and (4.39) the FWHM linewidth is given by

$$\Delta\nu_{Airy} = \Delta\nu_{FSR} \frac{2}{\pi} \arcsin\left(\frac{1 - \sqrt{R_1 R_2}}{2\sqrt[4]{R_1 R_2}}\right). \quad (4.40)$$

The finesse of the Airy distribution of a FPI is defined as

$$F_{\text{Airy}} := \frac{\Delta\nu_{\text{FSR}}}{\Delta\nu_{\text{Airy}}} = \frac{\pi}{2} \left[\arcsin \left(\frac{1 - \sqrt{R_1 R_2}}{2 \sqrt[4]{R_1 R_2}} \right) \right]^{-1} \quad (4.41)$$

and is therefore only dependent on the mirror reflectivities R_1 and R_2 .

The Airy finesse is the determining property when it comes to the spectral resolution of the FPI. This can be made visible by comparing its message with the Taylor criterion for the resolution of two adjacent peaks. The Taylor criterion proposes that two spectral lines are resolvable when the separation of the maxima is greater than the FWHM. As displayed in figure 4.5, the Airy finesse is equal to the number of Airy distributions originating from light at certain frequencies ν_m which do not overlap at a point higher than half of their maxima. Hence, the Airy finesse describes the spectral resolution in a way that is consistent with the Taylor criterion.

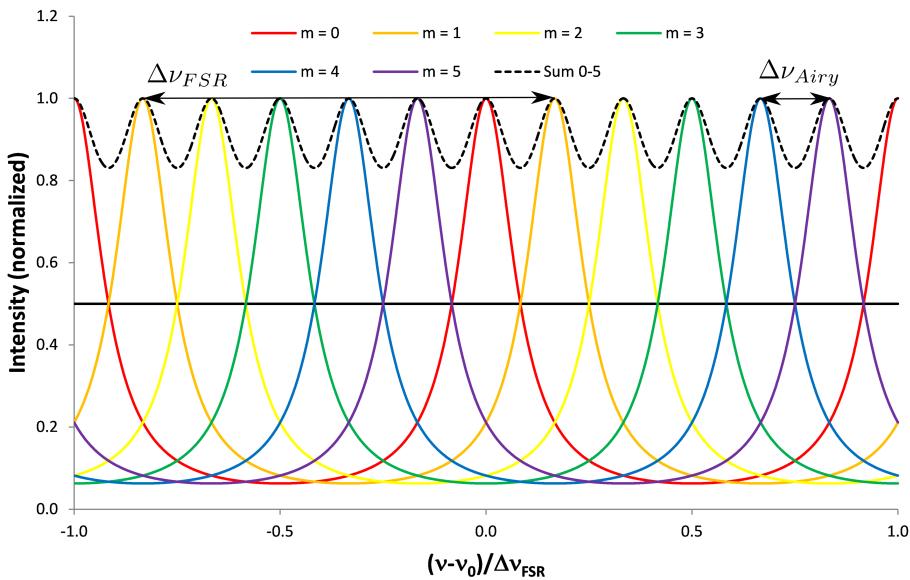


Figure 4.5.: Demonstration of the physical meaning of the Airy finesse F_{Airy} . The coloured lines are Airy distributions created by light at distinct frequencies ν_m , while scanning the resonator length. When the light occurs at frequencies $\nu_m = \nu_q + m\Delta\nu_{\text{Airy}}$, the adjacent Airy distributions are separated from each other by ν_{Airy} , therefore fulfilling the Taylor criterion. Since in this example $F_{\text{Airy}} = 6$ exactly six peaks fit inside the free spectral range. As can be seen in the figure the Airy finesse F_{Airy} quantifies the maximum number of peaks that can be resolved. [22]

4.3.5. Mode matching and spatial filtering

One fundamental challenge of Fabry Pérot interferometry is how to efficiently couple an incident beam of light into a given mode of the resonator. The following discussion is based on the work of Yariv, Yeh, and Yariv [23] and Meschede [20].

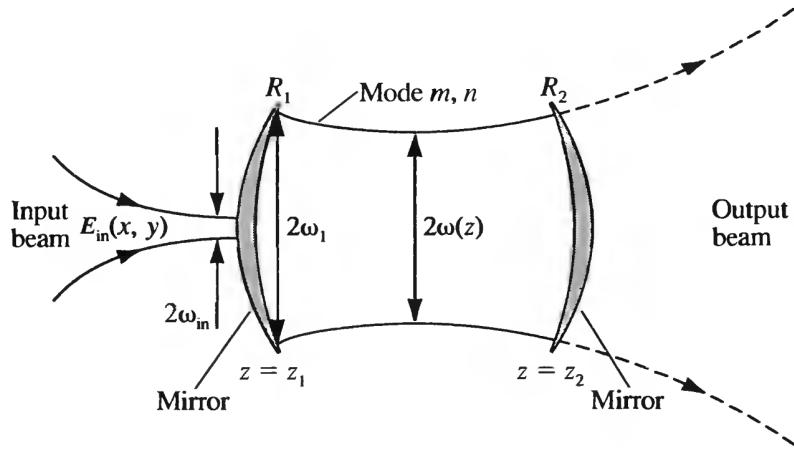


Figure 4.6.: Incident monochromatic beam of light exciting transverse mode m, n of a resonator [23]

In accordance with figure 4.6, an input beam E_{in} propagates into the resonator and potentially excite its modes $E_{mn}(x, y)$, where m, n are the transverse mode integers of the Gaussian beam of the optical resonator. Since $E_{mn}(x, y)$ describes a complete orthogonal set of wavefunctions they satisfy

$$\iint E_{mn}(x, y) E_{m'n'}^*(x, y) dx dy = 0 \quad \text{unless } m = m' \text{ and } n = n'. \quad (4.42)$$

and

$$E_{in}(x, y) = \sum_{mn} a_{mn} E_{mn}(x, y) \quad (4.43)$$

where a_{mn} are constants. By multiplying both sides of equation (4.43) with E_{mn}^* , integrating over the whole x - y -plane and using equation (4.42), the following expression can be obtained

$$a_{mn} = \frac{\iint E_{in}(x, y) E_{mn}^*(x, y) dx dy}{\iint E_{mn}(x, y) E_{mn}^*(x, y) dx dy} \quad (4.44)$$

The efficiency of coupling an incident field into a spatial mode E_{mn} is defined as

$$\eta_{mn} = \frac{\text{Power coupled into mode } mn}{\text{Total incident power}} = \frac{\iint |a_{mn} E_{mn}(x, y)|^2 dx dy}{\iint |E_{in}(x, y)|^2 dx dy}. \quad (4.45)$$

By inserting equation (4.44) into equation (4.45) the following expression can be obtained

$$\eta_{mn} = \frac{|\iint E_{in}(x,y)E_{mn}^*(x,y)dx dy|^2}{\iint |E_{in}(x,y)|^2 dx dy \cdot \iint |E_{mn}(x,y)|^2 dx dy}. \quad (4.46)$$

From equation (4.46) can be deduced, that for an input beam with the *same* spatial dependency as the mode to be excited

$$E_{in}(x,y) \sim E_{mn}(x,y) \quad (4.47)$$

all of the incident power goes into E_{mn} , i.e. $\eta_{mn} = 1$ and all other $\eta_{m'n'}$ are zero. Usually the fundamental TEM₀₀ mode is desired and equation (4.46) implies that a pure Gaussian beam excites only the fundamental mode and the interferometer will then irradiate a pure Gaussian beam as well. In practise, additional measures are necessary such as matching the radius of curvature by Gaussian beam focusing.

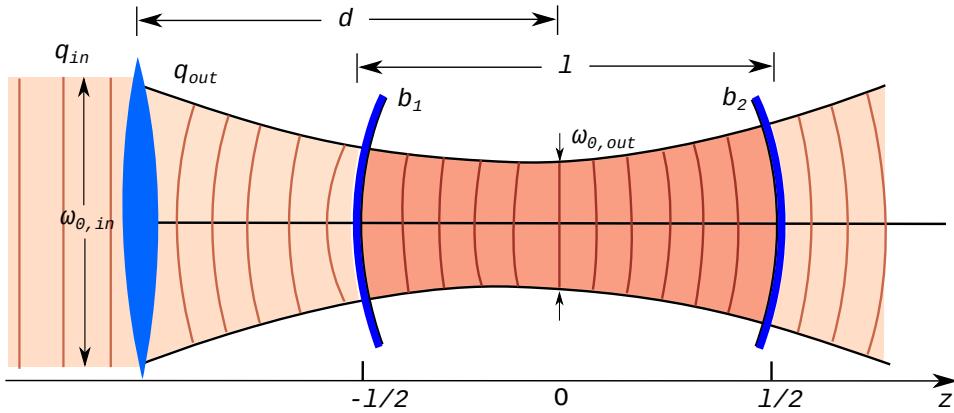


Figure 4.7.: Mode matching of an Gaussian beam into a Fabry Pérot interferometer. Incoming Gaussian beam described by q_{in} transformed by a lens into a Gaussian beam described by q_{out} . The parameters b_1 and b_2 describe the radii of the two mirrors.

In order to match the radius of curvature of the incoming Gaussian beam with the radius of curvature of the resonator a lens is inserted as depicted in figure 4.7. Light with a beam waist of ω_{01} gets focused into the resonator. Transformations by thin lenses can be described with the ABCD-rule introduced in subsection 4.2.1:

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ \frac{-1}{f} & 1 \end{pmatrix} \quad (4.48)$$

with f as the wavelength of the lens. The incoming beam described by q_{in} is transformed by the lens into a beam described by q_{out} according to equation (4.10) and (4.11)

$$q_{in} = z + i \frac{\pi n \omega_{0,in}^2}{\lambda} \quad \text{and} \quad q_{out} = \frac{q_{in}}{q_{in} \cdot \frac{-1}{f} + 1} = z + i \frac{\pi n \omega_{0,out}^2}{\lambda} \quad (4.49)$$

4. Building up a scanning Fabry-Pérot interferometer from scratch

with $n \approx 1$ for air. Together with equation (4.10) to following relation can be deduced

$$\omega_{0,out}^2 = \frac{\omega_{0,in}^2}{\left(1 - \frac{z}{f}\right)^2 + \left(\frac{\pi\omega_{0,in}}{\lambda f}\right)^2} \quad (4.50)$$

The radii of curvature have to match. For given mirrors (described by R_{mirror}) and lens (described by f) the input beam waist has to be adjusted according to equation (4.9) and (4.10)

$$R_{mirror} \stackrel{!}{=} R_{gauss}(z = l/2) \quad (4.51)$$

$$R_{mirror} \stackrel{!}{=} \frac{l}{2} \left(1 + \left(\frac{2z_{0,out}}{l}\right)^2\right) \quad (4.52)$$

$$R_{mirror} \stackrel{!}{=} \frac{l}{2} \left(1 + \left(\frac{2\omega_{0,out}^2 \pi}{l\lambda}\right)^2\right). \quad (4.53)$$

Inserting equation (4.53) into equation (4.50) results in the condition for mode matching

$$R_{mirror} = \frac{l}{2} \left(1 + \left(\frac{2\omega_{0,in}^2 \pi}{\left(\left(1 - \frac{z}{f}\right)^2 + \left(\frac{\pi\omega_{0,in}}{\lambda f}\right)^2\right) l\lambda}\right)^2\right). \quad (4.54)$$

One way to further suppress higher modes is *spatial filtering*. It can be seen in figure 4.2 that the effective area of a mode increases with its order (m, n). Figure 4.8 shows one way to suppress higher modes consisting of a focusing lens and a pin hole which diameter TEM₀₀ mode.

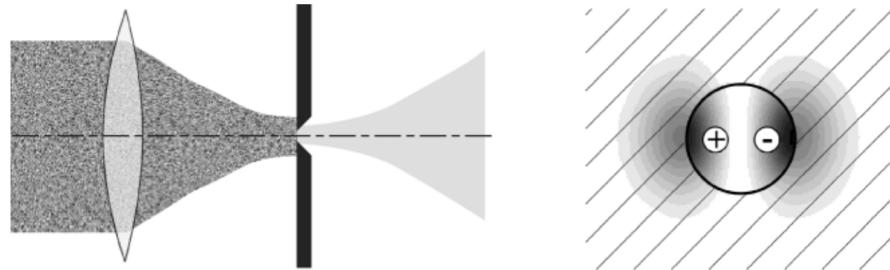


Figure 4.8.: Spatial filtering of Gauss modes. In front of the aperture, the beam consists of a superposition of multiple Gauss modes. In the example of TEM₀₁ is displayed, how higher modes are suppressed by the aperture. [20]

4.3.6. Confocal setup

If the incoming beam would represent a perfect TEM₀₀ mode, spatial filtering would not be necessary and mode matching wouldn't have to be done as precise. Unfortunately, this can not always be

guaranteed and mode matching plus spatial filtering is tedious and error prone. Arranging the mirrors of a FPI into a confocal arrangement reduces the need for these measures. By giving up the ability to choose different free spectral ranges with a given pair of mirrors, the confocal setup liberates from mode matching considerations as the cavity is mode degenerate, i.e the frequency of certain axial and transverse cavity modes are the same. The following discussion is based on Hercher [24].

A quasi-monochromatic beam of wavelength λ_0 is composed of transverse modes TEM_{mnq} , where the subscripts m and n denote the amplitude distribution of the normal mode on a surface of constant phase and q the number of axial modes inside the resonator. Each of these modes resonates for mirror separations satisfying

$$l = \frac{\lambda_0}{2} \{q + (1 + m + n) \cos^{-1} [(1 - l/b_1)(1 - l/b_2)]^{1/2}\} \quad (4.55)$$

where the parameters b_1 and b_2 describe the radii of the two mirrors as can be seen in figure 4.7.

For the confocal setup $l = b_1 = b_2$ which justifies the approximation

$$l \approx \frac{\lambda_0}{2} [q + (1 + m + n)]. \quad (4.56)$$

The modes resonate at mirror separations of either

$$l = \frac{\lambda_0}{2}(p + 1) \quad p \in \mathbb{N} \text{ and } (m + n) \text{ even,} \quad (4.57)$$

$$l = \frac{\lambda_0}{2}(p) \quad p \in \mathbb{N} \text{ and } (m + n) \text{ odd.} \quad (4.58)$$

If mode matching is not executed, it can be assumed that the incoming beam consists of an approximately equal number of even and odd transverse modes. The resonance cavity length l does not depend on n, m and q anymore but only on one integer p . The transversal modes are degenerate and fulfil

$$l = \frac{\lambda_0 p}{2}. \quad (4.59)$$

It can be additionally concluded from equation (4.59), that a change of $\lambda_0/2$ in the mirror separation scans through one free spectral range.

4.4. Simulation

The goal in building up a scanning Fabry Pérot interferometer is to resolve features of the emission spectra of GaAs quantum dots described in chapter 2. More precisely, it is intended to resolve the

4. Building up a scanning Fabry-Pérot interferometer from scratch

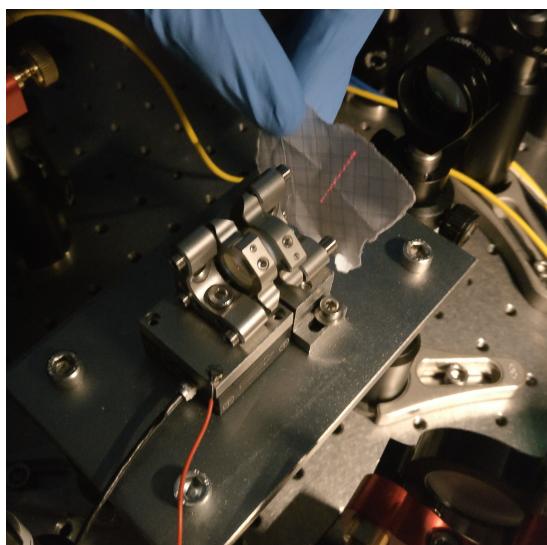
shape of the ZPL and the PSB. Equation 4.41 shows that the finesse is constant for a given pair of mirrors. When the spectrum to be resolved is broad a higher free spectral range $\Delta\nu_{FSR}$ has to be chosen, under the loss of resolution. When the spectrum contains fine details which need to be resolved a lower ν_{Airy} has to be chosen, which results in a lower free spectral range $\Delta\nu_{FSR}$. Hence, the thin ZPL and the broad PSB can not be resolved with the same setup. Instead, the mirror distances have to be adjusted and in the confocal setup discussed in subsection 4.3.6 the mirrors have to be exchanged as well.

4.5. Setup

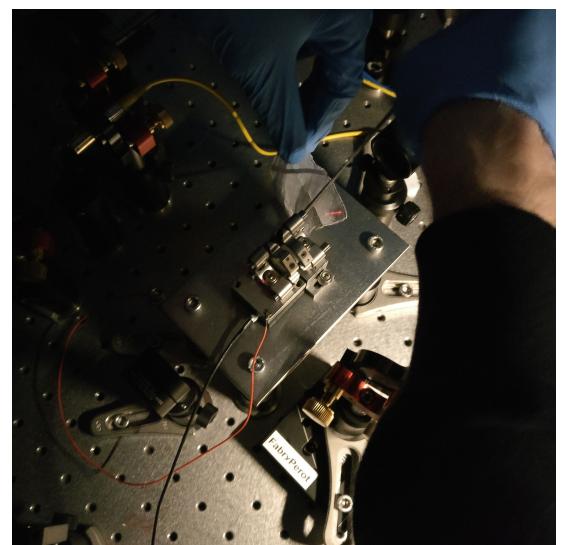
4.5.1. Flat mirrors

4.5.2. Concave mirrors

4.5.3. Confocal setup



(a)



(b)

Figure 4.9.: Fabry Pérot interferometer

4.6. Measurements and discussion

5. Summary and conclusion

6. Outlook

Appendix

Appendix A.

Acronyms

QD	quantum dot	3
GaAs	gallium arsenide.....	3
Al	aluminium	3
MBE	molecular beam epitaxy	3
CB	conduction band.....	3
VB	valence band	3
X	exciton	4
XX	biexciton	4
FSS	fine structure splitting	
ZPL	zero phonon line	7
PSB	phonon side band	7
HBT	Hanbury-Brown-Twiss	12
BS	beam splitter	12
FPI	Fabry Pérot interferometer	19
FWHM	full width at half maximum.....	26
ARP	adiabatic rapid passage	

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