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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**

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Usually, this the abstract is written when the whole thesis text is finished.



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# 1. Introduction

## 1.1. Setup

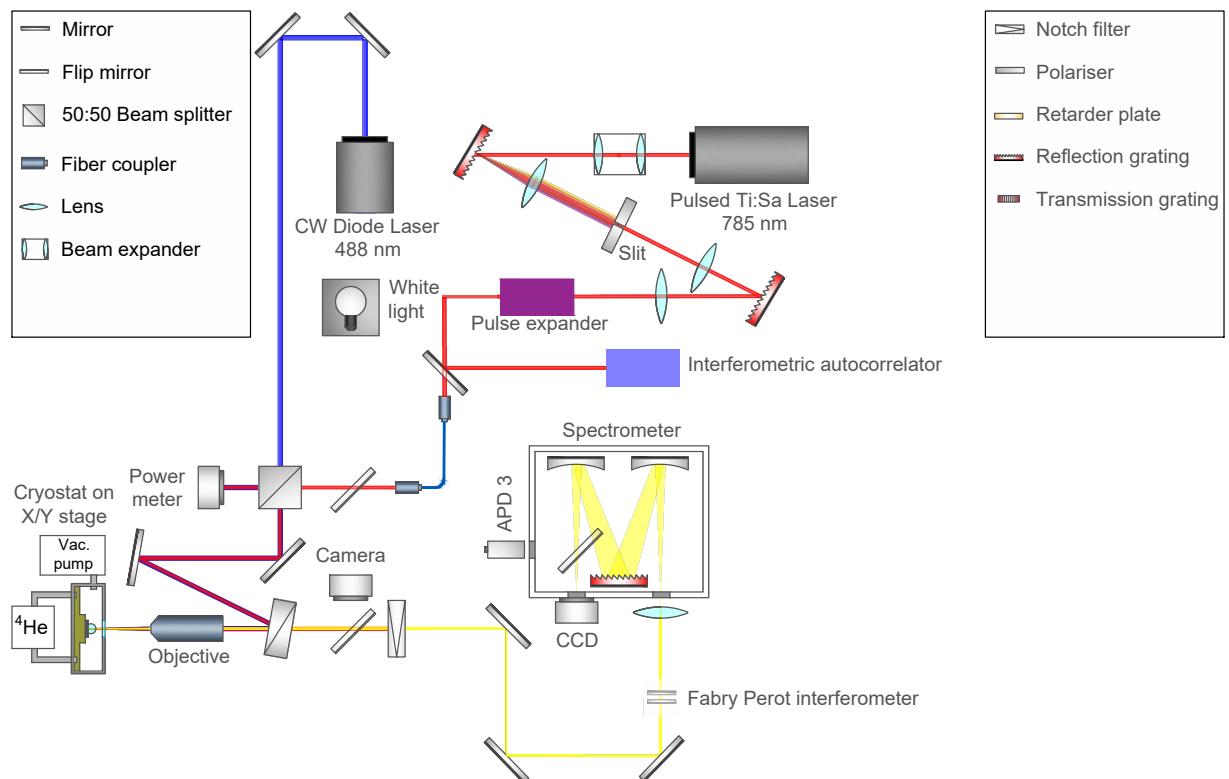


Figure 1.1.: Complete experimental setup, which was used in order to quantify the chirp of the Ti:Sa Laser and resolve spectral emission of a quantum dot.



## 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 ( $XX$ ).

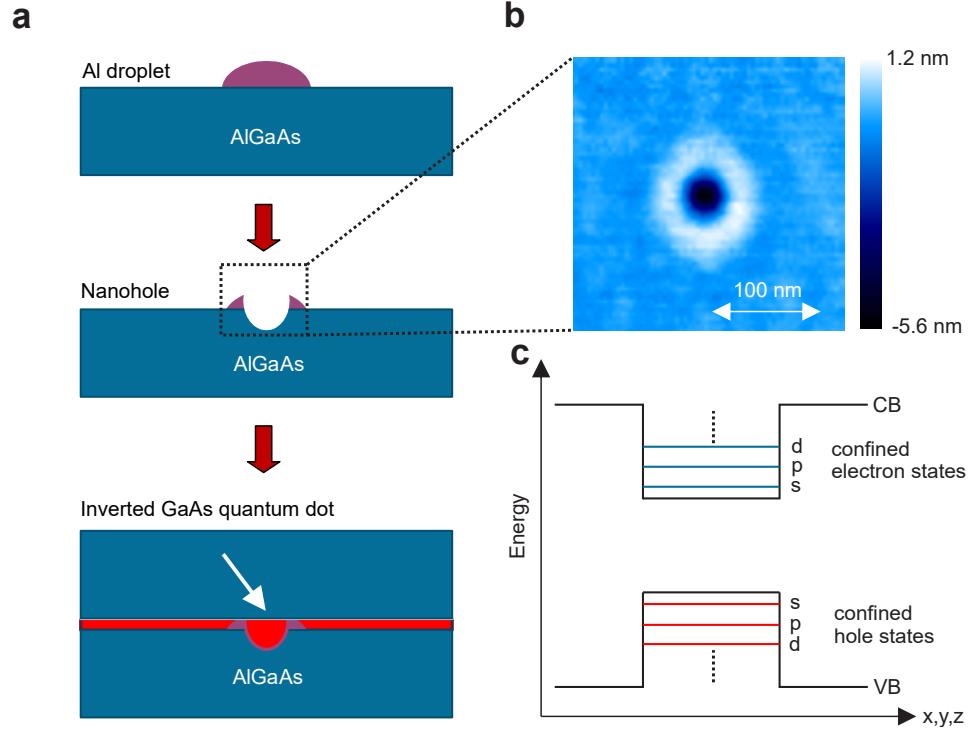


Figure 2.1.: (a) The growth process of a GaAs quantum dot by MBE.  
 (b) Atomic force microscopy (AFM) image of the nanohole before it is filled with GaAs.  
 (c) Conduction band (CB) and valence band (VB) of an optically active QD. [1]

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.

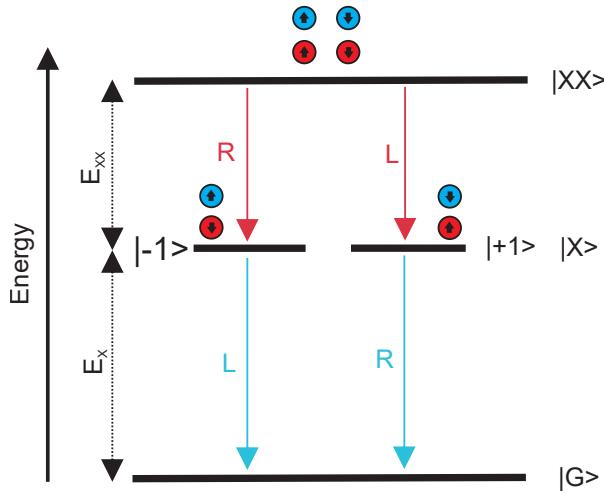


Figure 2.2.: Biexciton-esciton cascade in a QD. [1]

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.

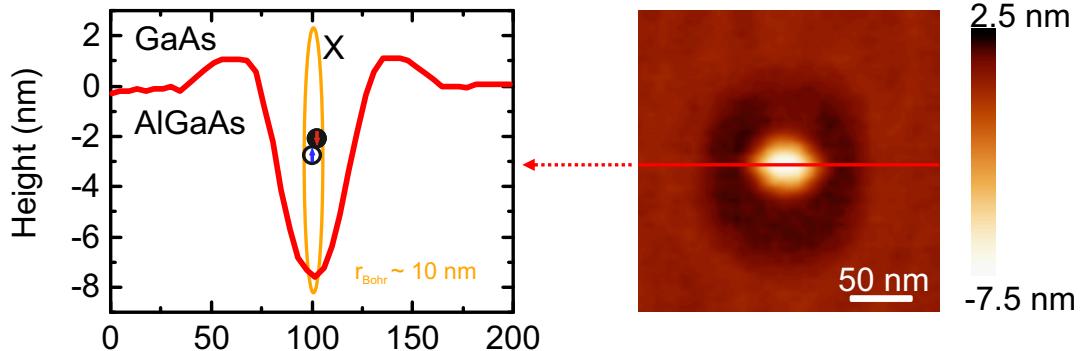
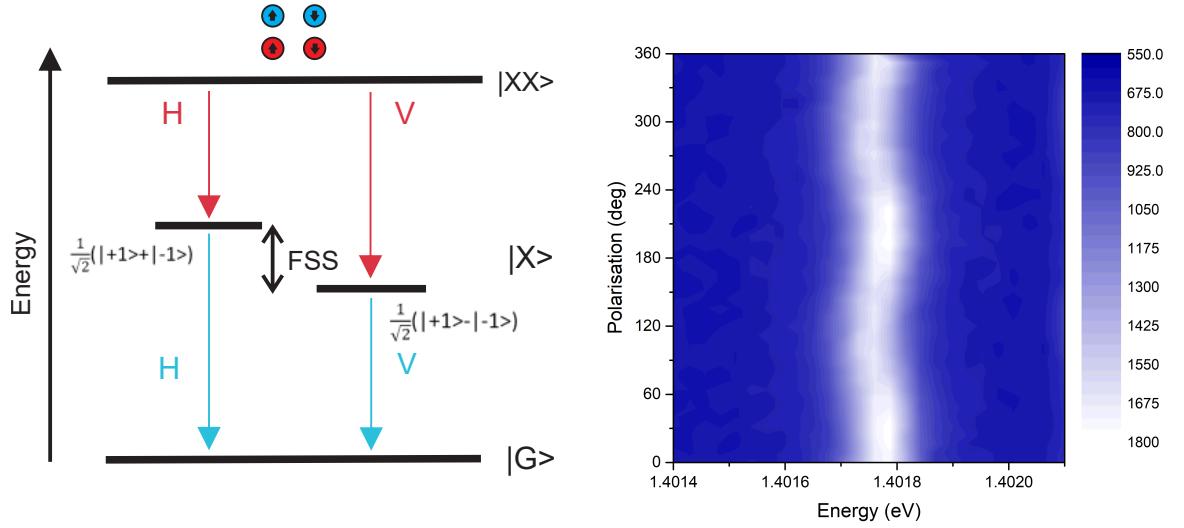


Figure 2.3.: Height profile (red) of a droplet-etched nanohole in an AlGaAs layer is shown in the left image. The orange line represents the wavefunction of the exciton which resembles the ground state of an hydrogen atom. Because of that the Bohr radius  $r_{\text{Bohr}}$  is denoted. The right image 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.

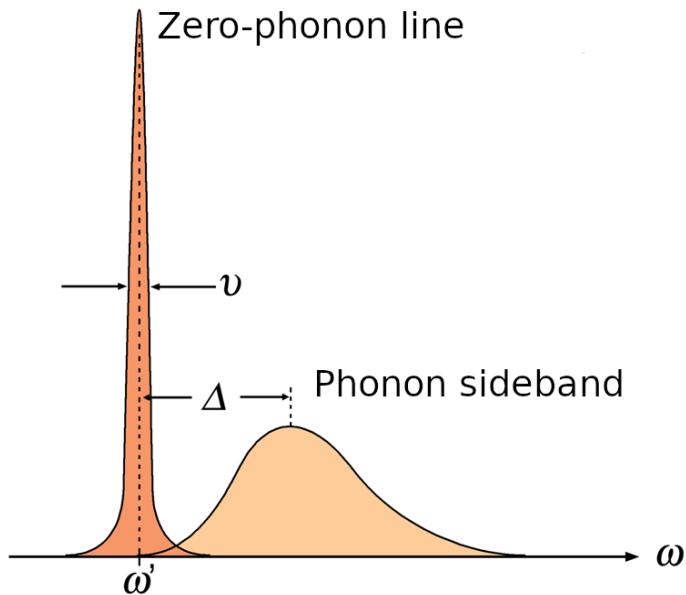
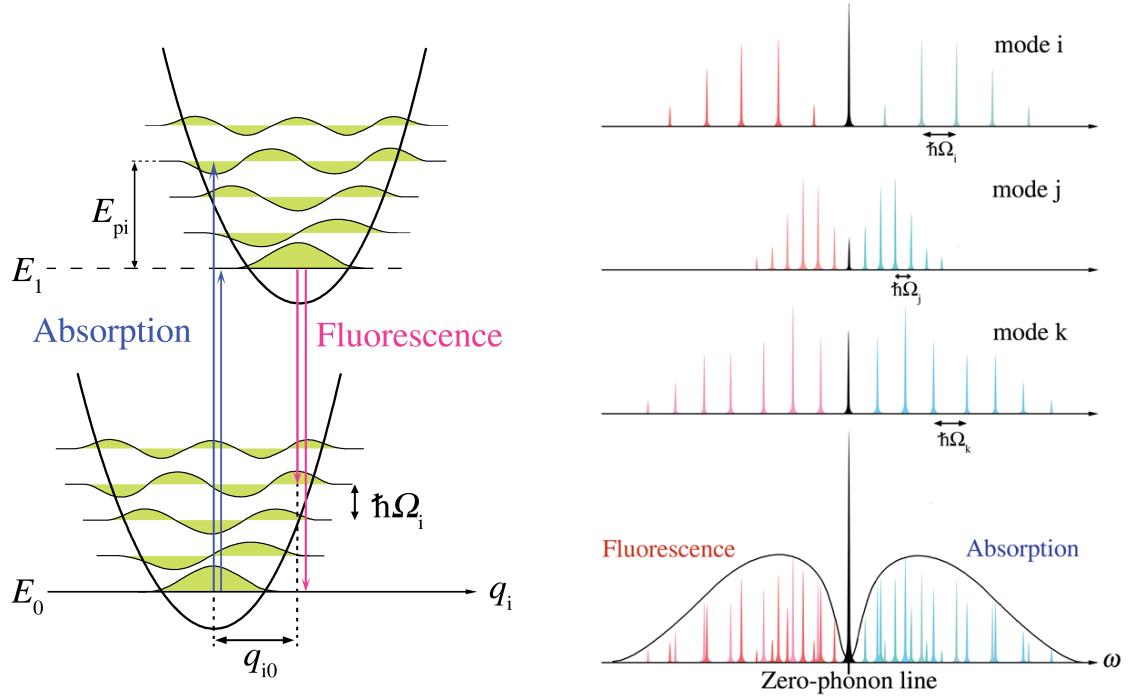


Figure 2.5.: Absorption line shape of an electronic excitation. The emission is mirrored at  $\omega'$ .

To determine the frequency gap  $\Delta$  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  $\lambda$  relates to  $\nu$  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  $\nu_0$

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

With equation (2.3) and the center wavelength of the zero-phonon line  $\lambda_0$  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 $\lambda_0$	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

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

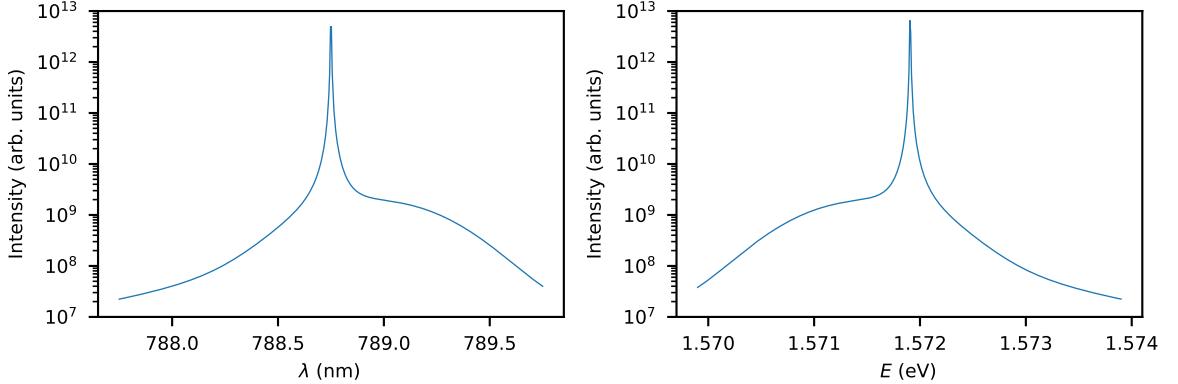


Figure 2.7.: Simulated exciton emission of a GaAs quantum dot plotted dependant on the wavelength  $\lambda$  and the Energy  $E$ . The parameters can be found in table 2.1.

## 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.

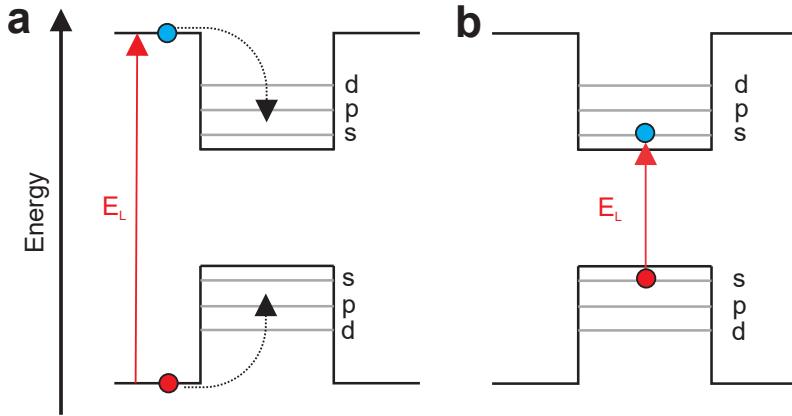


Figure 2.8.: Optical pumping of a QD by (a) above-band excitation and (b) resonant excitation [1]

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

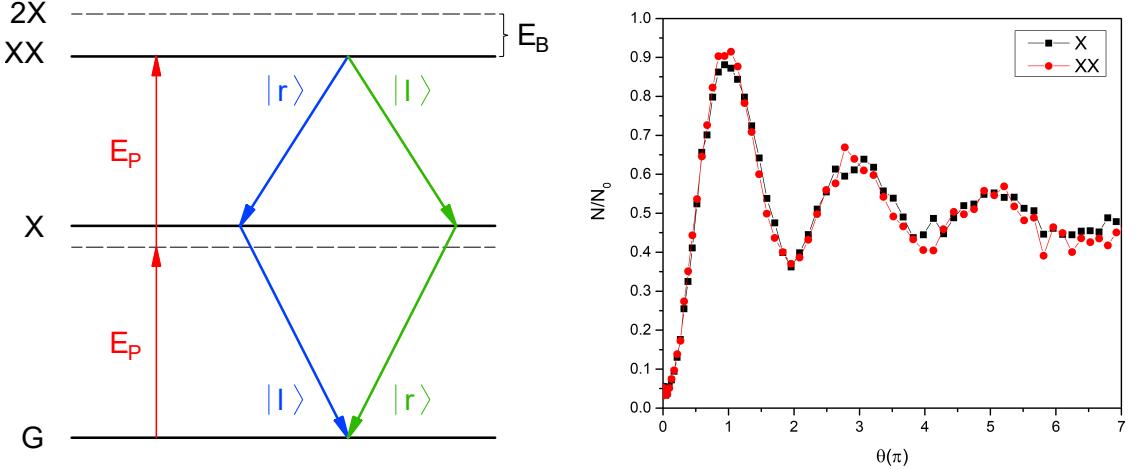
$$E_p = E_X - E_B/2 \quad (2.10)$$

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  $\theta$  as the pulse area in relation to the Rabi oscillations.  $\theta$  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  $\theta$ .  $N/N_0$  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

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

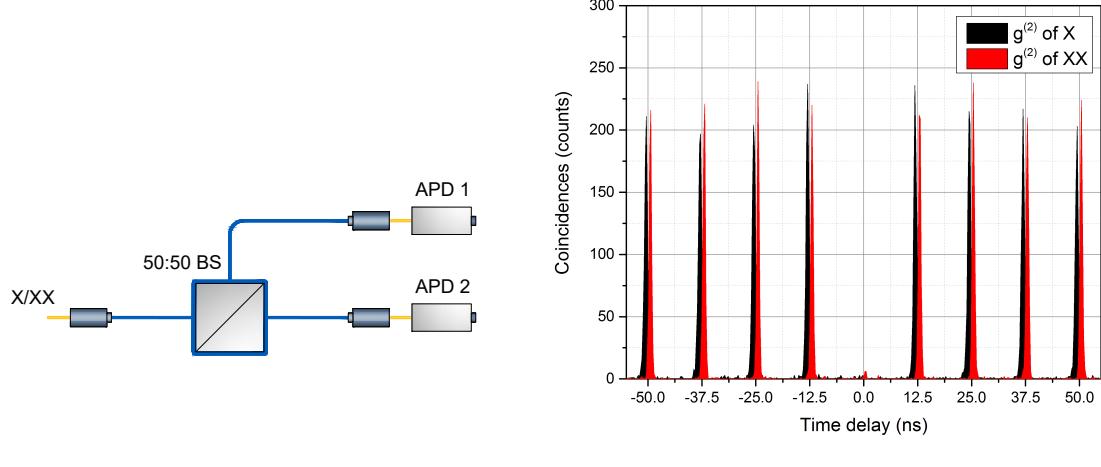
with  $I(t)$  as the light intensity and  $\tau$  as the time delay. When a single photon enters the input of the beam splitter (BS) it can only be measured at one output, but never at both simultaneously. Assuming a perfect single photon emitter, a coincidence measurement between APD1 and APD2 will 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

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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  $\tau_s$ . 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  $\kappa$ , 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.

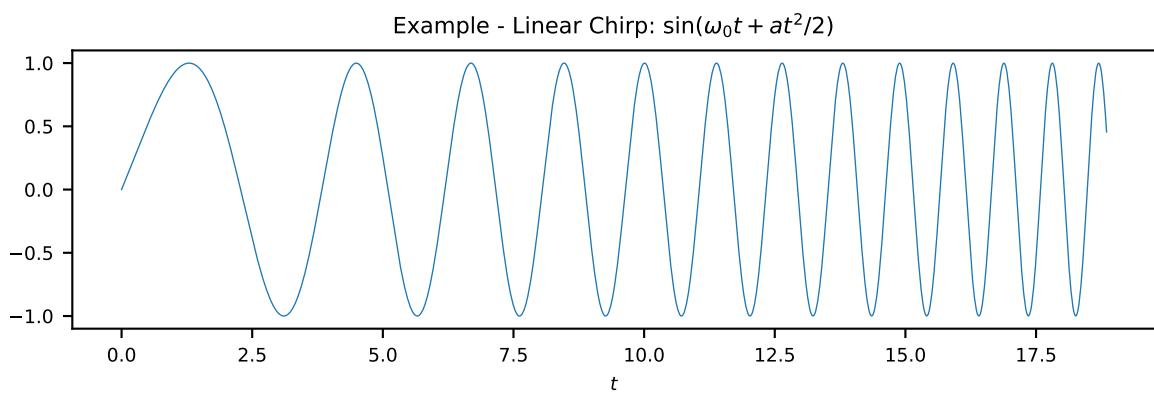


Figure 3.1.: A chirped sinusoidal wave which increases in frequency over time.

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  $\omega$  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  $\tau_0$ , the central frequency  $\omega$  and the chirp coefficient  $\alpha$ .

- Linear chirp of

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

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.

- Secant pulse:

- Pulse shape of

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

with the normalization constant  $A_{secant}$ , the pulse duration  $\tau_0$ , the central frequency  $\omega$  and the chirp coefficient  $\alpha$ .

- Linear chirp of

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

The following discussion in this chapter will assume laser pulses with a Gaussian shape.

### 3.3. Interferometric autocorrelation

In order to estimate the pulse width  $\tau_0$  interferometric autocorrelation (IAC) is used,. Basically, a nonlinear crystal is added to a Michelson interferometer in order to generate a signal governed by

$$I_M(\tau) = \int_{-\infty}^{+\infty} \langle |(E(t) + E(t - \tau))^2|^2 \rangle dt. \quad (3.3)$$

Here  $\langle \rangle$  denotes averaging over fast oscillations of the electric field and the integral stands for integration over the pulse envelope. Under the use of equation 3.2 it can be expanded to

$$\begin{aligned} I_M(\tau) = & 1 + 2 \int f(t)f(t + \tau)dt + \int f(t)f(t + \tau)\cos(2\omega\tau + 2\Delta\phi)dt \\ & + 2 \int f^{1/2}(t)f^{3/2}(t + \tau)\cos(\omega\tau + \Delta\phi)dt + 2 \int f^{3/2}(t)f^{2/2}(t + \tau)\cos(\omega\tau + \Delta\phi)dt \end{aligned} \quad (3.4)$$

where  $\Delta\phi(t, \tau) = \phi(t + \tau) - \phi(t)$  and  $\int f(t)dt = 1$ .

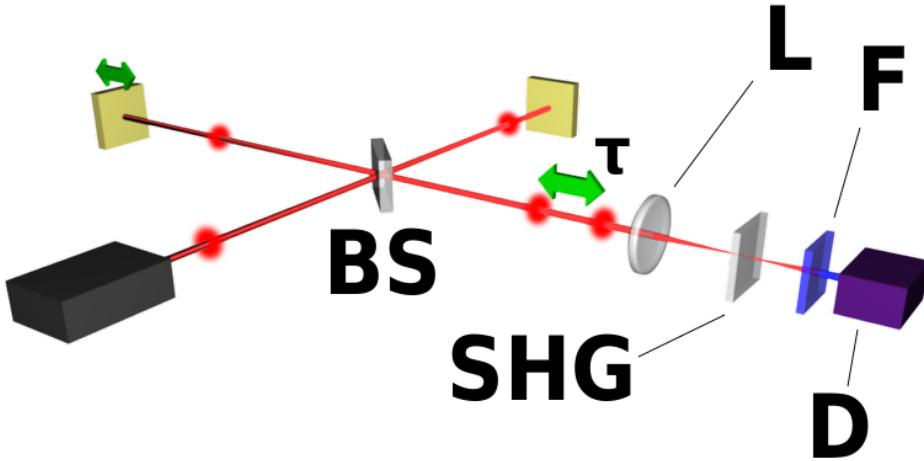


Figure 3.2.: Schematics of an interferometric autocorrelator, where L is a converging lens, SHG a second-harmonic generation crystal, BS a beam splitter and F a spectral filter to block the fundamental wavelength [18].

Unfortunately, the chirp parameter  $\alpha$  has hardly any measurable influence on the resulting signal. A modification to IAC introduced by Hirayama and Sheik-Bahae [17] makes it much more sensitive to temporal chirp. It is called modified-spectrum autointerferometric correlation (MOSAIC) and performs the following transformations on the IAC spectrum: the  $\omega$  terms are eliminated and the  $2\omega$  term is doubled. This spectral modification results in the MOSAIC signal

$$I_{M,filtered}(\tau) = 1 + 2 \int f(t)f(t + \tau)dt + 2 \int f(t)f(t + \tau)\cos(2\omega\tau + 2\Delta\phi)dt \quad (3.5)$$

### 3.4. 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 [19]. 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 3.3.

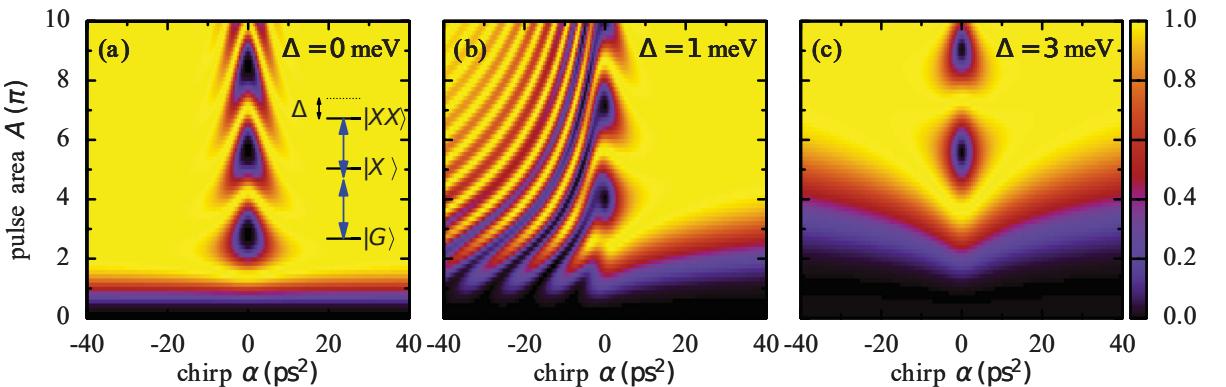


Figure 3.3.: Final biexciton occupation after chirped Gaussian pulse of pulse duration  $\tau_0 = 2\text{ ps}$ . It is plotted vertically as a function of the original pulse area  $A$  and vertically as a function of the chirp  $\alpha$  for biexciton binding energies of (a)  $\Delta = 0$ , (b)  $1$ , and (c)  $3\text{ meV}$  [16].

The central frequency is chosen so that for  $\alpha = 0$  it resonates to ground state biexciton transition, which is sketched in figure 3.3. For  $\alpha = 0$  Rabi oscillations are visible and its period depends strongly on the biexciton binding energy  $\Delta$ . However, for  $\alpha \gg 0$  biexciton preparation becomes insensitive to small variations to the pulse area  $A$  as long it exceeds a certain threshold. In the case of  $\alpha < 0$  this fails for moderate values of  $\Delta$  as can be seen in figure 3.3(b).

### 3.5. Simulation

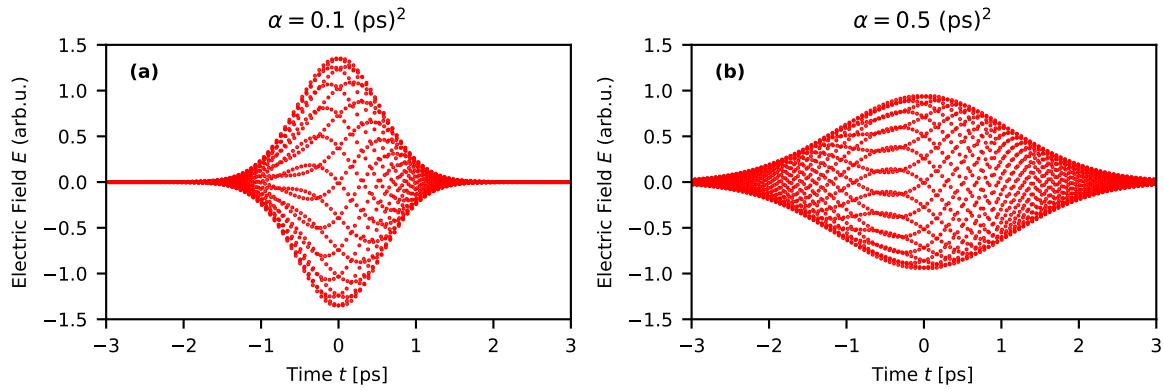


Figure 3.4.: Electric field  $E$  of Gaussian laser pulse of pulse duration  $\tau_0 = 0.5$  ps for chirp of (a)  $\alpha = 0 \text{ ps}^2$  and (b)  $\alpha = 0.5 \text{ ps}^2$

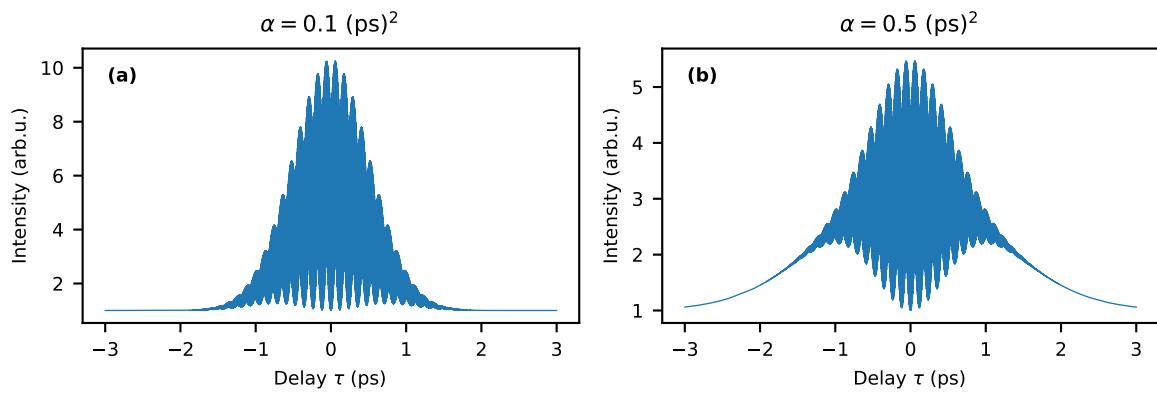


Figure 3.5.: Intensity of Gaussian laser pulse of pulse duration  $\tau_0 = 0.5$  ps with applied MOSAIC filter for chirp of (a)  $\alpha = 0 \text{ ps}^2$  and (b)  $\alpha = 0.5 \text{ ps}^2$

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

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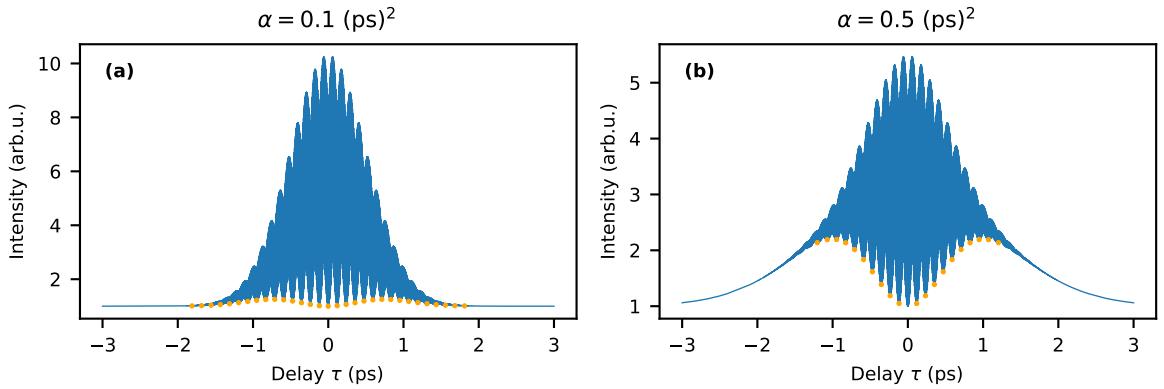


Figure 3.6.: Intensity of Gaussian laser pulse of pulse duration  $\tau_0 = 0.5 \text{ ps}$  with applied MOSAIC filter for chirp of (a)  $\alpha = 0 \text{ ps}^2$  and (b)  $\alpha = 0.5 \text{ ps}^2$ . The orange dots are results of a numerical peak finder algorithm, executed in order to find local minima.

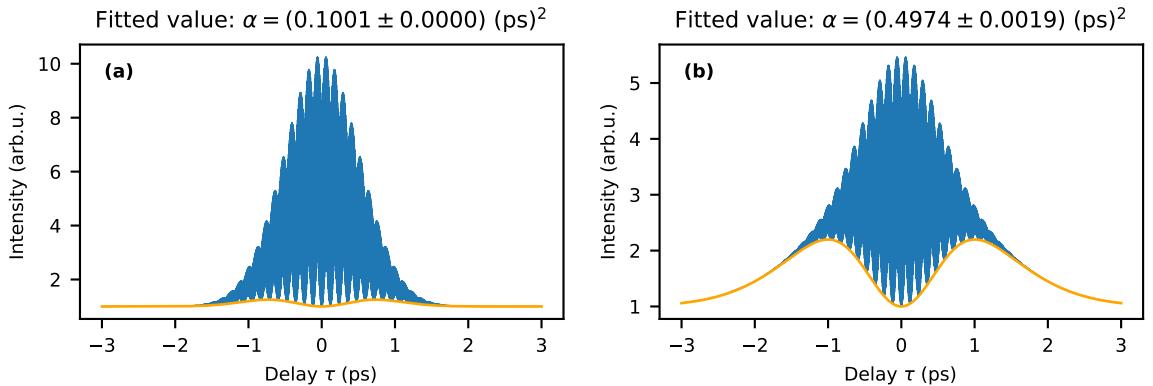


Figure 3.7.: Intensity of Gaussian laser pulse of pulse duration  $\tau_0 = 0.5 \text{ ps}$  with applied MOSAIC filter for chirp of (a)  $\alpha = 0 \text{ ps}^2$  and (b)  $\alpha = 0.5 \text{ ps}^2$ . The orange line is a fit for the lower envelope of the MOSAIC signal in order to obtain  $\alpha$ .

## 3.6. 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.[20]

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 [21]. 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

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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  $\rho$ . 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 TEM<sub>00</sub>) Gaussian mode has been constructed

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

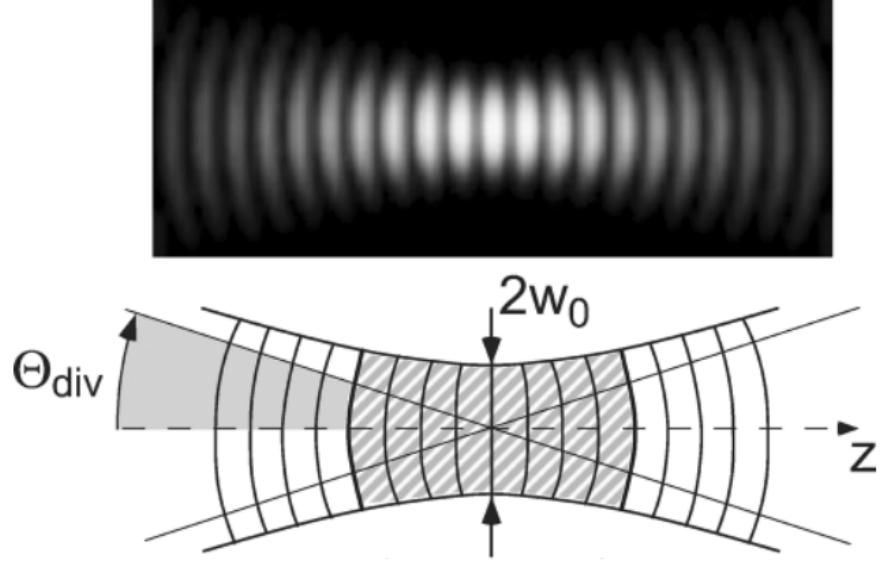


Figure 4.1.: A Gaussian beam near its beam waist. Near the center they resemble plan wave fronts, while outside they converge towards spherical wave fronts. Their Rayleighzone is shaded at the lower part of the figure.[21]

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 TEM<sub>00</sub>-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  $\omega_0$  describe the smallest beam cross section at  $z = 0$ . If the wave propagates inside a medium with the refractive index  $n$ ,  $\lambda$  has to be replaced with  $\lambda/n$ . 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  $(\omega_0, z_0)$  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 TEM<sub>00</sub> mode in equation (4.6). Examples of higher modes can be found in figure 4.2.

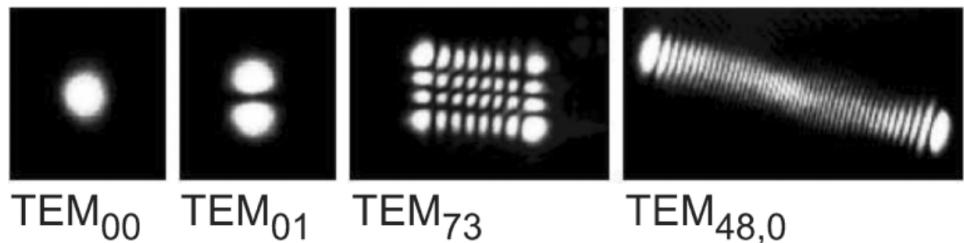


Figure 4.2.: Gaussian modes higher order of a simple Ti-sapphire laser. The asymmetry of the high modes are caused by technical inaccuracies of the resonator elements (mirrors, laser crystal).

## 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. [22].

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  $\tau_c$  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  $\nu$  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  $\varphi_s$  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  $\nu$  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  $\nu$  at which the light interferes constructively after one round trip. Two adjacent resonance frequencies differ in their round trip phase shift by  $2\pi$ . Hence, the free

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

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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  $\tau_c$ . With  $E_{q,s}$  representing the initial amplitude, the electric field at  $\nu_q$  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 [22], 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

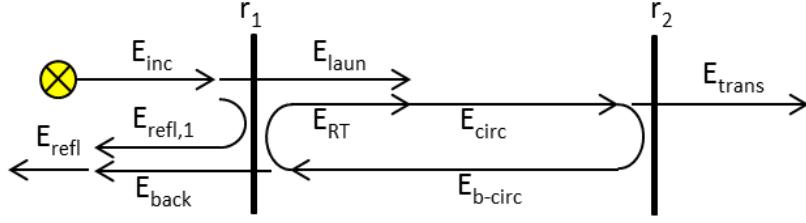


Figure 4.3.: FPI with electric field mirror reflectivities  $r_1$  and  $r_2$ . Indicated in this figure are the electric fields resulting from an incoming  $E_{inc}$ , the reflected field  $E_{refl,1}$  and transmitted field  $E_{laun}$ .  $E_{circ}$  and  $E_{circ,b}$  circulate inside the resonator, resulting in  $E_{RT}$  after one round-trip.  $E_{back}$  is the backwards transmitted field.[23]

$E_{inc}$  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

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

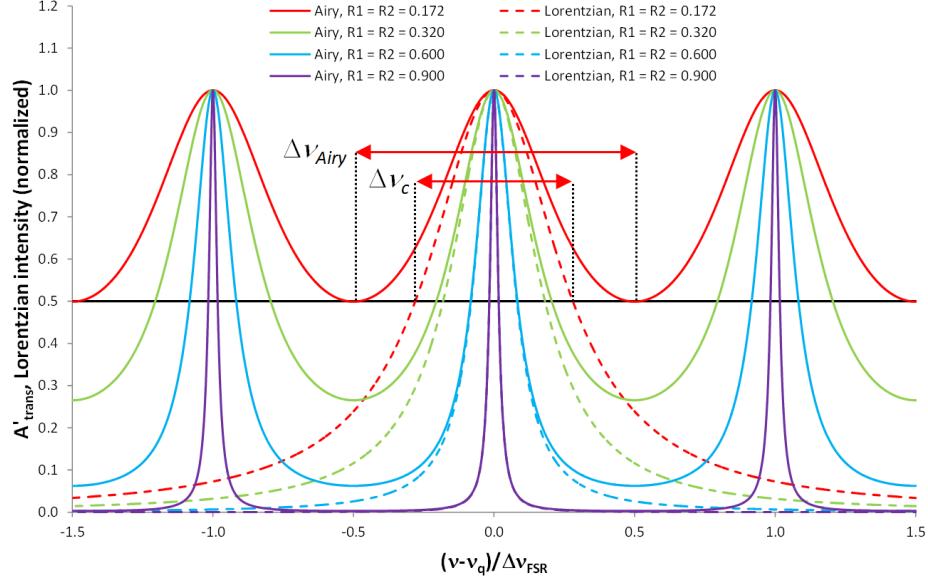


Figure 4.4.: Airy distribution  $A'_{trans}$  as described in equation (4.34) compared to the Lorentzian lines  $\gamma_{q,L}$  as described in equation (4.31)

#### 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  $\phi$  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  $\nu_m$  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.

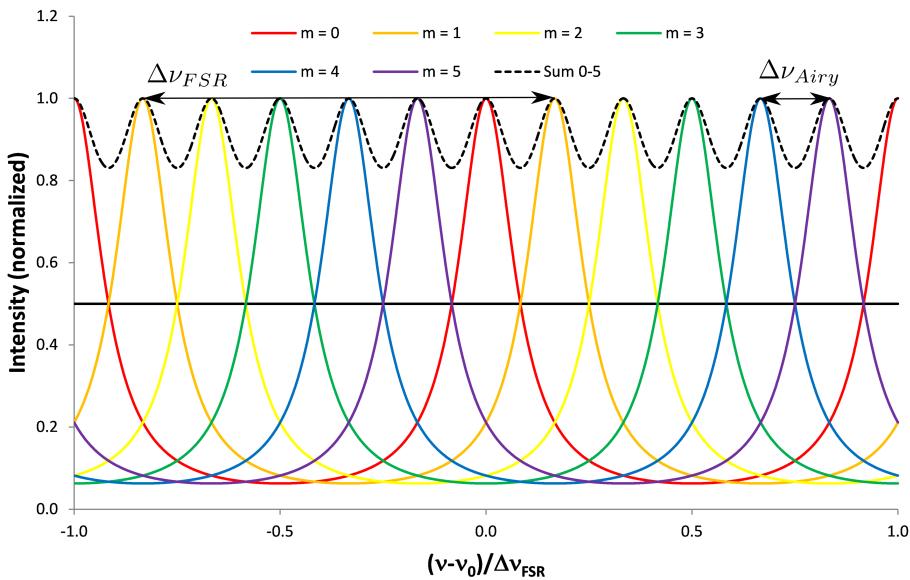


Figure 4.5.: Demonstration of the physical meaning of the Airy finesse  $F_{\text{Airy}}$ . The coloured lines are Airy distributions created by light at distinct frequencies  $\nu_m$ , while scanning the resonator length. When the light occurs at frequencies  $\nu_m = \nu_q + m\Delta\nu_{\text{Airy}}$ , the adjacent Airy distributions are separated from each other by  $\nu_{\text{Airy}}$ , 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  $F_{\text{Airy}}$  quantifies the maximum number of peaks that can be resolved. [23]

### 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 [24] and Meschede [21].

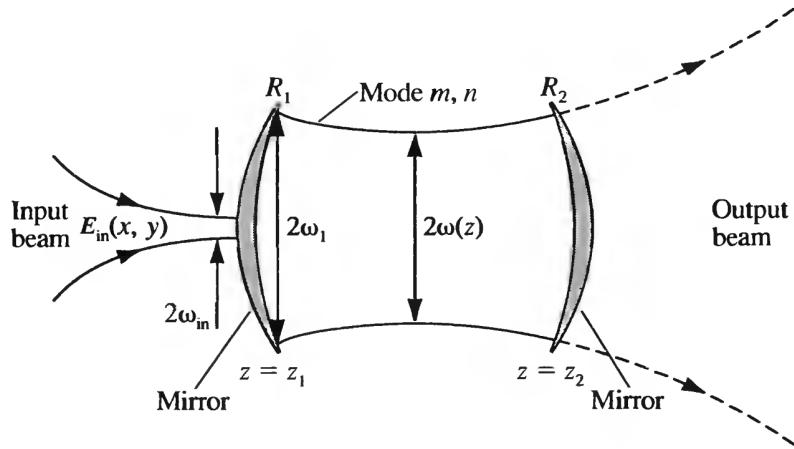


Figure 4.6.: Incident monochromatic beam of light exciting transverse mode  $m, n$  of a resonator [24]

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 TEM<sub>00</sub> 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.

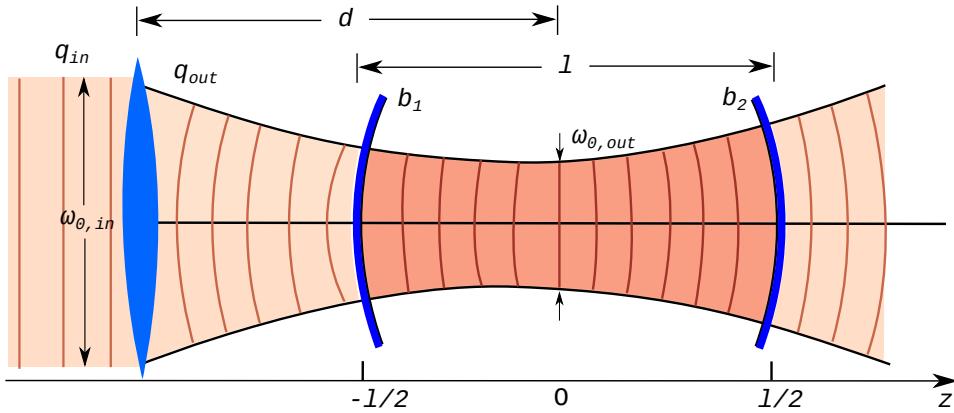


Figure 4.7.: Mode matching of an Gaussian beam into a Fabry Pérot interferometer. Incoming Gaussian beam described by  $q_{in}$  transformed by a lens into a Gaussian beam described by  $q_{out}$ . The parameters  $b_1$  and  $b_2$  describe the radii of the two mirrors.

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  $\omega_{01}$  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)

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

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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 TEM<sub>00</sub> mode.

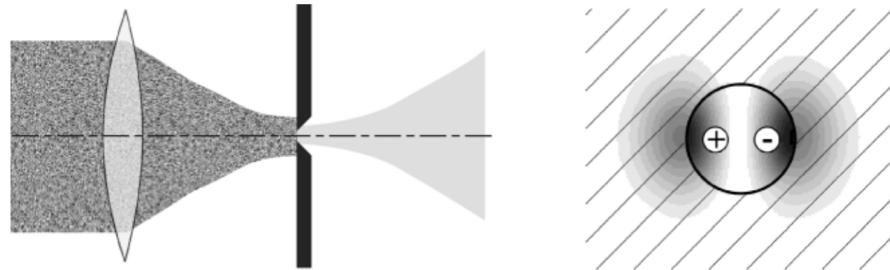


Figure 4.8.: Spatial filtering of Gauss modes. In front of the aperture, the beam consists of a superposition of multiple Gauss modes. In the example of TEM<sub>01</sub> is displayed, how higher modes are suppressed by the aperture. [21]

#### 4.3.6. Confocal setup

If the incoming beam would represent a perfect TEM<sub>00</sub> 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 [25].

A quasi-monochromatic beam of wavelength  $\lambda_0$  is composed of transverse modes  $\text{TEM}_{mnq}$ , 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

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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  $\nu_{Airy}$  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.

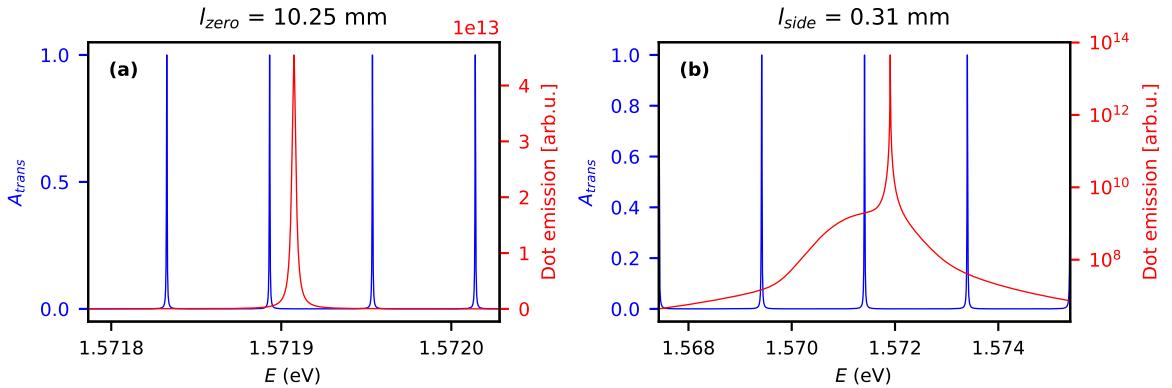


Figure 4.9.

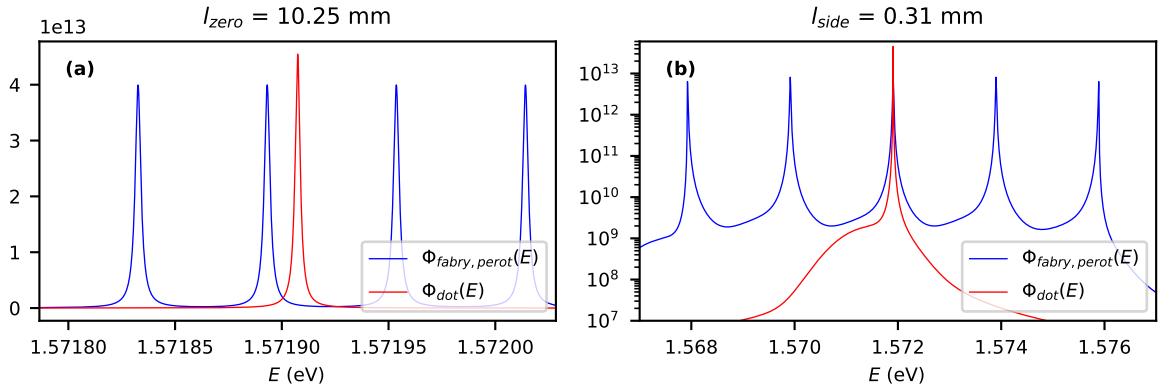


Figure 4.10.

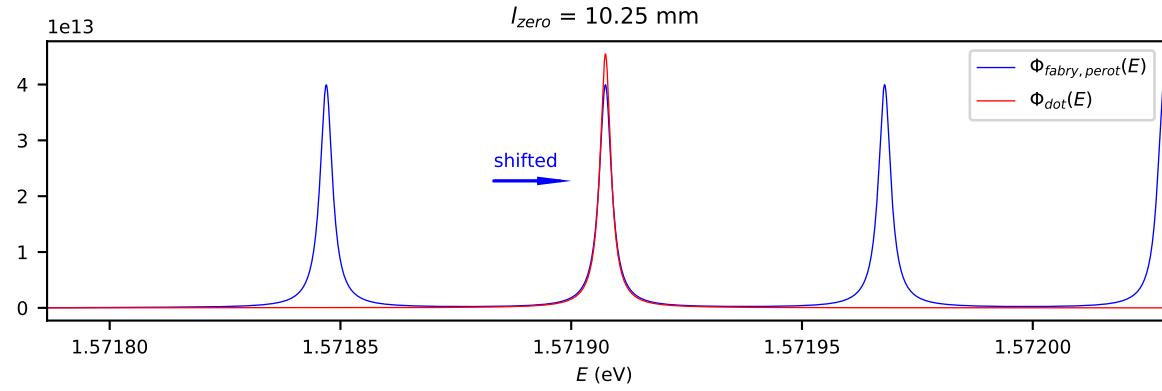


Figure 4.11.

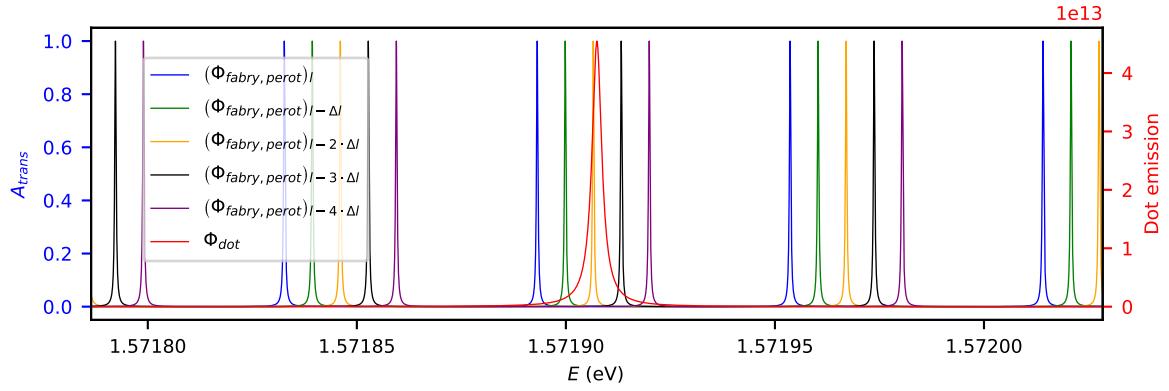


Figure 4.12.

## 4.5. Setup

Multiple FPI setups were built up in order to test their suitability to resolve QD emission. The first version featured planar mirrors, while their distance was coarse tunable with an adjustable platform and fine tunable with a piezo actuator. However this setup with planar mirrors proved to be highly unstable and was therefore discarded. The second version used smaller, planar-convex mirrors and a molybdenum ground plate. This resulted in a stable FPI which was also adjustable for various free-spectral ranges. The measurements discussed in section 4.6 are obtained with this setup. As will be noted in this section as well, the effort needed to mode-match for every measurement is too large

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to actually use it in further experiments. That is why the confocal setup will be used in the future, even though the freedom to adjust the free-spectral range is lost.

##### 4.5.1. Live avalanche photodiode mode

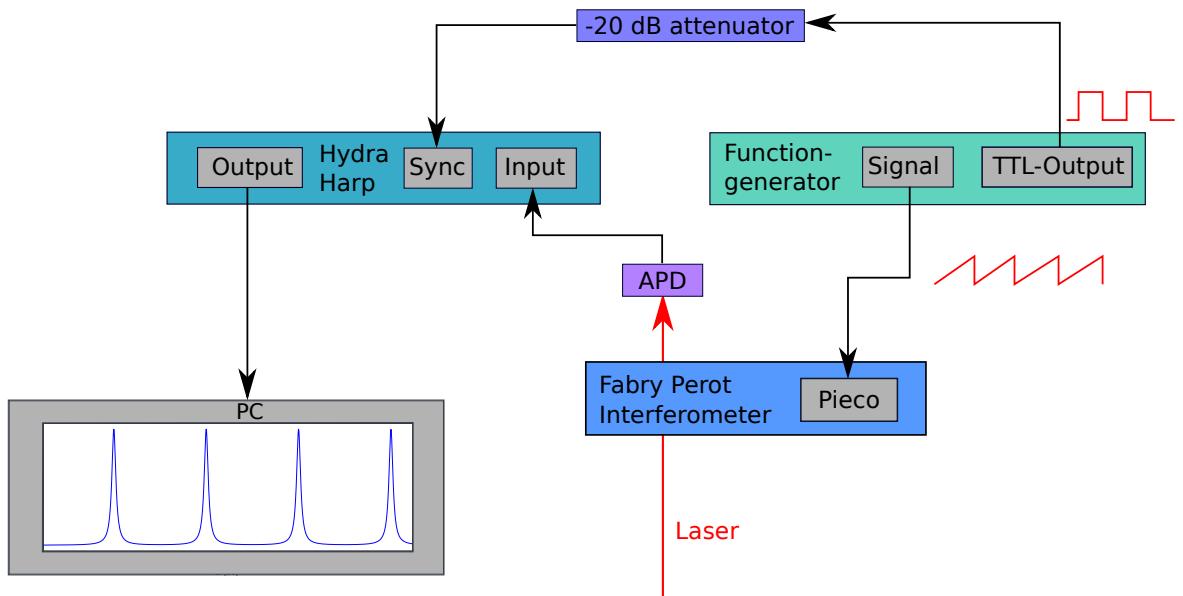


Figure 4.13.

#### 4.6. Measurements and discussion

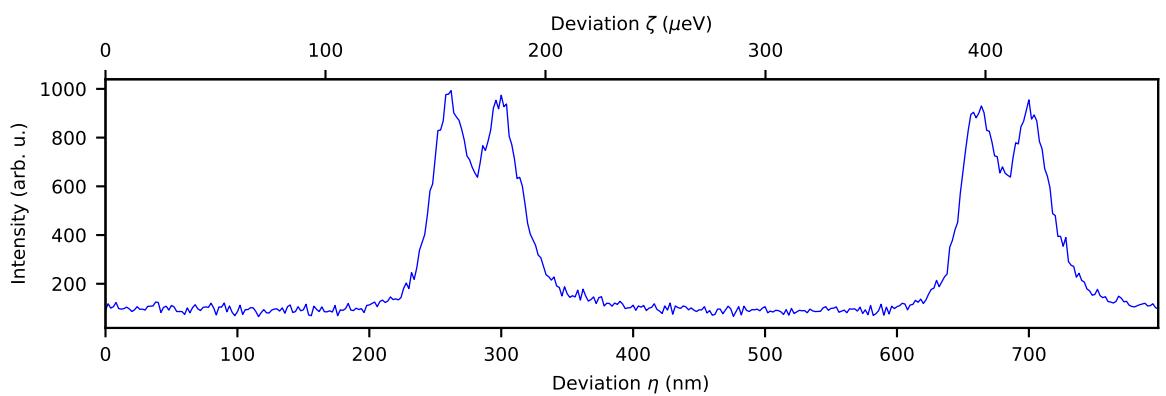


Figure 4.14.: Finestructure measurement of biexcition of a GaAs QD by passing thorugh FPI and sweeping the mirror distance. Ground mirror distance  $l$  was 2 mm.

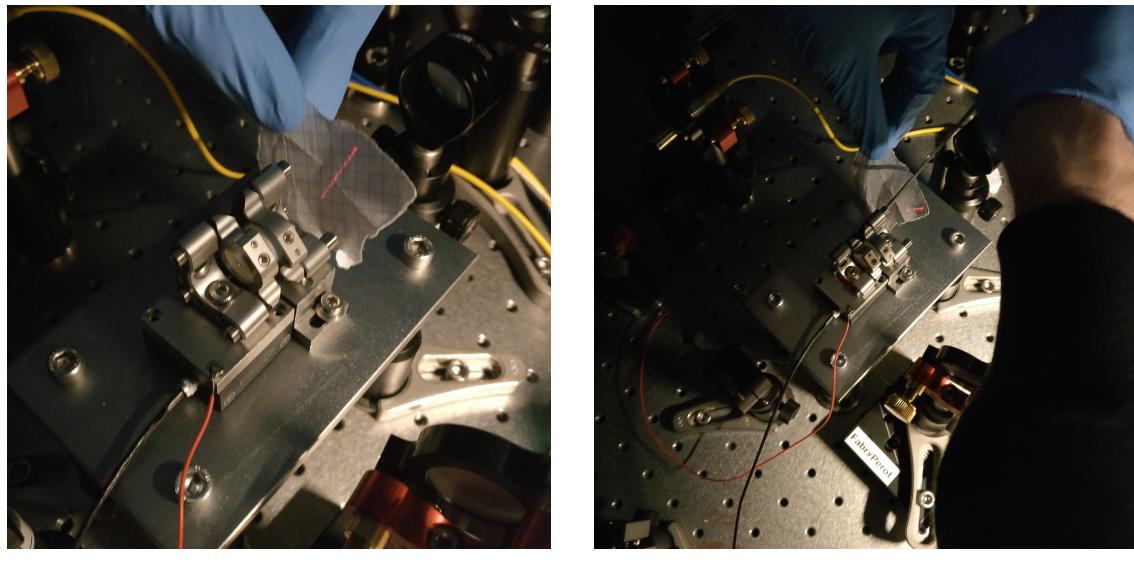


Figure 4.15.: Fabry P  rot interferometer



## **5. Summary and conclusion**



## **6. Outlook**



# **Appendix**



# Appendix A.

## Acronyms

<b>QD</b>	quantum dot .....	3
<b>GaAs</b>	gallium arsenide.....	3
<b>Al</b>	aluminium .....	3
<b>MBE</b>	molecular beam epitaxy .....	3
<b>CB</b>	conduction band.....	3
<b>VB</b>	valence band .....	3
<b>X</b>	exciton .....	4
<b>XX</b>	biexciton .....	4
<b>FSS</b>	fine structure splitting	
<b>ZPL</b>	zero phonon line .....	7
<b>PSB</b>	phonon side band .....	7
<b>HBT</b>	Hanbury-Brown-Twiss .....	12
<b>BS</b>	beam splitter .....	12
<b>FPI</b>	Fabry Pérot interferometer.....	21
<b>FWHM</b>	full width at half maximum.....	28
<b>ARP</b>	adiabatic rapid passage	
<b>IAC</b>	interferometric autocorrelation .....	17
<b>MOSAIC</b>	modified-spectrum autointerferometric correlation.....	17



# Bibliography

- [1] Daniel Huber. "GaAs quantum dots: A Dephasing-Free Source of Entangled Photon Pairs." PhD thesis. 2019 (cit. on pp. 3–6, 10–12).
- [2] Zh. M. Wang et al. "Nanoholes fabricated by self-assembled gallium nanodrill on GaAs(100)." In: *Applied Physics Letters* 90.11 (Mar. 12, 2007), p. 113120. ISSN: 0003-6951, 1077-3118. DOI: 10.1063/1.2713745. URL: <http://aip.scitation.org/doi/10.1063/1.2713745> (visited on 06/13/2019) (cit. on p. 3).
- [3] R. M. Stevenson et al. "A semiconductor source of triggered entangled photon pairs." In: *Nature* 439.7073 (Jan. 2006), pp. 179–182. ISSN: 0028-0836, 1476-4687. DOI: 10.1038/nature04446. URL: <http://www.nature.com/articles/nature04446> (visited on 06/17/2019) (cit. on p. 4).
- [4] Marcus Reindl et al. "Highly indistinguishable single photons from incoherently and coherently excited GaAs quantum dots." In: *arXiv:1901.11251 [cond-mat]* (Jan. 31, 2019). arXiv: 1901.11251. URL: <http://arxiv.org/abs/1901.11251> (visited on 06/04/2019) (cit. on p. 5).
- [5] M. Bayer et al. "Fine structure of neutral and charged excitons in self-assembled In(Ga)As/(Al)GaAs quantum dots." In: *Physical Review B* 65.19 (May 7, 2002). ISSN: 0163-1829, 1095-3795. DOI: 10.1103/PhysRevB.65.195315. URL: <https://link.aps.org/doi/10.1103/PhysRevB.65.195315> (visited on 06/17/2019) (cit. on p. 6).
- [6] Christian Schimpf. "Towards quantum teleportation with remote quantum dots." PhD thesis. 2017 (cit. on pp. 6, 10, 12, 13).
- [7] E. Peter et al. "Phonon sidebands in exciton and biexciton emission from single GaAs quantum dots." In: *Physical Review B* 69.4 (Jan. 26, 2004), p. 041307. ISSN: 1098-0121, 1550-235X. DOI: 10.1103/PhysRevB.69.041307. URL: <https://link.aps.org/doi/10.1103/PhysRevB.69.041307> (visited on 06/11/2019) (cit. on p. 7).

## Bibliography

---

- [8] Josef Friedrich and Dietrich Haarer. "Photochemical Hole Burning: A Spectroscopic Study of Relaxation Processes in Polymers and Glasses." In: *Angewandte Chemie International Edition in English* 23.2 (Feb. 1984), pp. 113–140. ISSN: 0570-0833, 1521-3773. DOI: 10.1002/anie.198401131. URL: <http://doi.wiley.com/10.1002/anie.198401131> (visited on 06/11/2019) (cit. on p. 7).
- [9] *Zero-phonon line and phonon sideband - Wikipedia*. URL: [https://en.wikipedia.org/wiki/Zero-phonon\\_line\\_and\\_phonon\\_sideband](https://en.wikipedia.org/wiki/Zero-phonon_line_and_phonon_sideband) (visited on 06/11/2019) (cit. on p. 8).
- [10] Eva Schöll et al. "Resonance fluorescence of GaAs quantum dots with near-unity photon indistinguishability." In: *Nano Letters* 19.4 (Apr. 10, 2019), pp. 2404–2410. ISSN: 1530-6984, 1530-6992. DOI: 10.1021/acs.nanolett.8b05132. arXiv: 1901.09721. URL: <http://arxiv.org/abs/1901.09721> (visited on 05/09/2019) (cit. on p. 9).
- [11] Takashi Kuroda et al. "Symmetric quantum dots as efficient sources of highly entangled photons: Violation of Bell's inequality without spectral and temporal filtering." In: *Physical Review B* 88.4 (July 18, 2013). ISSN: 1098-0121, 1550-235X. DOI: 10.1103/PhysRevB.88.041306. URL: <https://link.aps.org/doi/10.1103/PhysRevB.88.041306> (visited on 06/18/2019) (cit. on p. 10).
- [12] Peter Michler, ed. *Single semiconductor quantum dots*. Nanoscience and technology. OCLC: ocn248993461. Berlin: Springer, 2009. 389 pp. ISBN: 978-3-540-87445-4 978-3-540-87446-1 (cit. on p. 10).
- [13] S. Stufler et al. "Two-photon Rabi oscillations in a single In<sub>x</sub>Ga<sub>1-x</sub>AsGaAs quantum dot." In: *Physical Review B* 73.12 (Mar. 7, 2006). ISSN: 1098-0121, 1550-235X. DOI: 10.1103/PhysRevB.73.125304. URL: <https://link.aps.org/doi/10.1103/PhysRevB.73.125304> (visited on 06/19/2019) (cit. on p. 11).
- [14] Marcus Reindl et al. "Phonon-Assisted Two-Photon Interference from Remote Quantum Emitters." In: *Nano Letters* 17.7 (July 12, 2017), pp. 4090–4095. ISSN: 1530-6984, 1530-6992. DOI: 10.1021/acs.nanolett.7b00777. URL: <http://pubs.acs.org/doi/10.1021/acs.nanolett.7b00777> (visited on 06/19/2019) (cit. on p. 11).
- [15] J. Förstner et al. "Phonon-Assisted Damping of Rabi Oscillations in Semiconductor Quantum Dots." In: *Physical Review Letters* 91.12 (Sept. 16, 2003). ISSN: 0031-9007, 1079-7114. DOI: 10.1103/PhysRevLett.91.127401. URL: <https://link.aps.org/doi/10.1103/PhysRevLett.91.127401> (visited on 06/19/2019) (cit. on p. 11).

- [16] M. Glässl et al. "Biexciton state preparation in a quantum dot via adiabatic rapid passage: Comparison between two control protocols and impact of phonon-induced dephasing." In: *Physical Review B* 87.8 (Feb. 8, 2013). ISSN: 1098-0121, 1550-235X. DOI: 10.1103/PhysRevB.87.085303. URL: <https://link.aps.org/doi/10.1103/PhysRevB.87.085303> (visited on 05/13/2019) (cit. on pp. 16, 18).
- [17] Toshiyuki Hirayama and Mansoor Sheik-Bahae. "Real-time chirp diagnostic for ultrashort laser pulses." In: *Optics Letters* 27.10 (May 15, 2002), p. 860. ISSN: 0146-9592, 1539-4794. DOI: 10.1364/OL.27.000860. URL: <https://www.osapublishing.org/abstract.cfm?URI=ol-27-10-860> (visited on 05/13/2019) (cit. on pp. 16, 17).
- [18] *Optical autocorrelation - Wikipedia*. URL: [https://en.wikipedia.org/wiki/Optical\\_autocorrelation](https://en.wikipedia.org/wiki/Optical_autocorrelation) (visited on 06/25/2019) (cit. on p. 17).
- [19] H. Y. Hui and R. B. Liu. "Proposal for geometric generation of a biexciton in a quantum dot using a chirped pulse." In: *Physical Review B* 78.15 (Oct. 20, 2008). ISSN: 1098-0121, 1550-235X. DOI: 10.1103/PhysRevB.78.155315. URL: <https://link.aps.org/doi/10.1103/PhysRevB.78.155315> (visited on 06/24/2019) (cit. on p. 18).
- [20] Timo Kaldewey et al. "Coherent and robust high-fidelity generation of a biexciton in a quantum dot by rapid adiabatic passage." In: *Physical Review B* 95.16 (Apr. 10, 2017). ISSN: 2469-9950, 2469-9969. DOI: 10.1103/PhysRevB.95.161302. arXiv: 1701.01371. URL: <http://arxiv.org/abs/1701.01371> (visited on 12/11/2018) (cit. on p. 21).
- [21] Dieter Meschede. *Optik, Licht und Laser*. 3., durchges. Aufl. Studium. OCLC: 254422596. Wiesbaden: Vieweg + Teubner, 2008. 568 pp. ISBN: 978-3-8351-0143-2 (cit. on pp. 21, 22, 30, 32).
- [22] Nur Ismail et al. "Fabry-Pérot resonator: spectral line shapes, generic and related Airy distributions, linewidths, finesse, and performance at low or frequency-dependent reflectivity." In: *Optics Express* 24.15 (July 25, 2016), p. 16366. ISSN: 1094-4087. DOI: 10.1364/OE.24.016366. URL: <https://www.osapublishing.org/abstract.cfm?URI=oe-24-15-16366> (visited on 05/13/2019) (cit. on pp. 25, 26).
- [23] *Fabry-Pérot interferometer - Wikipedia*. URL: [https://en.wikipedia.org/wiki/Fabry%25E2%2580%2593P%C3%A9rot\\_interferometer](https://en.wikipedia.org/wiki/Fabry%25E2%2580%2593P%C3%A9rot_interferometer) (visited on 05/06/2019) (cit. on pp. 27, 29).
- [24] Amnon Yariv, Pochi Yeh, and Amnon Yariv. *Photonics: optical electronics in modern communications*. 6th ed. The Oxford series in electrical and computer engineering. OCLC: ocm58648003. New York: Oxford University Press, 2007. 836 pp. ISBN: 978-0-19-517946-0 (cit. on p. 30).

## Bibliography

---

- [25] Michael Hercher. "The Spherical Mirror Fabry-Perot Interferometer." In: *Applied Optics* 7.5 (May 1, 1968), p. 951. ISSN: 0003-6935, 1539-4522. DOI: 10.1364/AO.7.000951. URL: <https://www.osapublishing.org/abstract.cfm?URI=ao-7-5-951> (visited on 05/09/2019) (cit. on p. 33).