Faraday Filtering on the Cs-D$_1$-Line for Quantum Hybrid Systems

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Abstract—Narrow-band filtering of light is widely used in optical spectroscopy. Atomic filters, which rely on the Faraday effect, allow for GHz-wide transmission spectra, which are intrinsically matched to an atomic transition. We present an experimental realization and a theoretical study of a Faraday filter based on cesium and its D$_1$-line-transition ($6^2 S_{1/2} \rightarrow 6^2 P_{1/2}$) around 894 nm. We also present the prospects and visions for combining this filter with the single photon emission of a single quantum dot, which matches with the atomic transition. The option to lock the spectral position of a quantum dot is discussed at the end of this letter.

Index Terms—Atomic filter, Faraday filter, quantum dots, quantum hybrid devices.

I. INTRODUCTION

Over the past 50 years, narrow-band optical filters have been developed from alkaline gases whose filter effect is based on the Faraday effect [1]. Their main application is in filtering of near-atom-resonant light. Due to their high vapor pressure, the alkali atoms were investigated on their optical properties in such filters. In the early 1990s, many different atoms were studied and narrow-band filtering was described experimentally and theoretically [2], [3]. Today, more reports extend this work [4] and find astonishing properties, such as unpredicted narrow line-widths [5] or treat the problem as an optimization challenge [6].

Parallel to the studies on atomic filters, the spectroscopy of single solid-state emitters has become an active field of research, as they allow for high-rate single photon emission. It has recently been shown that solid state emitters can be optically interlinked to atomic systems [7]–[11]. One goal is the hybridization among various different systems, such that the optimal properties of diverse systems can be combined: For example, the coherence times of an atomic system can outperform solid state systems such as for example quantum dots (QDs). On the other hand single photon emission rates from a solid-state system are superior to the flux of photons from an atom or ion in a trap. A first challenge is the optical filtering of a single photon emitter. This allows to spectrally select a single emitter, which is subsequently matched to an atomic transition.

Here we present our experimental and theoretical results on Faraday filtering with hot atomic cesium vapor. The transmission spectrum on the cesium D$_1$-line was only recently
reported [12]. This spectrum is of interest for the combination between QDs and atomic cesium [9], since high quality QDs are routinely produced for this wavelength (894 nm). We implement a Cs-Faraday filter with a fixed permanent magnet. This simplifies the experimental configuration compared to electromagnetic coils. Our report describes the Faraday filter theoretically and experimentally and analyses experiments for the combination between a single QD and a Cs-Faraday filter.

The experiment is depicted in Fig. 1a. A few μW of a narrow-band titanium-sapphire laser (899-21, Coherent, CA) are delivered by an optical single-mode fiber to the experiment. The beam-waist is 2 · w0 = 4.5 mm. The laser detuning is monitored by a Fabry-Pérot cavity and the incident laser power into the experiment is monitored by an amplified photodiode. The polarization state of the light is then fixed with a Glan-Laser polarizer (Thorlabs GT10-B) and passes through an evacuated anti-reflection coated cesium vapor cell (Triad Technologies, CO), with an optical path length of 100 mm. The cell is externally heated with copper blocks at the optical windows by a feed-back loop controlled heater. The temperature stability is estimated to be better than 0.5°C.

The Faraday filter transmission is analyzed by photo-diodes behind a Glan-Taylor calcite prism. Both output ports are monitored. If summed they represent the Doppler spectrum. For convenient data acquisition, all signals are recorded by an oscilloscope, triggered by the lasers control box. A full data set was acquired with temperatures ranging from 35°C to 70°C. Eight axial magnetized ring-magnets (outer diameter × bore diameter × thickness = 100 × 60 × 20 mm3) introduce a very homogeneous longitudinal magnetic field of 37.5 mT. The homogeneity is calculated to be better than 2% in the inner 80 mm and deviates maximally 5% on the outer 10 mm (see Fig. 2). The field is estimated by a commercial Gauss meter and the atomic spectra, which were acquired earlier with a solenoid configuration. The field homogeneity of the experimental configuration was calculated with a numerical solver (Comsol Multiphysics 4.4). The ferrite based magnets retain their magnetization until 250°C, and are thus suitable also for higher temperature experiments. A comparable configuration with a permanent magnet was reported earlier [13].

For a theoretical description, the Faraday filter is modeled by calculating the electric susceptibilities of the cesium vapor [14]. This is performed by calculating the Hamiltonian \( H = H_0 + H_{\text{HFS}} + H_{\text{Zeeman}} \) and results in the complex susceptibilities \( \chi_{\pm} = \chi_{\pm}^\prime + i\chi_{\pm}^\prime \). Together with the length of the cell, \( L \), and the temperature, a Voigt line profile is obtained per transition. The combination of optical rotation by \( \pi/2 \) and simultaneous weak Doppler absorption leads to a preferred optical configuration. The transmission, \( T \), is calculated as

\[
T = \frac{1}{4} \left[ \exp \left( -\frac{\omega}{c} \chi^\prime L \right) + \exp \left( -\frac{\omega}{c} \chi^\prime' L \right) -2 \exp \left( \frac{\omega}{c} \left( \chi^\prime + \chi^\prime' \right) \right) \cdot \cos \left( \frac{\omega}{c} \left( \frac{\chi^\prime - \chi^\prime'}{2} \right) L \right) \right].
\]

We assume the Doppler broadening and the atomic density based on the same temperature. A detailed study of the theoretical estimated spectra is given in e.g. [4]. For the theoretical model a self-developed program [15] and additionally the package “ElecSus” [16] is used. The frequency axis was linearized by fitting the Fabry-Pérot transmission.

Fig. 1b,c and d show the acquired Faraday-filter spectra along with the theoretical prediction. Both output ports of the polarizing beam-splitter are monitored. The crossed output is the Faraday filter signal and other port is called X-Faraday filter signal (“cross Faraday”). The absolute transmission was estimated with a photo-diode at the input port of the filter and a far-off resonant point was assumed to be 100% transmission. Each spectrum was independently fitted. First, both temperature and B-field were set as free fit parameters. The same magnetic field of 37.5±0.5 mT was found for each temperature. This value was set to a fixed value in the following. The temperature axis plotted in Fig. 1c and d, was obtained as a free fit parameter. The fit for both polarization axes provided us the same temperature. However, a small deviation (0.4°C) between the actual experimental set point of the controller and the fit result was found.

This study aims for optimally combining the properties of atomic vapors with the single photon emission of a QD. A few studies have been showing such an optical interaction. Single photons, originating from a single molecule have been filtered with a Faraday filter already [8], [10]. With the presented data, this is the first experiment which should be applied to single photon emission from a QD. In the following we extend on the general filtering idea with two possible experiments:

At high excitation powers, the spectral emission of a QD is described by the dressed-state approach. The Mollow-triplet [17] introduces two side-bands, split by the Rabi frequency \( \Omega \). The photons are distributed over the three transitions (1/2 on the Rayleigh line, 1/4 per sideband) [18]. The emission from both side-bands is anti-correlated [19], [20], since each part of the split ground-state can only be reached
by an emission of the intermediate frequency. Only then, the other side-band is emitted. We find the Faraday filter as a convenient way to suppress the resonant scattering and to filter solely for the introduced side-bands. It is often required to suppress the coherent Rayleigh peak, which often is dominated by laser scattering. 

As a side effect, the Mollow-triplet can be tuned to have the two sidebands coinciding with the Cs-clock transition ($\approx 9.2$ GHz). When the Faraday filter is used, both sidebands will pass and the emitted photons can be “cascaded” as demonstrated in [20], whereas the Rayleigh middle peak is suppressed. By the given signal, $S$, from a single QD, the transmission of the sidebands through the filter needs to be optimized, and the resonant scattering needs to be suppressed. To analyze it a multiplication of the transmission function $T(\nu, B, T)$ and Mollow-triplet sidebands $S_{\text{Mollow SB}}$ is required:

$$S_{\text{Mollow SB}}(\nu, B, T) = S(\nu)\cdot T(\nu, B, T)$$  \hspace{1cm} (2)

where $S_{\text{Mollow SB}}$ describes the filtered Mollow side-band signal, as a function of the detection frequency $\nu$, magnetic field $B$ and the temperature $T$. This defines an integrated transmission efficiency: $\eta_{\text{eff}}(B, T) = \int S_{\text{Mollow SB}}(\nu) \, d\nu$. Note that the unit is the percentage of total transmission, and due to the limitation to the side-bands, this represents a number between 0 and 50%. This is shown in Fig. 3b, whereas in Fig. 3a the whole Mollow-triplet is considered. By varying the temperature ($20-200$ °C) and the B-field (0-100 mT), we find the optimal working conditions. Specifically, we find the best $\eta_{\text{eff}}$ between 35 and 45 °C, and above 25 mT (Fig. 3b).

The filter has to be operated below 40 °C, since otherwise the Rayleigh middle peak of the Mollow-triplet will be transmitted (compare Fig. 3a and b). The strength of the B-field does not dramatically increase the efficiency, $\eta_{\text{eff}}$, above 25 mT. By the given magnetic field of 37.5 mT the optimal temperature for a maximized transmission of the sidebands is found to be 35 °C–38 °C. Simultaneously, the suppression of the center is better than 40 dB over a range exceeding 4.1 GHz, centered between the two ground states of cesium. We now assume $10^5$ counts per second (cps) emitted by the QD, a reasonable number accordingly to previous work [20]. The overall transmission is expected to be 5%–7% of the sidebands with 2500 cps passing the filter in total (area under overall transmission curve in Fig. 3c). This value is comparable to the efficiency achieved with a Michelson interferometer [20] which is, however, thermally and mechanically susceptible. The Cs-Faraday filter is not only a more robust alternative, but can also be used to lock the emission of the QD as discussed below.

Locking a QD, which only shows a single transition (unlike the Mollow-triplet) to an atomic transition is a key step for further experiments. It ensures that the single photon emitter is spectral tuned to a follow up experiment with atoms. Tuning of the QD emission can be achieved by changing magnetic fields, the strain, or the DC-Stark effect. A first locking scheme to an atomic system has been presented by Akopian et al. [21]. The (re-)locking bandwidth was on the order of seconds. However, a single emitter can be conveniently locked by a dispersive lock signal, which is the comparison of two signals only, namely the $\sigma^+$ and $\sigma^-$ transmission through the vapor cell. Therefore, a slight modification of the presented Faraday filter scheme is required: The circular components can be independently analyzed when a quarter waveplate is introduced (Fig. 4a). This is equivalent to the dichroic atomic vapor laser lock [22]. Both output signals are subtracted, and the zero crossing of the result defines the lock-point. If the signal deviates from zero, the single photon emitter has to be spectral shifted.

Fig. 4b shows the lock signal for laser locking. The theory and experimental curves are in excellent agreement. When the photons originate from a quantum dot, the linewidth of the latter is widened to around 500 MHz [20]. With a single photon emission of $10^5$ cps., this implies that both detectors see far off-band the half of this value. At the lock point, the rate is reduced to approx. 15-20% by Doppler absorption.
at 38°C. This transmission is higher than for the case of the laser due to the larger linewidth. For a QD the flux is approx. 15,000 cps in each arm. If we assume uncorrelated noise, the noise of the signal S is calculated as shot noise: \[ N = \sqrt{S}. \] The signal to noise ratio (SNR) of the difference signal is \[ SNR = 2S/\sqrt{2S}. \] This leads to a SNR(1sec) = \[ \sqrt{15,000 \cdot \sqrt{2}}. \] For the stability of a subsequent lock, the SNR together with the slope of the lock signal are important. With the values as shown in Fig. 4b we estimate a changed flux of 20 detected photons per second and MHz at the lock point. The lock precision can be defined as \[ \left| \frac{\Delta S}{\delta \nu} \right| = \frac{\sqrt{2}}{N\sqrt{\Delta \nu}}. \] The slope for one second is \[ \delta S/\delta \nu = 20 \text{ cps}/\text{MHz}. \] This gives for a slow drifting emitter a value on the order of 10 MHz/\sqrt{Hz}. This means that the shot noise on the signal introduces a root mean square frequency uncertainty of 10 MHz if the system is monitored on a second timescale.

We have presented a study on the transmission of a Faraday filter on the cesium D1-line. We find an excellent match between the theoretical prediction and the experimental data for the entire parameter space. This allows to apply the presented results to single photon experiments with single solid state emitters. Since such experiments require sophisticated instrumentation, a robust solution based on a permanent magnet was introduced.

For experiments with QDs, not only a simple superimposed spectrum is of interest. The suppression of the Rayleigh line of the Mollow-triplet and locking the emitter to an atomic line extend the study and will allow for further experiments. Recently, this has been experimentally implemented [24]. In addition, experiments with slow light are of interest [11]. One option is to analyze the temporal shift between both output ports of such a filter. This compares to the early studies of slow light [25], [26].