ULTRANARROW FARADAY ROTATION FILTER FOR CREATING NARROWBAND ATOM-RESONANT ENTANGLED PHOTON PAIRS

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Ultranarrow Faraday rotation filter for creating narrowband atom-resonant entangled photon pairs

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Abstract. We describe experimental results on a novel optical filter based on the FADOF (Faraday Anomalous Dispersion Optical Filter) principle, and its application to production of atom-resonant entangled photon pairs at the D$_1$ line of atomic rubidium. The filter uses natural-abundance rubidium vapor in an axial magnetic field to produce Faraday rotation up to $\pi/2$ in the transparent regions adjacent to Rb absorption features. When the Faraday rotator is placed between crossed polarizers, the resulting system shows a 400 MHz FWHM transmission window with 70% peak transmission, and out-of-band rejection up to $10^5$. Using this device we demonstrate selection of atom-resonant photon pairs from a type-I cavity-enhanced spontaneous parametric downconversion source (CESPDC). We also present an exact calculation of the time correlations, i.e., the $g^{(2)}(T)$, of photons from the CESPDC. This is the first time fully-indistinguishable atom-resonant photon pairs have been observed.

Keywords: spontaneous parametric downconversion, atomic filter, entangled photon pairs

1. Introduction

Producing high-purity atom-resonant photon pairs has become an important objective in quantum optics because of the wide range of their interesting applications, which include experimental implementations of quantum memory and quantum communication schemes, such as quantum teleportation or quantum repeaters [10]. The key figures of merit that make the source applicable are brightness (rate of the pairs), narrow spectrum coinciding with an atomic resonance (or response of any other used memory material), and a spectral mode that enables efficient collecting of the light.

One of the widely used techniques to generate photon pairs is based on CESPDC, which allows one to concentrate the emission into the spectral modes of the cavity and a well-defined spatial mode, offering an advantage in spectral purity and high collection efficiency. Although the sources based on SPDC are non-deterministic (arrival times of the photons are inherently random), they can be used as a heralded sources of single
photons \[6, 7\] or entangled photon pairs \[9\].

However, spontaneous parametric down-conversion produces photons with a bandwidth much larger than atomic natural linewidths, and thus incapable of interacting efficiently with atoms and the materials used in quantum memory experiments. Cavity-enhancement of SPDC is a method that allows one to concentrate the emission of the photon pairs into the spectral modes of the cavity, but usually several cavity modes lie within the wide phase-matching profile that determines the bandwidth of the source. Therefore, the narrowband filter is essential in order to obtain from the cavity-enhanced SPDC process single photons with high spectral purity.

The typical approach to achieve a single-mode OPO output is filtering based on cascaded cavities \[5\], but it has several disadvantages: the filters are difficult to align, complex, and do not offer high rejection over a large bandwidth. An alternative is atomic filters that can offer relatively high background-rejection over large bandwidth, mechanical robustness, imaging capability and high transmission.

This thesis presents a work towards developing a type-I CESPDC source filtered so that the output photon pairs are in the single cavity spectral mode, which to our knowledge has not been reported in the literature. This kind of high-purity narrowband source of identical photon pairs has several potential applications, for example generation of quantum states with negative Wigner distribution (e.g. superposition of coherent states \[4\]), which requires a narrowband Type-I SPDC source, and bases on ”subtracting” (detecting by APD) one photon from the squeezed vacuum state \[5\]. A source of single-mode photon pairs also enables us to investigate the interference of two-photon component of a coherent state with identical photon pairs from squeezed vacuum, which is not possible with already demonstrated single-mode Type-II sources.

Our group has previously developed atom-based methods of filtering the OPO output, including a narrowband filter based on interaction-free measurement principle \[8\], that was applied to filter one mode out of a type-II CESPDC source. The filter presented in this thesis beats the previous atomic filter in terms of transmission, and what is more shows high off-resonance rejection rate, is robust, does not require any alignment and offers possibility to optimize the transmission spectrum for particular figures of merit. The new filter presented in this thesis is a Faraday Anomalous Dispersion Optical Filter (FADOF), with characteristics of the transmission spectrum that allow one to select a single frequency mode from the multi-mode output of a Type-I CESPDC light source. We demonstrated the first FADOF operating on Rb D\(_1\) resonance (795nm) \[1\], which is a wavelength widely used in various quantum optics experiments. The filter has 70% transmission and 445 MHz of full-width half-maximum bandwidth at the operating conditions optimal for the experiment. Since the bandwidth is narrower than the free spectral range of our CESPDC source we can filter the source so that almost
all of the transmitted correlated photon pairs come from the degenerate mode (i.e. the pairs consisting of indistinguishable photons).

2. Faraday anomalous dispersion optical filter

2.1. Overview of the method

The FADOF technique was first proposed in 1991 by B. Yin and T.M. Shay [2] as an ultra-narrow bandwidth optical filter for laser remote sensing (LIDAR) and free-space communications, offering several advantages over conventional interference filters. Experimental implementations of FADOF demonstrated so far use alkali atom resonances - Cs [13], Rb D_2 line [12], K D_1 line [14], K D_2 line [15], Na D_1 and D_2 lines [16], Ca [17]. We demonstrated the first FADOF filter on D_1 line in Rb, which shows a better performance than the same setup on Rb D_2 line, and better than resonances of other alkalis (comparison in [1]).

The simple FADOF consists of an atomic vapor cell between two crossed polarizers. A homogeneous magnetic field along the propagation direction induces circular birefringence in the vapor. The crossed polarizers block transmission away from the absorption line, while the absorption itself blocks resonant light. Nevertheless, Faraday rotation just outside the Doppler profiles of the absorption lines can give high transmission for a narrow range of frequencies. FADOF is simple and robust, but its performance depends critically on optical properties of the atomic vapor. What is more the spectrum can be adjusted and optimized for the particular application by changing operating conditions of the filter (magnetic field and temperature).

2.2. Theoretical calculation

We have developed a theoretical model, starting from first principles, allowing calculation of FADOF spectra for a given temperature and magnetic field. For reasons of space, we do not give a full description here, but limit ourselves to an overview. The calculation is described in [1] and Mathematica code to perform the calculations is available at arXiv [19]. The calculation agrees with experimental data, with better accuracy than other calculations found in literature.

2.3. Optimal conditions for the filter

The setup used to filter the light from the OPO was slightly altered with respect to that described in [1], so that it works for arbitrary input polarization. The light entering the FADOF was first split into two linear components using a beam displacer, and then the two beams were sent to the filter in order to undergo the Faraday rotation (Fig. 1). After the rubidium cell, each of the beams was again split into two linear components (in the same basis) using a Wollaston prism. Out of the four output beams, only the
Figure 1. Experimental setup of the OPO, the FADOF filter and detection system. Symbols: PBS: polarizing beam splitter, AOM: acoustooptic modulator, EOM: electrooptic modulator, APD: avalanche photodiode, BD: Beam displacer (YVO₄), WP: Wollaston prism, TOF: time-of-flight analyzer, VCO: voltage controlled oscillator, PM: polarization maintaining fiber, HWP: half-wave plate, QWP: quarter-wave plate, PD: photodiode

Figure 2. Reference D₁ absorption spectrum in room temperature (black), absorption spectrum in the filter operating temperature 365K (green) and theoretical (blue) and experimental (red) filter transmission spectra for 365K and 4.5mT of magnetic field. Zero on the frequency scale denotes a frequency of the transition between $^5\!S_{1/2}$ and $^5\!P_{1/2}$ fine levels without taking into account hyperfine splitting.

two that underwent the rotation by 90 degrees in the filter were coupled to the fibers and detected. The remaining two beams, containing the light rejected by the filter, were blocked.

Additionally, the setup also has been supplemented with a half-waveplate placed before the Wollaston prism, which enabled turning on and off the filter. When the waveplate was not rotating the polarization and the magnetic field and temperature were 4.5mT and 365K the filter was on, whereas with no magnetic field, room temperature of the cell and the waveplate rotating the the polarization by 90 degrees, almost all the light
was transmitted through the setup, a condition we refer to as "filter off."

The description of the calibration of magnetic field and temperature can also be found in [1].

We optimized the filter using a common criterion for experiments with photon pairs: we maximize the ratio of coincidences due to indistinguishable photon pairs to coincidences due to other photon pairs. In other words, the ratio of detected pairs from the degenerate mode to detected pairs from other modes. This leads to a slightly different optimum relative to other applications, e.g. LIDAR. Because of energy conservation, the two photons in any SPDC pair will have frequencies symmetrically placed with respect to the degenerate mode. To prevent the pair from reaching the detectors, it suffices to block at least one of the photons. In terms of filter performance, this means that it is possible to have near-perfect filtering even with transmission in some spectral windows away from the degenerate mode provided the transmission is asymmetrical (Fig. 3).

Optimizing by this criterion we find the optimal conditions for the filter performance in our experiment to be 4.5mT of magnetic field and the cell temperature of 365K. The theoretical and experimental transmission spectra are displayed on Fig. 2.

3. Light source

The source of photon pairs used in this experiment is an optical parametric oscillator, consisting of a bow-tie cavity with a periodically-poled KTP crystal inside [11]. Due to the energy conservation the pump photons (blue, 397nm) of frequency $2\omega_0$ are converted into pairs of photons with frequencies $\omega_0 + \delta$ and $\omega_0 - \delta$, for any $\delta$ that lies within phase-matching profile, which has a width of order of magnitude of 100GHz. Note that there is only one mode of frequency $\omega_0$ (the degenerate mode) that consists of pairs of identical downconverted photons. It the rest of the cases, the photons from one pair are in different cavity spectral modes, symmetrical with respect to the degenerate one.

3.1. Experimental setup

The experimental setup is presented in Fig. 1. We use a single-frequency diode laser, stabilized to the point "D" in Fig. 2, i.e. 2.7 GHz to the red of line centre. Saturated Absorption Spectroscopy (SAS) is used as a frequency reference for the Pound-Drever-Hall locking, but since the FADOF requires that we lock at the specific frequency, which does not coincide with any of the saturated absorption lines the locking is performed using an electrooptical modulator in order to create sidebands at a given frequency in the light injected to the spectroscopy setup. Therefore, adjusting the EOM frequency we can have a SAS resonance on one of the sidebands at the frequency that we want to lock at.
The laser light, locked at the correct frequency is then amplified by a tapered amplifier and frequency-doubled in a "SHG" part of the setup (Fig. 1). The output of the second harmonic generation cavity at 397nm, with the maximum power of 10mW, is used to pump the OPO. The cavity consists of two spherically curved and two flat mirrors (in bow-tie geometry) and a PPKTP crystal inserted between the curved mirrors, to coincide with beam waist inside. The cavity is not resonant with the pump light, which passes through the cavity only once and then is blocked. The squeezed vacuum, denoted on the figure as red dots, exits the cavity through one of the flat mirrors, is coupled to the polarization-maintaining fiber and transmitted to the FADOF filter setup, which was described in more detail in the previous section. After the filter the photons are detected by the APDs connected to the Time-of-flight analyzer, which is inserted into PC and driven by a C++ program.

The OPO cavity is locked using another beam, counterpropagating and with perpendicular polarization and frequency with respect to the parametrically interacting beams. Due to the birefringence of the elements of the cavity, the locking beam must have a frequency shifted with respect to \( \omega_0 \) so that the light that has the polarization of downconverted beam and has the frequency of the degenerate mode \( \omega_0 \) is resonant. The frequency shifted counterpropagating beam frequency is obtained from the first order of diffraction of the beam passing twice through the acoustooptic modulator. Additionally, since we observed that the counterpropagating beam introduced a lot of noise into the photon counts at the APDs obscuring the signal from the squeezed vacuum beam, a "chopped lock" was applied. This means that the experiment rapidly switches between periods of data acquisition and periods of stabilization. During periods of data acquisition the AOM is off, and thus no locking beam is present. During periods of stabilization the AOM is on, and an electronic "gate" circuit is used to block electronic signals from the APDs, preventing recording of detections due to the locking beam photons.

The OPO cavity was designed and built by a former PhD student of the group Ana Predojevic and optimized by the current PhD student Federica Beduini. I designed and built the FADOF filter and wrote the data-acquisition software (C++ kernel driving the Time-of-flight analyzer and several LabView programs for grabbing and processing the raw time-stamp data from the counter). Photon-counting experiments were performed by me and Federica Beduini.

3.2. Properties of the output state

The output state from the cavity-enhanced spontaneous down conversion is a squeezed vacuum state with the following representation in the Fock basis:

\[
|\psi\rangle = \frac{1}{\cosh(r)} \sum_{n=0}^{\infty} \tanh(r)^n |2n\rangle
\]

where \( r \) is a parameter proportional to effective nonlinearity and the crystal length. The most important feature of this state is the fact that it has only components that contain
even number of photons. In the presented experiments we deal with a very weak (small $r$) squeezed vacuum state, therefore we can neglect the higher order term and assume that the output state consists of photon pairs.

The spectrum of the output state is determined by the phase-matching profile (with width of order of magnitude of 100GHz) and cavity parameters, such as free spectral range (485MHz) and full-width half-maximum of the peaks (8MHz). The quantity we measure in order to characterize the correlations of the photon arrival times of the output quantum state of light is the $g^{(2)}(T)$ intensity correlation function, defined in terms of electric field operators by the following expression:

$$g^{(2)}(T) = \frac{\langle E^\dagger(t+T)E^\dagger(t)E(t)E(t+T) \rangle}{\langle E^\dagger(t)E(t) \rangle^2}$$

(2)

The $g^{(2)}(T)$ measurement is performed by splitting the light into two parts using a fiber beam splitter and then detecting the arrival times of the photons at each port (APD1 and APD2 on Fig. 1). The function is proportional to the histogram of differences of arrival times of photons detected at different ports.

4. Filtered down-conversion

In order to verify the performance of the filter we measured the $g^{(2)}(T)$ function of the OPO output light with and without the FADOF filter. During the experiment, the EOM frequency was adjusted so that the degenerate mode frequency coincides with the FADOF 70% transmission peak (Fig. 3). First, the photon arrival times at APD1 and APD2 were measured with the Faraday filter turned off. The results allowed us to calculate the histogram of arrival time differences $T$ which is proportional to the $g^{(2)}(T)$. The theoretical calculation of the $g^{(2)}(T)$ for the filtered OPO output (single-mode) can be found in [11]. Basing on the Bogoliubov transformations for double-ended cavity [18] they predict that for small pump power (far below threshold) the measured function should have the form of double exponential decay.

The same approach as presented in [11] is not appropriate for the multimode output,
Figure 4. (A): Multimode $g^{(2)}(T)$ from theoretical calculation in the Appendix. The cavity parameters are $r_1^2 = 0.922$, $r_2^2 = 0.994$. The artefacts on the comb structure result from binning the calculated correlation function into 1ns time bins, which is our detection resolution. (B): Theoretical singlemode $g^{(2)}(T)$ since the evolution of the annihilation and creation operators cannot be described with the help of a differential equation as in [18] for single-mode case. Therefore, we found the Bogoliubov transformation for the multimode case using the difference equations connecting the creation and annihilation operators of the field at two consecutive cavity roundtrips. Then, the $g^{(2)}(T)$ was calculated in the way analogous to the single mode case. The detailed calculation is presented in the Appendix. The resulting shape of the $g^{(2)}(T)$ (Fig. 4) has an envelope close to the double exponential decay and on top of that a comb structure with a period equal to the cavity round trip time (in our case 2.06 ns).

To summarize the theoretical expectations what we should observe is that with the FADOF filter off the $g^{(2)}(T)$ forms a double exponential decay peak with comb structure, and the structure disappears when we turn the filter on.

The experimental results are displayed on a Fig. 5. The comb-like structure with 2ns period was observed, with the visibility obscured due to the counting electronics resolution of 1ns (theoretically expected comb structure with the period of 2.06ns is very close to the Nyquist condition) and high level of background noise resulting mainly from accidental coincidences. Although the visibility of the comb structure was not very good (being around 100 counts per bin), it significantly exceeds the noise of the measurement that we expect from the Poissonian statistics (around 20 counts per bin).

The same experiment was performed with the FADOF filter on. The results are depicted on the Fig. 5. The comb structure observed due to multimode output was suppressed to the level below the Poissonian noise on the histogram, as predicted by theory. This indicates that the filter improves the spectral purity of the output light, which is also evident from the Fourier transforms of the two measured correlation.
functions (Fig. 6). The peak responsible for the modulation with 500kHz frequency (2ns period) disappears when the FADOF filter is on. Suppression of the modulation means that the spectral modes adjacent to the degenerate mode are not transmitted the FADOF, but not necessarily that there are no other conjugate modes passing at a distance from the resonance. Therefore, the next step of the experiment aims at proving that all the light passing through the filter is resonant with rubidium by showing that the correlation peak is suppressed when we pass the FADOF-filtered photons through a hot rubidium vapor cell that absorbs only resonant light.

5. Summary

The research presented in this thesis aims at developing a narrowband atom-resonant source of indistinguishable photon pairs, using a type-1 CESPDC source and an untra-narrow atomic filter. We demonstrated the first Faraday anomalous dispersion optical filter at 795nm, developing a theoretical model that calculates the filter spectrum from first principles, and agrees very well with the experimentally measured spectra. The performance of the filter was also verified by measuring the correlation of photon arrival times, observing that the structure that indicates multimode character of the OPO output disappears.
when the FADOF filter is active.
The ready source still needs to be optimized and characterized better, so as to identify and eliminate the sources of background noise and measure the $g^{(2)}(T)$ with better accuracy and determine to what extent the correlated pairs are single-mode.

References