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High-Capacity Atom-Photon Interfaces for Quantum Information

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14. ABSTRACT
Atom-photon quantum interfaces with entangled photons can enable unconditionally secure long-distance quantum communication (LDQC) by implementing quantum repeaters based on atomic ensembles to overcome the degradation of fidelity of quantum information over long distances. Moreover, the potential to encode an unbounded amount of information in the orbital angular momentum (OAM) of single photons could potentially enable LDQC with high capacity. We propose to demonstrate the physical systems which are fundamental building blocks for these high-capacity LDQC technologies based on OAM: a source of entangled photons carrying OAM in high dimensions compatible with atomic quantum memories; and a multimode atomic memory to store single photons with high-order OAM. We will use warm ensembles of Cesium atoms to generate entangled photons carrying OAM using a four-wave mixing process and to store single photons in high-dimensional spaces, and we will investigate the requirements for interfacing entangled photons in high dimensions and multimode quantum memories for enabling high-capacity LDQC technologies

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Final Report: Young Investigator Program Award

Title: High-Capacity Atom-Photon Interfaces for Quantum Information

AFOSR Award Number: FA9550-14-1-0300

Program Manager: Dr. Grace Metcalfe / former Dr. Tatjana Curcic

Performance Dates: 9/01/2014 – 8/31/2018

PI: Francisco Elohim Becerra Chavez

1. Abstract

This report summarizes the work realized during the entire period of the grant from 9/01/2014 to 8/31/2018 focused in the investigation of atom-photon interfaces with high capacity. In this report we divide the description of the work done in two periods: 9/01/2014- 8/31/2017, and 9/01/2017-8/31/2018. During the first period, our efforts focused on creating the infrastructure for the initial investigations of these atom-photon interfaces. In the second period, our efforts focused on developing techniques for preparation and measurement of states of light for achieving high fidelity and efficiency for the generation, control, and detection of states of photons carrying information in their transverse spatial degree of freedom, and on investigating techniques for quantifying and suppressing noise. Based on this work, we have updated our experimental system for continuing our research in the generation of quantum states photons in high dimensions with high fidelity and high degree of entanglement.

The key accomplishments and advancements during 9/01/2014- 8/31/2017 of this award include:

- Studies of stimulated four-wave mixing (FWM) in cold atomic ensembles of cesium.
- Preliminary studies of correlations of single photons from FWM.
- Investigations of state preparation and measurements of states of light carrying OAM.
- Development of stable and highly tunable narrowband filters for investigation of photon-photon correlations.
- Preliminary theoretical investigations of OAM correlations from spontaneous FWM. (This investigation is reported together with continued effort during 9/01/2017-8/31/2018.)

The key accomplishments and advancements during 9/01/2017-8/31/2018 of this award include:

- Studies of optical surface roughness by scattering measurements at the single-photon level.
- Demonstration of FWM from atomic ensemble in a low-noise setup.
- Study of methods for aberration correction based on two-mode interference, and methods based on adaptive algorithms for fast phase retrieval and distortion correction.
- Continuation of theoretical investigation of correlations of photons entangled in OAM.

The theoretical and experimental achievements during the period of the grant will the basis for our future investigations in high-dimensional atom-photon interfaces. Future efforts will be directed to the characterization and optimization of high dimensional entanglement, and for the control of high dimensional states from FWM in atomic ensembles. These future directions are briefly described at the end of the report.

2. Personnel

Graduate Student: Andrew Ferdinand, 100% September 2014- January 2018
Graduate Student: Nathaniel Ristoff, 100% September 2017- February 2018
Graduate Student: Matthew DiMario, 100% Summer 2018

PI, 1-month salary/year

3. Outcomes

The work performed during the period of this grant enabled the completion of a PhD thesis in January 2018. The reference for this PhD thesis is [1]:

Ferdinand, Andrew. "*Studies of Light Generation with Four-Wave Mixing in a Cold Atomic Ensemble*." (2018). http://digitalrepository.unm.edu/phyc_etds/177

The research supported by this award will also produce a Master's degree. The MS student will present her Master's thesis at the end of 2018. The Master thesis will include many of our studies of aberration correction with different methods for state generation and detection with high fidelity.

Oral Presentations

1. "*Four wave mixing in a cold atomic ensemble for the generation of correlated photons pairs,"* A. Ferdinand, and F. E. Becerra, 19th Annual SQuInT Workshop, Feb. 23-25 (2017); Baton Rouge, Louisiana.

2. "*Correlation in photon pairs generated using four-wave mixing in a cold atomic ensemble,"* A. Ferdinand, A. Manjavacas and F. E. Becerra, N8.00008, 48th Annual Meeting of the APS Division of Atomic, Molecular and Optical Physics (DAMOP) June 05–09 (2017); Sacramento, California.

3. "*Quantum technologies for optical communication*," F. E. Becerra, University of Oregon, April 27, 2017 (Physics Colloquium).

4. "*Tecnologías cuánticas para comunicaciones seguras a largas distancias*," F. E. Becerra, LX Congreso Nacional de Fisica, Monterrey, Mexico, October 11,2017, (Invited Talk).

5. "*Towards a low noise system for generating entangled photons in orbital angular momentum,"* N. Ristoff, A. Ferdinand, and F. E. Becerra, U07.00007, 49th Annual Meeting of the APS Division of Atomic, Molecular and Optical Physics (DAMOP) May 28-June 01 (2018); Ft. Lauderdale, Florida.

Poster Presentations

1. "*Towards generation of photons with orbital angular momentum correlation from atomic ensembles,"* A. Ferdinand and F. E. Becerra, No. 7, 17th Annual SQuInT Workshop, Feb. 19-21 (2015) Berkeley, California.

2. "*Experimental optimization of four wave mixing in a cold atomic ensemble, towards efficient generation of photon pairs,"* A. Ferdinand, X. Luo and F. E. Becerra, No. 21, 18th Annual SQuInT Workshop, Feb. 18-20 (2016); Albuquerque, New Mexico.

3. "*Studies of Four Wave Mixing in a Cold Atomic Ensemble for Efficient Generation of Photon Pairs,"* A. Ferdinand, X. Luo and F. E. Becerra, Q1.00075, 47th Annual Meeting of the APS Division of Atomic, Molecular and Optical Physics (DAMOP) May 23–27 (2016); Providence, Rhode Island.

4. "*Practical transmission matrix of a multimode fiber,"* N. Ristoff and F. E. Becerra, 19th Annual SQuInT Workshop, Feb. 23-25 (2017); Baton Rouge, Louisiana.

5. "*State Preparation and Measurement of Light with Orbital Angular Momentum with High Quality Using Spatial Light Modulators,"* L. Xijie and F. E. Becerra, 20th Annual SQuInT Workshop, Feb. 22-24 (2018); Santa Fe, New Mexico.

6. "*Towards a low noise system for generating entangled photons in orbital angular momentum,"* N. Ristoff and F. E. Becerra, 20th Annual SQuInT Workshop, Feb. 22-24 (2018); Santa Fe, New Mexico.

7. "*Study of Preparation and Measurement of Spatial Modes of Light in Different Bases,"* N. Ristoff, and F. E. Becerra, E01.00053, 49th Annual Meeting of the APS Division of Atomic, Molecular and Optical Physics (DAMOP) May 28-June 01 (2018); Ft. Lauderdale, Florida.

4. Introduction

Atom-photon quantum interfaces can allow for transferring quantum information between light and matter [1]. These interfaces are the building blocks of quantum channels and memories based on atomic systems for applications in quantum networks [2]. The goal of this project was the investigation of the requirements for increasing the amount of information that can be encoded in single photons and entangled photon pairs for transferring to atomic systems working as quantum memories with high multimode storage capacity. Increasing the dimensionality of quantum states and atom-photon interfaces brings advantages for information processing for communication, computation and metrology [3, 4, 5]. In our approach we investigate the spatial degree of freedom of single photons carrying information in the transverse profile of the field. We investigated the generation of photons from atomic ensembles carrying information in the orbital angular momentum degree of freedom. The generated photons can be entangled in many modes, i.e. in entangled qudit states, and are readily compatible with multimode quantum memories based on atomic ensembles.

Below we describe our work towards the realization of atom-photon interfaces with high capacity using the orbital angular momentum degree of freedom, and our theoretical work on understanding the entanglement content in the photons generated from FWM in atomic ensembles. We first describe the work performed before August 2017 on building the infrastructure for the studies of these interfaces. We then describe our current work towards the generation and optimization of entanglement from these interfaces.

5. Work performed during Sep. 2014- Aug. 2017

5.1 Studies of stimulated four-wave mixing (FWM) in cold atomic ensembles of cesium

Four-wave mixing in cesium atoms provides a way of generating light and entangled photons compatible with quantum memories based on atomic ensembles. As a first step of this project, we studied the generation of light from the FWM process in cesium (Cs) atomic ensembles. We built a 2-D magneto optical trap (2D-MOT) using laser cooling and trapping techniques, which shown in Figure 1. The 2D-MOT is prepared in the D2-line of Cs atoms, with a wavelength of 852 nm. The aspect ratio of the MOT is 20:1 longitudinal to transversal profile, which is favorable for the generation of photons along the axial direction.

This 2D-MOT has a higher number of atoms along one direction and can be prepared to have high optical depth (~10) which can be increased. The cigar-like-shape geometry of the cold atomic ensemble is favorable for the generation of photons along the axial direction. We use this 2D-MOT to perform the first studies for the generation of light from a stimulated FWM using a seed field. This seed field allows for finding the resonance of the FWM process and investigating the efficiency of the FWM process for different configurations of the energy levels in Cs involved in the FWM process.

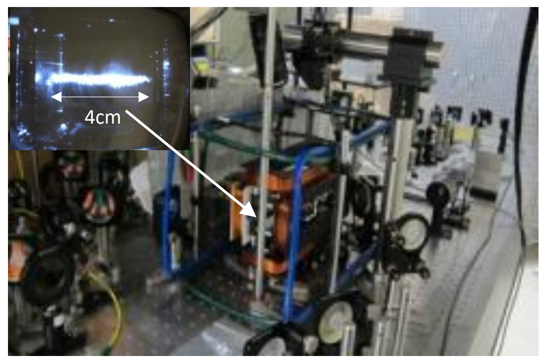

Fig. 1. Experimental setup for laser cooling and trapping of Cs atoms in a 2-D MOT. The background pressure is 10^{-10} torr. Inset shows the the cold ensemble of cesium atoms with an aspect ratio of about 20:1.

Figure 2(a) shows the double-lambda configuration of the energy levels in cesium for the investigation of the stimulated FWM process. In this process two pumps with frequencies ω_{P1} and ω_{P2} interact with the atomic ensemble. The seed field with frequency ω_S allows for efficient generation of "conjugate" light at frequency ω_{FWM} from FWM. Fig. 2(b) shows the experimental configuration for the study of stimulated FWM in the cold elongated cloud of cesium atoms. We used this experiment to perform an exhaustive search of the parameter space of parameters that are experimentally accessible in the FWM process to optimize the generation of light from stimulated FWM. Fig. 2(c) shows an example of the study for the generation efficiency for light from FWM as a function of power of the seed field for different levels of the pump powers and detunings from the corresponding atomic transitions. Other studies for efficiency of the generated light included relative polarizations of the pumps, seed and generated light, investigation of different duty cycles for loading the 2D-MOT, and different atomic configurations involved in the FWM process including 3-level and 4-level configurations. These studies allowed to determine the expected optimal parameters in our experiment for the efficient generation of quantum-correlated photons from the spontaneous FWM process.

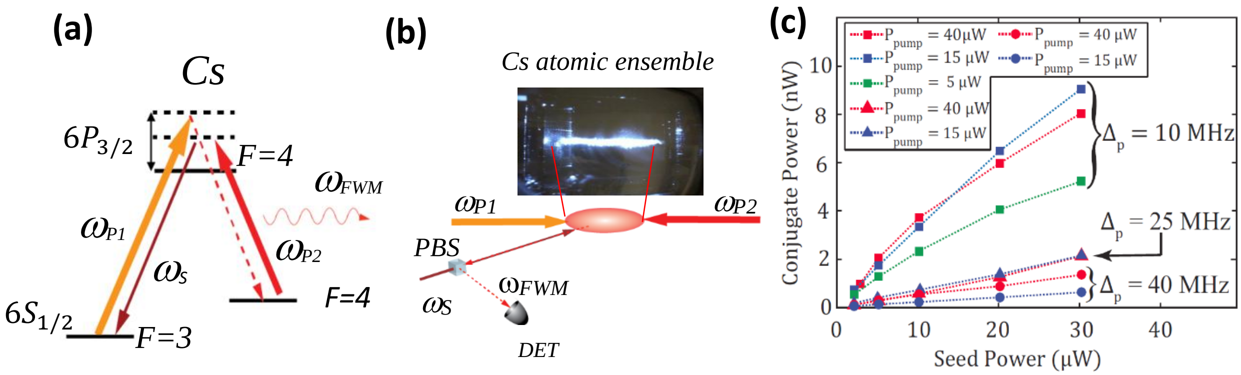

Fig. 2. Seeded FWM process in cesium (Cs). (a) Double-lambda configuration of the energy levels in Cs for the generation of light from stimulated FWM with pump fields with frequencies ω_{P1} and ω_{P2} and a seed field with frequency ω_S. The stimulated FWM process generates light with frequency ω_{FWM} in the phase-matched direction. (b) Experimental configuration; PBS, polarizing beam splitter; DET, detector. (c) Experimental study of the power of the generated conjugate light from stimulated FWM as a function of powers and pump "P1" detuning (Δ).

5.2 Preparation and measurement of states of light with high orbital angular momentum

Photons are ideal carries of classical and quantum information. They can travel over long distances in different links, such as fibers and free space channels. Moreover, different degrees of freedom of photon allow to increase the amount of information that can be encoded and transmitted in single photons. In our approach, we investigate the spatial degree of freedom of single photons carrying orbital angular momentum (OAM). The transverse degrees of freedom allow to access a high dimensional space, which increases the information carrying capacity of single photons. Moreover, due to the phase-matching condition requirement in FWM, the photons from a spontaneous FWM process are expected to be correlated in their OAM degree of freedom, and form entangled qudits in high dimensions. As a first step for the investigation of correlations in OAM we studied beam shaping techniques based on spatial light modulators (SLMs) for the preparation and detection of states of light carrying OAM.

Figure 3(a) shows the experimental setup for the study of preparation and measurement of states of light carrying OAM. We use phase-only SLMs to achieve arbitrary control the intensity and the phase of light [6], which allows for preparing arbitrary OAM states and state superpositions. A second SLM, SLM2, can then apply the inverse phase and intensity transformation, technique called phase flattening [7], that projects the desired state to be measured into a Gaussian mode. This mode can then be coupled into a single-mode fiber for projection and discrimination of states of single photons carrying OAM. In our study, we use image captured by a CCD camera at the Fourier plane of an imaging lens after SLM2 to discriminate different projected modes, and to investigate the fidelity and efficiency of projective measurements for OAM states and superpositions. Fig. 3(b) shows the input-output relation for the state preparation and measurements for states with OAM number from $l = -10$ to $l = 10$, corresponding to Laguerre Gauss modes LG_{0l}. We observe a high fidelity with a cross talk of less than 5%. Fig. 3(c) shows the projective measurements for superpositions of two OAM states of the form $|\psi\rangle = \frac{1}{\sqrt{2}}(|l\rangle + e^{i\phi}|-l\rangle)$ as a function of relative phase ϕ. These projections in two dimensional states are analogous to polarization states, and we observe a good performance for discrimination of states with different phases. The imperfections of the experiment and aberrations of the optical components prevent achieving higher fidelities for state preparation and measurement. We are currently investigating techniques for aberration correction using SLMs based on phase-retrieval algorithms with the goal of achieving high fidelities in the state preparation and measurement of states and superpositions in high dimensions. This investigation will be described below within the section discussing our current work on "Methods for aberration correction".

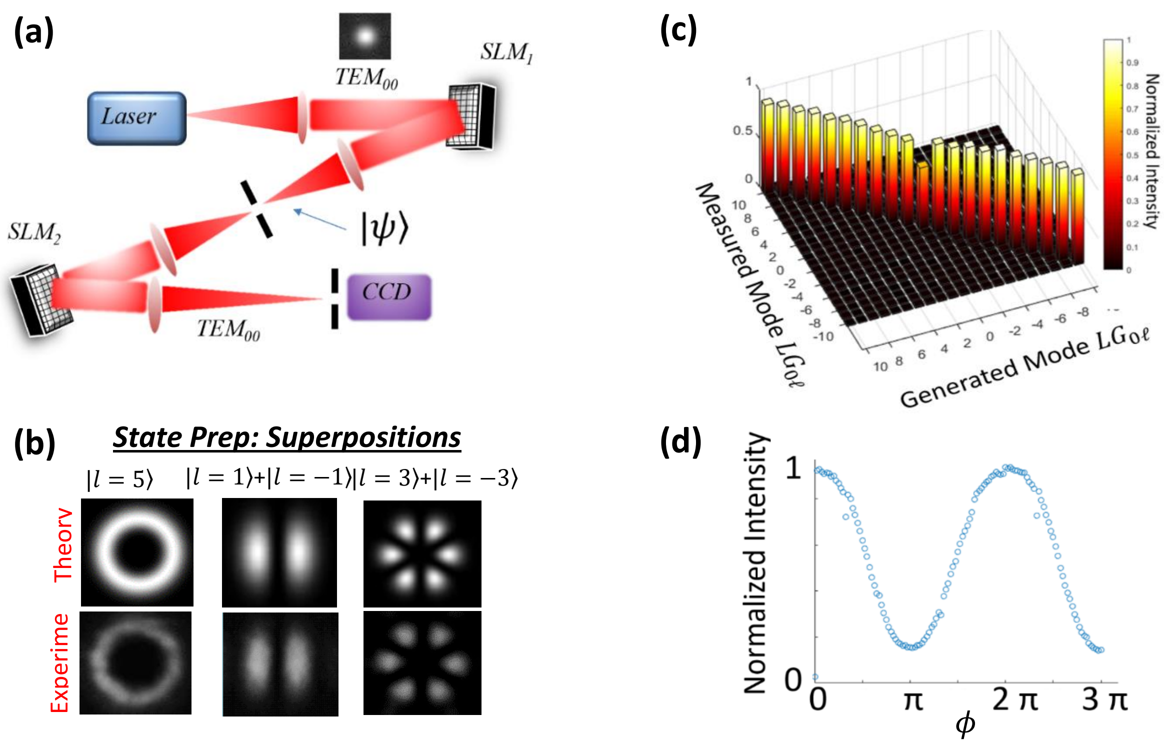

Fig. 3(a) Experimental configuration for the preparation and measurement of OAM states with SLMs. (b) Example of state preparation of OAM states and superpositions as seen in the CCD for $|l=5\rangle$, $|l=1\rangle+|l=-1\rangle$, and $|l=3\rangle+|l=-3\rangle$. (c) Input-output state matrix for state preparation and measurement from *l*=-10 to *l*=10. (d) Projective measurements onto superposition od states: $|\psi\rangle=\frac{1}{\sqrt{2}}\left(|l\rangle+e^{i\phi}|-l\rangle\right)$ shown for *l*=2.

5.3 Generation of correlated photon pairs from spontaneous four-wave mixing (FWM)

The spontaneous FWM process in atomic ensembles allows for the generation of entangled photons in different degrees of freedom. In our approach we investigated the generation of photons correlated in time from spontaneous FWM carrying information in the transverse degrees of freedom. We used the same energy levels as in our study of the stimulated FWM process. However, in the spontaneous FWM process, there is not a seed field. Instead, this process can generate correlated photons generated in the phase-matching direction, see Fig. 4 (a). These photos can be collected and detected by single-photon counters and their correlation can be investigated using coincidence counting techniques. We use a field-programable gate array to control the timing in our experiment and to perform data collection and coincidence analysis for the generation of correlated photons from spontaneous FWM.

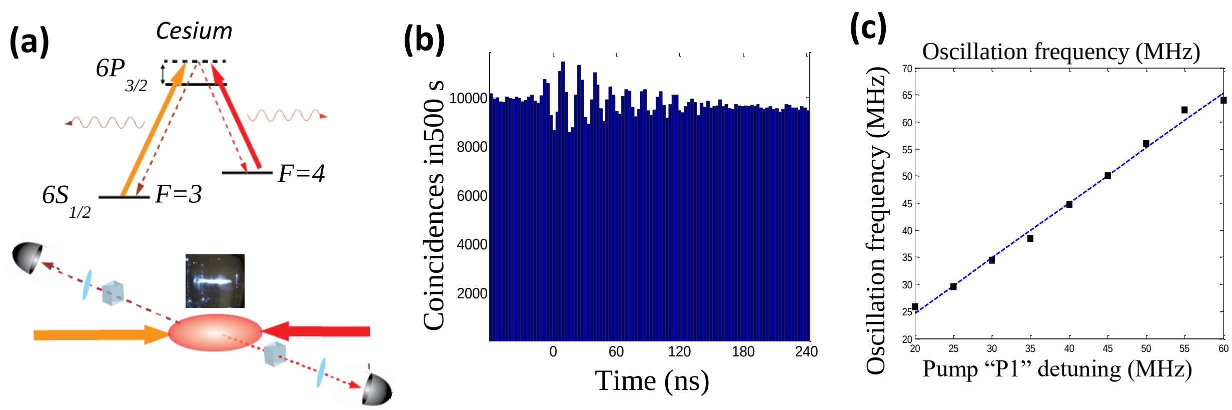

Fig. 4. Study of time-correlations between photons form spontaneous FWM in cesium. (a) Atomic configuration of the energy levels and experimental setup. (b) Coincidence count rate in 500 seconds between correlated single photons as a function of generation time delay. The correlations show a decay time of the order of 100 ns with oscillations that depend on the Pump "P1" frequency detuning, as seen in panel (c).

Figure 4(b) shows the coincidence counts integrated over 500 seconds of the generated photon pairs as a function of the relative delay, which describes the time that takes one photon to be generated given that the other photon has been generated. These time traces allow for investigation of the time correlations, coherence, and spectral properties of the photon pairs. We observe that these correlations show an exponential decay and oscillations. These features are due to the properties of the atomic structure and the properties of the FWM process. Fig. 4(c) shows the oscillation frequency of the time correlations of the photons as a function of pump-field detuning showing a linear dependence, which is consistent with previous experimental observations and theoretical predictions [8, 9].

In our experiment, however, the coincidence correlations of the generated photons always show a large background, which was mainly due to scattering from the strong pump fields and from the vacuum glass cell used to prepare the 2D-MOT. This large background prevented us to show that these correlations are actual quantum correlations. This problem drove us to investigate techniques for characterizing the surface quality of optical components producing scattering at the single-photon level, and to develop narrow-band frequency filters for suppressing background and scattering from the pumps in the single-photon counters, which prevent the demonstration of quantum correlations. Below I describe the steps taken in our experiment towards the demonstration of quantum correlations of these photons: (1) the development of narrow band filters, and (2) and testing the surface quality of vacuum cells for upgrading of our experiment with a high-quality glass cell with very low scattering.

5.4 Narrow-band frequency filters with long-term stability and large tunability

The correlated photons from spontaneous FWM are generated with frequencies that are very close to the frequencies of the pump fields. The difference in frequencies between the pumps and the generated photons range from a few tens of MHz to 9 GHz, depending on the atomic level configuration chosen for the FWM process. However, the pump powers range from 10 uW to 1mW, which correspond to about 10^{12}-10^{15} photons per second, see Fig. 2(c), compared to kHz generation rates for the generated photons, see Fig. 4(b). This puts a stringent requirement for any filtering technique with the goal of reducing background and scattering from the pump fields in the observed correlations in terms of frequency selectivity, transmission and rejection.

Following work in [10], we developed narrow-band frequency filters based on stable monolithic cavities with very high transmission and good stability, and that can be tuned over a wide range of wavelengths. We designed different frequency filters with different spectral properties and transmissions. We fabricated and characterized two, with properties that would be adequate for the experimental parameters. The discussion of our analysis for modeling and design of these filters is described in the PhD thesis of A. Ferdinand [11]. These studies investigated different cavity models and provide a back-to-back comparison of the designs that have been reported in the literature so far.

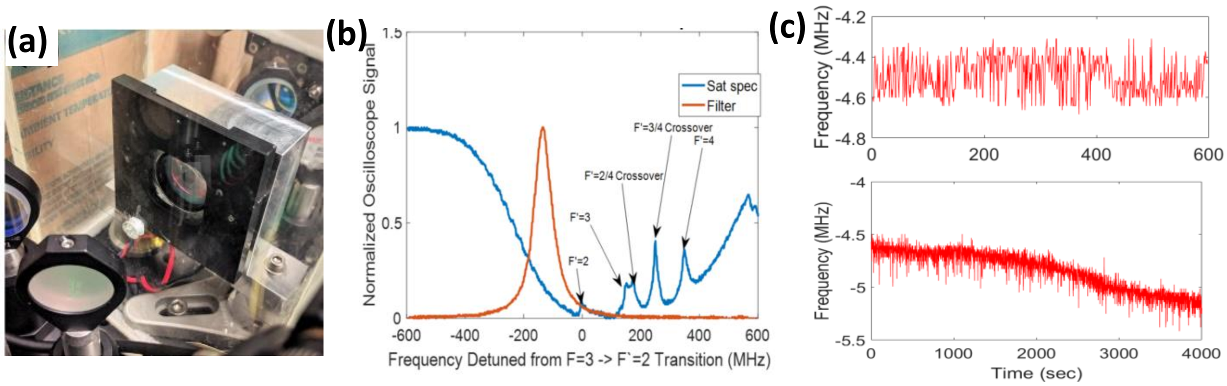

Fig. 5 Narrow-band frequency filters. (a) Picture of the filters fabricated in our laboratory (b) Normalized transmission intensity for the monolithic filter together with the normalized saturated absorption signal for cesium atoms in the D2 line at 852 nm in the transition 6S1/2, F=3 to 6P3/2, F'=2,3,4. (b) Short-term and long-term frequency drift. Maximum deviation observed in one of the filters was 0.2 MHz over 600 seconds and less than 1 MHz over 4000 seconds.

Figure 5(a) shows a picture of a narrow-band filter fabricated in our laboratory. The filter is kept on resonance by temperature control with stability within 0.04 K. The resonance frequency of the filter can be tuned by temperature with a tuning frequency resolution in the order of tens of kHz. Fig. 5(b) shows the transmission spectrum of the filter in orange with the signal from saturated absorption spectroscopy (sat-spect) in the D2 line of Cs at 852 nm. This signal allows for calibration of the filter resonance, and to investigate the tunability and stability of these filters. Fig. 5(c) shows the “short” term and the “long” term frequency drifts of the filter, calibrated with the sat-spect signal. We observe that this particular filter drifts less than 1 MHz within 1 hour, which is adequate for our experiments. Better temperature isolation and mechanical noise damping are expected to improve the performance of these filters. We tested the tunability of these filters by analyzing the performance of the filters in the D1 line of cesium at 892 nm, which is about 40 nm away from the designed wavelength. We observed a transmission of about 63%, compared to 70% at 850nm, and with high rejection at undesirable frequency bands. These filters will allow us to greatly suppress the background from the pump fields in the FWM for demonstrating quantum correlations of the generated photons. Moreover, these filters will also be useful for studies of atom-photon interfaces involving both the D1 and D2 lines, which is common in many atomic physics experiments [9].

6. Work performed during Sep. 2017- Aug. 2018

6.1 Surface characterization by scattering measurements at the single-photon level

The demonstration of quantum correlations in spatial degrees of freedom requires minimizing the background and ensuring that the spatial properties of the photons are maintained. As a second step to further suppress the background from the strong pump fields in our experiment, we investigated the scattering from different optical elements in our setup. While scattering affecting the photon-photon correlations is in general small and difficult to observe, by using single-photon counters to investigate the scattering from the strong pumps in a particular mode, we could determine the quality of the surface of different optical elements. We realized that the vacuum cell that we were using had a very poor surface quality and produced large scattering from the pumps. That prompted us to investigate the quality different glasses used for vacuum cells and other optical components in our setup. We tested several glass cells built from Pyrex and from fused silica with and without AR coating. This investigation allowed us to determine the best glass cells to use in experiments based on single-photon counting.

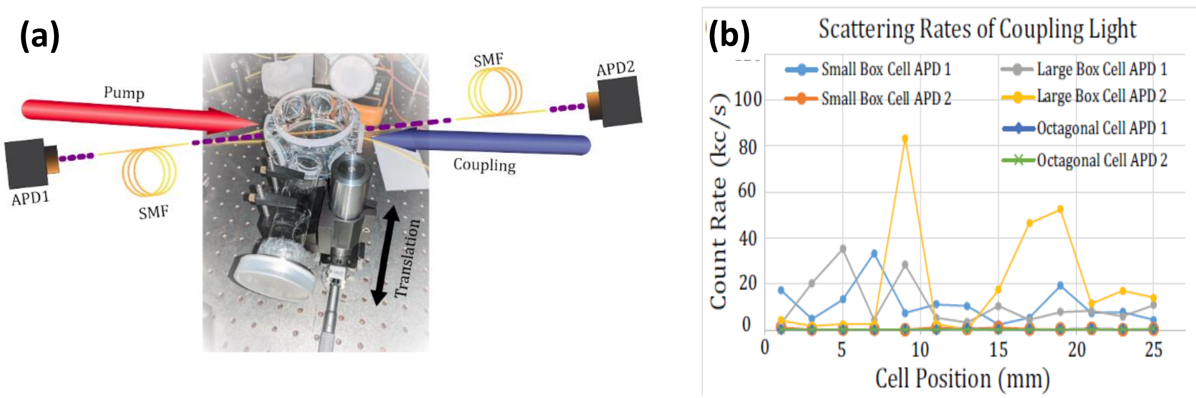

Fig. 6. Scattering measurements at the single-photon level. (a) Experimental setup for characterization of optical elements. This picture shows the cell under test, which is an octagonal fused silica cell with AR coated windows. (b) Scattering rates for different glass cells made of Pyrex glass and of fused silica as a function of the position of the cell to characterize the uniformity of the surface producing different levels of scattering.

Figure 6(a) shows the setup for the characterization of the surface quality of the glass cells by scattering measurements at the single-photon level. While the strong pump fields are incident in the glass cell, avalanche photodiodes (APDs) collect scattered photons in a particular mode defined by single-mode fibers. Scanning spatially the glass cell allows for investigating the roughness of the surface by observing the scattering of light at the single-photon level. Fig. 6(b) shows an example of the scattering rates for different cells made from Pyrex glass and from fused silica. We observe that the cells built with Pyrex glass produce scattering ranging from 10^3-10^5 counts per second, and in an uneven manner, which indicates poor surface quality. On the other hand, scattering from the cells built with fused silica always show scattering rates below 500 counts per second. This technique allows us to characterize the surface quality of different optical components over a very wide dynamical range, and identify faulty or low quality optical elements.

6.2 Second generation of experimental setup: 2D-MOT and light from FWM

The development of narrow-band tunable filters and the technique for determination of the surface quality based on scattering at the single-photon level described in Sec. **5.4** and **6.1**, respectively, will allow us to develop the next generation of our experiment. We are in the process of upgrading our experiment incorporating these advancements for lowering the background and scattering to demonstrate entangled photon in high dimensions. We have redesigned our vacuum system and the experimental setup to accommodate the fused-silica glass cell with high surface quality and AR windows. We have also made many upgrades in the laser systems and optics that will improve frequency and power stability of the setup, as well as damping mechanical vibrations.

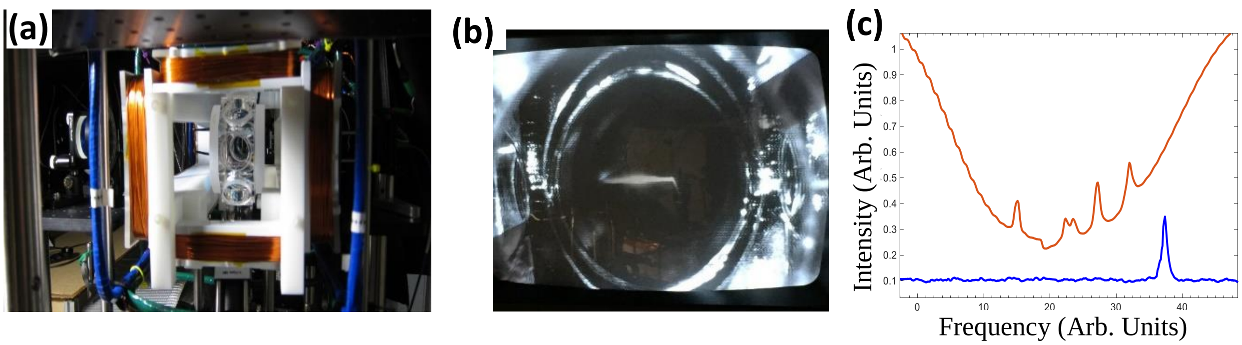

Fig. 7. Second generation of our experiment. (a) Magneto-optical trap setup with a fused-silica octagonal glass cell with AR coated windows. (b) Picture of the 2-D MOT. (c) Intensity of the generated light from stimulated FWM (blue) and saturated absorption signal of the seed field (orange), which is used for frequency calibration.

Figure 7(a) shows the second generation of our cold-atom experimental setup using the octagonal fused-silica glass cell. Visible are the MOT coils build on plastic bases to avoid magnetization due to the quadrupole fields, and to allow for fast switching of the MOT coils. Fig. 7(b) shows the 2-D MOT in this new setup. This setup will allow us to increase optical depths of the atomic ensemble by dynamically controlling detunings and magnetic fields for studies of quantum memory protocols. Fig. 7(c) shows the signal of the generated light from the stimulated FWM process described in Sec. **5.1** together with the saturated absorption spectroscopic signal for frequency calibration. We are currently investigating different configurations of the energy levels in cesium for the generation of light from FWM. Different configurations will generate light at different frequencies and detunings from the atomic transitions, and with different frequency separations with respect to the pump fields. These studies will allow us to determine the optimal configurations of the energy levels for the efficient photon generation, while allowing for efficient frequency filtering from the pumps. We expect to be able to demonstrate quantum correlations by the end of the year, and this system will be the basis for the future research described at the end of this report.

6.3 Continuation of theoretical investigation of correlations of photons entangled in OAM

In a continuing effort parallel to our experimental effort, we are investigating theoretically the generation of entangled photons from FWM carrying OAM. The quantum correlations in the spatial degrees of freedom of the photons generated from spontaneous FWM depend on the spatial, temporal, and spectral properties of the pump fields and the geometrical properties of the atomic ensemble. In our theoretical work we have focused on the analysis of the correlations in the OAM space to quantify the amount of entanglement of the generated photons. Ideally, we would want the photons from the FWM process to be generated in a perfect anti-correlated state $|\Psi_{ideal}\rangle = \sum C_l |l_S\rangle |-l_{AS}\rangle$, i.e. showing perfect correlations. Here, C_l describes the probability amplitudes, and the number of correlated modes can be inferred from the width of the probability distribution $|C_l|^2$ shown in Fig. 8(a). The FWHM of the distribution Γ, commonly called the spiral bandwidth [12], is used to quantify the number of correlated modes, and depends on different parameters in the process. Fig. 8(b) shows an example of the dependence of Γ with the size of the generated and collected single photons. However, our studies show that the state of the photons from FWM are not perfectly correlated in the OAM degree of freedom, so that the biphoton state is in general $|\Psi_{actual}\rangle = \sum A_{lm} |l_S\rangle |m_{AS}\rangle$, with A_{lm} the probability amplitudes including possible lack of correlations.

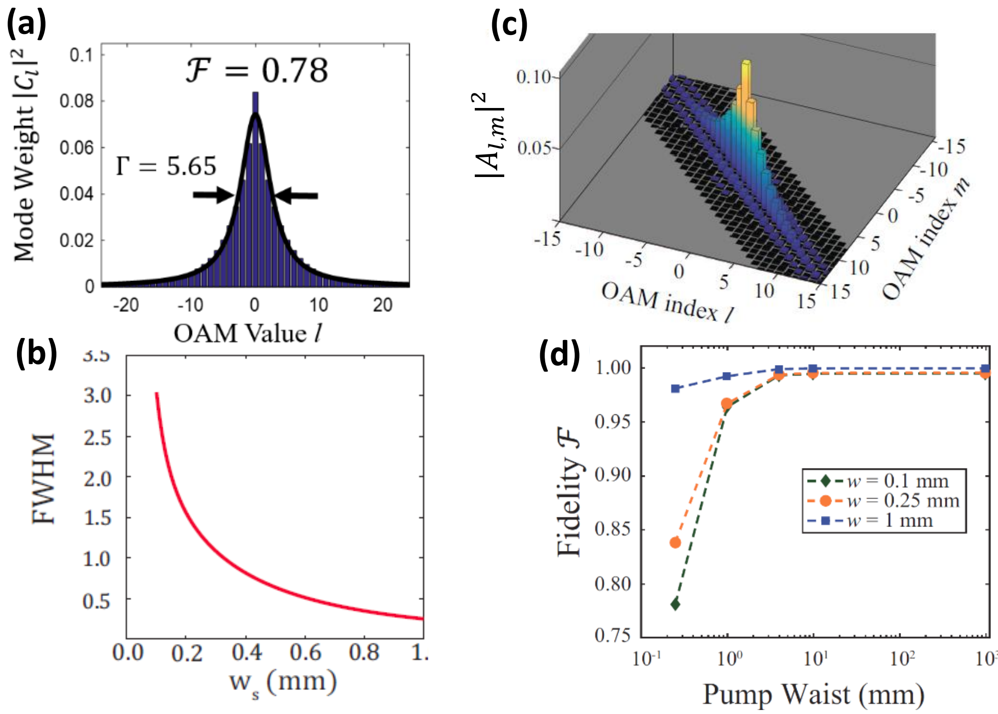

Fig. 8. Correlations of photons from FWM (a) OAM distribution $|C_l|^2$ of the generated photons assuming perfect OAM correlations. (b) Spiral bandwidth Γ as a function single-photon beam waist w_s for a collinear configuration. (c) Modal distribution $|A_{l,m}|^2$ without assuming perfect OAM correlations showing off-diagonal terms indicating imperfect OAM correlations. (d) Fidelity $\mathcal{F} = \sqrt{\sum |A_{l,-l}|^2}$ of the generated state with respect to a perfectly correlated state correlated in OAM l as a function w_p, and w_s.

Fig. 8(c) shows the distribution $|A_{lm}|^2$ showing non-zero weights for $l \neq m$, which indicates lack of correlations in the OAM degree of freedom. We quantify the amount of correlations using a fidelity measure $\mathcal{F} = \sqrt{\sum |A_{l,-l}|^2}$ which indicates the similarity with a perfect anticorrelated state $|\Psi_{ideal}\rangle$. Fig. 8(d) shows the fidelity $\mathcal{F}$ as a function of pump waist for different single-photon waists. In our numerical studies we observe that there is a general tradeoff between the number of correlated modes quantified by Γ and the fidelity with the ideal correlated state quantified by fidelity $\mathcal{F}$. The results of our theoretical studies allow for investigating the amount of correlation that can be generated from the FWM process, and these studies can be used as a guide for experiments for the generation of entangled photons with OAM in high dimensions. At the end of this report, we describe our current and future work that takes this theoretical study as a starting point to investigate the optimal modes for generation of entanglement form FWM. These investigations will allow for understanding the potential for atomic ensembles for generating high dimensional entanglement in the transverse degree of freedom of single photons.

6.4 Methods for aberration correction

Encoding information in the transverse degree of the field of single photons and ensuring that this information is maintained as it propagates through different optical channels requires understanding and correcting the aberrations of different optical elements. Moreover, performing measurements of entanglement in OAM, or in any spatial basis, with high fidelity requires optical systems to be aberration-free. We have investigated different methods for aberration correction with the goal of performing state preparation and state detection with high fidelity. In our first approach, we investigated a technique, commonly used for single atom microscopes [13], based on interference in the Fourier plane of a lens for phase retrieval and compensation, described in Sec. **6.4.1**. In the second approach, we investigated the Gerchberg-Saxton method with OAM [14] for both state preparation and measurement, described in Sec. **6.4.2**.

6.4.1 Interferometric method for phase retrieval and correction

The wave front distortion caused by an optical system can be characterized by phases-sensitive measurements based on an interference using SLMs [13]. This distortion can then be compensated by using SLMs to introduce the inverse phase transformation as the one caused distortion of the optical system. In our study of interferometric-based methods, we use an SLM to investigate the interference of different regions of an incoming light beam incident in the SLM to characterize optical aberrations. In this method, one small region of the SLM is used as a phase reference and the interference with light from another region of the SLM is observed by a pinhole detector, see Fig. 9(a). Analysis of the interference for different relative phases provides enough information to reconstruct the phase distortion map [13]. Fig. 9(b) shows the reconstructed phase map for our optical setup. This distortion can be compensated or corrected by encoding the conjugate phase map of the retrieved phase map in the SLM. This compensation allows for increasing the fidelity for state preparation and measurements in the spatial encoding.

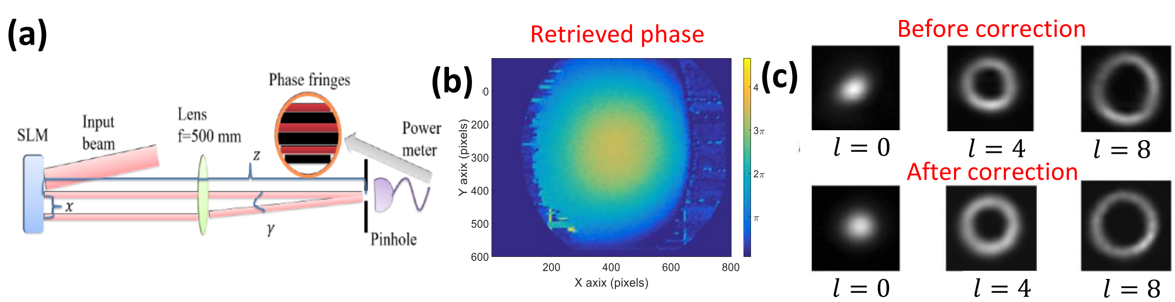

Fig. 9. Aberration detection and correction based on interferometric measurements. (a) Experimental setup. (b) Phase map retrieved for an optical setup. (c) Comparison for state preparation before and after aberration correction for OAM modes with $l = 0$, $l = 4$, and $l = 8$.

Fig. 9(c) shows examples for state preparation and measurements for three different modes: a Gaussian mode with $l = 0$, a $l = 4$ mode and a $l = 8$ mode before and after aberration correction. We observe that this method improves the quality of the prepared states, and we observe similar improvements when we use this method for measurements in the OAM basis. This study shows that the method used for atom microscopes also can be used for state preparation and measurements of states of light in the OAM basis.

6.4.2 Iterative method for phase retrieval and correction based on OAM states

We investigated a second method for phase retrieval based on Gerchberg-Saxton method using OAM states [14], which can provide advantages in terms of speed and precision for phase retrieval compared to the method described in Sec. **6.4.1**. This method uses an iterative algorithm to prepare a phase state with a SLM and to compare the expected image at the Fourier plane of an imaging lens to the observed image, see Fig. 10(a). This comparison provides information about the phase aberrations, and can be compensated with the SLM. Repeating this procedure allows to converge to a phase map that would generate the desired intensity profile in the Fourier plane of the lens with very small error. The retrieved phase map is not uniquely defined, but if the distortion of the optical system is not too large, this method for aberration correction shows a very good performance.

Figure 10(bi) shows the image in the Fourier plane of the lens for a prepared OAM mode with $l = 1$ when we introduce a phase distortion encoded in the SLM shown in Fig. 10(a). After using this iterative method, this phase distortion map can be retrieved and compensated with the SLM. The Fig. 10(bii) shows the image at the Fourier plane after compensation of the phase distortion showing a good performance for state preparation. We are currently applying this method for state preparation and measurement of OAM modes and superpositions in high dimensions. In addition, we are investigating possible improvements to this method using different decompositions for phase maps based on Zernike polynomials, which are used to characterize aberrations. We expect that this method will provide a better performance and can be applied to retrieve and compensate for large phase distortions.

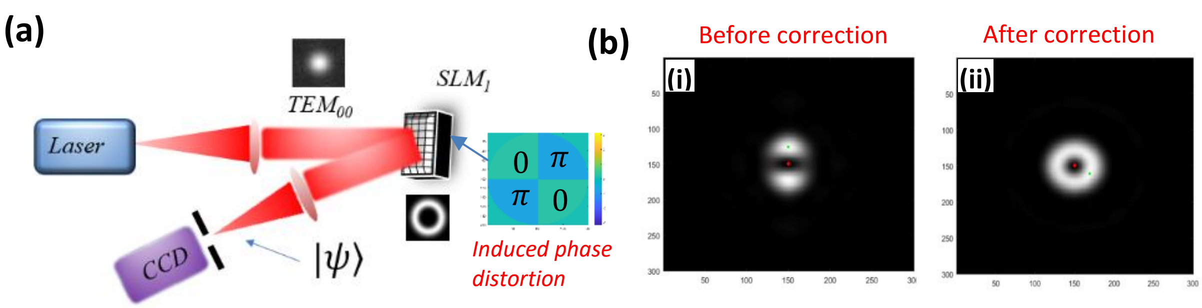

Fig. 10. Iterative method for phase retrieval and correction. (a) Experimental setup with introduced phase distortion map. (b) OAM mode with $l = 1$ as observed in the CCD at the Fourier plane of the lens with the introduced phase distortion, before and after phase retrieval and aberration correction.

7. Current and future research work

The research work performed and supported by this award is the basis for a continuing research effort in quantum networks with high information capacity based on single photons and atomic ensembles. Our future research based on the work reported here will focus on the theoretical and experimental investigation of the full potential of atom-photon interfaces using the spatial degrees of freedom of single photons for quantum information.

In our future research, we will continue our theoretical work focusing on the control of quantum correlations and the quantification of entanglement content of photons from FWM in atomic ensembles. We will investigate the multimode photon correlations from FWM by considering the complete transverse space and analyzing the photon correlations in the basis of eigenmodes of the process. Based on these theoretical studies we will experimentally investigate the generation of entangled photons from spontaneous FWM and multimode atom-photon interfaces with a high degree of entanglement. We will investigate how to optimize the quantum correlations with the goal of maximizing entanglement of the generated photons in the FWM process. We will investigate how to enable the generation of highly-controllable entangled states compatible with multimode atomic quantum memories for studies of high-dimensional atom-photon interfaces. This work will provide a better understanding of entanglement in high-dimensional spaces, and the potential for controlling quantum correlations of photons entangled in high dimensions for applications in quantum networks.

8. Summary

High-dimensional quantum systems provide advantages for computation, communication, and metrology compared to what can be achieved with two-dimensional systems. The research performed during the period of this award focused on the investigation of critical components for realizing high-dimensional atom-photon interfaces for applications in quantum networks with high information capacity based on atomic systems. During the period of the award, we built an experimental setup based on cold atoms for the investigation of correlated photons carrying information in their spatial degree of freedom based on FWM. We investigated different techniques for state preparation and measurement, and techniques for aberration correction to achieve high fidelity. We performed theoretical investigations for the generation of entangled photon pairs from atomic ensembles, which allow for analysis the correlations in OAM modes. We investigated techniques to suppress spurious background and scattering that mask the quantum correlations of the entangled photons, and we have updated our system that will allow for the investigation of quantum correlations in the transverse degree of freedom. This system will be the basis for our future investigations for the optimization of entanglement in high dimensions and the control of high-dimensional quantum systems. The work performed during the period of this award allowed for the completion of a PhD thesis of a graduate student in January 2018, and will also result in a Master's thesis by the end of 2018.

In our future research, we will continue our theoretical work on the study of quantum correlations and the quantification of entanglement of photons from FWM, we will experimentally demonstrate multimode atom-photon interfaces with high degree of entanglement, and we will investigate how to control high-dimensional entangled states compatible with multimode atomic quantum memories for studies of high-dimensional atom-photon interfaces and quantum networks.

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