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RESONANT SOURCE OF SQUEEZED STATES OF LIGHT

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During the duration of the grant we were able to achieve the main goal of the proposed work; namely, the generation of squeezed states of light on resonance with atomic systems. We generated two-mode squeezed states of light on-resonance with the D1 line in 87Rb with 5.4 dB of squeezing with the probe on resonance with the F=2 to F`=2 transition, 5.0 dB of squeezing with the conjugate on resonance with the F=1 to F`=1 transition, and 3.5 dB of squeezing with the probe and conjugate simultaneously on resonance with two different transitions. We then transferred the squeezing from the two-mode squeezed states to a single-mode squeezed state with 2.1 dB of squeezing on resonance with the F=2 to F`=2 transition.

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Abstract

This report summarizes the main accomplishments during the entire period of the grant from 9/30/2015 to 9/29/2019. During this time we were able to achieve the main goal of the proposed work; namely, the generation of squeezed states of light on resonance with atomic systems. The ability to generate quantum states of light on resonance with an atomic transition will enable an efficient interaction with cold atomic systems and will make it possible to enhance atomic based devices, such as interferometers and atomic clocks. We generated on-resonance two-mode squeezed states of light with a four-wave mixing (FWM) process in a double-lambda configuration in a Rb vapor cell. We then transferred the squeezing from a two-mode configuration to a one-mode configuration through the use of feedforward. For the case of two-mode squeezed states of light we generated 5.4 dB of squeezing with the probe on resonance with the F=2 to F'=2 transition in the D1 line of ^{87}Rb, 5.0 dB of squeezing with the conjugate on resonance with the F=1 to F'=1 transition in the D1 line of ^{87}Rb, and 3.5 dB of squeezing with the probe and conjugate simultaneously on resonance with two different transitions in the D1 line of ^{87}Rb. For the case of single-mode squeezed states of light we generated 2.1 dB of squeezing on resonance with the F=2 to F'=2 transition in the D1 line of ^{87}Rb. While we were able to generate narrowband on-resonance quantum states of light, the levels of squeezing were not as large as the ones we have been able to obtain when operating the FWM source off resonance. To overcome current limitations in our experiments and increase the levels of squeezing on resonance, we have worked on the use of external electric fields to shift the energy levels of the source to optimize the level of squeezing while keeping the generated quantum states of light on resonance with a bare unshifted Rb atom.

Main Results

The main accomplishment achieved during the grant period include:

- Implementation of an atomic-based source for the generation of narrowband two-mode squeezed states of light on resonance with different transitions of the D1 line of ^{87}Rb. In particular, we have generated 5.4 dB of squeezing with the probe on resonance with the F=2 to F'=2 transition, 5.0 dB of squeezing with the conjugate on resonance with the F=1 to F'=1 transition, and 3.5 dB with the probe and conjugate simultaneously on resonance [1].
- Implementation of a source for the generation of narrowband single-mode squeezed states of light on resonance with the D1 line of ^{87}Rb through the use of feedforward [2]. With this technique we obtained 2.9 dB of off-resonant single-mode squeezing from an initial two-mode squeezed state with 7.6 dB of squeezing and 2.1 dB of single-mode squeezing on resonance with the F=2 to F'=2 transition of ^{87}Rb from an initial two-mode squeezed state with 5.7 dB of squeezing.
- Performed a theoretical study of the effect of closely-spaced excited states on electromagnetically induced transparency [3]. Our calculations show that under some conditions the presence of the additional level can enhance the transparency level. However, the additional level limits the maximum

transparency level that can be achieved, even in the ideal case of no decoherence, when it is not possible to resolve the two excited states due to Doppler broadening.

- Implementation of a vacuum chamber with electrodes to apply a high voltage around a Rb atomic ensemble to Stark shift the energy levels of the source used for the FWM, with the goal of operating the FWM in an optimized off-resonance configuration while generating quantum states on resonance with an unshifted atom. We have observed a shift of the transition frequency of the D1 line of ^{85}Rb as large as 300 MHz when operating at the number densities required for the FWM. Even at such high voltages, apart from the expected frequency shift, the FWM spectrum and intensity difference squeezing are not significantly affected.
- Implementation of a detection technique based on a cavity for the characterization of the quantum properties of the generated quantum states of light. This technique offers advantages over the standard homodyne detection technique, as it is capable of characterizing correlations between sidebands that are assumed to be zero with homodyne detection.
- Implementation of FWM in Na with the goal of developing a source that can be used to interact with a Na BEC for quantum enhanced probing of the ultra-cold atomic system.

Personnel

Graduate Student: Saesun Kim; 100% from January 1, 2016 to July 31, 2019
Graduate Student: Tim Woodworth; 50% from January 1, 2016 to September 30, 2017
Graduate Student: Hua Wang; 50% from October 1, 2016 to December 31, 2016
Graduate Student: Gaurav Nirala; 100% from August 1, 2017 to September 30, 2018

PI, three months summary salary over duration of grant

Outcomes

The work performed as part of this award will be the core of a PhD thesis. In addition, it has led to the following publications and presentations:

Publications:

1. S. Kim and A.M. Marino, "Generation of ^{87}Rb-Resonant Bright Two-Mode Squeezed Light with Four-Wave Mixing," *Optics Express* **26**, 33366 (2018).
2. S. Kim and A.M. Marino, "Atomic Resonant Single-Mode Squeezed Light from Four-Wave Mixing through Feedforward," *Optics Letters* **44**, 4630 (2019).
3. S. Kim and A.M. Marino, "Effect of Closely-Spaced Excited States on Electromagnetically Induced Transparency," *arXiv*:1912.12267 [quant-ph] *to be submitted to Phys. Rev. A* (2019).
4. G. Nirala, M. Martinelli, P. Nussenzveig, and A.M. Marino, "Complete Characterization of Quantum States of Light with Resonant Analysis Cavity," *in preparation*.
5. Q. Zhang, H.G. Ooi, S. Kim, A.M. Marino, and A. Schwettmann, "Four-Wave Mixing in a Hot Sodium Vapor Cell," *in preparation*.

Presentations:

1. *DAMOP*, Sacramento, CA, June 2017 (poster)
"Electromagnetically Induced Transparency in a Double-Lambda System," S. Kim and A.M. Marino

2. *DAMOP*, Ft. Lauderdale, FL, May 2018 (oral presentation)
   "Generation of ^{87}Rb-Resonant Bright Twin Beams with Four-Wave Mixing," S. Kim and A.M. Marino

3. *DAMOP*, Ft. Lauderdale, FL, May 2018 (poster)
   "Four-Wave Mixing in Hot Sodium Vapor Cells," Q. Zhang, S. Kim, L. Narcomey, A.M. Marino, and A. Schwettmann

4. *DAMOP*, Milwaukee, WI, May 2019 (oral presentation)
   "Generation of Narrowband Bright Single-Mode Squeezed Light through Feedforward," S. Kim and A.M. Marino

5. *DAMOP*, Milwaukee, WI, May 2019 (oral presentation)
   "Complete Characterization of Bright Entangled Twin Beams with Analysis Cavity Method," G. Nirala, M. Martinelli, P. Nussenzveig, and A.M. Marino

6. *DAMOP*, Milwaukee, WI, May 2019 (poster)
   "Four-Wave Mixing in Hot Sodium Vapor Cells with Saturated Absorption," Q. Zhang, S. Kim, M. Peters, A.M. Marino, and A. Schwettmann

7. *DAMOP*, Milwaukee, WI, May 2019 (oral presentation)
   "Experimental Investigation of Four-Wave Mixing in Hot Sodium Vapor Cells," H.G. Ooi, Q. Zhang, S. Kim, A.M. Marino, and A. Schwettmann

Introduction

The main objective of this award was to develop a narrowband source of squeezed states of light that operates on atomic resonance in order to enable an efficient interaction with cold atomic systems. Such a source will make it possible to enhance atomic based devices, such as interferometers and atomic clocks, which will lead to the enhancement of positioning systems such as GPS and more accurate gyrometers and accelerometers. To achieve our objective, we implemented a source based on FWM in a double-lambda configuration in an atomic vapor cell. We first considered the generation of on-resonance two-mode squeezed states, in which the squeezing is distributed between two different optical beams. We then transferred the squeezing from a two-mode configuration to a single-mode configuration through the use of feedforward techniques. The use of this approach makes it possible to overcome the limitation of competing processes in other atomic-based sources for the generation of single-mode squeezed states of light.

Four-Wave Mixing Source

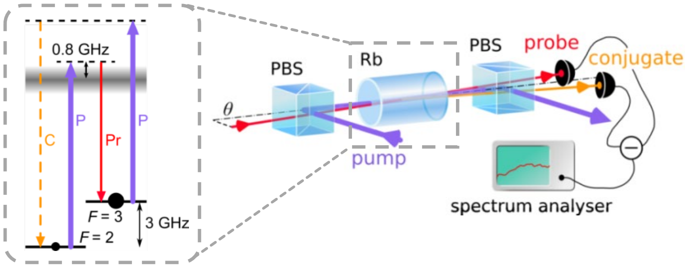

Fig. 1. Basic setup for the generation of two-mode squeezed states of light. The inset shows the double-lambda configuration, on which the FWM is based, in the D1 line of ^{85}Rb.

Our source of quantum states of light is based on a FWM process in a double-lambda configuration [4], see inset in Fig. 1. The source uses an atomic ensemble (^{85}Rb for most of our experiments) in a vapor cell as the required nonlinear medium, as this naturally leads to quantum states that are narrowband and close to atomic resonance. In the FWM process a strong beam, known as the pump, is combined with a weak beam, known as the probe, inside the vapor cell, as shown in Fig. 1. This leads to the generation of a new field, known as the conjugate, and the amplification of the input probe beam. For the optimum configuration in

^{85}Rb, the pump and probe are tuned to the blue of the D1 line (at 795 nm) by ~ 800 MHz and are resonant with a two-photon Raman transition between the two hyperfine ground states *F=2* and *F=3*. While for this optimum configuration we have been able to obtain 9 dB of squeezing [5], the system operates off resonance, around 0.8 GHz for the probe and 3.8 GHz for the conjugate.

On-Resonance Two-Mode Squeezed States of Light

The original proposals for the FWM process in a double-lambda configuration in an atomic system predict that large levels of squeezing can be obtained on resonance with such a system. These proposals are based on the use of electromagnetically induced transparency (EIT) to reduce the absorption on resonance while maintaining a strong FWM interaction [4, 6, 7]. However, residual absorption and competing process in the atomic system have been a limiting factor in operating the FWM on resonance. In its optimum, the FWM process on which the project is based operates ~ 1 GHz away from resonance. In this off-resonant configuration the FWM produces narrowband two-mode squeezed states (or twin beams), which are entangled and show large levels of relative intensity-difference squeezing [8].

Our initial approach to move from the off-resonant configuration to one in which either the probe or conjugate is on resonance with one of the transitions of the D1 line of ^{85}Rb focused on the use of anti-relaxation coatings and magnetic shielding to minimize any decoherence effects to enhance the EIT and reduce the absorption. Due to the large number density required for the FWM process, the cell needs to be heated to ~120°C. In order to operate at the required temperature, we explored the use of a high melting point anti-relaxation coating (OTS). With such a coating we were able to slightly increase the level of squeezing when operating in the off-resonant configuration. However, when the frequency of the probe was brought closer to resonance the absorption dominated the gain from the FWM process and no signal was obtained. We also performed experiments with longer cells at lower temperatures so that we could use anti-relaxation coatings such as paraffin, which have been shown to be more effective in reducing the probability of decoherence through spin flipping collisions with the walls of the cell [9]. Through the optimization of different parameters, we were able to observe 0.5 dB of intensity difference squeezing ~ 100 MHz to the

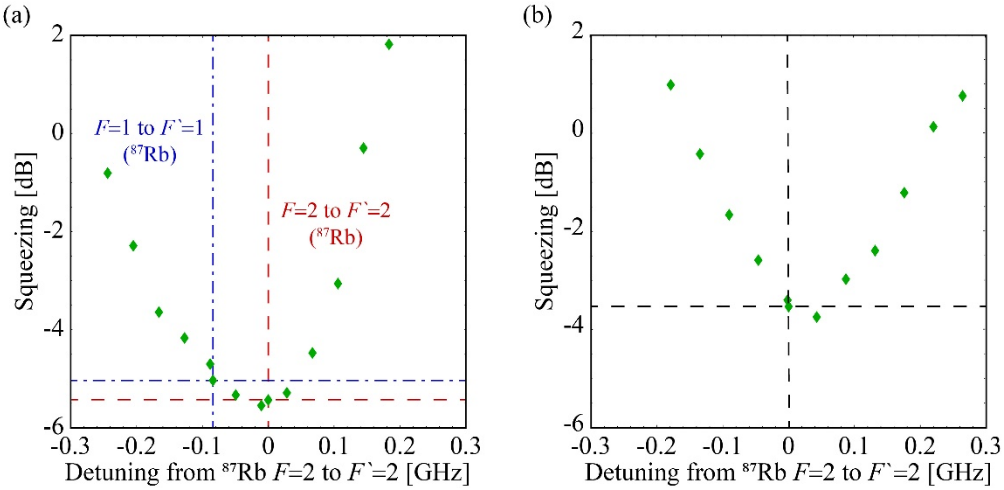

Fig. 2. On-resonance two-mode squeezed states of light. Intensity-difference squeezing measured as a function of the detuning of the probe from the D1 F = 2 to F' = 2 transition in ^{87}Rb. (a) Configuration in which either the probe or conjugate is on resonance with a transition in the D1 line of ^{87}Rb. The vertical and horizontal red dashed (blue dashed-dotted) lines indicate the frequency at which the probe (conjugate) is on resonance and the corresponding level of squeezing, respectively. (b) Configuration in which the probe and conjugate are simultaneously on resonance with transitions in the D1 of ^{87}Rb. The vertical and horizontal dashed lines indicate the resonance frequency for the probe and conjugate and the corresponding level of squeezing, respectively. Adapted from [1].

red of the $F=2$ to $F'=1$ transition of the D1 line. While we were also able to observe the generation of a conjugate beam on resonance, there was a significant amount of probe absorption that led to large levels of excess noise and thus no squeezing.

In order to better understand the limiting factors of the operation of the source on resonance, we performed a theoretical study of the effect of closely-spaced excited states on EIT. Among other things, our theoretical calculations show that the presence of two excited states with a separation smaller than the Doppler broadening makes it impossible to obtain perfect transparency even in the ideal case of no decoherence [3]. As a result, residual absorption is always present, which represents a significant limitation for the operation of the FWM process on resonance. In addition, we found that the transparency resonance due to EIT is broader than the one expected from a three-level model. These results could be relevant to quantum memories based on atomic vapor cells.

Given the that the use of anti-relaxation coatings did not achieve the expected results, we implemented an alternative approach to achieve the goal of generating on-resonance two-mode squeezed states of light. In particular, we took advantage of the proximity of the energy levels of the D1 line in ^{85}Rb and ^{87}Rb to operate the FWM in ^{85}Rb in a regime that generates two-mode squeezed states that are on resonance with ^{87}Rb. As shown in Fig. 2(a), with this approach we were able to obtain 5.4 dB and 5 dB of squeezing when one of the modes is on resonance with the $F=2$ to $F'=2$ or $F=1$ to $F'=1$ transition of ^{87}Rb, respectively. More interestingly, we also are able to obtain 3.5 dB of squeezing when both probe and conjugate are simultaneously on resonance with two different transitions in the D1 line of ^{87}Rb, as shown in Fig. 2(b). This result is significant, as it will make it possible to deterministically transfer the quantum correlations from the twin beams to remote atomic ensembles [10]. The main limitation to this approach is that in order to operate on resonance with the D1 of ^{87}Rb requires specific values for the one-photon detuning and two-photon detuning (for the double resonant case), which reduces the level of squeezing that can be generated with the FWM in ^{85}Rb.

Generation of Single-Mode Squeezing through Feedforward

While two-mode squeezed states of light can be used for quantum enhanced sensing applications and naturally exhibit entanglement, it has been shown that single-mode squeezed light is in general better suited for quantum enhanced sensing applications [11]. While on-resonance single-mode squeezed states of light have been generated with optical parametric oscillators (OPOs) [12-14] and atomic systems [15, 16], the levels of squeezing have been limited. For the case of OPOs, the generation of squeezed light at frequencies

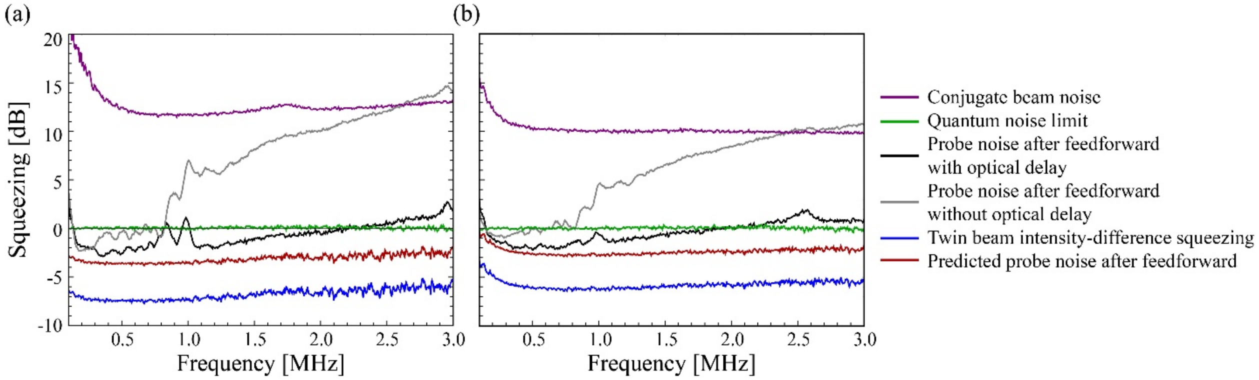

Fig. 3. Transfer of squeezing from a two-mode configuration to a one-mode configuration for the (a) off-resonance and (b) on-resonance configurations. The use of feedforward makes it possible to transfer the intensity-difference squeezing (blue trace) present in the two-mode squeezed states to a one-mode squeezed state configuration (black trace). The green trace shows the quantum noise limit or shot noise level while the red trace shows the predicted level of squeezing after the feedforward operation. Adapted from [2]

that are resonant with the D1 line of alkali atoms is not efficient due to the losses in the nonlinear crystal of the required UV pump light [17]. On the other hand, for atomic sources competing processes and absorption pose significant constraints. As such, increasing the level of squeezing obtained with these sources is not straight forward. In order to overcome these limitations, we have used a feedforward technique [18, 19] in which the squeezing is transferred from a two-mode configuration to a single-mode configuration.

In order to implement the feedforward, we generate bright two-mode squeezed state of light with the FWM process, as described above. After the FWM process the conjugate is detected with a 95% quantum efficient photodetector to measure its amplitude fluctuations. The probe beam is sent through an electro-optic modulator (EOM) to actively control the transmission and feedforward the measured fluctuations from the conjugate onto the probe amplitude. When implementing the feedforward operation we block the DC component of the measured conjugate signal and amplify the remaining fluctuations with an optimized gain before sending the signal to the EOM.

We consider two different configurations for the FWM source, one that is optimized to obtain the largest level of intensity-difference squeezing in an off-resonant configuration and a second one that is on resonance with the D1 *F=2* to *F'=2* transition in ^{87}Rb. For the off-resonant configuration we start with an intensity difference squeezing of 7.4 dB while for the resonant configuration the initial level of squeezing is of 5.8 dB. As shown in Fig. 3, with this technique we obtain a single-mode squeezed state with 2.9 dB of squeezing when tuned off resonance and 2.0 dB when tuned on resonance with the D1 *F=2* to *F'=2* transition in ^{87}Rb.

The levels of squeezing that we obtain are significantly lower than the initial levels of squeezing present in the two-mode squeezed state. Given that the squeezing is transferred from two beams to one beam, the maximum level of squeezing that can be obtained in the absence of losses is reduced by about 3 dB with respect to the initial intensity-difference squeezing. Losses associated with the EOM and optics required to implement the feedforward further reduce the level of squeezing. The theoretical level of single-mode squeezing taking into account these limitations is shown in Fig. 3 as the red trace. As can be seen, the levels of single-mode squeezing we were able to measure are close to the expected ones.

One of the main complications associated with the use of feedforward are due to the delay introduced by the electronics, which in our experiment was of ~ 70 ns. If this delay is not compensated, the squeezing after the feedforward can only be obtained over a very reduced bandwidth (see gray trace in Fig. 3). As a result, it is necessary to introduce a long optical delay line on the path of the probe before performing the feedforward operation. Additionally, the feedforward technique is sensitivity to the feedforward gain, which needs to be optimized. This makes it challenging to transfer the squeezing form a two-mode squeezed state to a single-mode squeezed state over a large range of frequencies.

Atomic State Dressing

While we were able to accomplish the main goal of the project of obtaining on-resonance two-mode and one-mode squeezed light, the levels of squeezing we were able to obtain are low compared to the ones we have previously achieved with the FWM source when operated away from resonance. In order to overcome this limitation, we have been working on the use of external fields to shift the energy levels of the source. This will effectively allow us to operate the source in the optimal off-resonant configuration while still being able to generate quantum states of light that are on resonance with a bare unshifted Rb atom. The ability to shift the energy levels will also provide the additional flexibility for the FWM source, as it will make it possible to tune the source over a significantly larger frequency range.

Our main focus has been on the use of the DC Stark shift to dress the energy levels of the source. To achieve this goal, we have designed and implemented a vacuum chambers with electrodes that make it possible to apply a high voltage around a Rb vapor ensemble to achieve the large potentials required to shift the energy levels. We have designed and tested several designs for the vacuum chamber, which each new design allowing us to go to higher potentials. Figure 4 shows the latest design that further isolates the electrodes and confines the Rb vapor to regions between them.

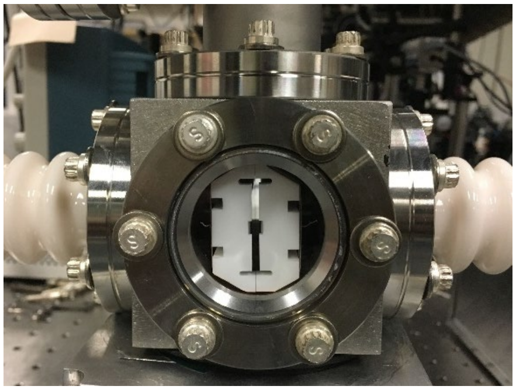

Fig. 4. Vacuum chamber with electrodes for atomic state dressing to implement an on-resonance source of squeezed states of light. A high voltage is applied to the electrodes that are held in place by a macor enclosure.

With the design shown in Fig. 4, we have been able to operate the high voltage vacuum chamber with up to 30 kV in the absence of Rb atoms. Once we add Rb to the vacuum chamber we are able to operate it with a voltage up to 23 kV at room temperature, which leads to a frequency shift of ~ 540 MHz. Given that the FWM requires a large number density to operate, we need to heat up the chamber to obtain the required number densities. At the temperatures required for the FWM, we have been able to operate the chamber at almost 15 kV for a frequency shift of ~ 240 MHz, as can be seen in Fig. 5(b). We have also performed a measurement of the frequency shift as a function of the applied voltage, see Fig. 5(a), to confirm that we observe the expected behavior for the Stark effect, red trace in Fig. 5(a), even at these high voltages.

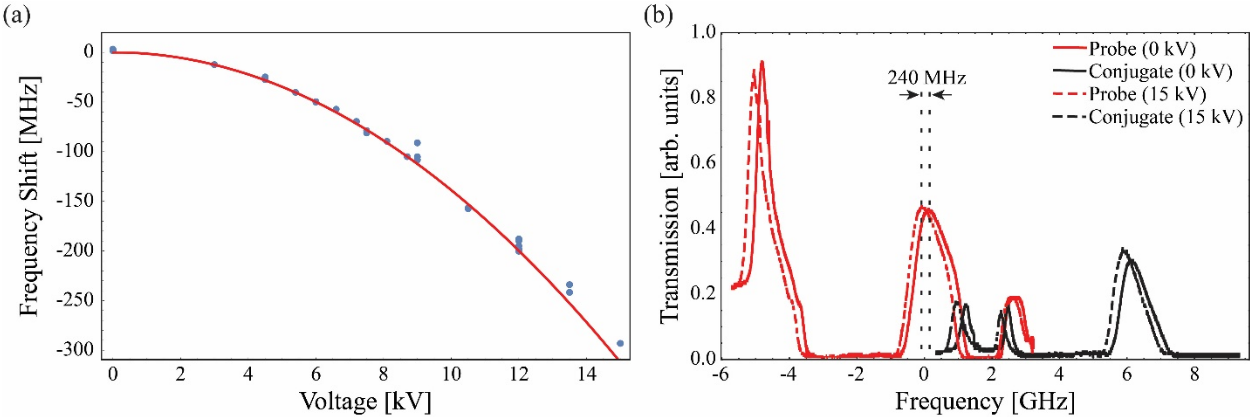

Fig. 5. Stark shift of the D1 line of ^{85}Rb in the presence of a DC voltage. (a) Measured frequency shift as a function of applied voltage on the electrodes of the high voltage vacuum chamber. We have observed shifts as large as 300 MHz. (b) Shift of the FWM transmission spectrum in the presence of a high voltage.

As can be seen in Fig. 5(b), except for the expected frequency shift, the transmission spectrum of the FWM is not modified when a high voltage is applied across the electrodes in the vacuum chamber. Our preliminary measurements show that the level of squeezing is not impacted either when the high voltage is applied. These results illustrate the viability of this approach to overcome the current limiting factors when trying to operate the FWM source directly on resonance. We are currently working on an updated design for the high voltage vacuum chamber that will allow us to obtain larger frequency shifts when operating at the number densities required for the FWM.

Cavity for Characterization of Quantum States

During the last two years of the project we have been studying the use of cavities to characterize the quantum states of light we are generating with our system. The standard technique to characterize squeezed states of light is homodyne detection. However, this technique is not able to provide a full characterization of the quantum properties of the light [20]. On the other hand, the use of a cavity offers an alternative that overcomes the limitations of homodyne detection by accessing correlations between sidebands that are assumed to be zero in homodyne detection. While this assumption is valid for most sources, they can be different from zero for narrowband sources. Our initial characterization with the cavities shows that there are correlations present in our two-mode squeezed states that cannot be measured through standard techniques. Once a full characterization is done of the two-mode squeezed states, we will use the cavity to completely characterize the properties of the single-mode squeezed state generated through feedforward.

Four-Wave Mixing in Sodium

During the last year and a half of the project, we have been working with the group of Prof. Arne Schwettmann at the University of Oklahoma to extend the results we have obtained in Rb to Na, with the goal of having a source that can be used to interface with their cold atomic system. The group of Prof. Schwettmann is working on spinor BECs in Na with the goal of implementing a quantum enhanced atomic interferometer. The interface of the BEC with squeezed states of light would enable, among other things, enhanced imaging for more precise characterization of their system.

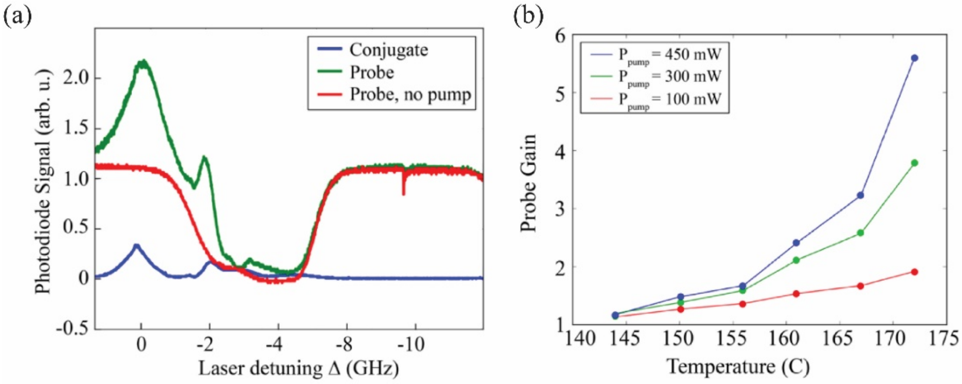

Fig. 6. Four-wave mixing in sodium vapor. (a) Transmission spectrum for the FWM process. Gain for the probe beam (green trace) and the generation of a conjugate beam (blue trace) can be seen. (b) Probe gain as a function of the temperature of the vapor cell for different pump powers. As the temperature is increased, the number density is increased, which leads to an increase of the gain of the FWM process.

One of the complications of implementing the FWM process in Na is that the ground state hyperfine splitting is smaller than the Doppler broadening at the high temperatures required to operate the FWM source. As a result, absorption is more of a problem in Na than it is in Rb. In spite of this limitation, we have been able to observe gain from the FWM along with the generation of a conjugate beam, as can be seen in Fig. 6(a). We are currently in the process of characterizing the FWM and the levels of gains that can be achieved. We have observed gains as large as ~ 6, as can be seen in Fig. 6(b). While these results show the viability of implementing the FWM in NA, we have not been able to observe squeezing. We continue to explore different approaches to minimize the losses on the probe beam and optimize the different parameters in order to generate squeezed light at Na frequencies.

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