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Squeezed light from 4-wave mixing: toward sensitive imaging and measurement applications

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14. ABSTRACT The field of quantum and nonlinear optics has long highlighted the demonstration of the unique features of the quantum world in the context of light. Taking advantage of the quantum properties of light to make advances in the context of metrology and measurement science has been the practical goal of our lab, and of the work supported under this grant. Our goal has been to investigate the quantum advantage in multiple-spatial-mode imaging applications as well as to work with the multiple frequency modes that are available through the generation of squeezed light from four-wave mixing (4WM) in atomic vapors. We have worked to improve lowfrequency squeezing and to demonstrate phase-sensitive optical amplification and its applications in a number of different scenarios.			
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“Squeezed light from 4-wave mixing: toward sensitive imaging and measurement applications”

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Abstract

The field of quantum and nonlinear optics has long highlighted the demonstration of the unique features of the quantum world in the context of light. Taking advantage of the quantum properties of light to make advances in the context of metrology and measurement science has been the practical goal of our lab, and of the work supported under this grant. Our goal has been to investigate the quantum advantage in multiple-spatial-mode imaging applications as well as to work with the multiple frequency modes that are available through the generation of squeezed light from four-wave mixing (4WM) in atomic vapors. We have worked to improve low-frequency squeezing and to demonstrate phase-sensitive optical amplification and its applications in a number of different scenarios.

Accomplishments

Research Objectives:

We proposed a number of activities based around the generation of squeezed light from a nonlinear four-wave mixing process in warm rubidium vapor. We stressed the characterization and application of low-frequency squeezing properties of the 4WM source and hoped to apply this source to applications like direct image subtraction on a camera. We will also proposed investigate the phase-sensitive amplifier (PSA) configuration, which produces single-mode quadrature squeezing. We intended to discontinue work on “fast light” materials when the experiments that were underway at the beginning of the grant were finished. We intended to push toward the use of diode lasers for squeezed light generation so that this sort of experiment could potentially be more easily moved out of the laboratory.

A number of specific research topics were proposed, including generating squeezing at very low measurement frequencies, as this is necessary for direct image subtractions on integrating cameras. We intended to further our characterization of the 4WM squeezing process and study optical memory for squeezed light. In addition, we intended to study phase-sensitive amplifiers and fast light transmission through such a device. Other measurement problems include interferometry, bright image formation through 4WM, and the use of diode lasers as pump sources. We will comment in more detail on these various topics below.

Background

Quantum optical science commonly relies on nonlinear optical processes that have been shown to be able to lead to optical states with interesting quantum properties. These states often have noise and correlation properties that can be used to obtain a “quantum advantage” in optical measurements. In particular "squeezed states" of light can have fluctuations that are smaller than the usual shot noise limit, and can be used to improve measurement sensitivity. In particular, two-mode squeezed states can produce correlations between two beams of light allow high-precision measurements to be made on one beam by using the other as a reference.

In 2007 we developed a nonlinear optical technique for generating squeezed states of light. This technique is based on the process of four-wave mixing near a Rb atomic resonance. This technique has proven to be fairly easy to implement and robust to operate, and it has been adopted by a number of groups around the world. Using small (~1 cm long) vapor cells warmed to about 120 C and light from diode or Ti:sapphire lasers we are able to make measurements with up to a factor of 10 improvement over conventional "classical" optical techniques. In the simplest implementations the technique does not require the use of an optical cavity to enhance the field strength and quantum correlations can be created amongst many pairs of spatial modes. In this way imaging experiments with squeezed light can be performed. We continue to explore the applications of this technique and summarize here our accomplishments during this grant period.

During the grant period the covid pandemic disrupted the normal progress of research at the University of Maryland, where our labs are located, at the Joint Quantum Institute. A one-year no-cost extension was obtained in order to finish work on the grant.

Our work has concentrated on phase-sensitive amplification, sensitive nonlinear interferometry techniques, and the development of phase-conjugate optics, as well as the further development of the basic 4WM technique. In addition, we have studied cluster state generation for measurement-based quantum computing applications, again based on this squeezed light source. During the grant period one graduate student, Meng-Chang Wu, supported by this grant finished with a PhD [1] in August 2020.

Objectives: Study phase-sensitive amplification and fast light transmission through a PSA

Most of the work that we do is based on an off-resonant 4-wave mixing (4WM) process in Rb vapor developed in our labs in 2007 [2]. A single pump beam at a frequency near the atomic resonance is sent through a vapor cell and a weak probe can be sent through at the appropriate phase-matching angle to be amplified and to generate a conjugate beam, as indicated in Fig. 1. This works surprisingly well to generate 2-mode squeezed light – the key feature being that it is a parametric process based on a ground state coherence (so that there is no spontaneous emission noise), and that it is detuned far enough from resonance that there is very little re-absorption loss in the system. Most of the work that we have done relies on generating 2-mode squeezing or twin beams of light that display intensity-difference and phase-sum squeezing (and since these are conjugate variables, quantum entanglement is produced). These two beams are approximately +3 GHz and -3GHz from the pump frequency. If you look at this as a gain process on a seed beam that also generates a “twin” conjugate beam, it can be seen as a phase-insensitive amplifier (PIA) for the input seed. Noise is added in the process of the gain, as there is a vacuum-seeded conjugate input that also gets amplified.

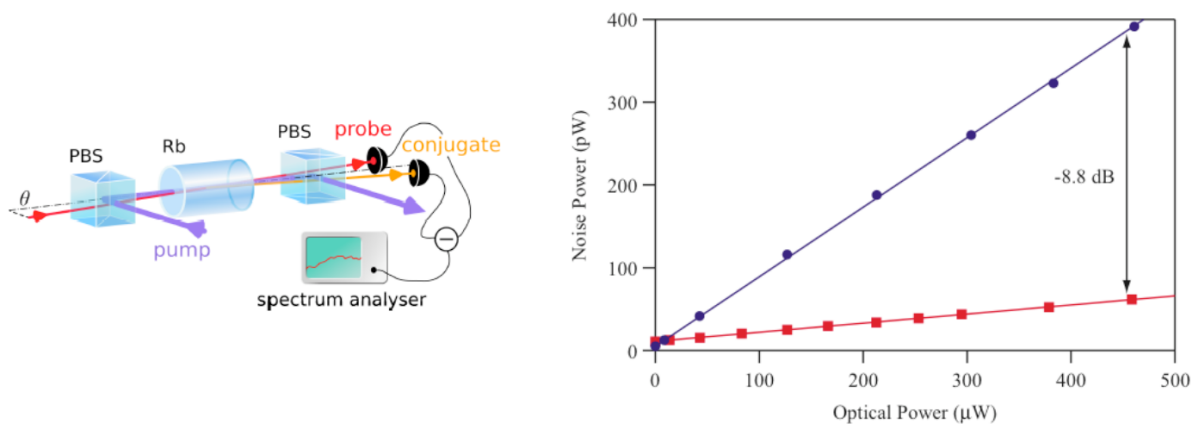


Figure 1. Sketch of experiment for generating 2-mode squeezing from 4-wave mixing. PBS is a polarizing beamsplitter. A pump is sent through a Rb vapor cell and a probe beam, orthogonally polarized to the pump, is intersected with the pump at a small angle. A conjugate beam is generated at the symmetric angle on the other side of the pump. The probe and conjugate beams are detected, subtracted, and the noise power is recorded on an rf spectrum analyzer. The plot on the right shows the noise power at 1 MHz (in a 300 kHz bandwidth) as a function of the total optical power detected. The black points represent the shot noise level and the red points show the noise from the 2-mode intensity-difference squeezing, showing about 8.8 dB less noise at high powers.

We have also done some work on a phase sensitive amplifier (PSA) – essentially pumping with two beams at the probe and conjugate frequencies for the above process and injecting a signal at the center frequency. A somewhat different detuning is required, as indicated in Fig. 2. In this case one can obtain noiseless gain (or stimulated absorption), depending on the input phase with respect to the pumps. This is a remarkable quantum feature of this process. The price for the noiseless gain is the phase sensitivity of the process; only one quadrature of the light can be noiselessly processed at a time.

One experiment that we have performed is to make an approximation of a “perfect detector”. We have arranged so that the PSA will amplify the intensity noiselessly. If you try to measure squeezed light with a detector with, for example, a 50% quantum efficiency, you will lose most of the quantum nature of the signal. Immediately in this case you can measure no more than 3 dB of squeezing, even with a perfectly squeezed initial state. If you place a noiseless amplifier with a gain of 4 in front of the detector, however, you can regain almost all of the quantum nature of the signal. (Our PSA can only operate noiselessly up to a gain of about 4 before other “parasitic” 4WM processes add noise.) If the amplifier and the loss could work “deterministically” you would only need a factor of 2 gain – but since both the gain and loss are stochastic you only get a truly “perfect detector” in the limit of infinite gain.

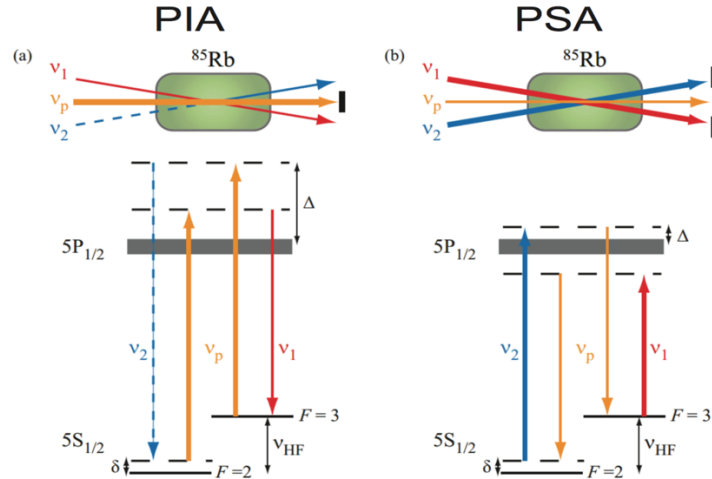


Figure 2. PSA/PIA level diagrams and geometry. (a) In the case of the phase-insensitive amplifier the pump and only one of the sideband frequencies are injected. The vacuum input on the remaining mode allows for the phase insensitivity. (b) In the phase-sensitive case all of the required fields are injected and the relative phases of these fields are important. The detunings of the beams from the atomic resonance also need to be different to obtain good PSA operation.

In our work we demonstrate the ability of a phase-sensitive amplifier (PSA) to pre-amplify a selected quadrature of one mode of a two-mode squeezed state in order to improve the measurement of two-mode quantum correlations that exist before degradation due to optical and detection losses. We use 4WM) to generate bright beams in a two-mode squeezed state. One of these two modes then passes through a second 4WM interaction in a PSA configuration to noiselessly pre-amplify the desired quadrature of the mode before loss is intentionally introduced. We demonstrated an enhancement in the measured degree of intensity correlation and intensity-difference squeezing between the two modes and published this work in Ref. [3].

We have also made some “information transfer through a PSA” measurements. When one sends a signal into a PSA in the “gain quadrature” (say along the y-axis of phase space) it is simply amplified by the gain G . If the signal is in the de-amplifying quadrature (say along the x-axis of phase space) it is de-amplified by a factor of $1/G$. On the other hand, if the signal is in some combination of these quadratures, along some arbitrary axis, some of the signal will be amplified, some de-amplified, and the output will be a signal that will be rotated in phase space by an amount dependent on G . This appears to be a sort of phase-advance or delay, somewhat akin to fast or slow light dispersion effects (although here it depends on the input phase, instead of on the frequency).

It is interesting to examine how the transfer of information through such a system behaves - if for no other reason, then to see how causality is preserved. We generated a quantum-correlated pair of beams, again by 4WM, and measure the mutual information between them. We then send one of these beams through the PSA and again measure the mutual information. This allows us to see how the PSA works – we can get a (small) signal advance or delay that depends on the input phase, but at the phases where the PSA acts noiselessly there is neither an advance or a delay. Thus, it shows no violation of causality (which is no surprise), and tells us that it can preserve

quantum-level intensity correlations. Unlike in the case of slow and fast light, where re-phasing of frequency components is the cause, this analogous effect is due to a redistribution of power between unbalanced signal sidebands, and the advance or delay is dependent on the optical phase of the input. The PSA adds energy, and also changes the frequency spectrum of the input. We showed that the advances and delays observed in a PSA implemented using four-wave mixing in a warm rubidium vapor are consistent with the expected behavior of an ideal PSA [4].

Related publications [reference numbers from bibliography]:

- [3] “Improved measurement of two-mode quantum correlations using a phase-sensitive amplifier,” T. Li, B. Anderson, T. Horrom, B. Schmittberger, K.M. Jones, and P.D. Lett, *Opt. Expr.* **25**, 21301 (2017). (perfect detector)
- [4] “Signal advance and delay due to an optical phase-sensitive amplifier,” N. R. Brewer, T. Li, K. M. Jones, and P. D. Lett, *Opt. Expr.* **28**, 14573 (2020).

Objectives: Squeezing development/characterization and squeezing at very low measurement frequencies

The most basic imaging experiments – imaging a beam on a camera – have always been difficult to improve with squeezed light because we have had a very hard time even reaching the shot noise level on an integrating detector such as a CCD camera. While early on we could obtain good levels of squeezing (approaching 10 dB) at frequencies around 1 MHz, there is always a large amount of technical noise as at frequencies approaching DC. When integrating over lower frequencies this noise always dominated. With recent advances in generating squeezed light at low frequencies we can now avoid this issue and hopefully move ahead with some of the imaging experiments.

The advance for bright squeezed light is really a simple technique. If you seed with an intensity of 1 and have a gain of, say, 10 on the seed, then the output beams have intensities 10 and 9; the same amount of light is added to each beam in the process but at DC there is always obviously going to be an imbalance. Indeed, the imbalance due to the seed extends to frequencies above DC as well. If, however, one splits the seed power and inject 0.5 into each of the probe and conjugate directions, then the photodetectors see the same amount of light even at DC [5]. This simple solution works quite well, as shown in Fig. 3, and should enable an array of new experiments.

This simple picture is complicated by several issues, which we have been investigating in some detail. For instance, this approach means that we now have two colors of light falling on each photodetector and we will need to either align these beams very carefully or do some fancy software alignment if one wants to subtract individual pixels or spatial modes. There is also a problem that, at least at higher intensities, bright modes talk to one another in the nonlinear medium (the Rb vapor). That is, if two probe beams and two conjugate beams overlap in the vapor cell, one probe will be correlated to not only its conjugate, but the other probe and conjugate beams as well. This effect has been seen in other contexts and is referred to as two-beam coupling; it is basically another degenerate 4WM process that exchanges energy between same-frequency near-resonant beams [6].

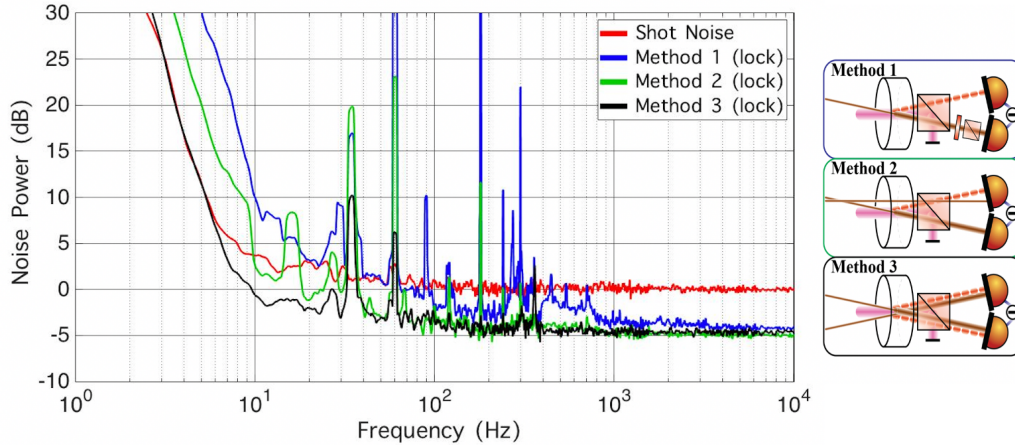


Figure 3. Bright-beam, 2-mode, low-frequency squeezing results and sketches of the three different intensity-balancing methods used. Method 1 – attenuation of the seeded beam after the gain. Method 2 – an extra seed beam is passed around the gain to balance the original seed light. Method 3 – dual seeding through the gain.

Two-beam coupling between different bright spatial modes in the atomic vapor can ruin squeezing at frequencies on the order of the atomic linewidth and below. This complicates some forms of quantum imaging using these systems – in particular, any system that has such spatial modes intersecting in the gain medium. We have shown that seeding the 4WM process with skew rays, that do not intersect, can eliminate the excess noise caused by 2-beam coupling, as seen in Fig. 4. To avoid 2-beam coupling in bright, seeded images, it is important to re-image the object in the gain medium, instead of focusing through it, so that pixels of spatial information do not intersect in the gain medium [7].

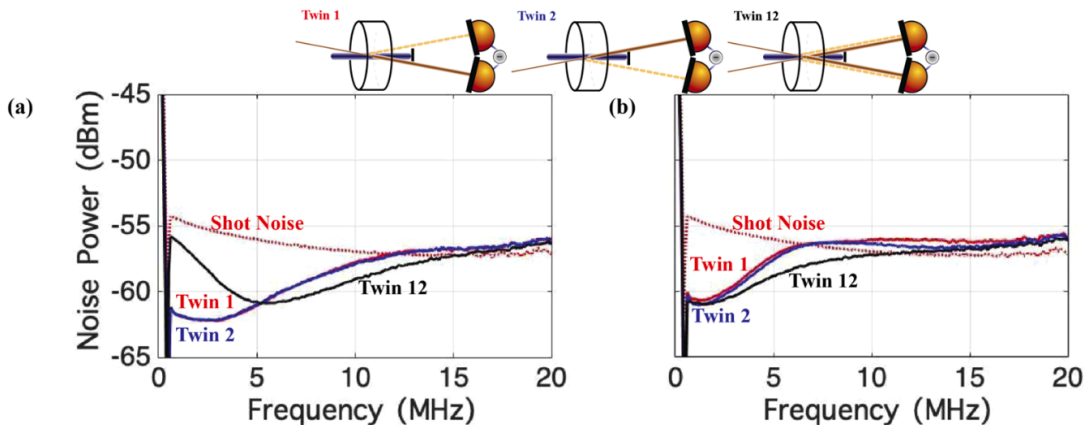


Figure 4. Spectrum of the intensity-difference squeezing versus measurement frequency of (a) crossed rays and (b) skew rays. Shown are shot noise (red dashed curve), spectra of two independent single seeded processes labeled “Twin1” (red curve) and “Twin2” (blue curve), and dual seeded 4WM labeled “Twin12” (black curve). Crossed rays: both of these seeds are present at half the power of the single seeds and crossed at the center of the pump beam in the 4WM gain region. Skew rays: two probe beams are offset from the center of the pump beam in opposite directions. The total output optical power for each trace is $800 \mu\text{W}$. The 4WM gain ≈ 10 in each case (pump power = 680 mW , cell temperature = $122 \text{ }^\circ\text{C}$, $\Delta = 800 \text{ MHz}$, $\delta = -2 \text{ MHz}$). The resolution bandwidth (RBW) is 300 kHz and the video bandwidth (VBW) is 100 Hz for these measurements.

Different physics seems to be going on at high frequencies than at low frequencies. There also seem to be rather dramatic differences between using a diode laser, versus using a Ti:sapphire laser, as the pump source for the 4WM. In Fig. 5 intensity-difference noise spectra for two pairs of beams (probe-conjugate and conjugate-probe on the detecting photodiodes). The noise in the intensity-difference squeezing for a pair of these beams shows approximately 15 dB of excess noise at frequencies above 15 MHz. This is interesting because similar spectra, when taken using a Ti:sapphire laser as a pump, smoothly approach the shot noise level from below and reach shot noise at frequencies around 20 MHz. When both pairs of beams are allowed to hit the detectors the bulk of this noise is seen to cancel. This implies that the noise is somewhat “deterministically” written onto one of the beams, and can be subtracted from a pair in much the same way that the low-frequency 2-beam coupling is. In fact, it seems that the probe beams, which are nearer to the atomic resonance carry the bulk of the excess noise, much as the 2-beam coupling seems to be primarily between probe-frequency beams, but is much weaker at the larger-detuned conjugate frequencies. We do not understand the origins of the high-frequency noise from diode laser sources, so there is still much to learn in this regard.

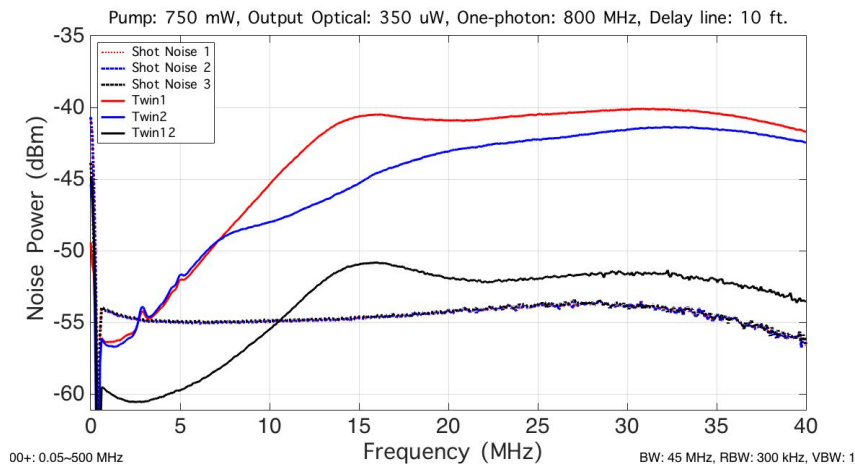


Figure 5. High-frequency excess noise from diode lasers. The noise in the intensity-difference squeezing for a probe/conjugate pair of beams hitting the balanced detectors shows noise well above the shot noise level, while two pairs of probe/conjugate and conjugate/probe light beams hitting the same detectors shows that this noise can mostly be subtracted in the high frequency regime, while improving the squeezing level in the low frequency range.

While the semiconductor laser systems promise to be less expensive and more portable, the large amounts of excess noise that appear in the squeezing spectrum when using them could severely limit their usefulness. We discovered that the noise is not being generated by the semiconductor tapered amplifiers that we used to amplify the light, but that the problem is in the diode lasers that are used to seed the process. That is, if the tapered amplifier is seeded with light from a Ti:sapphire laser instead of a diode, the noise disappears (in spite of the fact that the measured linewidth of the diode is smaller than that of the Ti:sapphire laser). Since diode laser technology seems essential to being able to move squeezed-light-based quantum sensors out of the laboratory, more study of these problems needs to be done.

We have also demonstrated the limitations of imperfect homodyne visibility in this system in measuring entanglement [8]. While cavity-based single-spatial-mode systems have well-defined and isolated spatial modes that are squeezed or have quantum properties impressed upon them, the free-space 4-wave mixing schemes that we commonly use allow for many neighboring spatial modes to be squeezed at once. If a small portion of an uncorrelated but squeezed mode is collected the noise is much higher than if a small portion of a neighboring vacuum mode is collected instead. For bright beams when all of the beam is collected this is generally not a problem but this leads to a rapid degradation of the squeezing measured by a homodyne detector if the signal overlap for vacuum-squeezed modes with the local oscillator is not perfect. We select a set of probe modes and attempt to collect the same set of conjugate modes by adjusting the local oscillator and measuring the fringe contrast with a bright alignment beam. We quantified this and can usually obtain a 97% to 98% overlap level. We find that as the gain (controlled by pump power) is increased for a fixed mode overlap the squeezing level will improve, and then start to degrade as the noise rises in the small percentage of uncorrelated modes that are collected, as seen in Fig. 6. As these modes are not correlated, it is equivalent in noise to mixing-in the anti-squeezed quadrature of the modes we are interested in. We have examined methods of improving the joint mode overlap beyond our usual level by using spatial light modulators to shape the local oscillator beams.

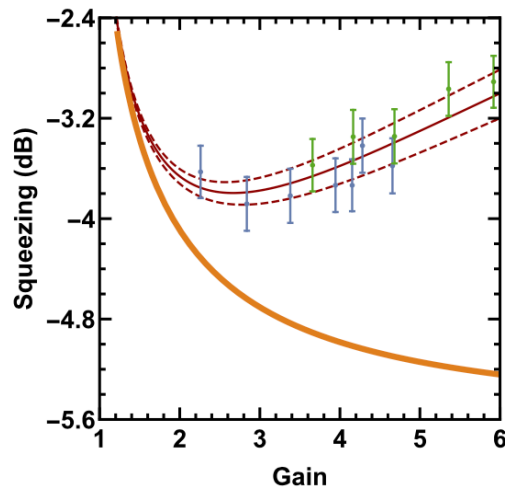


Figure 6. Two-mode vacuum squeezing as measured with a dual homodyne set-up as a function of gain for a fixed pair of local oscillators. As the noise present in a small amount of uncorrelated modes that are detected increases it limits the amount of squeezing that can be measured.

The excess noise at low frequencies in bright-beam squeezing that is discussed above is generally attributable to noise imbalance in the twin beams due to the seed beam. The dual-beam seeding is a way to get around this, and works quite well, however the implication of this is that without the seed, the problem should not exist. That is, vacuum-seeded twin-beam squeezing should show squeezing to low frequencies without having to play tricks. The fact that the Rb 4WM system does not require a cavity to have good gain and squeezing means that the acoustic noise that commonly couples to a cavity is not present either. For unseeded 4WM about 4.5 dB of squeezing below the shot noise level is measured over a 10 second observation time, as

shown in Fig. 7. The squeezing level is limited simply by the homodyne overlap discussed above and in [8]. The low-frequency limit here is simply set by the observation time and spectrum analysis settings.

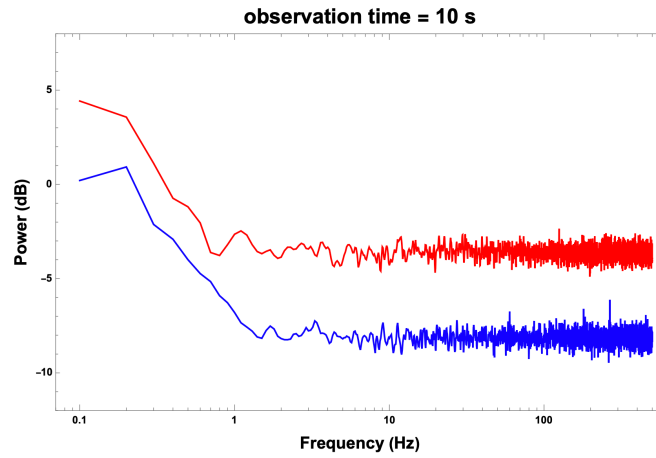


Figure 7. Two-mode vacuum squeezing at low frequencies measured with a 10 second observation time. The red curve is a measurement of the shot noise, and the blue curve shows squeezing down to below 1 Hz.

A new source of sub-shot-noise anti-correlated light from competing 4-wave mixing processes in Rb vapor was demonstrated. Based on previous experiments in other groups that demonstrated classical (anti-)correlations, we implemented a near-resonance pumping scheme that establishes a ground-state population coherence in rubidium vapor that one can scatter light off of. In this scheme two off-resonant 4-wave mixing processes compete at a level that produces sub-shot-noise anticorrelations in the generated frequencies of light. Being near resonance the power requirements are quite low, but re-absorption in the vapor limits the squeezing levels that we have obtained. We have demonstrated approximately -1.5 dB of intensity-sum squeezing of the two beams of light generated in this new system. We have examined this system theoretically [9]. The experimental demonstration has not been published yet.

Related publications:

- [5] “Twin beam intensity-difference squeezing below 10 Hz,” M.-C. Wu, B. Schmittberger, N., Brewer, R. Speirs, K. M. Jones, and P. D. Lett, *Opt. Expr.* **27**, 4769 (2019).
- [7] “Two-beam coupling in the production of quantum correlated images by four wave mixing,” Wu, M.-C., Brewer, N., Speirs, R. Jones, K. M., Lett, P. D., *Optics Express* 29, 16665 (2021)
- [8] “Effect of imperfect homodyne visibility on multi-spatial-mode two-mode squeezing measurements,” P. Gupta, R. W. Speirs, K. M. Jones, P. D. Lett, *Opt. Expr.* **28**, 652 (2020).
- [9] “Quantum treatment of cavity-assisted entanglement of three-level atoms and two fields in an electromagnetically-induced transparency configuration,” Xihua Yang, Nicholas Brewer, and Paul D. Lett, *Phys. Rev. A* 105, 023711 (2022)

Objectives: Optical memory and camera-based image subtractions

While we had planned to continue work with optical memories based on the gradient echo Rb vapor memory that we had worked with in the past, once we moved the experiments and apparatus from the NIST campus to the UMD/JQI campus we did not have a good motivating experiment to work on. The state of the art in the optical memory community in other labs had developed longer-lived and higher-fidelity memories, and we did not have a method to surpass those results. In particular, the barrier for our experiments is the difficulty of separating the controlling-beam frequency from the stored-light frequency in our multi-spatial-mode memory. In our case using a cavity or interference-type filter is very lossy, and this was a deterrent for seeing quantum signals. While we still retain the ability to reconstruct these experiments, we have no current plans to do so.

We have attempted to make camera-based image subtractions of twin beams, but they rely on more than just the ability to produce the low-frequency squeezing discussed above. The major barrier to achieving these measurements is now simply scattered light. The limited "well depth" of a CCD camera means that the integrated intensity that can be used to illuminate the camera must be small if the camera shutter time is long. We opted to pulse the seed light for the twin beams to limit the amount of light to the camera, but we found that scattered pump light would still overwhelm the signal. While homodyne detection allows effective filtering on a photodiode without saturating it, using any local oscillator on the camera would saturate it. To attempt to reduce scattered pump light we pulsed the pump beam as well as the probe seed. Unfortunately, if both pump and probe seed are pulsed together the optical pumping that is necessary for efficient 4WM does not take place, so that the pump needed to be pulsed for longer than the probe seed. We settled on pulse lengths, created by an acousto-optic modulator, of about 3 microseconds for the pump, with the probe seed pulsed on for the last 1 microsecond of the pump time. Unfortunately, this was still insufficient to reduce the scattered pump light to the point where the quantum correlations of the twin beams became detectable. In order to create faster shuttering we purchased a Pockels cell so that we could create an artificial shutter (really effectively a fast $\sim 10^{-3}$ attenuator) to place in front of the camera to further reduce the scattered light background. At this point, due to personnel changes and other equipment complications we have interrupted the camera experiments.

As the camera imaging experiments were originally set up using a diode laser/tapered amplifier apparatus, the 2-beam coupling issues discussed above in the context of squeezing development were a major concern. The discovery of the high-frequency excess noise on the 4WM signal from the diode-based source, also discussed above under the squeezing development section, implied that, until that was mitigated, these experiments would not be successful. We have not been able to fully understand the high-frequency noise source and plan to return to camera-based measurements based on a Ti:sapphire-based 4WM source at a later date. We have not yet published anything about our findings on excess noise from the diode source.

Objectives: Studies on nonlinear SU(1,1) interferometry

We have been building what are known as "SU(1,1) interferometers". The name is based on the symmetry group used to describe them – in this case "normal" interferometers built with mirrors

and beamsplitters are SU(2) and described by this “rotation group”. The SU(1,1) group represents “boosts,” and these interferometers are based on having gain (or stimulated loss) in the device. The ultimate sensitivity of a “normal” interferometer scales as one over the square root of N, with N being the number of photons measured. The sensitivity of the nonlinear SU(1,1) interferometer can be $1/N$. The first one of this class of interferometers proposed was a Mach-Zehnder design with the beamsplitters replaced by 4WM gain cells. A first cell is pumped and generates pairs of photons into the probe and conjugate modes, as in Fig. 8. With a $\pi/2$ phase shift between the pump and these measurement modes, if you then recombine them in another 4WM cell no light should emerge in the measurement modes (all the probe-conjugate pairs should reconvert into pump photons). If there is a phase shift in one of the arms a signal appears as light in these modes.

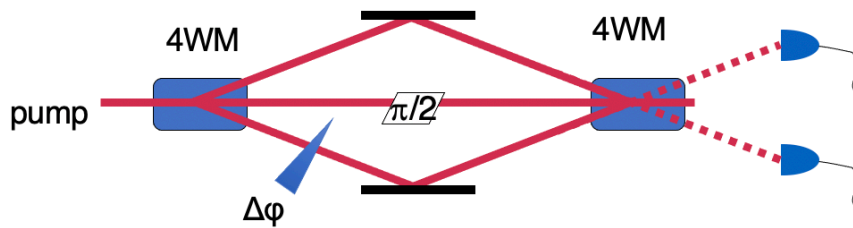


Figure 8. A sketch of an SU(1,1) interferometer based on 4-wave mixing. The first 4WM interaction creates correlated probe/conjugate photon pairs. A $\pi/2$ phase shift on the pump beam allows the probe/conjugate pairs to recombine to produce pump photons in the second interaction region. A phase shift in one of the arms causes light to emerge to hit the detectors. The phase sensitivity is proportional to $1/N$, where N is the number of photons detected.

There are many complications, and the interferometer is fundamentally difficult to implement in the lab, if for no other reason than that scattered pump light is hard to suppress. One way to do this is by using homodyne detection, which allows one to both filter out the pump frequency and amplify the small signal field by multiplying it with the local oscillator field. There is also a problem with loss in the interferometer – if a photon is lost from one path, then its pair cannot be reconverted to the pump frequency in the second interaction and it appears as noise in the signal. While thinking about this we discovered that we could do just as well in creating an interferometer without the second vapor cell, as shown in Figure 9. The basic idea is that, if we have a homodyne detector, then we already have an interferometer, say between the probe beam out of the 4WM and the local oscillator for that beam. If that beam has the phase shift in it, then the entire signal comes from that “sub-interferometer”. On the other hand, the conjugate beam has noise that is highly correlated to that of the probe beam, and we can use that to help subtract noise, thus increasing the signal-to-noise ratio of the measurement. We experimentally demonstrated this “truncated” SU(1,1) interferometer, beating shot noise by 4 dB [10].

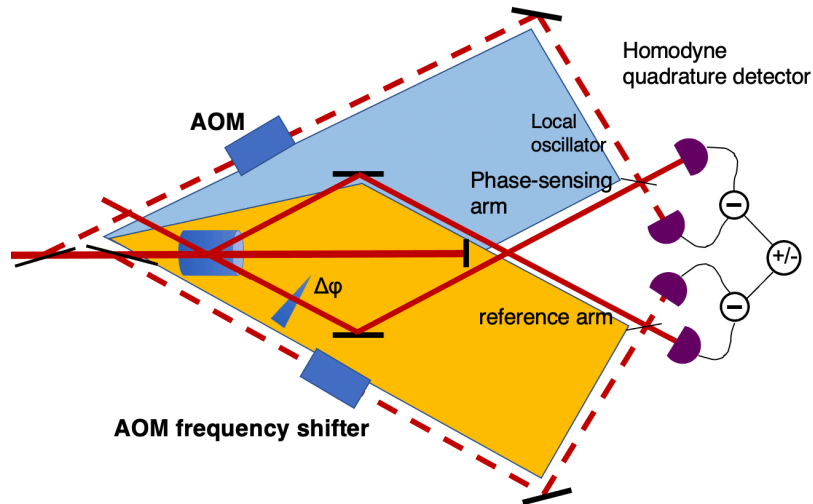


Figure 9. A sketch of a truncated SU(1,1) interferometer. The second 4WM interaction is removed and homodyne detection is used. The local oscillators for the homodyne detectors create interferometers for each arm. Both are noisy, but correlated, allowing the noise to be subtracted and the signal to be detected at the quantum Cramer-Rao bound.

We have also published work that investigates the theory and performs some numerical simulations of the performance of this new interferometer design [11]. In that work we showed how to optimize the homodyne detection scheme and demonstrated theoretically that it can saturate the quantum Cramer-Rao bound for phase estimation. In a later paper we extended those results by taking into account loss in the truncated SU(1,1) interferometer and determining the optimized homodyne detection scheme for phase measurement. The optimization involves electronically attenuating one of the homodyne detector signals before combining the two for a phase measurement. We experimentally demonstrated that this optimized scheme achieves a reduction in noise level, corresponding to an enhanced potential phase sensitivity, compared to a typical homodyne detection scheme for a two-mode squeezed state. In doing so, we also demonstrate an improvement in the degree to which we can beat the standard quantum limit with this device [12], as shown in Fig. 10.

Related publications:

- [11] “Optimal phase measurements with bright- and vacuum-seeded SU(1,1) interferometers,” B. E. Anderson, B.L. Schmittberger, P. Gupta, K.M. Jones, and P.D. Lett, *Phys. Rev. A* **95**, 063843 (2017).
- [12] “Optimized phase sensing in a truncated SU(1,1) interferometer,” P. Gupta, B. Schmittberger, B. E. Anderson, K. M. Jones and P. D. Lett, *Opt. Expr.* **26**: 391 (2018).

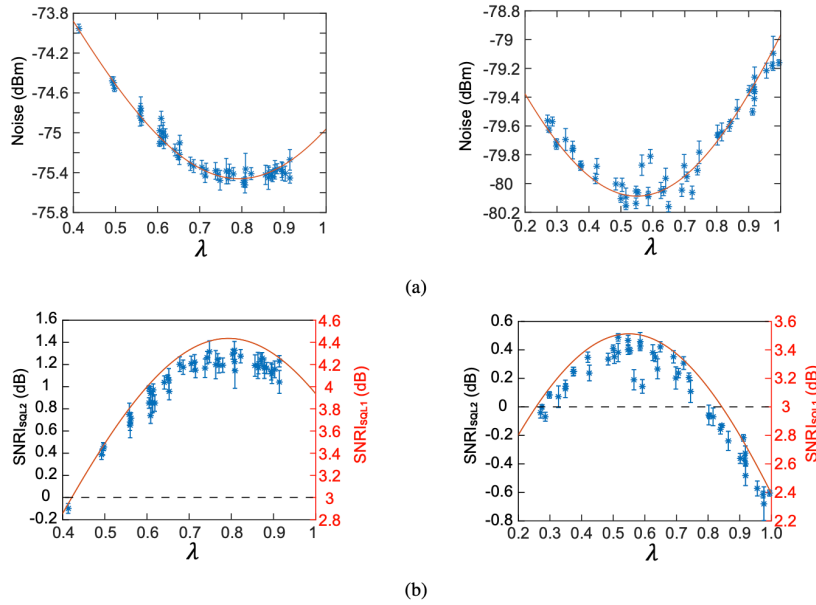


Figure 10. a) Noise in the joint homodyne detection with squeezed light as a function of the attenuation parameter λ . b) Improvement in the SNR as a function of the attenuation λ over the conditions of SQL1 (SNR_{SQL1}) where we compare the sensitivity of our truncated SU(1,1) interferometer with the sensitivity of a truncated Mach-Zehnder interferometer in which the second beam splitter is replaced with two homodyne detectors. In addition, we compare to SQL2 (SNR_{SQL2}) where we only perform homodyne detection on the beam passing through the phase object. The left side plots have an estimated 4WM gain of 1.67, a probe transmission of 76% and a conjugate transmission of 79%. The right side plots have an estimated 4WM gain of 1.2, a probe transmission of 73% and a conjugate transmission of 76%. The gain and the loss values were estimated from the theoretical fit of the data. In these fits, we assume that the probe suffers 3% more loss than the conjugate beam, which we measure experimentally and occurs because the probe is closer to the absorption resonance of ⁸⁵Rb.

How were the results disseminated to communities of interest?

Dissemination to scientific audiences was done by publication of research results and review papers in archival journals. A number of talks were given at universities and at scientific conferences. Partly due to the covid pandemic, there were no significant outreach activities to the general public.

Review papers:

Lawrie, B., Lett, P. D., Marino, A., Pooser, R., “*Quantum Sensing with Squeezed Light*,” ACS Photonics, 6, 1307 (2019).

Glorieux, Q., Aladjidi, T., Kaiser, R., and Lett, P., "Hot vapors for nonlinear and quantum optics," New J. of Physics, to be published (arXiv: 2209.04622).

Impacts

Development of the principal discipline(s) of the project

The advances in "squeezed light" generation from nonlinear optical processes in Rb vapor will allow quantum noise reduction to be extended to new areas of quantum sensing and generally to new areas of quantum optical science. The squeezing, or shifting of noise from one variable into another, is an important technique in the quantum world. The reduced measurement noise that can be produced is applicable in a broad range of sensors, from cantilever displacement in atomic force microscopes and sensitive imaging at very low light levels, to optical interferometry to detect small displacements or movements.

The area of quantum-enhanced interferometry has seen a renewal. Although the basic ideas behind some of our work originated in the 1980's and 90's, the interest and activity in this area has been much larger in the last decade than it was at that time. The technologies available today allow us to take advantage of the quantum properties of light much more readily than in the past so that, while the potential benefits of the noise reduction have not changed, the prospects of achieving these benefits have improved greatly.

We have investigated a broad array of capabilities of our technique for generating quantum-correlated light. While many such experiments, including our past experiments, examined what could be done with reduced noise in many spatial modes (pixels), we have now been able to examine potential uses of the range of independent frequencies in which squeezed light can be generated with our source as well. The applications to creating the type of states required for quantum computing make this a valuable demonstration system, even if it is not well-suited to quantum computing in the long term. While our system does not have the ability to process information quickly, we can explore the construction of the required quantum states and apply the lessons learned from it to other, more appropriate, systems.

Much of what has been discovered in our studies about generating squeezed light with semiconductor diode lasers versus crystal-based titanium-sapphire lasers is specific to the applications studied here, but it is cautionary that the detailed character of the light sources used can have important impacts on quantum-level properties of the light that is produced. As quantum technologies become a more important part of our world we will need to be careful about how we extend our tools from one application to another; all lasers are not alike.

Optical phase sensitive amplifiers, which were studied here, are useful in communications, and in particular long-haul information transfer. While the particular design of the phase-sensitive amplifiers studied here is not used at communications (telecom) wavelengths, the properties studied (noise properties and sensitivity to operating parameters) are able to be generally applied in these other contexts as well. While the phase-sensitive advance and delay of signals is not generally discussed, these are properties of all phase-sensitive amplifiers. The potential to use phase-sensitive amplifiers in sensing applications, for example to overcome imperfect detector efficiency, will be increasingly important in quantum networks, sensing and communication applications. In addition, phase-sensitive amplifiers in the microwave frequency regime, rather than optical, are being developed and can apply the techniques learned here as well.

Other disciplines:

It is not likely that the results of the present research will find applications in disciplines beyond those concerned with science and technology. In terms of engineering disciplines, we can take a lesson from our studies of generating squeezed light with semiconductor diode lasers versus crystal-based titanium-sapphire lasers. Once again, the detailed character of the light sources used can have important impacts on quantum-level properties of the light that is produced – even though both are called lasers, the detailed quantum properties of the light produced can be very different.

We can hope that, long-term, the imaging and sensing techniques, as well as the light correlation properties can have an impact in biological imaging and chemical sensing. A number of potential low-light-level bio-imaging applications could take advantage of the increased sensitivity of squeezed light. The extra effort and cost involved in creating quantum-correlated light has made this an insufficiently attractive option at this point, however, as techniques develop and costs are reduced, there will be areas of biological research where the increased sensitivity will have an impact.

Quantum correlations can potentially be used for chemical sensing, driving reactions, and enabling two-photon imaging where dyes susceptible to two-photon absorption can be used to tag organisms. While there is still some debate as to how low the light level is where this sort of effect saturates, and whether or not the signals will be sufficient to obtain an advantage from this sort of application, a large number of groups are pursuing it because the pay-off could be large.

Development of human resources

Over the duration of this project it has supported a number of postdoctoral scholars (13 individuals for varying lengths of time) who have gone on to work in industry, academic and governmental research, and education. Three graduate students were partially or fully supported on this grant. One graduate student completed his Ph.D. thesis based on projects directly related to this grant. In addition to this, the project provided opportunities for three undergraduate summer students (two students of color, one female; funded through other sources) to work with the people on this project and to participate in cutting-edge optics research. Their participation in the research funded here has encouraged at least one of them to continue in science-related research, as she went on to do graduate work in astronomy.

Several collaborating faculty members (B. Anderson, American University; K. Jones, Williams College) have participated in the funded research. In doing so this made available to them facilities here at the JQI that they would not have access to at their home institutions. Their participation also enriched and advanced the research undertaken.

Two international faculty visitors (L. de Araujo, USP, Brasil; X. Yang, Shanghai, China) each spent a year with us. We introduced them to experimental methods and problems that were not available to them at their home institutions and their participation has advanced the work here and changed the direction of their work at their home institutions.

Impact on society beyond science and technology

The squeezed-light imaging technology that we have been developing – in particular, the ability to achieve quantum-enhanced sensitive detection of small signals - is being taken up by a start-up company with the intent to apply it to medical imaging problems. The increased sensitivity that can be obtained using our imaging techniques allows lower-intensity light to be used for medical imaging applications, potentially causing less damage to living tissue or organisms. While these applications will probably not be widely used in the near-term, it is possible that the developed technologies could be useful in research applications.

Changes

Problems or delays

The technical problems encountered have been mostly discussed in the results section above. In particular, the direct camera-based measurements and optical memory experiments section describes how the excess light-scattering and the high-frequency noise from the diode-laser-based 4WM source that we discovered have delayed these experiments.

The covid pandemic generally slowed the progress of the lab and resulted in the one-year no-cost extension to the grant, due to problems hiring a postdoctoral associate.

Expenditure Impacts

The covid pandemic, and consequent restrictions on research at the university, led us to restrict the group size so that we could continue work at the level of only one person per laboratory space for an extended period. In addition, reduced opportunities for recruiting postdoctoral candidates at in-person meetings led to delayed hiring and to our not spending out the funds on the anticipated schedule. We requested and obtained a one-year no-cost extension to the grant. During the past year we were able to hire an additional postdoctoral scholar to work on and complete work on the project.

Technical updates

Optical Cluster states and nonlocal modulation

Measurement-based quantum computing for continuous variables is an interesting option that has been proposed for optical quantum information processing. Measurement-based, or one-way quantum computing uses cluster-states, where the initial state and the entanglement required for computation are built into the constructed multi-mode quantum state, and a series of (conditional) measurements is carried out that encodes the computational program. While all of the aspects of this type of computing have not been put together in one system, the type of cluster states required for it have been constructed in several different optical systems. Large 1-dimensional (1-D) optical cluster states [13-16] have been created in the time and frequency domains, with up to several million states in the time domain and thousands in the frequency domain. (In addition, the creation of similarly-structured optical cluster states based on the spatial degrees of freedom has been proposed in the same 4-wave mixing system that we use [17].) In our system the quantum bits are continuous-variable frequency modes of the field, or qumodes. 1-D cluster states, however, are insufficient to implement general controlled-logic gates and 2-D cluster states are required for general quantum information processing. 2-D cluster states have been created in the time domain [18,19]. To implement error-correction

codes, however, 3-D cluster states will be required. A method of constructing cluster states in the frequency domain using electro-optic modulators (EOMs) has recently been proposed that is quite general and flexible and would enable the construction of higher-dimensional cluster states [20]. We have begun to implement this idea in our 4WM system and demonstrate its ability to generate such entangled states.

While our particular configuration for measurement-based quantum computing is clearly not scalable due to its limited bandwidth, we feel that it is good for demonstrating the ability to generate n-dimensional cluster states and to perform some basic tests on the entanglement structure of these states.

The single-pass 4WM scheme that we use leads to a continuous spectrum of 2-mode vacuum-squeezed light over an approximately 20 MHz frequency bandwidth. This light can be thought of as a series of independent frequency modes, where each resolvable frequency band in the probe beam is correlated to a corresponding frequency band in the conjugate beam. Since this is a free-space 4WM process the number of independent frequency modes is not determined by the mode structure of a cavity, for instance, but only by the measurement resolution. If we can resolve two frequency “bins” in the probe light with the measurement, they should be independently correlated to two conjugate bins. An advantage of the limited bandwidth that we have is that we can perform a single measurement over the entire spectrum by digitizing the homodyne signals, and then performing all the filtering and analysis in software. The experimental approach is sketched in Fig. 11. We have demonstrated that ≈ 5 Hz-wide bins in our system can be viewed as independent 2-mode squeezing sources, and these bins could probably be made smaller at the cost of increasingly long measurement times.

Using such software-defined frequency bins as our qubits or qumodes, we can then proceed to construct entangled networks or graph states comprised of such modes by mixing them with an electro-optical modulator (EOM). A recent paper [21] points out how an EOM can be used as a multi-port beamsplitter to construct a set of entangled frequency modes. Our implementation of the idea in Ref. [20] is sketched in Fig. 11.

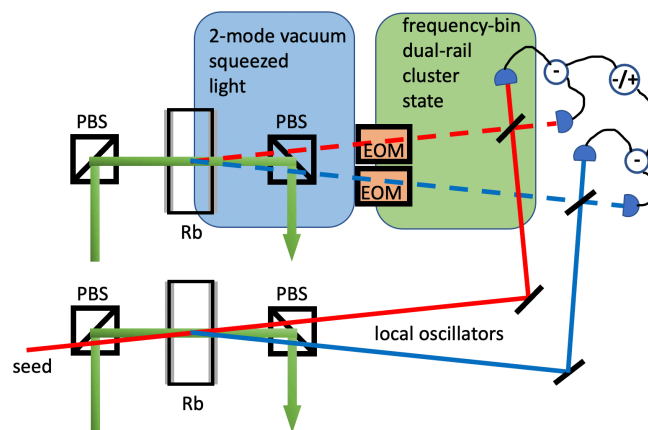


Figure 11. Experimental set-up for cluster state generation using 4-wave mixing in Rb vapor to generate 2-mode squeezing and electro-optical modulators (EOM) to further entangle the frequency modes in each beam. A separate pump beam is used to generate bright local oscillator beams for the homodyne detection.

At the present we have constructed 1-D cluster states and experimentally determined their structure to be as predicted. The fidelity of these states, however, is still being improved and we are in the process of investigating the construction of 2-D cluster states in this apparatus.

The use of EOMs in the above experiments has made clear that the quantum states involved are subject to nonlocal modulation. This nonlocality is conceptually similar to the nonlocal dispersion compensation implemented in short-pulse experiments [22]. We have performed an experiment to display this effect. As outlined in Fig. 12, a modulation (or frequency mixing) is imposed on one beam by EOM1. By putting the same signal onto a second EOM this original signal can be added-to by placing the second EOM in positions 1 or 2, or cancelled by placing it in positions 3 or 4. Similarly, with the EOM in position 1 an in-phase driving adds to the mixing of the frequency modes, while an out-of-phase driving can cancel it completely, as shown in the data on the right. Even though the detectors and EOMs can be placed far from one another the quantum correlations can be recovered or destroyed in this way.

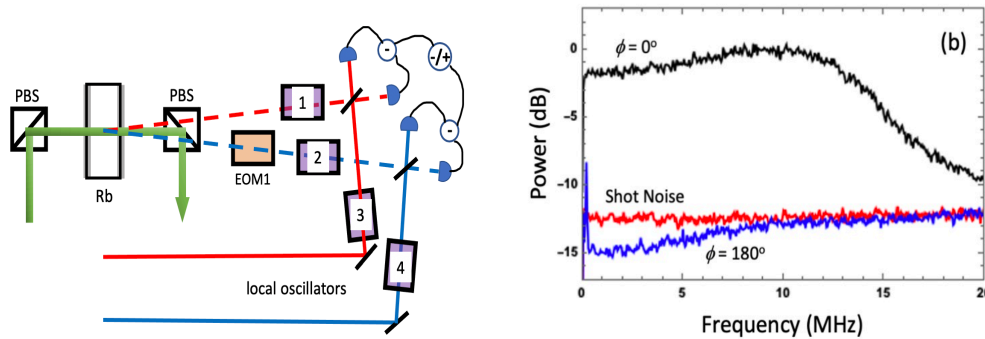


Figure 12. (left) The 2-mode squeezed state, detected by balanced homodyne detection and local oscillators, can be scrambled by EOM1 and an EOM in any of the 4 other indicated positions, either in the signal or local oscillator beams, can be made to “unscramble” the state. (right) Data taken with the second EOM in position 1 and driven in-phase, showing excess noise, and out-of-phase, showing a recovery of the squeezing.

Phase-conjugate optics

A new direction that we have begun to explore is the use of the 4-wave mixing gain in various configurations of optical parametric oscillators. Given the large gain that is achievable in the atomic vapor we have not felt the need to put the gain medium into a cavity in the past. By introducing cavities to create feedback in several different schemes we have demonstrated a new 4WM oscillator based on phase-conjugate optics that is extremely stable. This stability against acoustic noise allows a whole range of interesting new physics to be explored.

In Fig. 13 two ring resonators based on 4WM in Rb vapor are shown. On the left is a normal ring resonator, where either the probe or conjugate beam is fed-back onto itself. With high gain this can lase even with a lossy cavity, although a long cavity is required to ensure that a cavity mode is present within the 20 MHz gain bandwidth of the 4WM. On the right is phase-conjugate resonator where one output mode is fed back into the input of the other mode. The 4WM medium here creates a glancing-angle phase-conjugate mirror. The mirror serves as a 100%

output coupler for the incoming frequency, but “reflects” the conjugate frequency with gain large enough to overcome cavity losses. The cavity lases even when the cavity length is too short to ensure that a normal resonator of that length would have a cavity mode in the gain bandwidth, and the effective cavity length is represented by two round trips of the cavity, so that the mode spacing is half of that of the normal resonator, as seen in Fig. 14.



Figure 13. Ring resonators for optical parametric oscillators. (left) A normal singly-resonant OPO ring resonator with either the probe or conjugate frequency oscillating, selected by an etalon. (right) A phase-conjugate mirror resonator denoted “weird resonator” that circulates, alternately, the probe and its correlated conjugate frequencies. (In fact, both frequencies will fill the cavity simultaneously.)

In this cavity the phase conjugate mirror can compensate for all acoustic-frequency disturbances, and very narrow lasing linewidths can be obtained. While the quantum-noise-limited (Schawlow-Townes) linewidth cannot be observed in many systems, it is apparently straightforward here. If we construct a fiber-based ring cavity it is easy to measure the $1/(L^2)$ scaling of this spontaneous-emission-limited linewidth by swapping-in longer and longer fibers without disturbing the other parameters of the system. This is shown on the right in Fig. 14.

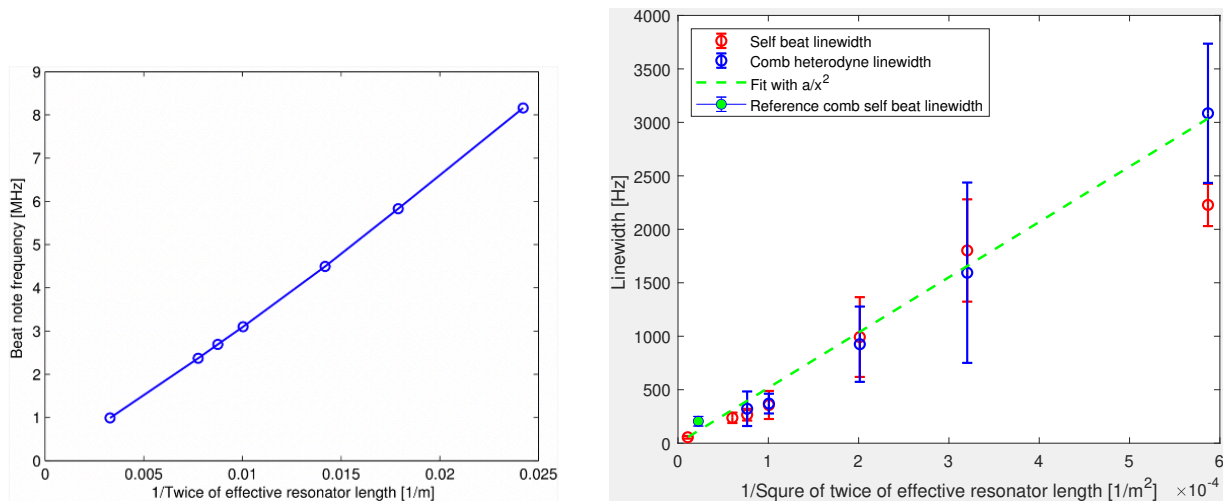


Figure 14. (left) Cavity mode spacing as a function of the inverse of twice the cavity length for the phase-conjugate resonator. Cavity linewidth as a function of the square of the inverse of twice the cavity length, leading to <50 Hz linewidths for the longest cavities used.

These resonator systems, when operated with a long cavity where multiple modes can lase, can also form what are known as dissipative Kerr solitons. The output is then a balance of gain and

loss, as in any laser, but also of dispersion and nonlinearity in the system [23]. The resulting stable, repetitive, pulsed output is associated with an optical frequency comb spectrum, with evenly-spaced frequencies. Such frequency combs have become an invaluable tool in a number of areas, and their implementation in photonic ring resonators has revolutionized a number of spectroscopic applications.

The feature of the 4WM-based dissipative Kerr solitons discovered here is that, while the dispersion must be engineered into the construction of a photonic ring resonator, here it can be altered by simply tuning the pump frequency. A variety of such soliton waveforms are shown in Fig. 15, along with their rf power spectra. The fact that the solitons are long and their frequency spectra are narrowband limits the applications, but allows the direct observation of the waveforms. The study of soliton collisions and other transient behavior such as turn-on dynamics are made possible in this time domain by quickly switching either the gain or loss levels.

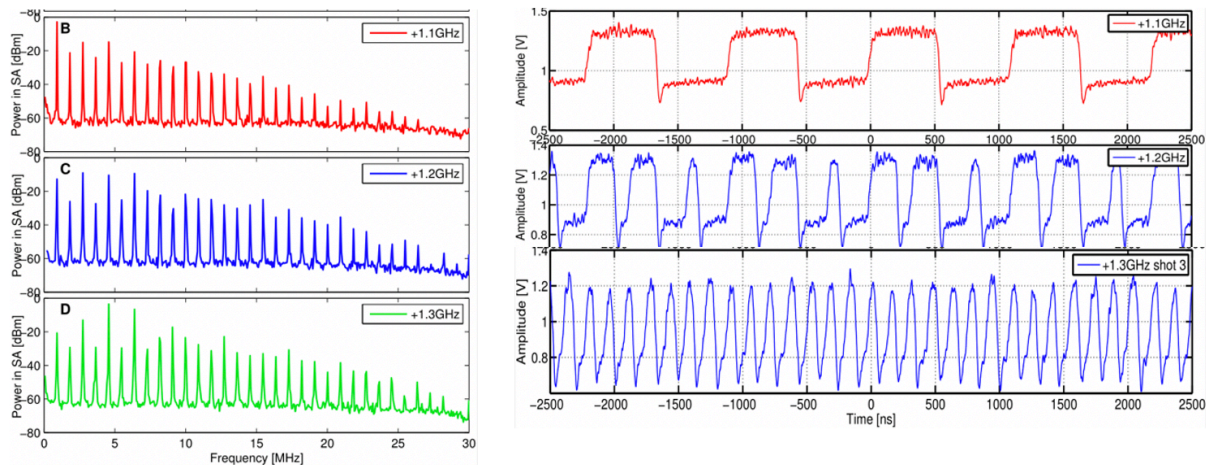


Figure 15. Various solitons observed in the time domain and their rf spectra. The cavity fiber length is 107 m. The pump detuning from the atomic resonance is, from top to bottom, 1.1 GHz, 1.2GHz and 1.3GHz; the pump power is fixed for the three cases.

The 4WM process used here is the same as the one that is used to generate quantum correlations in our other experiments. Unfortunately, the loss levels in these cavities is too high to preserve the quantum correlations as the optical systems are presently constructed. Cavity-dumping should allow us to transiently see the quantum correlations that are generated in the system at the appropriate pump detunings.

Related publications:

“Investigations on phase conjugation based on nondegenerate four wave mixing in a Rb vapor cell,” J. Zhao, Z. Zhou, P. D. Lett, *SPIE Proceedings Volume 11700, Optical and Quantum Sensing and Precision Metrology*; Editor(s): S. Shahriar and J. Scheuer 1170021 (2021), <https://doi.org/10.1117/12.2586674>

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