

# Realization of low frequency and controllable bandwidth squeezing based on a four-wave-mixing amplifier in rubidium vapor

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We experimentally demonstrate the creation of two correlated beams generated by a nondegenerate four-wave-mixing amplifier at  $\lambda = 795$  nm in hot rubidium vapor. We achieve intensity difference squeezing at frequencies as low as 1.5 kHz which is so far the lowest frequency to observe squeezing in an atomic system. The squeezing spans from 5.5 to 16.5 MHz with a maximum squeezing of  $-5$  dB at 1 MHz. We can control the squeezing bandwidth by changing the pump power. Both low frequency and controllable bandwidth squeezing show great potential in sensitivity detection and precise control of the atom optics measurement. © 2011 Optical Society of America  
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High quality quantum light sources have become an important research area in quantum optics. In 1985, R. E. Slusher for the first time demonstrated squeezed light based on four-wave mixing (FWM) in an optical cavity [1]. This work experimentally showed the nonclassical properties of the electromagnetic field. Basically, we can define a high quality quantum light source as squeezed light with large noise suppression below the shot noise level (SNL). Furthermore, squeezing bandwidth and low frequency squeezing are also important characteristics of squeezed states. Up to now, several methods have been explored to obtain squeezed states. The fundamental and frequently used squeezing technique is the optical parametric oscillator which consists of nonlinear crystals and cavities to build up the nonclassical states very efficiently [2]. Using these methods, very strong single mode squeezing has been realized in the past few years. For example, vacuum squeezing levels of  $-10$  dB were achieved in 2008 [3] and Mehmet *et al.* obtained up to  $-11.5$  dB squeezing last year [4]. By contrast, without any optical cavity and mode cleaner, FWM has gradually become another popular method for squeezing generation due to its simple experimental setup. As much as  $-9.2$  dB squeezing has been reported [5] in hot rubidium vapor since the first work of McCormick's group in 2007 [6].

Since the first proposal of applying squeezed states to high sensitivity detection [7], many groups made great efforts and have successfully generated low frequency squeezing at the submegahertz range [8–10]. Generation of low frequency squeezing at atomic transition wavelengths is also interesting for electromagnetically induced transparency-based quantum information protocols and other applications [10]. Our work is derived from this motivation and inspired by previous work such as the creation of beams with a low frequency quantum correlation based on FWM in hot rubidium vapor [11]. In this Letter, we report the realization of low frequency and controllable bandwidth squeezing based on a nondegenerate FWM

process in hot rubidium vapor at the optical D1 transition. We achieve as low as 1.5 kHz intensity difference squeezing with a maximum squeezing of  $-5$  dB at 1 MHz, and we can precisely tune the squeezing bandwidth by changing the pump power. Our experimental results suggest that this method is a good way to create quantum light sources with tunable, broad bandwidth, which shows great potential in the application of precise metrology and quantum information.

We carry out our experiment with a Ti:sapphire laser (Spectra-Physics) tuned about 1 GHz to the blue of the D1 line of rubidium ( $5S_{1/2} \rightarrow 5P_{1/2}$ , 795 nm) with a line width of about 30 kHz. This laser supplies coherent light used to interact with rubidium atoms in a hot vapor cell, resulting in a strong FWM, or nonlinear phase-insensitive amplification process [12] and generates correlated twin beams—the probe and the conjugate with a  $-6$  GHz frequency difference.

Figure 1 shows the energy diagram of the  $^{85}\text{Rb}$  D1 line which forms a double- $\lambda$  system and the schematic diagram of the experimental setup. The output power of the laser is 1 W. A polarizing beam splitter (PBS) is used to split the beam into a weak seed probe beam and a much stronger pump beam. The seed beam is red detuned about 3 GHz by using an acousto-optic modulator (AOM) (Brimrose). The AOM is driven by an RF signal generator (Agilent, N9310A). The polarization of the pump and probe are chosen perpendicular to each other, so the pump field can be filtered out after the vapor cell with a Glan-Thompson polarizer. By using a Glan-Laser polarizer we combine the weak probe and strong pump with an angle of  $0.4^\circ$ . The crossing point is in the center of a 12 mm long vapor cell which is filled with isotopically pure  $^{85}\text{Rb}$  and heated to  $120^\circ\text{C}$ . Both faces of the cell are antireflection coated to achieve a transmission efficiency larger than 98%. The pump beam waist at the crossing point is  $550\ \mu\text{m}$ , while the probe beam waist is  $300\ \mu\text{m}$ . The amplified probe after the vapor cell, along

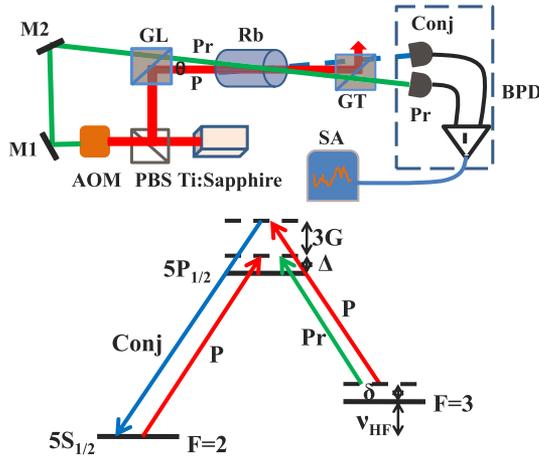


Fig. 1. (Color online) Top: experimental setup. PBS: polarizing beam splitter; AOM: acoustic optical modulator; GL: Glan–Laser polarizer; GT: Glan–Thompson polarizer; M: mirror; BPD: balanced photodetector; SA: spectrum analyzer. Bottom: energy level diagram of the  $^{85}\text{Rb}$  D1 line. P: pump, Pr: probe, Conj: conjugate;  $\Delta$ : one photon detuning.  $\delta$ : two photon detuning.  $\nu_{\text{HF}}$ : hyperfine structure.

with the generated conjugate with the same polarization, are separated from the pump beam by a Glan–Thompson polarizer with an extinction ratio of  $10^5:1$ . The probe and conjugate are directly sent to a balanced photodetector (BPD, Thorlabs PDB150) with two high quantum efficiency (96%) photodiodes. It subtracts the photocurrent with a switchable gain (usually  $10^5$  V/A) and sends the signal to a spectrum analyzer to perform a noise level analysis at a certain frequency range.

First, we establish the correlation, namely the intensity difference squeezing between the probe and the conjugate. There are many factors, technologically and physically, that can affect the FWM gain, and therefore the squeezing, as mentioned in previous work [13]. Here we give a description of the key elements in this system for maximum squeezing: (i) the atomic density in the cell which is controlled by the temperature directly effects the nonlinearity of the system. Too low temperatures result in low atomic densities and therefore a weak nonlinear process, whereas at too high temperatures other unwanted processes arise such as resonant absorption and spontaneous emission. We found  $120^\circ\text{C}$  works the best for our setup. (ii) The crossing angle between the probe and the pump plays a pivotal role in the photon-atom interaction. We can get intensity difference squeezing at a small range of angles but  $0.4^\circ$  shows maximum noise reduction, which agrees well with the previous experimental result by Boyer's group [14]. (iii) As shown in Fig. 1, in the double- $\lambda$  system two strong pump beams and a weak probe field are mixed and the conjugate field is generated. Here the probe beam is red detuned to the pump by 3 GHz, and the conjugate is blue detuned by 3 GHz. Take the frequency of the pump to be  $\omega$ , the transition frequency of the ground state ( $5S_{1/2}$ ,  $F=2$ ) and the excited state ( $5P_{1/2}$ ) is  $\Gamma$ , and the probe and conjugate frequencies are  $\omega_-$  and  $\omega_+$ , respectively. Define one photon detuning  $\Delta$  as  $\omega-\Gamma$  and two photon detuning  $\delta$  as  $\omega-\omega_-\nu_{\text{HF}}$  ( $F=2 \rightarrow F=3$ ).  $\Delta \approx 0.8$  GHz and  $\delta \approx 4$  MHz are the optimum values which cannot only build strong coherence of the atomic system to generate correlated

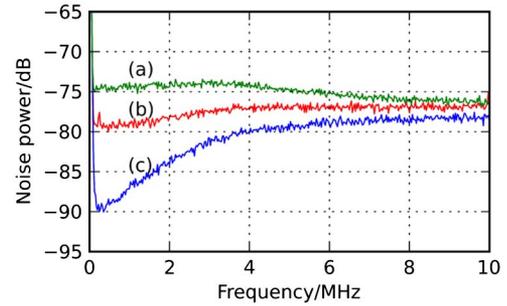


Fig. 2. (Color online) Noise power. (a) SNL, (b) intensity difference squeezing between the probe and the conjugate, and (c): the background noise level. 100 kHz RBW and 1 kHz VBW.

beams, but also avoid much spontaneous emission from the atomic ensemble. Furthermore, it is critical to make sure that the seed probe field is shot-noise limited, otherwise the excess noise will overwhelm the quantum noise reduction.

With a 400 mW pump and a  $10\ \mu\text{W}$  probe seed as well as the conditions mentioned above, the amplified probe is about  $80\ \mu\text{W}$  and the conjugate is about  $70\ \mu\text{W}$ . The transmission (90%) of the probe is measured by blocking the pump. Both the probe and conjugate are sent to a BPD, the intensity difference noise between the probe and the conjugate is subtracted by the BPD and then analyzed by a spectrum analyzer (Agilent E4411B), as demonstrated in Fig. 2. To measure the SNL, we guide a coherent laser beam, whose power is  $150\ \mu\text{W}$ , equivalent to the total power of the probe and conjugate, splitting it 50/50 and sending the resulting beams to the BPD. The measurement is taken with 100 kHz resolution bandwidth (RBW) and 1 kHz video bandwidth (VBW).

Second, we investigate the squeezing properties in the low frequency region with the pump power set to 400 mW. We use an fast Fourier transform (FFT) spectrum analyzer (SRS SR770) whose bandwidth spans from the DC to 100 kHz. As shown in Fig. 3, we observe relative intensity squeezing of a  $80\ \mu\text{W}$  probe and a  $70\ \mu\text{W}$  conjugate at frequencies as low as 1.5 kHz. This is, to the best of our knowledge, 1 kHz lower than the best result obtained from an atomic system at this wavelength. The RBW of the FFT spectrum analyzer is 31.25 Hz for this measurement.

Another important characteristic is the squeezing bandwidth. A large bandwidth is always useful for communication, and squeezed light has been proven to be a

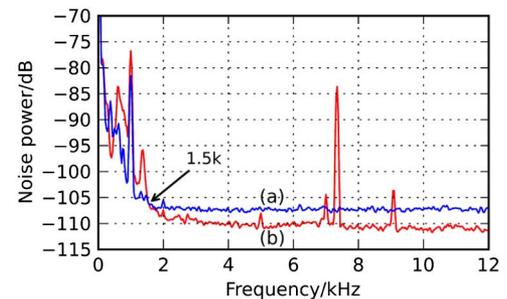


Fig. 3. (Color online) Low frequency noise power spectrum from the FFT spectrum analyzer with 31.25 Hz RBW. (a) SNL, and (b) intensity difference squeezing between the probe and the conjugate.

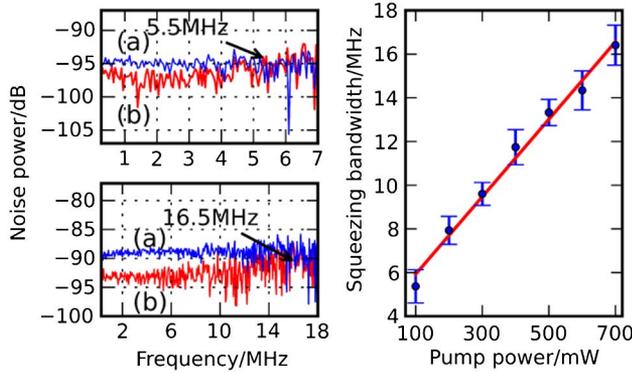


Fig. 4. (Color online) Left: squeezing when pump power are 100 mW (top) and 700 mW (bottom), (a) shows SNL and (b) is squeezing. Right: squeezing bandwidth versus pump power with measured data (dots) in our experiment and linear fit of the data (straight line). 100 kHz RBW and 1 kHz VBW.

good source for quantum communication, so squeezed states with high bandwidth are good candidates for the future high efficient quantum communication. In our experimental setup, we can get squeezing with a bandwidth of 16.5 MHz. The squeezing bandwidth is acquired by reading where the squeezing curve crosses the shot noise curve at the high frequency crossing point, which is much higher than the low frequency squeezing crossing point at the several kilohertz level. In addition to that, we found the pump power has a capacity to control the squeezing bandwidth of this FWM amplifier. But the gain of the photodetector in these measurements is set to  $10^4$  V/A to be able to measure the whole squeezing bandwidth. We change the pump power from 100 to 700 mW with the other parameters fixed and measure the squeezing bandwidth. In Fig. 4, the left picture shows when the pump power is 100 mW, the squeezing bandwidth is about 5.5 MHz, if we increase the pump power to 700 mW, the squeezing bandwidth goes up to about 16.5 MHz. The right picture demonstrates the squeezing bandwidth as a function of the pump power; the dots with the error bars are the experimental data, while the straight line is a linear fit which suggests a strong linear relationship between the squeezing bandwidth and the pump power. This diagram shows that we can precisely control the squeezing bandwidth from 5.5 to 16.5 MHz by changing the pump power. However, because the Glan-Thompson polarizer cannot completely filter out the pump, there will be more scattering background from the pump if the pump is too strong, which will bring the squeezing into bandwidth saturation and prevent us from going to higher pump power.

In conclusion, we have demonstrated experimentally generation of low frequency and broadband strong cor-

related twin beams based on a FWM amplifier in a rubidium vapor cell. Intensity difference squeezing down to 1.5 kHz is a great improvement in a low frequency squeezing study and opens the way of its application in atom optics research operating at the wavelength of atomic transition. Furthermore, a method of controlling the squeezing bandwidth by changing the pump power is discussed here, which promises great potential in quantum measurement, precise metrology, and quantum information.

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