Generation of quadrature squeezing down to 10 Hertz by single photon modulation on cesium D2 line

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Abstract: We report the generation of quadrature squeezed light resonant on cesium (Cs) D2 line down to 10 Hertz for the first time, and the maximum squeezing is 5.57 dB. The probe power injected into the optical parametric amplifier (OPA) is reduced to the single-photon level, and the squeezing angle is controlled by the single-photon modulation locking meanwhile the influence of probe light noise on low frequency squeezing is effectively suppressed. The generated low frequency squeezed light will improve the measurement sensitivity of Cs atomic magnetometer in audio frequencies band and even below, and this method can be applied to gravitational wave (GW) detection.

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1. Introduction

Squeezed light is an important source in many areas of continuous-variable quantum physics since its first generation in 1985 [1]. With their excellent quantum features, squeezed light, especially when resonant on atomic transition, plays an important role in quantum communication [2,3], quantum storage [4,5], the interaction between light and atoms [6–8], and precision measurement [9–12]. An Optical parametric oscillator (OPO) or OPA in a subthreshold is a general device for the generation of squeezed light. Many experiments produced squeezing at megahertz and hundreds of kilohertz frequencies since the laser noise and various technical noises are very close to the shot-noise limit (SNL) in these analysis frequency bands [13,14]. However, in some practical cases, such as GW detection [15], biological magnetic measurement [16,17], and the interaction between light and atomic medium [18–20], the analysis frequency is tens of Hertz or even lower. With the development of precise measurement, the shot-noise of the light has become the final limitation of the measurement [21]. Therefore, the preparation of squeezed light at low frequency is needed for improving the signal-to-noise ratio (SNR) of the measurement and increasing the measurement sensitivity [22]. In fact, a GW observatory operating beyond the SNL has been realized experimentally [23,24], and the sensitivity of the LIGO interferometers above 50 Hz is improved up to 3 dB by squeezed states [25]. Squeezed-light-enhanced atomic magnetometers have been demonstrated recently [26]. In 2010, Wolframm et al. employed squeezed light as the probe of the rubidium atomic magnetometer and demonstrated the sensitivity improvement from 46 nT (Hz1/2)−1 to 32 nT (Hz1/2)−1 around the analysis frequency of 120 kHz with a squeezing level of 3.2 dB [27]. The above quantum-enhanced atomic magnetometer were all
fulfilled in the kilohertz range where the squeezing is easily prepared and the magnetic signals can be lightly detected. However, for the analysis frequency of the audio band, especially at tens of Hertz or even lower, the signal will be submerged in the high background laser noise, and the sensitivity will become worse, so it is particularly important to prepare the squeezed light in this band.

Observing squeezing in low frequency band is difficult because there are a lot of noises in this band. There are two kinds of noises: one is various technical noises in the detection system, such as mechanical vibration, parasitic interference, beam pointing noise, etc [28,29]. The other is the laser noise of the control light, such as the pump, probe, and lock beam, of the OPA coupling in the squeezed light [30]. These noises can easily corrupt the squeezing level in the low frequency band, or even completely overwhelm the squeezing. In addition, a balanced homodyne detector (HD) with low noise and high common-mode rejection ratio (CMRR) in the low frequency band is also required [31].

Many researchers have made extensive and deep studies on the generation of squeezed light in the low frequency band [32–34]. In 2004, McKenzie et al. developed a quantum noise locking (QNL) method, and obtained a squeezed vacuum state down to 280 Hz at 1064 nm [30,35]. However, the pump phase was not controlled here, which means that the squeezing angle was free to evolve. In 2006, Valbruch et al. generate a squeezed vacuum state at 1064 nm down to 1 Hz by eliminating parasitic interference and laser noise successfully [31]. The low frequency squeezing results shown above were at a GW detection wavelength of 1064 nm, and for interacting with the atomic media, the wavelengths resonant on the atomic transition lines need to be chosen. For the Cs D_2 line, as the wavelength of 852 nm is considerably shorter than 1064 nm, problems of absorption and heating effect arise. The absorption of periodically poled KTiOPO_4 (PPKTP) crystal at 852 nm is much larger than 1064 nm, which is about 1 %/cm at 852 nm and about 10 %/cm at 426 nm, while about 0.02 %/cm at 1064 nm [36]. The absorption losses will result in the degradation of the squeezing level and the heating effect will lead to the instability of the cavity length stabilizing and pump phase controlling, this limits the squeezing band toward low analysis frequencies. So, the analysis frequencies of the generated squeezed light at the atomic transition lines reported at present are all in the kilohertz band [37–41], and the squeezing angle were free evolving.

Controlling the squeezing angle is the basic problem for squeezed light applications and it is necessary to precisely control the squeezing angle in many applications. In order to improve the sensitivity of GW detection in the Advanced LIGO detector, squeezed state with tuning squeezing angle by a filter cavity is required [42,43]. Moreover, in the quantum-enhanced Mach-Zehnder interferometer, for improving the SNR of the measurement the squeezed state with a squeezing angle of π/2 is employed [44]. It is also found that the anti-bunching effect of the squeezed coherent state can be produced by controlling the squeezing angle [45]. Furthermore, the polarization-squeezed light can be achieved by combining a dim quadrature squeezed beam which squeezing angle is 0 or π/2 with a bright coherent beam or another quadrature squeezed beam on a polarizing beam splitter (PBS) [46,47]. Common control schemes rely on the injection of a weak and phase modulated probe light at the fundamental frequency into the squeezed light source. It has been shown that even lowest probe powers will introduce large amounts of classical noise such as probe light noise, cavity detuning and pump light noise at audio frequencies and below, squeezing can no longer be achieved [30]. In 2006, Valbruch et al. first proposed a coherent control method to control the squeezing angle of the squeezed vacuum state and the relative phase to the local light [48]. This method needs a frequency-shifted light to stabilize the cavity length and another frequency-shifted control light to control the pump phase and the local phase, respectively. So, two separate lasers had to be used and the controlling system was complex.

In this letter, we presented a single-photon modulation locking (SML) to control the squeezing angle meanwhile the influence of probe light noise on low frequency squeezing is effectively suppressed. By suppressing the noise in the low frequency band, a broadband
quadrature squeezed light down to 10 Hertz resonant on Cs D₂ line are obtained experimentally with the maximum squeezing of 5.57 dB, which is the lowest squeezing band on the atomic transition lines reported at present. The entire system is stable enough for long-term measurement needs. The generated low frequency squeezed light can be subsequently used to replace the coherent probe light of the Cs atomic magnetometer to improve the SNR of the measurement.

2. Experiment setup for squeezing towards the audio frequencies

Many obstacles limit the squeezing to the audio frequencies and below. At these frequency regimes, there are a lot of technical noise source, such as laser intensity noise, mechanical fluctuation, beam jitter, parasitic interference, and electronic noise. The most important source is the laser noise, because Ti: Sapphire laser has high background noise at low frequencies. This noise will be easily coupled into the squeezed light. To avoid noise coupling, we use a frequency-shifted and phase-modulated field to stabilize the cavity length and reduce the seed power injected into the OPA to avoid the influence of probe laser noise on the low frequency squeezing.

The experimental system is shown in Fig. 1. The main laser is a low-noise tunable Ti:sapphire laser (Msquare Co.) which the frequency is locked to the D₂ line of Cs at 852.3 nm by the polarization spectroscopy method. Squeezed light is generated from a subthreshold OPA which is pumped by a 426.2 nm pump light generated by a second harmonic generator (SHG). The cavity of the OPA has a bow-tie-type ring configuration consisting of two spherical mirrors (radius of curvature of 50 mm) and two flat mirrors. One of the two flat mirrors is the output coupler and the transmittance is T = 0.11, whereas the other three mirrors are highly reflective for the fundamental wavelength of 852.3 nm, the concave mirrors are highly transmittance at 426.2 nm. The cavity round trip length is 407 mm. A 10-mm-long type-I PPKTP crystal (Rai col Crystals) is placed between the two spherical mirrors. The crystal is specially anti-reflecting-coated to reduce the intra-cavity losses, which is placed in a copper-made oven and the temperature is stabilized to 46.5°C, for optimization. The beam waist size inside the crystal is 22.7 μm. In order to stabilize the cavity length without bringing the noise of the lock light into the generated squeezed light, a semiconductor laser (Waviclelaser Co.) which is locked to Cs D₁ line at 894.6 nm by the saturation absorption spectroscopy method is employed. We use an avalanche photodiode (APD, C30659-900-R5B) to record the faint lock light signal. By tuning the modulation frequency, the sideband frequency of the 894.6 nm lock light and the 852.3 nm probe light are both simultaneously made to resonate with the OPA cavity and locked using the Pound-Drever-Hall technique. Various methods are used for mitigating the parasitic interference in the HD detection. Optical components with minimal surface roughness for reducing the amount of scattering are used, beam dumps are carefully placed to dump the scattered photons and the phase fluctuations in the scattered fields are decreasing by reducing the vibration in the optical system. In addition, a triangular ring cavity, mode cleaner (MC), is built in the local path to decrease the beam pointing noise meanwhile increasing the interference visibility of the homodyne. Besides, stable cavity design and usage of ultra-stable mirror mounts also help to increase mechanical stability. Finally, the whole optical system is built on an air-floating and highly stable optical platform and shielded by a sound-proof cover to mitigate the sound variation in the surrounding. To detect squeezing in the low frequency band, a homemade HD is utilized, the average CMRR in the test frequency range from 10 Hz to 300 kHz is about 55 dB and the electric dark noise is 7 dB below the SNL of 2 mW local light at 10 Hz and is more than 10 dB above 100 Hz.
Fig. 1. Schematic of the experimental setup. SHG: second harmonic generator, OPA: optical parametric amplifier, MC: mode cleaner, HD: balanced homodyne detector, OI: optical isolator; HR: high-reflectivity mirror; λ/2: half-wave plate; PBS: polarization beam splitter; BS: beam splitter; ND: neutral-density filter, EOM: electro-optical modulator; FB: feedback control circuit, PD: photodetector, BPD: balanced photodetector, PZT: Piezoelectric Transducer, SPCM: single-photon counting module, DAS: data acquisition system. The dash black lines indicate the electronics for the phase control process. G: amplifier circuit (Gain), M: mixing circuit, BPF: band-pass filter; ED: envelope detector; LPF: low-pass filter.

For controlling the local phase in HD detection, a QNL method is used. The error signal was generated by dithering the local phase with 34 kHz and demodulating the noise power of HD. The noise power was detected using a spectrum analyzer (Hewlett Packard-8590D, zero span at 2 MHz, resolution bandwidth (RBW) = 300 kHz, video bandwidth (VBW) = 30 kHz) then demodulated with a lock-in amplifier (Stanford Research System-SR830) with a modulation frequency of 34 kHz and amplitude of 0.23 V, and then fed back to PZT1. By switching the phase in the proportional-integral-derivative (PID) controller, either a squeezed phase or an anti-squeezed phase locking can be achieved. Finally, the noise power was measured by a spectrum analyzer (Rohde & Schwarz, FSV-4). When no light is seeded, we measure the squeezing traces at 5 kHz as the homodyne phase was varied. The results are shown in Fig. 2, a squeezing of 5.70 dB is obtained and the anti-squeezing is 13.68 dB. The observed squeezing level $R_-$ and anti-squeezing level $R_+$ are calculated as follows [49]:

$$R_\pm = 1 \pm \eta^2 \xi \rho \frac{4x}{(1+x)^2 + 4\Omega^2},$$

(1)

Where $R_\pm$ is the generated squeezing/anti-squeezing levels without taking account of the phase fluctuation, with quantum efficiency of the photodiode $\eta = 0.99$, the homodyne visibility $\xi = 0.985$, propagation efficiency $\zeta = 0.912$ which the lower propagation efficiency is mainly due to the splitting ratio of 95/5 BS, and the escape efficiency of the cavity $\rho = T/(T + L) = 0.879$, where $T$ is transmittance of the output coupler, $L$ is the intracavity losses. $x = \sqrt{P/P_o}$ is normalized pump power, $P$ is pump power, $P_o = 165 mW$ is the oscillation threshold of the OPA. $\Omega = f/\gamma$ is normalized frequency, $f$ is measurement frequency by a spectrum analyzer, $\gamma = c(T + L)/l$ is the OPA cavity decay rate, which $l$ is round trip length of the cavity. And the expected squeezing level at 5 kHz is 6.01 dB.
Fig. 2. Observed noise power as the phase of the homodyne is scanned with the pump power of 100 mW and local power of 2 mW. (a) Shot noise limit. (b) Local phase is locked at the squeezed quadrature. (c) Local phase is scanned. (d) Local phase is locked at the anti-squeezed quadrature. These levels are normalized to make the shot noise limit at 0 dB. Measurement frequency is 5 kHz with RBW = 2 kHz, and VBW = 30 Hz. Electronic noise (21 dB below SNL) was subtracted from the data. Traces (a), (b), and (d) are averaged from 10 measurements. The observed squeezing/anti-squeezing levels are -5.70 dB, +13.68 dB, respectively.

3. Generation of quadrature squeezed state down to 10 hertz

In order to observe squeezing in the low frequency band, the seed power should be decreased as much as possible [30]. So, we have reduced the probe power injected into the OPA to the single-photon level, and proposed a single-photon modulation method to control the squeezing angle, which can not only achieve the controlling of the squeezing angle, but also avoid the probe light noise coupled into the squeezed light.

We use a 95/5 BS to divide a small portion of the generated squeezed light for controlling the squeezing angle. Because the probe light is injected into the OPA from a highly reflective mirror with a reflectivity greater than 99.99%, the power entering in the cavity is extremely low. When the seed power is 1 nW, the average photon number of the probe light injected into the cavity is only 0.076, through the experimental measurement. Such weak light requires the use of SPCM to detect the signal. Moreover, in the type-I parametric down-conversion, except for the fundamental frequency $\omega_0$, some other pairs of down-conversion fields with nondegenerate frequencies of $\omega_m = \omega_0 \pm m \Omega_{\omega_0}$ may also simultaneously on resonance in the cavity, with $\Omega_{\omega_0}$ as the free spectral range of the cavity and $m=1, 2, \ldots$. In order to detect the interference signal between the photons generated by parametric down-conversion and the injected probe light distinctly, it is necessary to filter out the frequency modes different from the fundamental frequency. Therefore, two etalons are employed to filter out the unwanted modes before the squeezed light enters the SPCM. The lengths of the etalons are 3 mm and 11 mm, respectively. An 852 nm bandpass interference filter is used to remove other light. By scanning the pump phase, the interference signal generated by the phase-sensitive parametric process is then obtained. The output of the SPCM is divided into two parts: one enters into a data acquisition system (QuTag) to acquire the photon count rate, and the other is demodulated with a lock-in amplifier (SR830) with a modulation frequency of 34 kHz and amplitude of 0.45 V, and then fed back to PZT2. The control electronics for the phase controlling are indicated by black dashed lines in Fig. 1.

When the seed power is 3 nW (the average photon number of probe light injected into the OPA is 0.23) and the pump power is 100 mW, by locking the pump phase to 0 (parametric amplification with squeezing angle of $\pi/2$) the count rate results are shown in Fig. 3 (a). The
oscillation signal is the interference signal of the photons when the pump phase is scanned, and the back part is the result of phase locking. The count rate is 1.95 MHz with only the pump light which come from the photons generated by the parametric down-conversion and the background counts (less than 1 kHz). When there is only probe light in the cavity, the count rate is 90 kHz. Similarly, When the seed power is 4.5 nW and the pump power is 90 mW, by locking the pump phase to $\pi$ (parametric de-amplification with squeezing angle of 0) the count rate results are shown in Fig. 3 (b). The phase fluctuation within 1000 s of locking to $\pi$ and 0 is 26.1 mrad and 11.7 mrad, respectively, and the stability is in the same order as reported [49–52]. The experimental results show that the squeezing angel controlling at the single-photon level of the probe light injected into the cavity can be realized by the SML.

With the help of the pump phase controlling, a squeezing angle-controlled quadrature squeezed states can be generated in the experiment. As the squeezing angle is locked to 0 and the local phase is locked at the squeezed quadrature by QNL in the HD, a quadrature squeezed light is observed experimentally. The squeezing spectrum between 10 Hz and 300 kHz is shown in Fig. 4. The seed power is 3 nW, the local power is 2 mW, and the pump power is 100 mW. Trace (a) shows the SNL. The squeezing is shown in trace (b). Trace (c) shows the anti-squeezing of 13.80 dB above the shot noise and is flat. The electric dark noise is subtracted from the data. As the results show, we obtained a broadband quadrature squeezed light down to 10 Hz. Besides, it can be seen from trace (b) that although the seed power is extremely low and the average photon number of probe light injected into the cavity is 0.23, the squeezing around 10 Hz is degradation due to the roll-up laser noise of probe field and the imperfect CMRR of HD in this frequency band. The peaks at 160 Hz and 25 Hz is the extra noise in the electric circuits and the peaks at 34 kHz and 238 kHz are the modulation frequency of the lock-in amplifier and its harmonic, respectively. The peaks at 30 Hz and 50 Hz are owing to the noise of the SML electric circuits. For a significant portion of the shown spectrum, the shot noise variance was squeezed by an average value of 5.57 dB. In addition, the squeezing is slightly smaller than the vacuum squeezing of 5.70 dB due to the phase fluctuation introduced by the SML. Taking account of the phase fluctuation with a Root-Mean-Square (RMS) of $\theta$, the observed squeezing level $R'_z$ and anti-squeezing level $R'_+\text{ were calculated as follows [49]}$:

$$R'_z = R_z \cos^2 \theta + R_z \sin^2 \theta.$$  

(2)

Where $R_z$ is the generated squeezing/anti-squeezing levels of the squeezed vacuum light. According to the results of the squeezing and anti-squeezing levels, the calculated phase

![Fig. 3. Experimental results of the pump phase controlling by the SML, in which figure (a) shows the phase locking to 0, corresponding to the parametric amplification with squeezing angle of $\pi/2$, and figure (b) shows the phase locking to $\pi$, corresponding to the parametric de-amplification with squeezing angle of 0. The bin width of the data acquisition is 20 ms.](image)
fluctuation of the SML is 18.0 mrad, which is in agreement with the result obtained by the count rate above.

Fig. 4. Measured noise spectrum for (a) the SNL, (b) the quadrature squeezed light, and (c) the anti-squeezed light. All traces are pieced together from two FFT frequency windows: 10 Hz-1 kHz and 1 kHz-300 kHz with RBW = VBW = 1 and 2 Hz, respectively. Each point is the averaged RMS value of 200 and 100 measurements in the respective ranges. The electronic dark noise has been subtracted from the data. The peaks at 30 Hz and 50 Hz in trace (b) are due to the noise of the SML circuits.

To demonstrate the squeezing in tens Hertz band, we used the zero span mode of the spectrum analyzer to obtain a noise spectrum at 10 Hz and 70 Hz with a scan time of 10 s. The squeezing angle is locked to 0, the pump power is 100 mW and the local power is 2 mW. As shown in Fig. 5, where Fig. 5 (i) is the result at 10 Hz and (ii) is at 70 Hz, trace (a) shows the shot noise, trace (b) is the observed quadrature squeezing, and trace (c) is the observed anti-squeezing. Electronic dark noise has been subtracted from the data. Each measurement point is the averaged RMS value of 400 measurements. The observed squeezing is 2.85 ± 0.41 dB at 10 Hz and 5.64 ± 0.39 dB at 70 Hz, respectively. We point out that each measurement trace in Fig. 5 lasted for more than an hour, thereby demonstrating long term stability of our system. In order to further evaluate the long term stability of the system, the noise of the quadrature squeezed light at 10 kHz is recorded continuously for 1 hour. The fluctuation of the observed squeezing is ±0.17 dB for 1 hour. The experimental results show that the whole system can operate stably for a long time.

Fig. 5. Observed noise power levels in zero span mode. (a) SNL. (b) The quadrature squeezing. (c) The anti-squeezing. These levels are normalized to make the shot noise level 0 dB. (i) Observed noise power at 10 Hz with RBW = 5 Hz and VBW = 1 Hz. Electronic noise (7 dB
below SNL) was subtracted from the data. The observed squeezing is \(2.85\pm0.41 \text{ dB}\). (ii) The results at 70 Hz with RBW = 30 Hz and VBW = 1 Hz. Electronic noise (10 dB below SNL) was subtracted from the data. The observed squeezing is \(5.64\pm0.39 \text{ dB}\). All traces are RMS averaged from 400 measurements.

4. Summary

We have presented results demonstrating broadband OPA quadrature squeezed light down to 10 Hertz resonant on Cs D\(_2\) line. The vacuum fluctuation was squeezed maximum 5.57 dB for a significant portion of analysis frequencies. Besides, we have presented a single-photon modulation locking, which the probe light injected into the cavity is on the single-photon level, to control the squeezing angle meanwhile avoiding the influence of probe laser noise on the low frequency squeezing as much as possible. The above experimental results benefit from the low noise balanced detector and the effective reduction of technical noise, especially parasitic interference. The whole system can operate stably for a long time, and the fluctuation of the observed squeezing at 10 kHz in 1 hour is \(\pm0.17 \text{ dB}\). Two other methods are used to maintain the OPA operation: a frequency-shifted locking beam and the QNL method.

The generated squeezed light resonating with the atomic transition will extend the precision measurement related to atoms to audio band and below. Squeezed states in the low frequency regime can be used to create entanglement between light and atoms to push a light-atom interferometer beyond its SNL [53]. And the quadrature squeezed light can be used to prepare entangled states resonant with atomic transition [3] and also can be used for precise measurement at low frequencies [54]. In addition, the quadrature squeezed light combined with a coherent light can be used to prepare polarization squeezed light, which can be used for precise magnetic measurements [27], quantum information networks [55], and the generation of spin squeezing in atomic ensembles [6]. Based on our investigations, we believe that squeezed states at even lower frequencies with also higher degrees of squeezing can be generated by further reduction of the technical noise and reduction of optical losses.

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