Generation of a stable low-frequency squeezed vacuum field with periodically-poled KTiOPO$_4$ at 1064 nm

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We report on the generation of a stable continuous-wave low-frequency squeezed vacuum field with a squeezing level of 3.8 ± 0.1 dB at 1064 nm, the wavelength at which laser interferometers for gravitational wave (GW) detection operate, using periodically poled KTiOPO$_4$ (PPKTP) in a sub-threshold optical parametric oscillator. PPKTP has the advantages of higher nonlinearity, smaller intra-crystal and pump-induced seed absorption, user-specified parametric down-conversion temperature, wider temperature tuning range, and lower susceptibility to thermal lensing over alternative nonlinear materials such as MgO doped or periodically poled LiNbO$_3$, and is, therefore, an excellent material for generation of squeezed vacuum fields for application to laser interferometers for GW detection.

Injection of squeezed vacuum states into the output port of laser interferometers for gravitational wave (GW) detection is a promising technique for enhancing the sensitivity of future detectors, such as Advanced LIGO [1], which are expected to be operational in the next few years. Large squeeze factors in the GW band (10 Hz to 10 kHz), and stable, long-term operation are among the key requirements that a squeeze source must satisfy in order to be used in long baseline GW detectors with large duty factor [2]. Squeezed vacuum fields are typically generated using nonlinear crystals in sub-threshold optical parametric oscillators (OPOs). Consequently, the choice of nonlinear material is critical, since it determines several important parameters, such as nonlinearity, phase-matching type, absorption loss, pump-induced seed absorption loss, laser damage threshold, photo-refractive damage threshold, and susceptibility to thermal lensing. Moreover, since all GW detectors presently use high power Nd:YAG lasers sources at 1064 nm, generating squeezed vacuum states at 1064 nm is also essential.

Presently, squeezed state sources for GW detectors at 1064 nm use OPOs comprising magnesium oxide (MgO) doped lithium niobate (LiNbO$_3$) crystals [3, 4]. LiNbO$_3$ is a widely used nonlinear material with good long-term stability. MgO doping increases its laser damage threshold and reduces the effect of green-induced infrared absorption (GRIIRA) [3], but also increases impurity and inhomogeneity in the crystal, thereby increasing intra-crystal absorption and scattering losses, which place a limit on the attainable level of squeezing. In this Letter, we report on the generation of a squeezed vacuum field using an alternative material, periodically poled KTiOPO$_4$ (PPKTP) at 1064 nm.

KTiOPO$_4$ (KTP) offers several advantages over LiNbO$_3$. It has a higher laser damage threshold, higher resistance to photo-refractive damage, and lower susceptibility to thermal lensing. These properties are especially critical for the long-term stability of OPOs pumped by cw visible sources [4]. KTP has an effective nonlinear coefficient, $d_{\text{eff}}$, comparable to LiNbO$_3$ at 1064 nm, and has been shown to generate relatively high levels of quantum correlations [3, 5]. Furthermore, recent progress in the electric field poling of flux-grown KTP has made periodically poled KTP (PPKTP) an even more promising candidate. With its high nonlinearity of $|d_{\text{eff}}| \approx 10.8$ pm/V, PPKTP is a competitive alternative to periodically poled LiNbO$_3$ (PPLN) and LiTaO$_3$ (PPLT). Poling-induced losses of PPKTP are much lower than those of PPLN. For these reasons, higher squeezing levels are attainable with PPKTP at realistically available pump powers.

Since birefringent phase matching is not used in periodically poled crystals, temperature tuning of their refractive indices in the ordinary and extraordinary axes is not required. The only requirement on the temperature control is to maintain the grating period against thermal expansion. The typical FWHM of the effective parametric down-conversion temperature for PPKTP at 1064 nm is 5°C, whereas it ranges from a few tens to several hundred mK for LiNbO$_3$ (depending on its length). This property is particularly vital for the long-term stability requirement of GW observatories, since the system is robust against temperature variations, unlike the birefringent phase-matching case. The low phase-matching temperature (typically around room temperature) and large effective temperature range of PPKTP also significantly reduce difficulties in fabrication of ovens for temperature control.

Observation of squeezing in the GW band has been reported by McKenzie et al [6] and Vahlbruch et al [7]. Both groups used MgO:LiNbO$_3$, achieving squeezing levels of about 3 to 4 dB. Here we demonstrate the generation of a squeezed vacuum field at 1064 nm using PPKTP at 1064 nm. This is, to our knowledge, the first time that
squeezing at 1064 nm using PPKTP is reported. This squeeze source has all the advantages of stability and ease of operation that PPKTP offers, at a wavelength suitable for GW detectors.

PPKTP has previously been used in a cw OPO to generate squeezed states, but not at 1064 nm. Aoki et al. reported the generation of squeezed light in sideband modes of cw light at 946 nm using a PPKTP crystal in an OPO and observed the squeezing level of 5.0 ± 0.1 dB and the anti-squeezing level of 12.7 ± 0.1 dB [9]. More recently, Takeno et al. observed 9.01 ± 0.14 dB of cw squeezing at 860 nm using a PPKTP crystal in a bow-tie cavity [10]. Hirano et al. also observed the generation of pulsed squeezed light from a single-pass degenerate optical parametric amplifier (OPA) with a PPKTP crystal pumped by a cw second-harmonic field and reported the squeezing level of 3.2 dB and the anti-squeezing level of 6.0 dB at 1064 nm [11]. To the best of our knowledge, these are also the highest levels of pulsed and cw squeezing ever obtained.

The schematic of the experiment is shown in Fig. 1. The apparatus is mainly composed of (i) the second-harmonic generator (SHG), (ii) the optical parametric oscillator (OPO), (iii) the homodyne detector, (iv) the frequency- and intensity-stabilizer, and (v) the phase-locked subcarrier (LASER2). The main light source is a Nd:YAG Master Oscillator Power Amplifier laser (LASER1). The laser is frequency- and intensity-stabilized using the LIGO pre-stabilized laser system [12].

The SHG is a cavity composed of a 6.5 mm long 5% MgO:LiNbO3 crystal (PhotonLaserOptik Inc.) with an anti-reflection coated flat surface and a high-reflective curved surface and an output coupling mirror with a radius-of-curvature of 50 mm. The radius-of-curvature and reflectivity of the curved surface of the crystal are respectively 8 mm and 99.95% at both 1064 nm and 532 nm. The output coupler, with reflectivities of 95.0% at 1064 nm and 4.0% at 532 nm, is mounted on a piezoelectric transducer (PZT) as an actuator that controls the cavity length. The SHG cavity is locked by the Pound-Drever-Hall technique. The SHG cavity is enclosed in an oven and the crystal is maintained at 114.05 °C to optimize the SHG conversion efficiency. The SHG cavity is pumped by 1.1 W of the 1064 nm from the MOPA laser and generates 320 mW at 532 nm, which is used as a pump field in the OPO cavity.

The OPO is a cavity composed of a 10 mm long PPKTP crystal (Raicol Inc.) with anti-reflection coated flat surfaces and two coupling mirrors with a radius-of-curvature of 10 mm. The reflectivities of the input and output coupling mirrors are 99.95% at both 1064 nm and 532 nm and 92.0% at 1064 nm and 4.0% at 532 nm respectively. The OPO cavity length is 2.3 cm. The crystal is maintained at 33.5 °C to optimize the 1064/532 parametric down-conversion. When pumped by the second-harmonic pump at frequency 2ω0 and operated below threshold, the OPO correlates the upper and lower quantum sidebands of a vacuum field that enters the OPO around the center frequency ω0 [13]. The correlation of the quantum sidebands appears as a squeezed vacuum field. A second laser beam (LASER2) that is shifted by 642 MHz with respect to ω0 is used to lock the OPO cavity in a TEM00 mode. This frequency-shifted light is orthogonally polarized to the vacuum field that seeds the OPO cavity in a TEM00 mode, and to the pump field.

The generated squeezed vacuum field is triggered by the coherent local oscillator (LO) field and measured with a homodyne efficiency of 99%, using a balanced detector comprising a 50/50 beamsplitter (HBS) and a homemade balanced photodetector that has two ETX500T photodiodes (JDS Uniphase) with matched quantum efficiencies of 93%. The difference between the two optical responses is amplified and measured by the spectrum analyzer (HP8591E). The HBS and balanced PD form an opto-electrical Mach-Zehnder interferometer to extract the linear response of the squeezed vacuum field. The squeeze angle is locked by the noise-locking technique [14], and the low-frequency measurements are made with a spectrum analyzer (Stanford Research Systems SR785).

We measured the fixed-frequency, zero-span spectra of...
FIG. 2: (Color online) The fixed-frequency spectra of (a) shot noise, and (b) squeezed/anti-squeezed noise power when the squeeze angle was scanned as a function of time. The measurements were done at 900 kHz with zero frequency span. The resolution bandwidth (RBW) is 100 kHz and the video bandwidth (VBW) is 3 kHz. The squeeze angle was scanned using PZT3 with a ramp function at 10 Hz. The electronic noise was 9.2 dB below the shot noise level, and was subtracted from the squeezing/anti-squeezing and shot noise spectra.

FIG. 3: (Color online) The broadband spectra of (a) shot noise and (b) squeezed shot noise. The squeeze angle was noise-locked without any coherent light. The electronic noise was 5.1 dB below the shot noise level at low frequencies, and was subtracted from the squeezing and shot noise spectra. The spike at 13.2 kHz and its higher harmonic are due to the modulation of PZT3 for the noise-locking technique.

In conclusion, we have demonstrated the generation of a stable cw low-frequency squeezed vacuum field with a squeezing level of $3.8 \pm 0.1$ dB at 1064 nm, suitable for laser interferometers for GW detection, using PPKTP in a sub-threshold OPO. The large squeezing levels and excellent stability of PPKTP make it an excellent material for use in squeezing-enhanced GW detectors. The attained squeezing level at low frequencies is limited by the availability of higher pump power and lower intracavity losses. Since PPKTP is less susceptible to photorefractive damage and thermal lensing, a higher squeezing level can be achieved with higher pump power and an OPO output coupling mirror with a lower reflectivity. For the moderate pump power level and vacuum seeding used, we did not observe gray-tracking, a known problem for KTP.

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[1] http://www.ligo.caltech.edu/docs/M/M060056-07/M060056-07.pdf
[2] A. Abramovici, W. Althouse, R. Drever, Y. Gursel, S. Kawamura, F. Raab, D. Shoemaker, L. Sievers, R. Spero, K. Thorne, R. Vogt, R. Weiss, S. Whitcomb, and M. Zucker, Science 256, 325 (1992).
[3] K. McKenzie, N. Grosse, W. P. Bowen, S. Whitcomb, M. B. Gray, D. E. McClelland, and P. K. Lam, Phys. Rev. Lett. 93, 161105 (2004).
[4] H. Vahlbruch, S. Chelkowski, B. Hage, A. Franzen, K. Danzmann, and R. Schnabel, Phys. Rev. Lett. 97, 011101 (2006).
[5] Y. Furukawa, K. Kitamura, A. Alexandrovski, R. K. Route, M. M. Fejer, and G. Foulon, Appl. Phys. Lett. 78, 1970 (2001).
[6] T. Y. Fan, C. E. Huang, B. Q. Hu, R. C. Eckardt, Y. X. Fan, R. L. Byer, and R. S. Feigelson, Appl. Opt. 26, 2394 (1987).
[7] J. Laurat, T. Coudreau, N. Treps, A. Maitre, and C. Fabre, Phys. Rev. Lett. 91, 213601 (2003).
[8] S. Feng and O. Pfister, Opt. Lett. 29, 2800 (2004).
[9] T. Aoki, G. Takahashi, and A. Furusawa, Opt. Exp. 14, 6930 (2006).
[10] Y. Takeno, M. Yukawa, H. Yonezawa, and A. Furusawa, arXiv:quant-ph/0702139 (2007).
[11] T. Hirano, K. Kotani, T. Ishibashi, S. Okude, and T. Kuwamoto, Opt. Lett. 30, 1722 (2005).
[12] J. Rollins, D. Ottaway, M. Zucker, and R. Weiss, Opt.
Let. 29, 1876 (2002).

[13] C. M. Caves and B. L. Schumaker, Phys. Rev. A 31, 3068 (1985).

[14] K. McKenzie, E. E. Mikhailov, K. Goda, P. K. Lam, N. Grosse, M. B. Gray, N. Mavalvala, D. E. McClelland, J. Opt. B: Quantum Semiclass. Opt. 7, S421 (2005).