Generation of a stable low-frequency squeezed vacuum field with periodically poled $KTiOPO_4$ at 1064 nm

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We report the generation of a stable continuous-wave low-frequency squeezed vacuum field with a squeezing level of 7.4 ± 0.1 dB at 1064 nm, the wavelength at which laser-interferometric gravitational wave (GW) detectors operate, using periodically poled $KTiOPO_4$ (PPKTP) in a subthreshold optical parametric oscillator. The squeezing was observed in a broad band of frequencies above 700 Hz where the sensitivity of the currently operational GW detectors is limited by shot noise. PPKTP has the advantages of higher nonlinearity, smaller pump-induced seed absorption, and wider temperature tuning range than 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. © 2008 Optical Society of America

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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 to be used in long-baseline GW detectors with a large duty factor [2]. Squeezed vacuum fields are typically generated by using nonlinear crystals in subthreshold 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, photorefractive damage threshold, and susceptibility to thermal lensing. Moreover, since all GW detectors currently use high-power Nd:YAG lasers sources at 1064 nm, generating squeezed vacuum states at 1064 nm is also essential.

Currently, 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 [5], but also increases impurity and inhomogeneity in the crystal, thereby increasing intracrystal absorption and scattering losses, which place a limit on the attainable level of squeezing. In this Letter, we report 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 photorefractive damage, and lower susceptibility to thermal lensing. These properties are especially critical for the long-term stability of OPOs pumped by cw visible sources [6]. KTP has an effective nonlinear coefficient, d_{eff}, comparable with that of $LiNbO_3$ at 1064 nm and has been shown to generate relatively high levels of quantum correlations [7,8]. 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 $|d_{\mathrm{eff}}| \simeq 10.8$ 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 downconversion temperature for PPKTP at 1064 nm is 5°C, whereas it ranges from a few tens to several hundred millikelvins 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

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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.* [3] and Vahlbruch *et al.* [4]. Both groups used MgO:$LiNbO_3$, achieving squeezing levels of about 3–6 dB. Here we demonstrate the generation of a squeezed vacuum field at audio frequencies 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 5.6 ± 0.1 dB and the antisqueezing 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 with a PPKTP crystal pumped by a cw second-harmonic field and reported the squeezing level of 3.2 dB and the antisqueezing level of 6.0 dB at 1064 nm [11]. These are among the highest levels of pulsed and cw squeezing ever obtained.

The schematic of the experiment is shown in Fig. 1. The apparatus is composed mainly of (i) the second-harmonic generator (SHG), (ii) the 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 (MOPA) laser (LASER1). The laser is frequency and intensity stabilized by using the LIGO prestabilized laser system [12].

The SHG is a cavity composed of a 6.5 mm long 5% MgO:$LiNbO_3$ crystal (Photon LaserOptik Inc.) with an antireflection-coated flat surface, 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 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, using the Pound–Drever–Hall technique. The SHG cavity is enclosed in an oven to maintain the crystal at 114.05 °C for optimal SHG conversion efficiency. It 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 antireflection-coated flat surfaces and two coupling mirrors, each with a radius of curvature of 10 mm. The reflectivities are 99.95% at both 1064 and 532 nm for the input coupler and 92.0% at 1064 nm and 4.0% at 532 nm for the output coupler. The OPO cavity length is 2.3 cm. The crystal is maintained at 33.5 °C to optimize the 1064/532 parametric downconversion. When pumped at frequency $2\omega_0$ 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 ω_0 [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 ω_0, and is orthogonally polarized to the vacuum field that seeds the OPO, is used to lock the OPO cavity in a TEM_{00} mode.

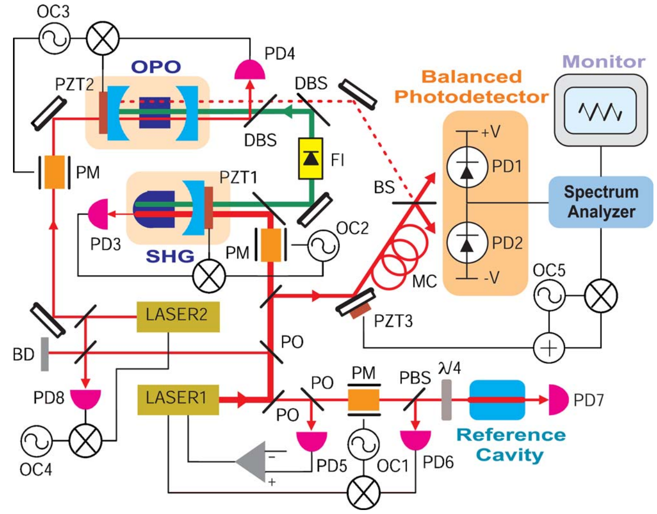

Fig. 1. (Color online) Schematic of the experiment. LASER1, Nd:YAG MOPA laser; LASER2, Lightwave 126 laser; FI, Faraday isolator; MC, mode-cleaning fiber; PM, electro-optic phase modulator; DBS, dichroic beam splitter; PBS, polarizing beam splitter; BS, 50/50 beam splitter; BD, bean dump; PO, pickoff mirror; $\lambda/4$, quarter-wave plate; PD1–PD8, photodiodes; OC1–OC5, LOs (13.3 MHz, 16.7 MHz, 49.5 MHz, 624 MHz, and 13.5 kHz). Solid lines, coherent fields; dotted line, squeezed vacuum field. The low-frequency spectrum analyzer (Stanford Research Systems SR785), which is not shown in the figure, is used to measure the broadband spectrum of the balanced photodetector output.

The generated squeezed vacuum field is triggered by the coherent local oscillator (LO) field and measured with a homodyne efficiency of 99% by the homodyne detector, composed of a 50/50 beam splitter and a balanced photodetector with two photodiodes (JDS Uniphase ETX500T) with matched quantum efficiencies of 93%. The difference between the two optical responses is amplified and measured by a spectrum analyzer (HP8591E). The squeeze angle is locked by the noise-locking technique [14].

We measured the fixed-frequency, zero-span spectra of the shot noise and squeezed/antisqueezed shot noise, shown in Fig. 2, when scanning the squeeze angle. The periodic oscillation of the squeeze angle can be seen in the figure. We also measured the spectra of the shot noise and squeezed shot noise when the squeeze angle was noise locked. The result is shown in Fig. 3. Broadband squeezing of 7.4 ± 0.1 dB

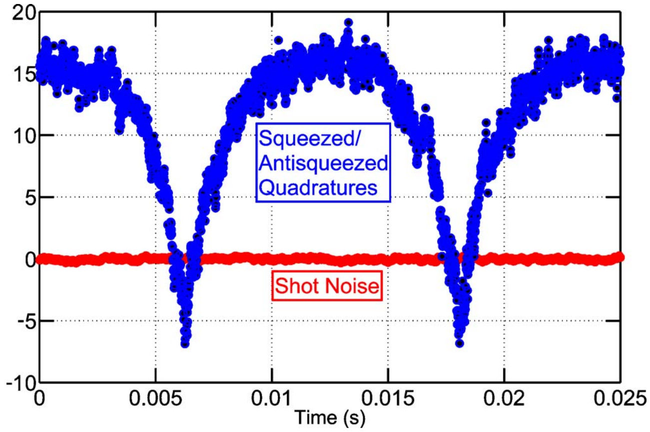

Fig. 2. (Color online) Fixed-frequency spectra of shot noise and squeezed/antisqueezed noise power when the squeeze angle was scanned as a function of time. The measurements were done at 900 kHz with zero frequency span. The resolution bandwidth is 100 kHz, and the video bandwidth is 3 kHz. The squeeze angle was scanned by the PZT (PZT3) with a ramp function at 10 Hz. The electronic noise was 17.4 dB below the shot-noise level.

at frequencies above 3 kHz is observed. The noise increase at low frequencies is due to scattering of the LO light from the homodyne detector. To observe squeezing at lower frequencies requires careful shielding of the LO- or ambient-light-induced scattered photons from coupling to the OPO cavity. This was demonstrated very well in [3,4], and is not part of the initial goals of the present experimental demonstration.

In conclusion, we have demonstrated the generation of a stable cw low-frequency squeezed vacuum field with a squeezing level of 7.4 ± 0.1 dB at 1064 nm, suitable for laser interferometers for GW detection, using PPKTP in a subthreshold OPO. The attained level of squeezing was limited by the escape efficiency (or pump power) and detection efficiency. Since PPKTP is not susceptible to photorefractive damage and thermal lensing to some extent, if a higher pump power were available, the escape efficiency could be increased by using lower output coupler reflectivity. Similarly, improvement of 85% overall detection efficiency achieved would also lead to a still higher observed squeezing level. The large squeezing levels and excellent stability of PPKTP make it an excellent material for use in squeezing-enhanced GW detectors. Although gray tracking is a known problem for KTP, we have not observed it in this demonstration, likely because we use moderate pump power and no coherent seed light.

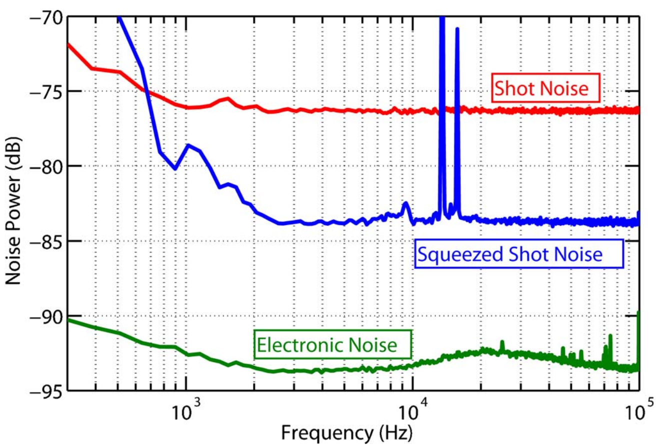

Fig. 3. (Color online) Broadband spectra of shot noise, squeezed shot noise, and electronic noise. The spectra were averaged 2000 times. The squeeze angle was noise locked without any coherent light. The spikes at 13.5 kHz and 15.7 kHz are due to the modulation of the PZT (PZT3) for the noise-locking technique.

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