Audio-Band Frequency-Dependent Squeezing for Gravitational-Wave Detectors

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Quantum vacuum fluctuations impose strict limits on precision displacement measurements, those of interferometric gravitational-wave detectors among them. Introducing squeezed states into an interferometer's readout port can improve the sensitivity of the instrument, leading to richer astrophysical observations. However, optomechanical interactions dictate that the vacuum's squeezed quadrature must rotate by 90° around 50 Hz. Here we use a 2-m-long, high-finesse optical resonator to produce frequency-dependent rotation around 1.2 kHz. This demonstration of audio-band frequency-dependent squeezing uses technology and methods that are scalable to the required rotation frequency and validates previously developed theoretical models, heralding application of the technique in future gravitational-wave detectors.

Introduction.—Quantum vacuum fluctuations permeate the entirety of space. Ordinarily benign, these jittering fields impose the strictest limit on the precision of microscopic measurements. In particular, these quantum fluctuations limit the performance of interferometric gravitational-wave detectors as they attempt to make the first observations of ripples in the very fabric of space-time [1–3].

Naturally present in all modes of the electromagnetic field, the vacuum state possesses equal uncertainty in each of its two quadratures. However, it is possible to redistribute the uncertainty, in accordance with the Heisenberg uncertainty principle, to produce a squeezed state, with reduced variance in one quadrature at the expense of increased variance in the orthogonal quadrature (see Fig. 1).

In 1981 Caves proposed the injection of squeezed vacuum, in place of coherent fluctuations, in order to reduce high-frequency shot noise in gravitational-wave interferometers [4]. Yet it is only recently, after decades of research, that squeezed light sources capable of operating in the audio band (10 Hz–10 kHz), the frequency range of interest to terrestrial gravitational-wave interferometers, have become available, with the most advanced sources currently being optical parametric oscillators (OPOs) [5–9] offering more than 10 dB of squeezing (corresponding to approximately a threefold reduction in noise amplitude).

Although squeezed light injection has been successfully demonstrated in the GEO600 and LIGO Hanford interferometers [10–13], a simple frequency-independent squeezed vacuum source is not sufficient for the present generation of detectors [14]. To realize broadband noise reduction one must rotate the vacuum's squeezed quadrature as a function of frequency in order to counter the rotation effected by the optomechanical coupling between the interferometer's 40 kg mirrors and the nearly 1 MW of circulating laser light [15]. Specifically, the squeezed quadrature must rotate by 90° around 50 Hz, equivalent to storing the entangled photons for 3 ms [16–18].

While a proof-of-principle experiment suggested the feasibility of this approach more than ten years ago [19], frequency-dependent vacuum squeezing at audio frequencies, and the additional technical noise couplings it entails, remained unexplored until now.

Here we store spectral components of a squeezed state for 128 μs in a 2-m-long, high-finesse optical resonator to produce frequency-dependent rotation at 1.2 kHz. We furthermore validate the theoretical description of the new noise sources which limit the level of detectable squeezing [18].

This first demonstration of frequency-dependent squeezing in the audio-band uses technology and methods that are scalable to the required rotation frequency, heralding application of the technique in all future gravitational-wave detectors [20].

Production of frequency-dependent squeezing.—The appropriate frequency-dependent quadrature rotation can be achieved by reflecting a standard frequency-independent squeezed vacuum state off a low-loss optical resonator known as a filter cavity [17,18,21,22]. Spectral components of the squeezed vacuum that lie within the linewidth of the cavity experience a change in their phase upon reflection; those outside the linewidth do not. By operating the filter cavity in a detuned configuration, differential phase can be imparted upon the upper and lower squeezed vacuum sidebands, leading to frequency-dependent quadrature rotation.

The frequency range over which rotation takes place is set by the filter cavity storage time τ_{storage}.

$$\tau_{\text{storage}} = \frac{1}{\gamma_{\text{fc}}}, \qquad (1)$$

where $\gamma_{\text{fc}} = \pi c/(2L_{\text{fc}}\mathcal{F})$ is the half-width-half-maximum-power linewidth (in radians per unit time) of a cavity with length L_{fc} and finesse $\mathcal{F}$, c being the speed of light.

To implement frequency-dependent squeezing in Advanced LIGO [1] a 3 ms storage time is required, comparable to the longest ever recorded [23]. As optical
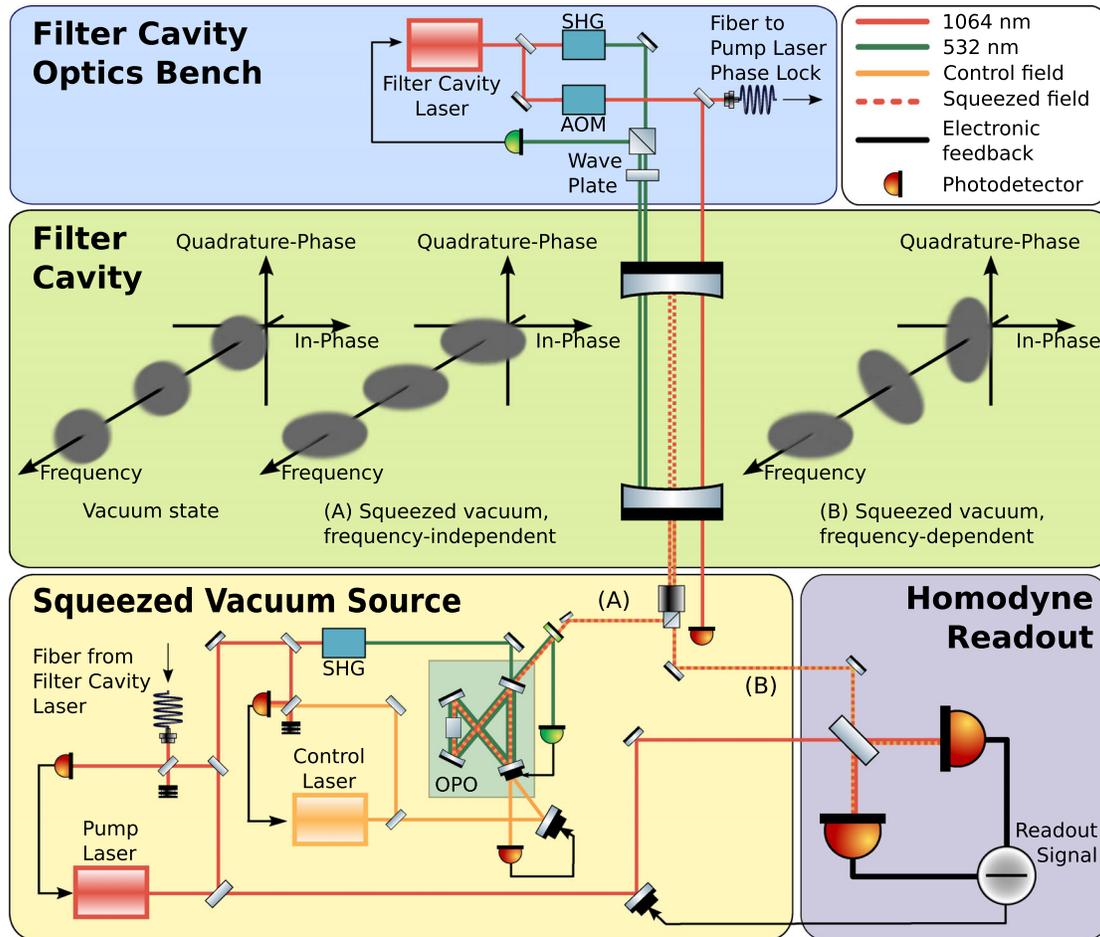
FIG. 1.   Audio-band frequency-dependent squeezed vacuum source. Frequency-independent squeezed vacuum is produced using a dually resonant subthreshold OPO operated in a traveling-wave configuration. The OPO is pumped with light provided by a second harmonic generator (SHG). The generated squeezed state is subsequently injected into a dichroic (1064/532 nm) filter cavity along path (A) where it undergoes frequency-dependent quadrature rotation. A Faraday isolator redirects the returning squeezed field along path (B) towards a homodyne readout system where frequency-dependent squeezing is measured.

losses severely limit the finesse and storage time achievable for a given cavity length [24], experimental realization of such cavities is extremely challenging, with the only prior demonstration of quadrature rotation having targeted MHz frequencies [25]. Nevertheless, filter cavities represent the best prospect for developing an audio-band frequency-dependent squeezed vacuum source in the near future, with other techniques restricted by thermal noise [26], low-frequency performance [27], or decoherence [28].

In this Letter we describe the first instance of frequency-dependent squeezing at audio frequencies, the first demonstration of the 90° rotation required for Advanced LIGO and similar detectors, and the first demonstration of quadrature rotation of a squeezed vacuum state [29]. By injecting light from a squeezed vacuum source into a filter cavity and measuring the noise spectrum of the reflected field as a function of quadrature phase, we demonstrate 90° quadrature rotation of a squeezed vacuum state at 1.2 kHz. This result establishes frequency-dependent squeezing as a

viable technique for improving the sensitivity of gravitational-wave interferometers.

Our experimental apparatus consists of a broadband squeezed vacuum source, a detuned filter cavity producing the desired frequency-dependent rotation of the squeezed quadrature, ancillary systems which set the detuning of the filter cavity, and a balanced homodyne detection system for measuring the squeezed state (see Fig. 1). Key parameters of the system are listed in Table I.

The squeezed vacuum source is built around a traveling-wave OPO cavity [5,7] resonant for both the 532 nm pump light and the 1064 nm squeezed vacuum field it generates. Our OPO outputs 11.8 ± 0.5 dB of squeezing via parametric down-conversion in a nonlinear periodically-poled KTP crystal.

After leaving the OPO, the squeezed field is reflected off a 2-m-long Fabry-Perot filter cavity, inducing rotation of the squeezed quadrature for spectral components that lie within the cavity linewidth. The filter cavity storage time is
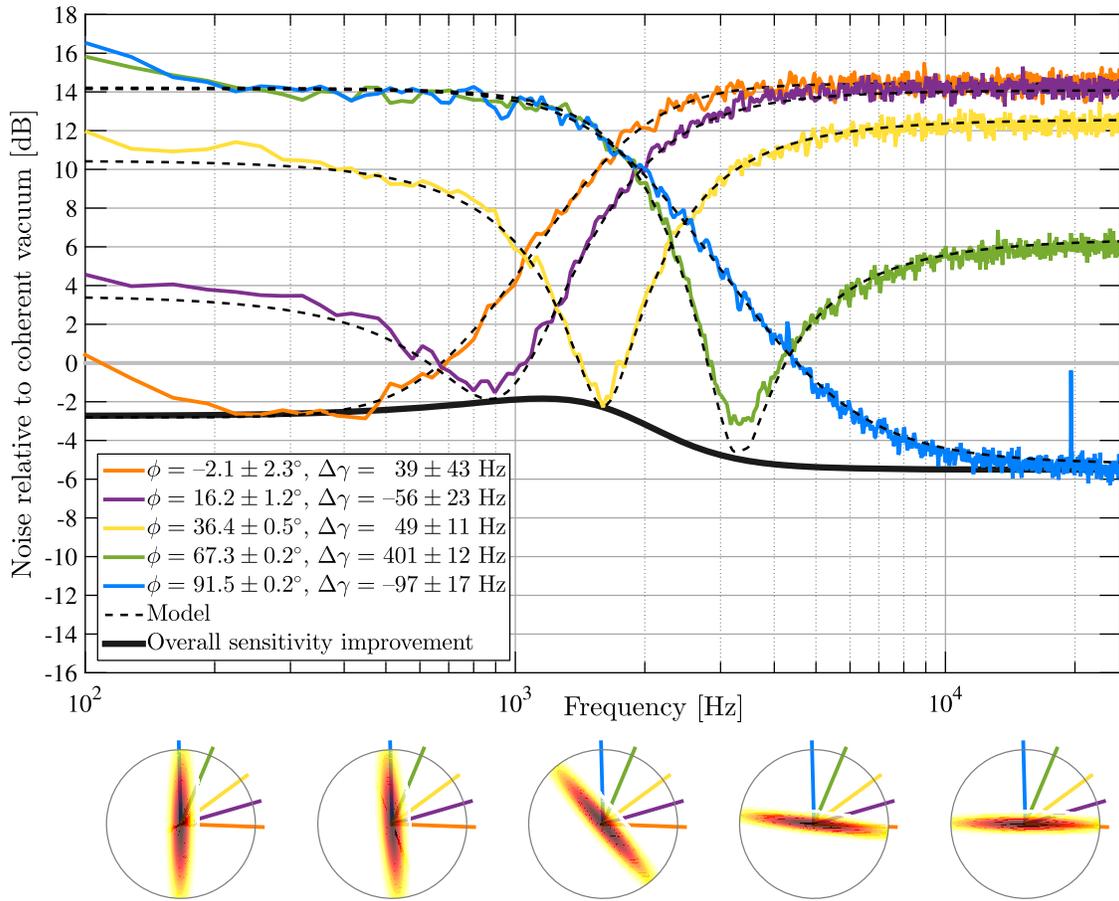
FIG. 2.   Demonstration of frequency-dependent squeezing. Measured noise relative to that due to the naturally occurring vacuum state (shot noise) as a function of sideband frequency and readout quadrature ϕ. The difference between the experimental filter cavity detuning (offset from resonance) and the desired value of 1248 Hz is denoted by $\Delta\gamma$. Dashed curves represent the output of the model described in [18] using the parameters given in the legend and Table I. The solid black curve provides an estimate of the overall improvement achievable if this frequency-dependent squeezed vacuum source were applied to the appropriate interferometer. Ellipses illustrate the modeled squeezing magnitude and angle (Wigner function) at the frequency at which they are located. The measured noise is given by the projection of the ellipse onto the appropriately colored readout vector.

128 μs and has a finesse of $\sim$30000 for 1064 nm light. The inferred cavity round-trip loss, excluding input coupler transmissivity, is $L_{rt} = 7$ ppm [24], corresponding to a decoherence time, defined by

$$\tau_{\mathrm{decoherence}} = \frac{-2L_{\mathrm{fc}}}{c\ln(1 - L_{\mathrm{rt}})}, \qquad (2)$$

of 1.8 ms. The cavity also features a low-finesse ($\sim$150) 532 nm resonance which is used to stabilize the detuning of the squeezed field relative to the filter cavity. For reasons of cost and complexity, the filter cavity was constructed using fixed mounts on a standard optical table. Suspending the filter cavity optics on isolated platforms, standard practice at gravitational-wave observatories, will offer reduced length noise and additional actuators with which to facilitate cavity control.

Finally, balanced homodyne detection [5,30] is used to measure the squeezed state after reflection from the filter cavity. The output of the homodyne detector is used to fix the quadrature of the squeezed state relative to the local oscillator field using the coherent control technique [31].

Measured quantum noise spectra are presented in Fig. 2. The data are normalized with respect to the value detected with unsqueezed vacuum fluctuations such that the reported values describe the deviation from shot noise due to the addition of squeezing.

Rotation of the squeezed quadrature occurs near 1 kHz. Squeezing levels of 5.4 ± 0.3dB and 2.6 ± 0.1dB are observed at high and low frequency, respectively. Weaker squeezing at low frequencies is due to the spectral selectivity and internal losses of the filter cavity, which result in some decoherence of the squeezed state. To achieve the desired quadrature rotation, the central frequency of the squeezed vacuum field is held close to filter cavity resonance; low-frequency squeezing sidebands thus interact with the filter cavity whereas high-frequency sidebands are reflected and incur very little loss.

TABLE I. Parameters of our frequency-dependent squeezed vacuum source. Entries marked by an asterisk were determined most accurately through fitting to recorded data. In all cases fitting produced values in keeping with independent measurements and their uncertainties.

Parameter	Value
Filter cavity length	1.938408 ± 0.000006 m
Filter cavity storage time	127.5 ± 2.5 μs
Filter cavity decoherence time	1.8 ± 0.4 ms
OPO nonlinear gain*	12.7 ± 0.4
OPO escape efficiency	$95.9 \pm 1\%$
Propagation loss*	$11.9 \pm 0.9\%$
Homodyne visibility	$96.6 \pm 1\%$
Photodiode quantum efficiency	$93 \pm 1\%$
Filter cavity round-trip loss*	7.0 ± 1.6 ppm
Frequency-independent phase noise (rms)*	31 ± 7 mrad
Filter cavity length noise (rms)*	$(7.8 \pm 0.2) \times 10^{-13}$ m
Filter cavity-squeezed vacuum mode coupling	$97 \pm 2\%$

A quantum noise model that includes realistic, frequency-dependent decoherence and degradation mechanisms was used to evaluate our results [18]. While all aspects of our system were meticulously characterized, certain parameters were most accurately quantified through fitting this model to the measured data using Markov chain Monte Carlo methods [32] (see Table I). With the exception of filter cavity detuning and readout quadrature angle, which are different for each of the five measurements reported, a single value for each system parameter was determined using all available data sets. In all cases, fitted values were consistent with direct measurements, given their uncertainties. Furthermore, the close agreement between our measured data and the quantum noise model, presented in Fig. 2, indicates that all significant sources of squeezed state decoherence and degradation are well modeled.

Control of filter cavity detuning: The output of a 500 mW, 1064 nm Nd:YAG solid state laser (filter cavity laser, Fig. 1) was split into two portions: the first was frequency doubled and used to lock the laser to the filter cavity with a bandwidth of 30 kHz; the second was double-passed through an acousto-optic modulator (AOM) and used to phase lock the pump laser to the filter cavity laser. The result of this setup is that the frequency offset of the pump laser, and therefore the squeezed vacuum, from resonance in the filter cavity was stabilized and could be controlled by varying the drive frequency of the AOM. In order to produce the desired 90° quadrature rotation, the offset was set to the filter cavity half-width-half-maximum-power frequency. A flexible control scheme of this kind is useful as variations in filter cavity loss or modest amounts of mode mismatch can be compensated for by small changes in filter cavity detuning [18].

Impact of technical noise: Optical loss, mode mismatch, and squeezed quadrature fluctuations (or phase noise) cause decoherence and a reduction in measurable squeezing [18,33]. For instance, an ideal squeezed vacuum source with our operating parameters should produce 15.6 dB of squeezing, yet, as expected when the deterioration due to the above listed effects is taken into account, the level we measured was below 6 dB.

Each source of loss leads to decoherence of the entangled photons which make up a squeezed vacuum state. Losses outside the filter cavity affect all frequencies equally and arise due to imperfect optics, nonunity photodiode quantum efficiency, and imperfect overlap between signal and local oscillator beams. The overall detection loss in our system was 29%. Detection loss can be reduced through use of improved polarization optics [34], superior photodetectors and active mode matching [35].

The treatment of filter cavity losses is more complicated due to their frequency dependence [18]. As an indication, the total loss of our cavity was approximately 16% on resonance. Advances in this area are limited surface quality of available cavity optics [24].

Mitigating the above-mentioned technical noise effects, rather than concentrating on generating stronger squeezing at the source, is currently the most profitable route toward improved performance.

Scaling for gravitational-wave detectors: While this demonstration of frequency-dependent squeezing has brought the squeezed quadrature rotation frequency 4 orders of magnitude closer to that required by gravitational-wave detectors, it is still a factor of ~20 away from the 50 Hz target of Advanced LIGO. However, detailed measurements of losses in long-storage-time cavities [24], and calculations of the impact of these losses on the performance of frequency dependent squeezing [18], indicate that a 16 m cavity, a factor of 8 longer than that employed in this demonstration, with a finesse roughly 3 times higher, will be sufficient for Advanced LIGO. Neither of these scalings are experimentally onerous or challenging in the context of Advanced LIGO. The resulting filter cavity would have a storage time of 2.5 ms and $\tau_{\text{decoherence}} \simeq 0.7$ ms, which is sufficient to maintain a modest level of squeezing below the rotation frequency [14,18].

Based on the results presented here, previous experimental work [11,13,24,36], and extensive theoretical studies [14,18,37], the authors and other members of the LIGO Laboratory have begun the process of designing and building a full-scale prototype frequency-dependent squeezed light source for Advanced LIGO.

Conclusions.—The principal goal of this endeavor was to demonstrate frequency-dependent quadrature rotation in a band relevant to gravitational-wave detectors, informing the design of all future squeezed light sources in the field. A frequency-independent squeezed vacuum source is only able to reduce noise in the band in which its (fixed)

low-noise quadrature is well-aligned to the interferometer signal field. In this case, the observed noise reduction would be approximated by a single one of the curves shown in Fig. 2. For example, squeezing the quadrature phase, as previously demonstrated in LIGO and GEO600, would reduce noise at high frequency and increase noise at low frequency, as described by the blue, $\phi = 90°$, curve. The equivalent frequency-dependent source offers equal performance at high frequency but a relative improvement of nearly a factor of 10 in strain amplitude at low frequency.

Our demonstration of quadrature rotation of squeezed vacuum at audio frequencies, with a relatively short filter cavity and well-understood noise performance, leaves a clear path toward scaling to longer storage times and higher levels of squeezing.

Extrapolating our results to the case of Advanced LIGO, we find that the reduction of quantum noise with frequency-dependent squeezing increases the volume of the detectable universe by about a factor of 2. Larger gains, up to nearly a factor of 10 in volume, are achievable when frequency dependent squeezing is combined with other improvements [20].

Beyond Advanced LIGO, all present ideas for future detectors rely on frequency-dependent squeezing [38–40]. This demonstration of audio-band frequency-dependent-squeezing establishes its applicability to future gravitational-wave detectors despite the many challenges posed by low-frequency operation.

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