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Einstein-Podolsky-Rosen quantum entanglement for future gravitational-wave detectors

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Abstract. Quantum Noise limits the sensitivity of gravitational wave interferometers across the full detection band (10 Hz – 10 kHz). Current detectors mitigate quantum noise through frequency-dependent squeezing using large, detuned filter cavities. However, such infrastructure poses challenges for future detectors like the Einstein Telescope, which require more compact and cost-effective solutions. A promising alternative uses Einstein-Podolsky-Rosen (EPR) entanglement to achieve frequency-dependent squeezing without external filter cavities. We are developing an experiment in Virgo's R&D squeezing laboratory at the European Gravitational Observatory to investigate EPR-based frequency-dependent squeezing in the audio band. The project involves researchers from INFN groups and universities in Italy and institutions in South Korea. After a brief introduction to the scientific motivation, this work describes the main components and summarizes the current status of our experiment and its potential impact on third-generation gravitational wave detectors.

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1 Scientific Background and Motivation

Gravitational waves (GWs) are distortions of space-time generated by accelerating massive objects, such as compact binary mergers—currently the only observed sources—and potentially by rotating neutron stars and supernovae. Since LIGO's first detection in 2015 [1], the LIGO-Virgo-KAGRA (LVK) Collaboration has observed over 90 events (O1–O3) and issued more than 228 public alerts during the O4[1], advancing our understanding of black hole physics, neutron stars, cosmology, and fundamental physics. Virgo [2], LIGO [3], and KAGRA [4] are large-scale Michelson interferometers with suspended mirrors and Fabry-Perot cavities, sensitive to displacements as small as 10^{-18} m in the 10 Hz–10 kHz range. In third-generation detectors like the Einstein Telescope (ET) [5] and Cosmic Explorer [6], quantum noise (QN) becomes a dominant limitation. QN manifests itself as shot noise (SN) at high frequencies and radiation pressure noise (RPN) at low frequencies, intersecting at the Standard Quantum Limit (SQL), the minimum QN achievable without quantum manipulation. To mitigate QN, current detectors use squeezed light and filter cavities (FCs). Squeezed states reduce quantum fluctuations in one quadrature of the field, and FCs rotate the squeezing angle with frequency (frequency-dependent squeezing, FDS), enabling broadband QN suppression beyond the SQL [7, 8]. ET will require multiple and long filter cavities, one 1 km FC for the high-frequency interferometer (ET-HF) and two 5 km FCs for the low-frequency one (ET-LF) [5], posing major engineering challenges in terms of system integration. A promising alternative involves EPR-entangled squeezed states [9], which may match or exceed FC performance with a much simpler infrastructure. Recent studies suggest EPR squeezing could replace at least one ET-LF cavity [10]. Our experiment aims to demonstrate EPR-based FDS at audio frequencies, bridging the gap between previous MHz-range demonstrations [11, 12] and the detection band of GW interferometers, thus supporting its potential integration into ET. Preliminary simulations' results of the EPR effect in Virgo are published in [13], and recalled in Fig. 2.

2 Experimental setup and status

This section describes the configuration of the table-top experiment developed to generate and manipulate EPR-entangled squeezed states, aimed at validating the conditional squeezing scheme at audio frequencies relevant for large-scale GW observatories. Given the limited length of this paper, we omit the detailed derivation and formalism of EPR. For a comprehensive presentation of the EPR basic principle, we refer the reader to the original proposal paper [9] and our earlier work [13, 14]. A conceptual layout of the optical setup is shown in Fig. 1.

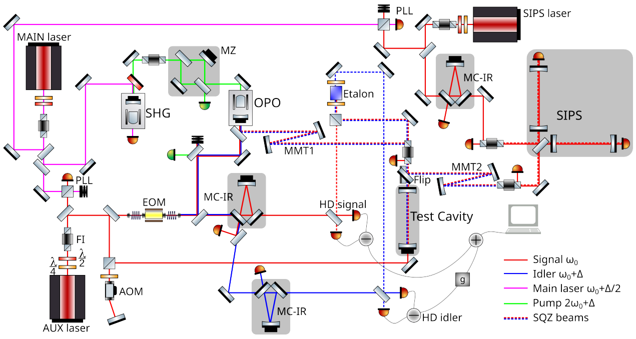

Figure 1: Simplified optical scheme of the EPR experiment, from [14]. A flip mirror allows either the injection of EPR squeezed beams into the Test Cavity, or into the suspended interferometer SIPS.

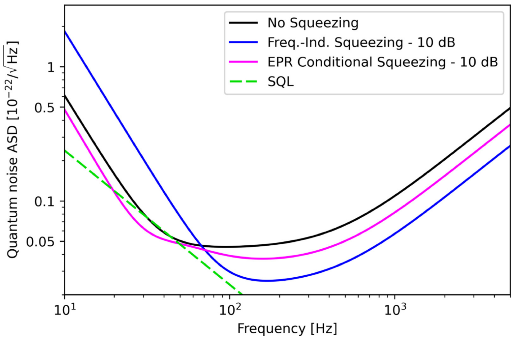

Figure 2: Simulated QN curves, from [13], for the Virgo case. With optical losses of 150 ppm for the arm, 300 ppm for the central BS, and 10% in injection and detection, EPR would already be beneficial.

The experiment builds upon a previous setup used to demonstrate frequency-independent squeezing [15], and extends it to enable EPR-based frequency-dependent squeezing. It employs two solid-state Nd:YAG lasers, operating at 1064 nm, the same wavelength used in room-temperature GW interferometers, referred to as the main and auxiliary lasers.

2.1 Laser sources

The auxiliary laser provides multiple beams throughout the system, serving critical roles in cavity locking, stabilization of squeezing level and angle, and as reference beams for frequency and phase control. The

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[1] `https://gracedb.ligo.org/superevents/public/O4/` at the date 31/08/2025

main laser, frequency-shifted by $\Delta/2$, is frequency-doubled via second-harmonic generation to $2\omega_0 + \Delta$ and used to pump parametric down-conversion (PDC) in a nonlinear crystal, producing EPR-entangled squeezed beams. The required frequency detuning Δ is established and maintained via an optical phase-locking loop (PLL) between the two lasers.

2.2 Optical Parametric Oscillator

At the heart of the system is the Optical Parametric Oscillator (OPO), a resonant cavity containing the nonlinear crystal where PDC occurs. Pumped at $2\omega_0+\Delta$, the OPO emits signal and idler fields at ω_0 and $\omega_0+\Delta$, respectively, with Δ chosen to match the OPO free spectral range (FSR = 3.8 GHz), thus ensuring resonance and minimal optical loss for both beams. In the sideband picture, this results in entanglement between the upper sideband of the signal and the lower sideband of the idler, and vice versa. A bright alignment beam, used for alignment purposes, shares the same polarization as the squeezed beam and also resonates in the cavity to reproduce the squeezed vacuum optical path and transversal geometry. Both the locking beam and the bright alignment beam have an optical mode-matching $> 95\,\%$ and allow steady lock and operation of the OPO with $\sim 100\,\%$ duty cycle.

2.3 Test Cavity

The EPR-entangled squeezed beams are first injected into a linear test cavity (TC) with FSR = 380 MHz and linewidth $\gamma = 2.05$ MHz, to realize the squeezing angle rotation for the idler. Fine control of the detuning Δ enables fulfillment of the tuning condition (Eq. 4 in [14]), by keeping the idler detuned and the signal resonant. The cavity length is actively stabilized using the Pound-Drever-Hall locking technique, implemented via radio frequency modulation and an orthogonally polarized locking beam.

2.4 Suspended Interferometer SIPS

The ultimate goal of the experiment is to inject the EPR-squeezed beams into the dark port of a suspended table-top interferometer named SIPS (Suspended Interferometer for Ponderomotive Squeezing) [16, 17]. SIPS is a Michelson-Fabry-Perot interferometer with two-stage monolithic suspensions made of fused silica, designed to operate in a regime where quantum RPN becomes the dominant contribution in the audio band. The system is expected to exhibit sensitivity to RPN from a few tens of Hz to a few kHz. Several design features enhance SIPS performance, including ultra-low mechanical losses through fused silica suspensions (inspired by Virgo's design), optimized mirror mass and coatings, and operation in a high-vacuum environment down to 10^{-9} mbar to prevent effects from residual gas fluctuations [16]. While the interferometer is not recycled, its configuration inherently suppresses common-mode noise due to laser fluctuations. To compensate for the relatively short arm length ($L = 350$ mm), the optical cavities are designed with a very high finesse of $\mathcal{F} = 23000$, ensuring sufficient optical storage time. However, this requires a robust and sophisticated control system for locking. Current work focuses on developing the local control of each suspended optic, as well as the longitudinal control of arm cavities [17].

2.5 Mode Matching Telescopes

Given the strong impact of optical losses on squeezed states, efficient mode matching between the OPO and the downstream systems is crucial. To this end, a reflective mode-matching telescope (MMT) has been developed and tested, achieving sub-percent optical losses due to minimal mismatch or misalignment. The system uses semi-kinematic mounts for ease of alignment. An advanced version using adaptive optics is under design to dynamically compensate for mode distortions during interferometer locking.

2.6 Mode Cleaners

Three triangular mode cleaner (MC) cavities are required in our setup, as in the scheme of Fig. 1: two for each local oscillator (LO) of idler and signal beams, one for the suspended interferometer SIPS [18]. All MC cavities have been assembled and characterized. Their optical parameters (finesse, FSR, FWHM) and high-order mode suppression (>20dB) are as expected by design.

2.7 Etalon

A monolithic linear cavity is introduced to separate the idler and signal EPR squeezed beams, once they are transmitted by the test cavity or by SIPS, before the squeezing measurements at the balanced homodyne detectors [19].

2.8 Balanced Homodyne Detectors

The measurement of the squeezing level is performed via balanced homodyne detection. Each squeezed beam is combined with a local oscillator beam and directed onto a pair of photodiodes; the difference signal reflects the quantum noise level relative to the LO shot noise. To ensure high purity and phase stability, the LOs are cleaned using the two triangular mode cleaner cavities (see Sect. 2.6), and the temperature-stabilized etalon (Sect. 2.7) with FSR $= 2\Delta$ is employed to spatially separate the signal and idler fields for twin homodyne detection [19]. The homodyne detector electronic board employs the self-subtracting scheme to directly provide the difference photocurrent with reduced electronic noise. It features audio and radio filters, with bandwidths of (0.01 - 100) kHz and (0.4 - 28) MHz, respectively. It has been tested to have a common-mode rejection ratio (CMRR) of 60 dB, and a clearance with respect to the LO shot noise of up to 17 dB at an incident optical power of 2.5 mW per photodiode.

2.9 Digital Acquisition and Control

All experimental operations are managed by a digital acquisition and control (DAQ) system built on DSP boards with configurable ADC/DAC channels. A finite-state machine framework governs the system, enabling real-time monitoring, automatic recovery from unlocks, and high duty cycle operation. As demonstrated in [15], this approach enables >80% duty cycle in unattended mode. The control software is currently being expanded to support the additional optical components specific to the EPR setup.

3 Conclusions

In this paper, we present a table-top experiment designed to test EPR conditional squeezing as a method for QN reduction in next-generation GW detectors. The main goal is to demonstrate this scheme at audio frequencies, relevant for large-scale GW observatories, where it has not yet been experimentally validated. As described in Sect. 2, the nonlinear cavities have been assembled and aligned, achieving a >90 % mode matching. The green beam is generated by the Second Harmonic Generator (SHG) cavity, currently under optimization. The MC cavities have been assembled and characterized; their optical parameters (finesse, FSR, FWHM) and higher-order mode suppression match design expectations. The MMT has also been aligned and its output beam characterized; a paper on its design is in preparation. The final testbed is SIPS, a suspended interferometer with high-finesse FP cavities, engineered to have thermal noise below the radiation pressure noise. While EPR-based squeezing has been shown at MHz frequencies, it remains unobserved in the audio band in a suspended cavity [11, 12]. Validating this technique at the R&D level would represent a key step toward its implementation in third-generation detectors, potentially enhancing sensitivity to faint astrophysical signals and advancing both fundamental physics and cosmology.

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