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Einstein–Podolsky–Rosen squeezing experiment for future gravitational-wave detectors

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ABSTRACT

Next-generation Earth-based gravitational-wave (GW) detectors, such as the Einstein Telescope and Cosmic Explorer, will be at least an order of magnitude larger and more sensitive than current ones. Their quantum noise reduction systems, using linear filter cavities, will also scale up. To reduce system size and complexity, the EPR conditional squeezing scheme has been proposed as a cost-effective alternative to km-long filter cavities, while also aiming at lower optical losses. This experiment is designed to validate EPR conditional squeezing in a suspended small-scale interferometer limited by quantum radiation pressure noise, in the frequency band relevant to large-scale GW observatories, ranging from a few tens of Hz to a few kHz. It incorporates advanced methods such as reflective mode-matching telescopes and an automated data acquisition system.

1. Introduction

Gravitational waves (GWs) are ripples in the fabric of space–time, generated by the acceleration of massive objects in astrophysical events such as compact binary coalescences, which represent the only class of sources observed so far, but also spinning neutron stars and supernovae. After the first direct detection of GWs by the Laser Interferometer Gravitational-Wave Observatory (LIGO) in 2015 [1], the LIGO-Virgo-KAGRA (LVK) Collaboration has contributed to opening the new era of multimessenger astronomy, with the observation of 90 GW events in the past observing runs, and the release of more than 200 low-latency public alerts during the ongoing run O4 [2]. This wealth of data will help in shedding light on stellar and intermediate-mass binary black hole mergers, neutron star physics, and cosmological tensions.

Ground-based detectors, such as LIGO [3], Virgo [4], and KAGRA [5], consist of Michelson interferometers with suspended mirrors acting as test masses, enhanced by kilometer-scale Fabry–Perot arms. GWs passing through the interferometer slightly displace the test masses, leading to a phase shift in the laser light recombined at the beam splitter. As the typical strain of a GW signal is $h \sim \Delta L/L \lesssim 10^{-21}$ in the audio frequency band (10 Hz–10 kHz), the displacement sensitivity of these instruments is on the order of $\Delta L \lesssim 10^{-18}$ m.

Quantum noise (QN) poses a significant challenge for present and future detectors, such as the Einstein Telescope (ET) [6] and Cosmic Explorer (CE) [7]. It arises from the intrinsic counting error of photons at the detection photodetector, i.e. shot noise, already dominating the noise budget of present GW detectors at high frequencies, and from radiation pressure fluctuations that couple with the displacement of the test masses in low frequency bands. These two effects equal each other at the Standard Quantum Limit (SQL), that represents the ultimate level of noise achievable with no manipulation of the quantum states of light. Due to the foreseen advancements in the suppression of other noise sources, QN is expected to be a limiting factor in all frequency bands for next-generation detectors.

In order to mitigate QN, the LIGO detectors have been employing squeezed light injection together with a 300 m filter cavity [9], and the

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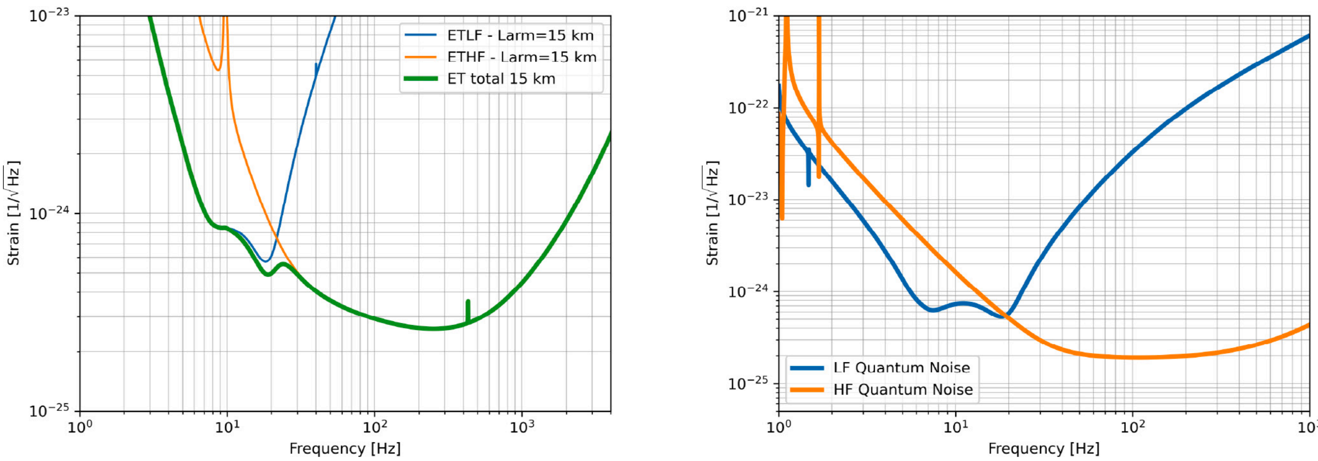

Fig. 1. Overall sensitivity budget (left) and quantum noise curves (right) for ET-HF and ET-LF, in the 2L configuration. Generated with [8].

Virgo experiment has commissioned an analogous setup [10]. Quantum squeezed states of light exhibit reduced variance in one of the two components of the field, i.e. its quadratures. The suppression factor is quantified by the squeezing parameter r.

The filter cavities implement frequency-dependent squeezing (FDS) to measure the GW signal on the best field quadrature at any frequency, and this leads to a broadband QN reduction, even overcoming the SQL. The currently proposed lengths of the ET filter cavities are $L_f = 1$ km for the high-frequency detector (ET-HF) and $L_f = 5$ km for the low-frequency detector (ET-LF), to cope with the unprecedented sensitivity target shown in Fig. 1. Furthermore, ET-LF needs a couple of filter cavities [6]. Their large underground infrastructure substantially complicates the engineering challenge for the construction of ET, and the excavation of extra tunnels would raise its economic impact and realization time. Like the rest of the interferometer, the filter cavities also require ultra-stable environments with enhanced seismic isolation and vacuum systems, and precise control of cavity alignment and length.

Therefore, we report here the status of the implementation of an optical tabletop demonstrator of a proposed alternative way to achieve FDS [11] that could avoid the presence of the filter cavities and, at the same time, ensure similar or better performances. It relies on the generation of Einstein–Podolsky–Rosen (EPR) entangled pairs of squeezed beams. In the case of the double filter cavity proposed for ET-LF, a recent work [12] shows that the EPR approach can avoid requiring at least one of them. This experiment aims at filling the existing gap between the experimental demonstrations already done at radio frequencies [13,14] and the need for providing a proof in the audio frequencies for GW detection, to build a robust scientific case for real implementation in the ET detector.

In Section 2 we review the working principles of both the filter cavity and the EPR schemes. In Section 3 we describe the setup and the status of our experiment.

2. Frequency-dependent squeezing from filter cavities to conditional EPR scheme

The power spectral density of QN, referred as equivalent GW strain signal, can be computed in the two-photon formalism [15] with a transfer matrix approach. The quantum operator of the vacuum input field to the dark port of the interferometer can be indicated with the vector $\hat{\mathbf{a}}^T = [\hat{a}_c, \hat{a}_s]$ whose entries are the two-photon cosine and sine quadratures, respectively.

The simplest scenario implies a lossless setup with a tuned interferometer. Naming $\hat{\mathbf{a}}$ the vacuum input field to the dark port of the interferometer, the output field $\hat{\mathbf{A}}$ is:

$$\hat{\mathbf{A}}(\Omega) = \begin{pmatrix} 1 & 0 \\ -\mathcal{K}(\Omega) & 1 \end{pmatrix} \hat{\mathbf{a}} \tag{1}$$

where Ω represents the sideband frequency, corresponding to the GW signal frequency, and

$$\mathcal{K}(\Omega) = \frac{2J\gamma}{\Omega^2\,(\gamma^2 + \Omega^2)}$$

is the optomechanical coupling between input cosine quadrature $\hat{a}_c$ that correlates to the output sine quadrature $\hat{A}_s$, containing also the GW signal. J is a quantity that scales linearly with the optical power in the Fabry–Perot arms, and $\gamma = cT/4L$ stands for the frequency bandwidth of the interferometer, seen as a single optical cavity with input arm mirror power transmittivity equal to T.

The resulting single-sided power spectral density reads as:

$$S(\Omega) = \frac{4\hbar}{mL^2\Omega^2}\left(\mathcal{K}(\Omega) + \frac{1}{\mathcal{K}(\Omega)}\right). \tag{2}$$

The optomechanical coupling manifests as radiation pressure noise in the first term, visible in frequencies below the SQL (see right panel of Fig. 1). Since squeezing is indeed a correlation between quadratures, the interferometer squeezes the input vacuum field at low frequencies. The second term stands for detection shot noise. SQL is met when $\mathcal{K}(\Omega_{SQL}) = 1$.

Squeezing can be accounted for with a dedicated matrix that collects the auto- and cross-correlation spectra between quadratures, $\mathbb{S}[r,\theta]$ (see e.g. Eq. 75 of [16]), where θ is the squeezing angle. In particular, $\theta = 0$ corresponds to the output of an optical parametric oscillator (OPO), and reduces shot noise while increasing radiation pressure noise.

Filter cavities modify θ in specific frequency bands, by acting asymmetrically on the sidebands of the input squeezed beam. This alteration is governed by pivotal parameters of the cavity, i.e. its bandwidth γ_f, and the detuning δ_f of the circulating light relative to the resonance frequency of the cavity. Passing the input vacuum field $\hat{\mathbf{a}}$ first into an OPO squeezer, and then to an ideal filter cavity, it is converted to:

$$\hat{\mathbf{a}} \longrightarrow \mathbb{P}[\theta_f(\Omega)]\,\mathbb{S}[r,0]\hat{\mathbf{a}}$$

where $\mathbb{P}[\theta_f(\Omega)]$ is a 2D rotation matrix by a freq.-dependent angle $\theta_f(\Omega)$. As extensively shown in e.g. [16], the frequency-dependent rotation of the squeezing ellipse, considering a loss factor ϵ, is described by:

$$\theta_f(\Omega) \simeq \arctan\frac{(2-\epsilon)\gamma_f\,\delta_f}{(1-\epsilon)\gamma_f^2 - \delta_f^2 + \Omega^2}. \tag{3}$$

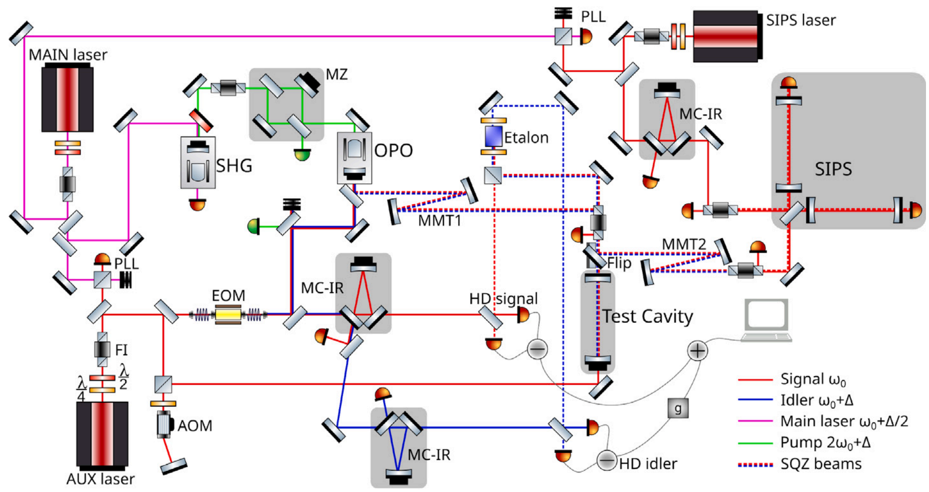

Fig. 2. Conceptual scheme of the EPR experiment.

In essence, the goal of the filter cavity consists in achieving an optimal rotation around the SQL frequency Ω_{SQL}, compensating the coupling effect of the interferometer for $\Omega \lesssim \Omega_{SQL}$. Under lossless conditions, the optimal tuning parameters are:

$$\gamma_f = \delta_f = \frac{\Omega_{SQL}}{\sqrt{2}} \qquad \text{with} \qquad \gamma_f = \frac{c}{4L_f\mathcal{F}}\,. \tag{4}$$

For detectors like LIGO and Virgo, having $\Omega_{SQL} \approx 2\pi \times 60$ Hz, these conditions put stringent requirements. The performance of a filter cavity scales as $\sim L_f/A_f$, where L_f is the cavity length and A_f are the round-trip losses. Hence, the filter cavity must be long to provide the necessary bandwidth, and exhibit minimal optical losses. Furthermore, the entire system must be isolated from environmental noise sources with suspensions, to be sensitive to quantum noise starting from a few Hz.

The EPR conditional squeezing strategy offers an innovative alternative by leveraging the GW interferometer itself as a high-quality optical resonator [11]. As Eq. (3) implies, a detuning is required to impress a frequency-dependent rotation to the squeezing ellipse. This approach eliminates the need for an external FC by introducing a pair of EPR-entangled squeezed beams: *signal* at ω_0 and *idler* at a detuned frequency $\omega_0 + \Delta$. The interferometer, tuned to ω_0 in the conventional scheme, only rotates the squeezing ellipse of the idler beam. By applying a freq.-dependent gain g_{opt} to the squeezing level of the idler, the power spectral density of the operator $\hat{a}^g_{-\phi} = \hat{a}_{-\phi} - g_{opt}\hat{b}_\phi$ is minimized, with $\hat{a}_{-\phi}$ and $\hat{b}_\phi$ being specific quadratures of the signal and idler fields. This process allows the detection of one quadrature of the idler field to reveal the opposite squeezed quadrature of the signal field, enabling FDS at ω_0. The resulting QN spectrum features a broadband suppression with respect to Eq. (2):

$$S(\Omega) = \frac{4\hbar}{mL^2\Omega^2\cosh(2r)}\left(\mathcal{K}(\Omega) + \frac{1}{\mathcal{K}(\Omega)}\right). \tag{5}$$

A possible shortcoming of the EPR conditional squeezing strategy is that the lossless suppression factor $1/\cosh 2r$ is lower than the one provided by the filter cavity scheme, i.e. $\exp(-2r)$. It is worth stressing that these values only hold under lossless conditions, and that the effect of optical losses is higher with an external filter cavity.

3. Experimental setup

This section details the configuration of the tabletop experiment designed for the creation and manipulation of EPR entangled states. A conceptual optical scheme is shown in Fig. 2. The setup is an extension of a previous version to test frequency-independent squeezing [17]. It includes two laser sources, called main and auxiliary laser. They are both solid-state Nd:YAG lasers operating at a wavelength of $\lambda_0 = 1064$ nm, as for room-temperature GW detectors.

The auxiliary laser generates several beams across the setup, needed to lock the optical cavities, control the stability of the squeezing level and the squeezing angle, and set reference beams for frequency locking and squeezing detection.

The main laser, detuned by $\Delta/2$, undergoes second-harmonic generation at $2\omega_0 + \Delta$ and pumps spontaneous parametric down-conversion to generate EPR-entangled beams. This detuning is controlled with a dedicated optical phase-locking loop (OPLL) with the auxiliary laser.

As already mentioned in Section 2, the essential component is the Optical Parametric Oscillator (OPO), an optical cavity that hosts a non-linear crystal where spontaneous parametric down-conversion of light occurs. Being pumped at a frequency of $2\omega_0 + \Delta$, the signal-idler separation Δ is inherited by the vacuum squeezed output photons, at frequencies ω_0 and $\omega_0 + \Delta$. In this experiment, Δ corresponds to the free spectral range (FSR) of the OPO, 3.8 GHz. This allows perfect resonance of both signal and idler beams, ensuring the lowest optical losses. The entanglement between signal and idler can be described in the sideband picture, where the upper sideband of the signal is entangled with the lower sideband of the idler, and vice-versa.

As a first validating step, we inject the EPR-entangled beams into a linear test cavity having FSR = 380 MHz and $\gamma = 2.05$ MHz. Fine tuning of Δ allows to fulfill the condition in Eq. (4) for the idler, keeping the signal in resonance. The final scientific goal consists in the injection of the EPR pair of squeezed beams into the dark port of a small-scale interferometer called SIPS [18,19]. SIPS (Suspended Interferometer for Ponderomotive Squeezing) is a tabletop Michelson-Fabry–Perot interferometer with two-stage suspended optics, designed to operate in the regime where radiation pressure noise is the limiting factor, within the audio frequency band of large-baseline GW detectors. We expect to be sensitive to quantum radiation pressure noise from several tens of Hz.

Innovative features of SIPS include the use of monolithic suspensions for its optical components of fused silica, following the same principle as the Virgo detector. They are crucial to minimize thermal noise, together with the selection of mirror masses, suspension parameters, and coatings, in order to make radiation pressure noise the dominant contribution. Moreover, SIPS will operate in high vacuum with a residual pressure down to 10^{-9} mbar, to guarantee almost perfect beam propagation and avoid measurement noise due to air fluctuations. Although SIPS is not recycled to avoid further increasing the complexity of the system, the interferometric configuration allows for the cancellation of common-mode noises.

Given that $\gamma \propto 1/L\mathcal{F}$, we compensate for the relative shortness of the arm cavities ($L = 350$ mm) by increasing the finesse up to

$\mathcal{F} = 23000$. This very high value of finesse constitutes a significant challenge for developing a global control system strategy for locking SIPS. At the moment of writing, studies are ongoing to implement the local control system of each suspended optics and to set up a strategy for the longitudinal global control of the Fabry–Perot arms.

Since squeezing heavily suffers from optical losses, matching elements between the OPO and the testbed for EPR, whether it is the linear test cavity or SIPS, are fundamental not to degrade the generated squeezing level. In this context, a mode-matching reflective telescope has been developed and successfully tested, delivering an almost perfect output beam with sub-percent losses due to residual optical mismatch and misalignment. The mode-matching telescope features semi-kinematic mounts to ease alignment and operation.

The balanced homodyne detection scheme is used to measure the squeezing level. A reference local oscillator (LO) is combined with the squeezed beam and sent towards two photodiodes. The differential photocurrent is proportional to the squeezing level with respect to the shot noise level of the LO. The relative phase shift between the input fields corresponds to the detected field quadrature $\hat{a}_{\phi}$. Two triangular mode cleaner cavities are used to prepare a clean and stable LO for both signal and idler. Twin homodyne detectors are needed to measure the signal and idler fields. The beams are spatially separated with a monolithic temperature-controlled etalon with $\mathrm{FSR} = 2\Delta$ [20].

The whole experimental apparatus is controlled with a robust DAQ system based on DSP boards equipped with ADC/DAC channels and configured digitally. Finite-state machine controls are implemented at the DSP level, allowing real-time status monitoring, corrective action, and automatic recovery from unlocks for all the apparatus. As stated in [17] for the previous setup, this control software easily reaches an overall duty cycle of above 80% in unsupervised mode. Extension and upgrade of the system are ongoing to accommodate the additional optical elements of the EPR setup with respect to the old version.

4. Conclusions

In this paper, we present a tabletop experiment to probe the EPR conditional squeezing scheme for quantum noise reduction in next-generation Gravitational waves (GW) detectors. The main scientific goal of the experiment is to validate EPR conditional squeezing technique at audio frequencies for GW observatories.

The final test bench for the EPR scheme is SIPS, a suspended high-finesse interferometer that mimics a GW detector. Dedicated studies have been carried out to reduce its thermal noise below radiation pressure noise, making it sensitive to quantum noise reduction brought by quantum entanglement [18]. Despite other experimental demonstrations in the MHz band, the EPR effect has never been observed in the audio frequency band and in a suspended optical cavity.

A validation of the EPR conditional squeezing at the R&D stage would be highly beneficial for next-generation GW experiments. Addressing this challenge is crucial for realizing their full potential, enabling the observation of fainter and more distant sources, and pushing the boundaries of astrophysical, cosmological, and fundamental physics discoveries.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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