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Broadband Quantum Noise Reduction In A Small-Scale Suspended Interferometer With Quantum Entangled Squeezed Beams

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Abstract
General relativity predicts the existence of gravitational waves (GWs), ripples in spacetime that are now observable to highly sensitive interferometers. However, quantum noise poses a significant challenge for gravitational wave (GW) interferometers, influencing the entire bandwidth range (10-10,000 Hz) of the current GW detectors. At higher frequencies, shot noise (SN) predominates, while at lower frequencies, radiation-pressure noise (RPN) becomes the limiting factor, reducing both sensitivity and measurement precision. Squeezing techniques are implemented to address this issue by confining uncertainty within one quadrature of the light field. Starting from the observing run, O4 Virgo and LIGO have enhanced this method through frequency-dependent squeezing (FDS). By employing a 300-meter-long detuned filter cavity, the squeezing ellipse is rotated, allowing phase squeezing at high frequencies to reduce and amplitude squeezing at low frequencies to mitigate RPN, ultimately refining detection capabilities across the frequency spectrum. A promising alternative technique to reduce quantum noise across the entire sensitivity band uses Einstein-Podolsky-Rosen (EPR) quantum entanglement. This approach involves injecting two entangled squeezed beams at different frequencies into the dark port of the interferometer, enabling it to act as both a filter cavity and a gravitational wave detector. The Suspended Interferometer for Ponderomotive Squeezing (SIPS) adopts a large-scale GW detector layout, with a Michelson configuration and Fabry-Perot arm cavities. This system was initially thought to generate FDS in the GW frequency band using the ponderomotive technique. To enhance stability, a precise local control system was developed for the main optics of SIPS, which are suspended in a double pendulum configuration with monolithic fibers to reduce thermal noise. Advanced PXI-based data acquisition and position-sensitive detectors (PSDs) monitor angular and linear displacements, while real-time signal processing in LabVIEW enables corrective actuation, marking a significant step toward improved alignment and noise reduction in GW interferometry. The paper highlights the current status of SIPS, focusing on the local control strategy, underscoring its potential impact on the field.
Keywords: *Gravitational Waves, Quantum Optics, Squeezing, Interferometer*

1. INTRODUCTION

Gravitational Waves (GWs), first predicted by Albert Einstein in 1916 as a consequence of his General Theory of Relativity, are ripples in the fabric of spacetime caused by some of the most energetic and cataclysmic events in the universe. The first direct detection of GWs by the LIGO (Laser Interferometer Gravitational Wave Observatory) - Virgo Collaborations in 2015 marked a pivotal moment in modern physics, opening an entirely new observational window into the cosmos [1]. These waves, generated by events such as black hole mergers and neutron star collisions, carry unique information about their sources and the nature of gravity, inaccessible through electromagnetic observations alone. Since this groundbreaking detection, GW astronomy has rapidly evolved, thanks to further upgrades implemented in the second generation of GW detectors, like Advanced LIGO [2] and Advanced Virgo [3], which increased their sensitivity and observation time. However, these detectors are fundamentally limited by various sources of noise, particularly the quantum noise, which dominates at both low and high frequencies. At high frequencies, the shot noise arising from the quantum uncertainty in photon arrival times predominates. At low frequencies, the radiation pressure noise, caused by quantum fluctuations in photon momentum, perturbs the motion of the interferometer's suspended mirrors. These quantum noise components set an intrinsic limit to the mirror's position measurement, the so-called Standard Quantum Limit (SQL), posing a fundamental challenge to enhance detector sensitivity.

In response to the demand for even greater sensitivity, the European scientific community has proposed the Einstein Telescope (ET), a future third-generation underground GW observatory. The ET is designed to be ten times more sensitive than current detectors, covering a broader frequency range (from 1 Hz to 10 kHz) with unprecedented precision [4]. This improvement would enable the detection of a significantly larger number of sources, including those at cosmological distances and earlier epochs of the Universe. However, achieving such sensitivity requires innovative noise reduction strategies, particularly to overcome the quantum noise that dominates in the most scientifically informative frequency bands.

The technique widely applied for quantum noise suppression uses squeezed light, wherein the quantum uncertainty is redistributed between the phase and amplitude quadratures of the light field. When applied appropriately, this can reduce one component of the quantum noise at the expense of the other, the so-called Frequency-Independent Squeezing (FIS). However, for GW detectors operating across a wide frequency range, a FIS is insufficient, instead, Frequency-Dependent Squeezing (FDS) becomes essential. FDS rotates the squeezing ellipse as a function of frequency, enabling phase squeezing at high frequencies (to suppress shot noise) and amplitude squeezing at low frequencies (to mitigate radiation pressure noise). The current implementation of FDS involves injecting squeezed vacuum states through a detuned filter cavity approximately 300 m in length [5].

Fig. 1 illustrates the optical design of ET, considering that each interferometer will be composed of a component operating at low frequencies (ET-LF) and one at high frequencies, and incorporating a quantum noise reduction system based on the integration of filter cavities, following the FDS technique employed in current-generation interferometers [6]. The schematization of fig. 1 is valid for both the triangle and L-shaped optical layouts of ET proposed and under study. As shown, ET-HF and ET-LF use laser sources of different wavelengths, 1064 nm and 1550 nm, respectively coupled with squeezed light injections to reduce quantum noise across a broad frequency range. For low-frequency sensitivity, from a few Hz up to approximately 30 Hz, cryogenic silicon optics and two filter cavities will be employed, whereas the high-frequency configuration incorporates a single filter cavity and fused silica optics. The system is designed to operate in three distinct modes: a low-frequency configuration using cryogenic silicon optics, a mid-frequency setup combining both laser wavelengths, and a high-frequency regime that emphasizes squeezed light injection. This versatile design enhances GW detection sensitivity across the full observational bandwidth by leveraging advanced quantum optical techniques and thermally optimized materials like fused silica (at room temperature), and cryogenic materials such as silicon or sapphire, although each introduces significant practical and engineering challenges.

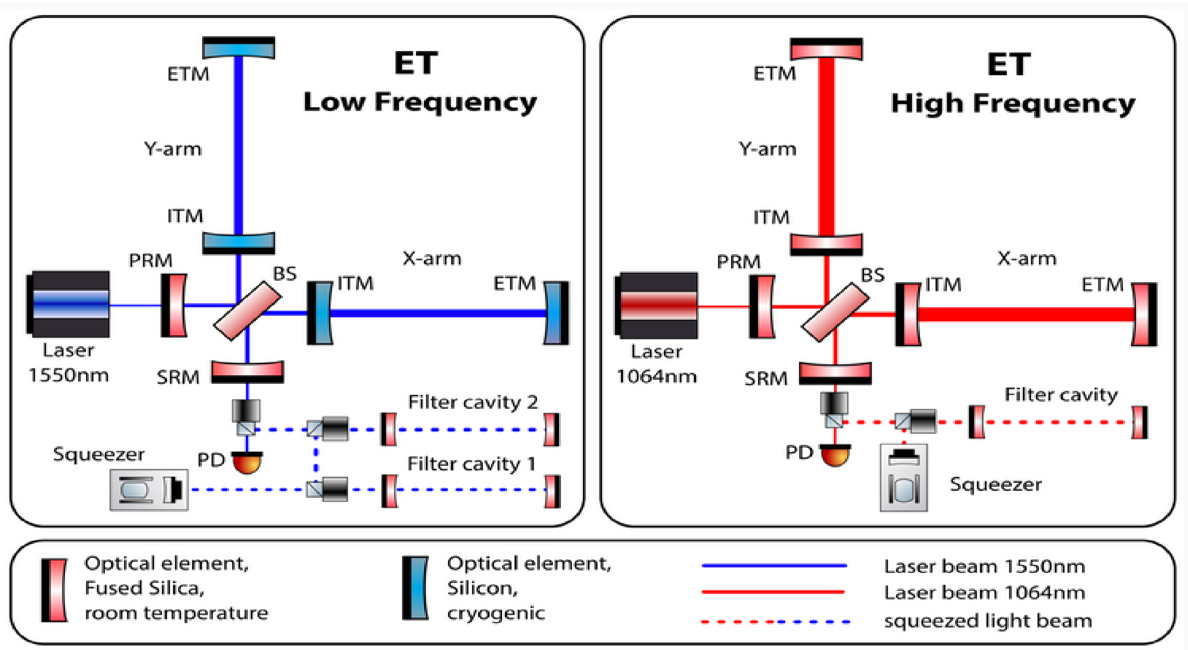

Fig.1 Schematic of Dual-Wavelength Interferometer with Squeezed Light Injection and Filter Cavities [6].

To overcome these limitations, an alternative approach to quantum noise reduction is proposed, based on Einstein-Podolsky-Rosen (EPR) quantum entanglement [7]. This method utilizes two entangled beams, known as the signal and idler, generated via a nonlinear optical process such as the parametric down-conversion in a non-degenerate Optical Parametric Oscillator (OPO). These beams exhibit strong quantum correlations, allowing for a novel implementation of FDS without requiring long filter cavities. As shown in Fig. 2, both the signal and idler beams are injected into the dark port of the interferometer. The interferometer itself acts as a filter cavity, rotating the squeezing angle across the detection band. The entanglement between the signal and idler beams is exploited after their parallel detection, allowing frequency-dependent squeezing without requiring long filter cavities. First, it removes the need for large-scale, detuned filter cavities, simplifying the optical layout and reducing optical losses. Second, it provides a more integrated and potentially more stable configuration, as the interferometer can simultaneously function as a gravitational wave detector and a quantum filter. Third, it opens the door to new theoretical and experimental advancements in quantum optics and quantum information theory, further enriching the toolkit available for GW detection.

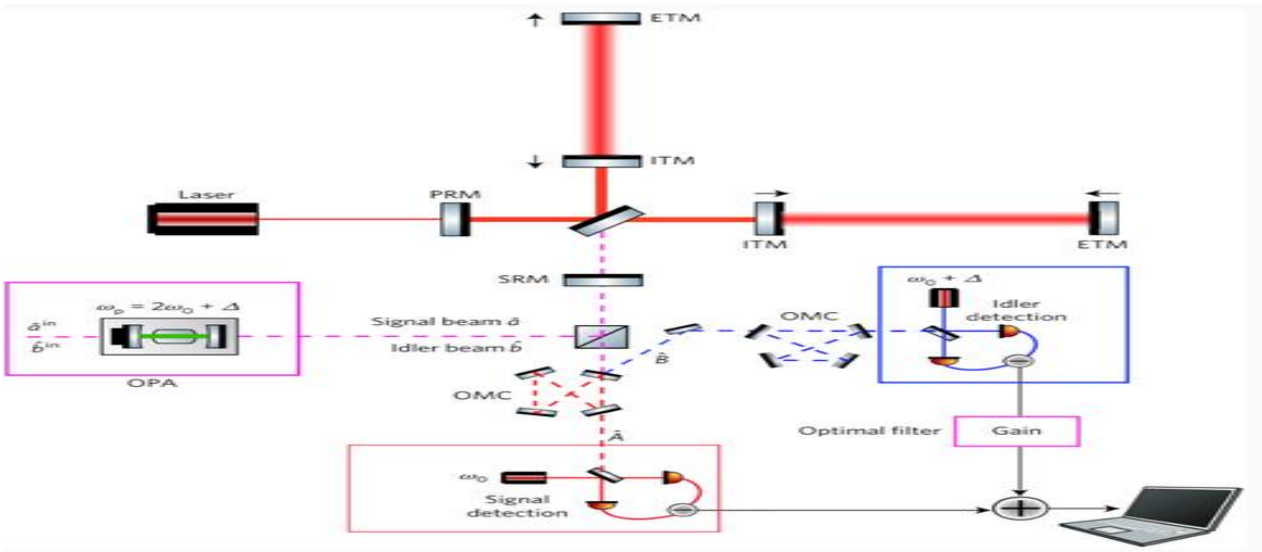

Fig.2 Optical configuration of FDS via EPR entangled beams proposed by Ma et al [7].

2. EPR-SIPS experiment

The Suspended Interferometer for Ponderomotive Squeezing (SIPS) represents a promising experimental platform for implementing quantum noise reduction techniques in the GW frequency band, employing a tabletop interferometer that replicates the optical layout of large-scale GW detectors [8]. Integrating EPR entanglement into the SIPS configuration represents a crucial step toward achieving broadband frequency-dependent squeezing, a key requirement for next-generation detectors such as the Einstein Telescope.

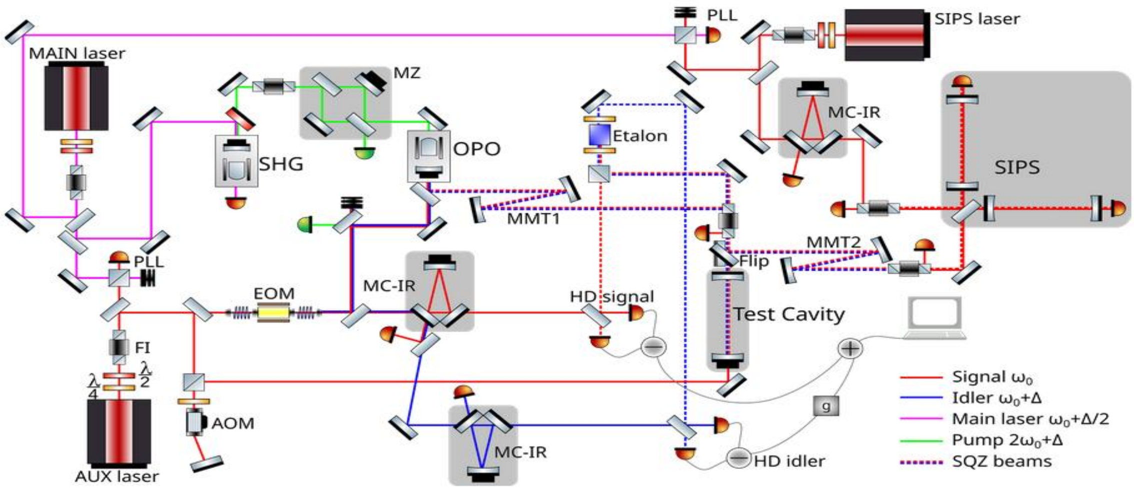

Fig. 3 SIPS with integration of EPR optical setup [9].

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As illustrated in Fig. 3, the experimental setup consists of a sophisticated optical system designed to generate and manipulate squeezed light through nonlinear optical components. The configuration employs three lasers: the MAIN laser, the AUX laser, and the SIPS laser. The MAIN laser operates at frequency $\omega 0+\Delta/2$ and provides the second-harmonic pump beam for squeezed light generation (green path). The AUX laser supplies beams for the control of optical cavities and for measuring the squeezing level, while the SIPS laser is used to illuminate the small-scale interferometer. The Second Harmonic Generation (SHG) module doubles the frequency of the MAIN laser to produce the pump beam at $2\omega 0+\Delta$ (purple path), which drives the Optical Parametric Oscillator (OPO) (green path). The OPO generates two beams: the signal at $\omega 0$ (red dashed path) and the idler at $\omega 0+\Delta$ (blue dashed path). The pump beam is controlled using a Mach-Zehnder Interferometer (MZI), allowing fine adjustment of pump power for optimal squeezing conditions. In parallel, the Electro Optic Modulator (EOM) and Acoustic Optic Modulator (AOM) generate the locking and coherent control beams, enabling precise control of phase, amplitude, and frequency stabilization. Phase-Locked Loops (PLLs) ensure stable frequency relationships among all lasers. Furthermore, Mode Cleaners for infrared light (MC-IRs) are employed to filter and stabilize the local oscillator beams used in homodyne detection. Squeezed vacuum states are depicted as dashed lines, indicating their propagation throughout the system as shown in Fig. 3. By embedding EPR squeezing within this finely tuned suspended interferometer, SIPS acts as a scalable prototype for future large-scale, quantum-enhanced detectors. It showcases how compact, high-precision systems can generate and harness entanglement for practical metrology applications, marking a foundational step toward integration into the Einstein Telescope framework [9].

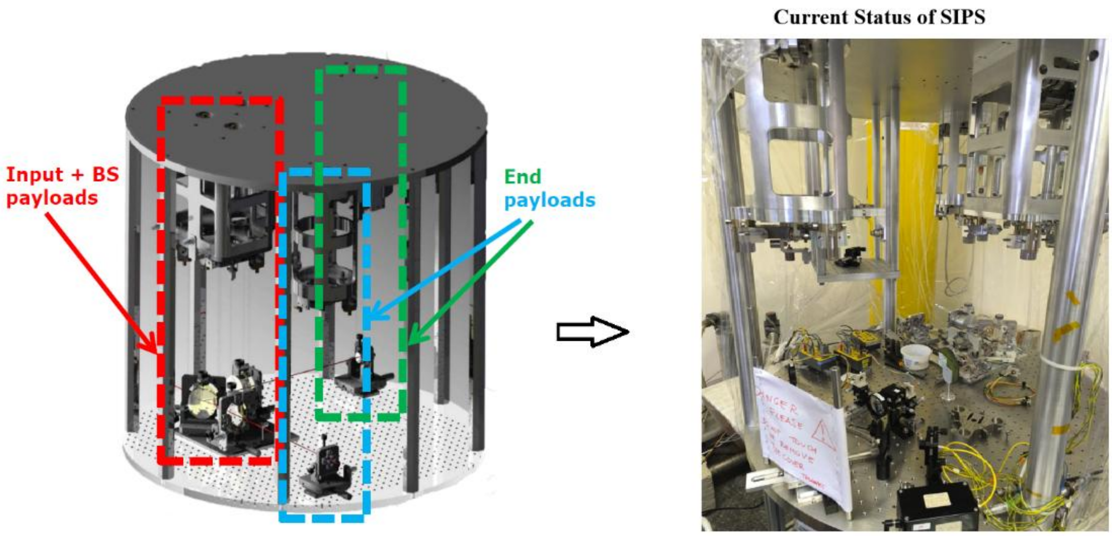

Fig.4 Current optical configuration of the SIPS experiment in Rome, Italy.

The SIPS optical design includes a carefully engineered laser injection path, beginning from a high-stability laser source (λ = 1.064 µm) that is mode-cleaned using a triangular Input Mode Cleaner (IMC) cavity. The IMC ensures the laser beam has a pure Gaussian mode profile and filters out unwanted transverse modes. The beam is then directed toward the main interferometer, mode-matched to Fabry-Perot arm cavities with lengths of 350 mm and a mirror radius of curvature (RoC) of 250 mm. This entire system is constructed on a compact optical bench with strict mechanical constraints of 800 mm in height and 960 mm in diameter, originally designed to be suspended at the SAFE Super Attenuator (Facility at EGO-Virgo), for seismic noise filtering, and to use monolithic Virgo-like fibers for thermal noise suppression.
The suspended optics, with mirror masses strategically chosen to optimize performance, include lightweight end mirrors (~10 g) to enhance sensitivity to radiation pressure noise, and heavier input and beam splitter mirrors (~300 g) to ensure stability and facilitate suspension. The optical spring effect, enhanced by cavity finesse (~2.3×10^4), contributes further to enhance quantum radiation pressure noise, and finally, an input power of 2.5 W provides sufficient circulating power (~0.1 MW) [10].

3. **Control Strategies for SIPS**

Achieving quantum-limited sensitivity in SIPS requires highly stable control over both angular and longitudinal degrees of freedom [8]. The optical components suspended via monolithic fibers to minimize thermal noise must be precisely aligned and actively stabilized to maintain resonance within the Fabry-Perot cavities. For this purpose, a combination of Position-Sensitive Detectors (PSDs), coil-magnet actuators, and advanced feedback electronics is employed to monitor and correct the motion of suspended mirrors in real-time.

A central element of the longitudinal control system is the Pound-Drever-Hall (PDH) locking technique, which ensures that the laser remains resonant with the cavity despite environmental perturbations. In this scheme, the input laser is first phase-modulated by an Electro-Optic Modulator (EOM), generating sidebands around the carrier frequency. While the carrier reflects depending on the cavity detuning, the sidebands do not resonate and serve as stable references. When the reflected light is detected by a photodiode, interference between the carrier and sidebands creates a sensitive error signal that indicates how far the cavity is from resonance. This error signal is then fed into a feedback loop that actuates the cavity input mirror, dynamically adjusting its position to correct for any deviation. The PDH method offers high bandwidth and precision, making it ideal for the delicate environment of SIPS. By continuously locking the cavity with this technique, SIPS maintains the stringent optical conditions required for the detection of squeezed light, ensuring that EPR entanglement and frequency-dependent squeezing are preserved throughout the operation.

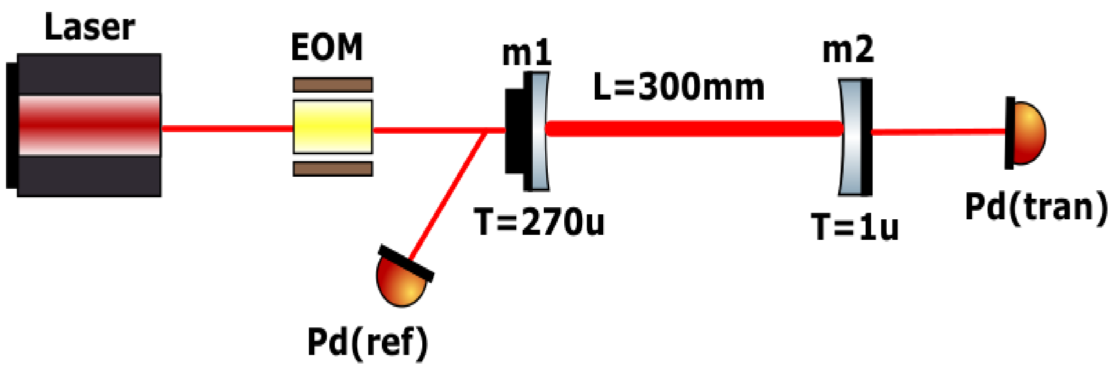

Fig. 5 Schematic of the PDH Locking Scheme for a Fabry–Perot Cavity.

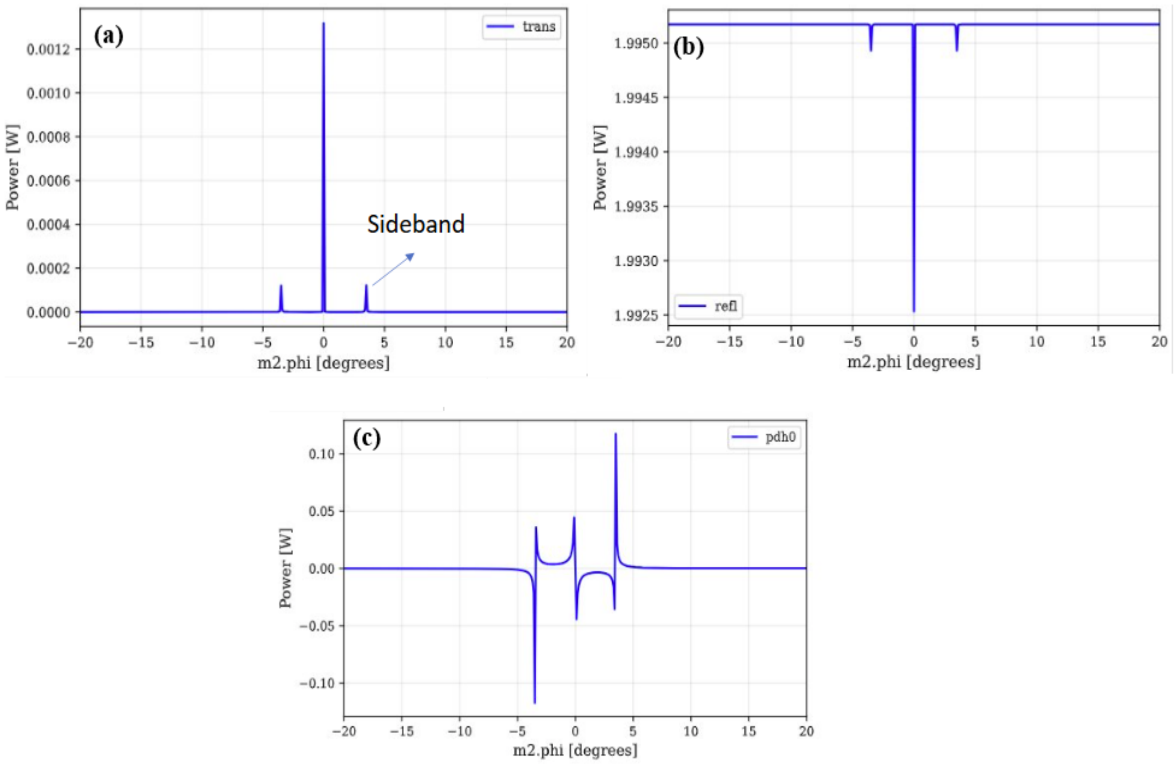

Fig.6 (a) Transmitted power. (b) Reflected power. (c) PDH error signal vs cavity detuning.

In the simulation conducted using FINESSE, as shown in Fig. 5, a Pound-Drever-Hall (PDH) locking scheme was implemented with a phase modulation frequency of 210 MHz. The laser beam, modulated by an Electro-Optic Modulator (EOM), is injected into a 300 mm Fabry–Perot cavity formed by mirrors m1 and m2. The reflected signal is used to extract the PDH error signal, which exhibits a clear zero-crossing at resonance, making it well-suited for feedback control. The plots of transmitted and reflected power highlight the presence of modulation sidebands and a resonance dip, respectively. The 210 MHz modulation provides sufficient spectral separation between the carrier and sidebands, enabling precise phase discrimination and enhancing the sensitivity of the error signal. These results confirm the effectiveness of the chosen modulation frequency for stabilizing the cavity in a suspended interferometer such as SIPS, as illustrated in Fig.
A simulation was also performed using a green laser beam ($\lambda \approx 532$ nm) with a modulation frequency of 210 MHz. The transmitted and reflected power plots exhibit a sharp resonance near zero cavity detuning, similar to the IR case but with slightly lower power buildup due to wavelength dependent optical parameters, as shown Fig. 7. The corresponding PDH error signal maintains its characteristic zero-crossing shape, confirming that even at shorter wavelengths, the technique remains effective for generating a usable locking signal.

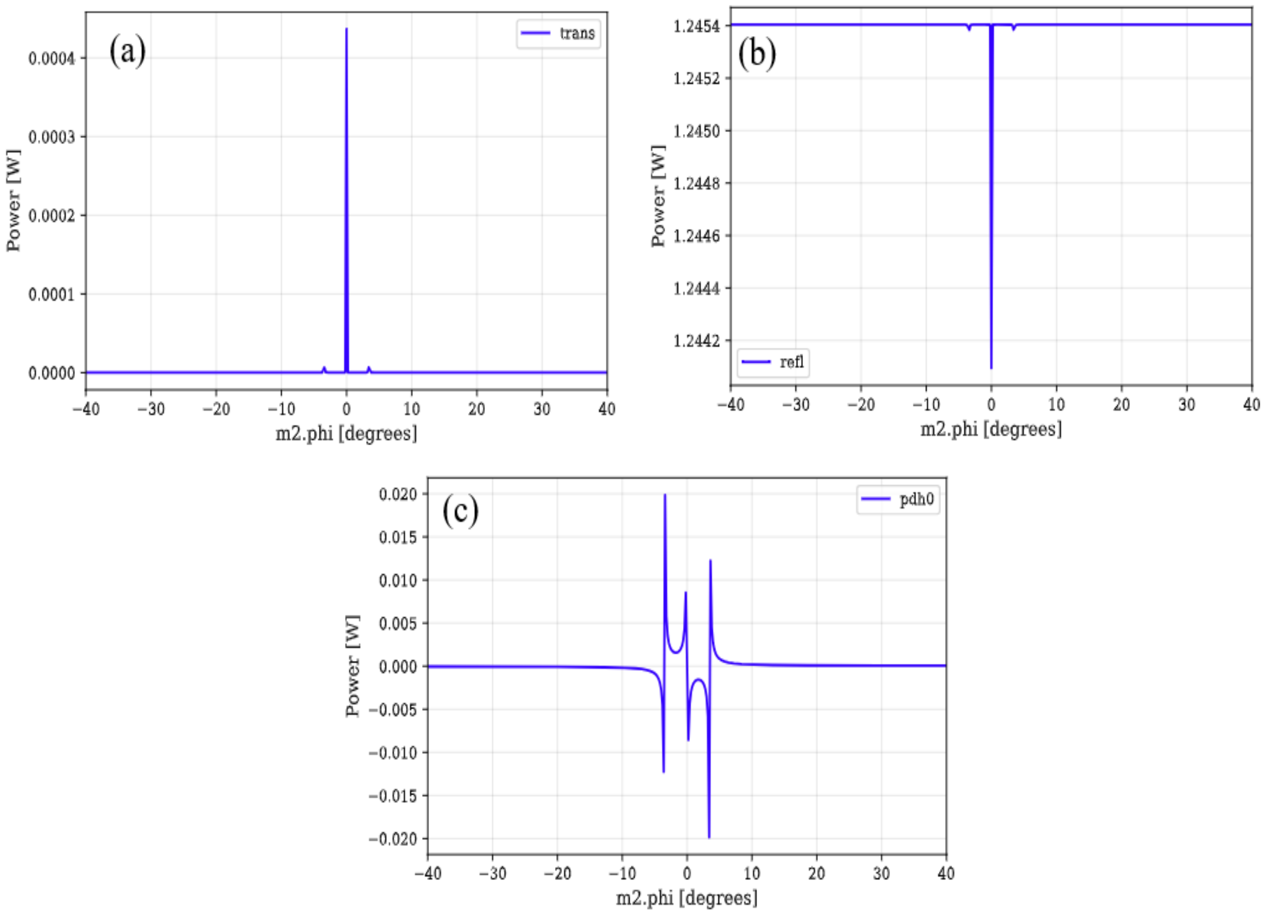

Fig.7 (a) Transmitted power. (b) Reflected power. (c) PDH error signal vs cavity detuning.

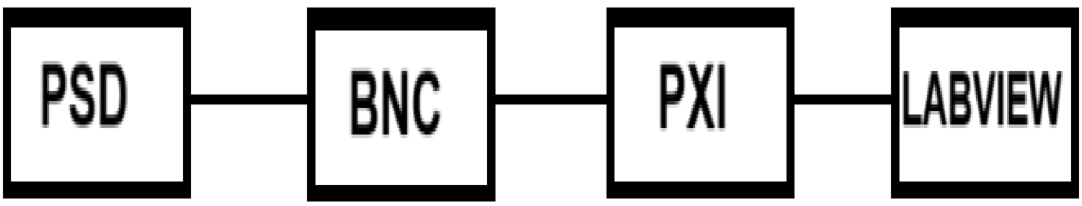

Fig. 8 Signal acquisition and control flow from PSD to LabVIEW using BNC and PXI system

The signal acquisition chain for local control in SIPS manages multiple degrees of freedom, including angular displacement (pitch and yaw), longitudinal motion along the optical axis, and pendulum modes. Analog signals from the 4-quadrant Position Sensitive Detector (PSD) are transmitted via BNC cables to the PXI-based data acquisition system, which digitizes the inputs for processing. These signals are then visualized, recorded, and processed in real-time through feedback loops implemented in a custom LabVIEW interface, enabling precise monitoring and control of mirror alignment and dynamic stability, as depicted in Fig. 8.
The local control system of the SIPS interferometer is designed to maintain stable alignment and positional accuracy of the suspended optical components. For each optical element to control, signals from two PSDs, one placed at the focal plane and the other at the image plane, are amplified and read via BNC connections, then digitized through an 8-channel National Instruments PXI system, which serves as the core of the data acquisition and control architecture. Each PSD monitors angular displacements (pitch and yaw), while coil-magnet actuators apply precise corrective forces to suspended mirrors. A custom LabVIEW-based interface was developed to process these signals in real time, enabling dynamic feedback control with high precision.

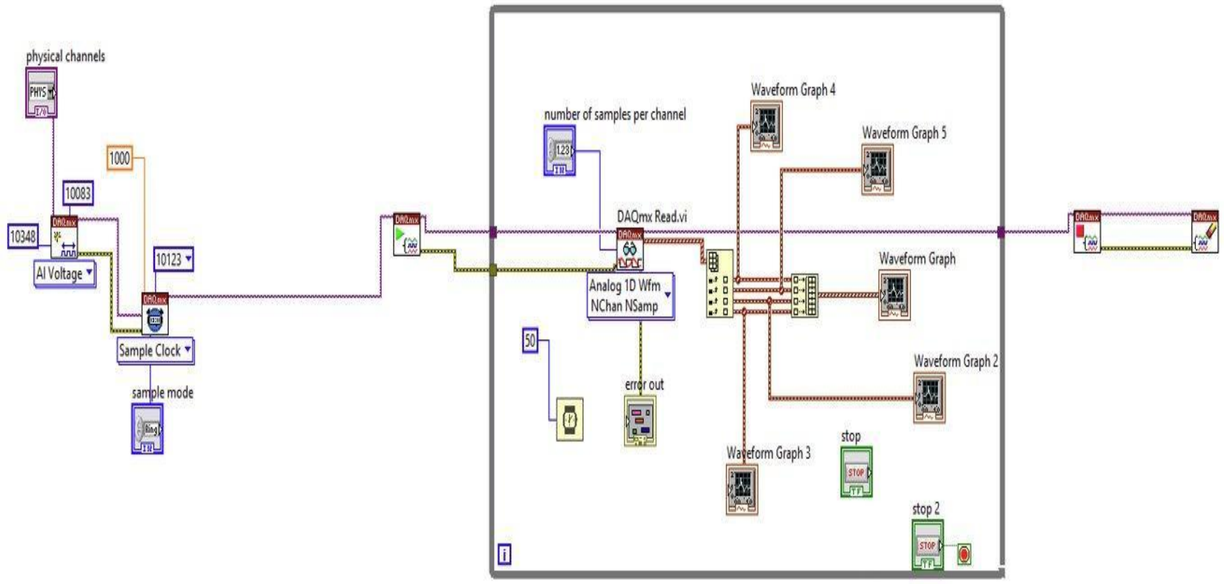

Fig. 9 LabVIEW program to acquire and debug signals from multiple channels.

The LabVIEW program shown in Fig. 9 was developed to acquire and monitor signals from multiple analog input channels using a PXI-based data acquisition system. Although a similar program was developed by L. Giacoppo during her PhD using LabVIEW 2021, our system uses the 2023 version, which introduced compatibility issues requiring us to develop a new program from scratch [11]. Each waveform graph displays the real-time signal from a separate channel, allowing debugging and verification of input stability. This program served as a critical step in validating the BNC connections and ensuring the system was ready for integration with the 4-quadrant PSD sensor. To validate the BNC signal acquisition path and ensure reliable data handling within the LabVIEW-PXI framework, a signal generator was used to inject a test signal with a frequency of 1.21 Hz and an amplitude of 200 mV. This initial setup allowed real-time monitoring and waveform acquisition through LabVIEW, verifying the correct operation of the BNC connections, amplifier response, and PXI digitization. The successful execution of this test confirmed the system's readiness for more advanced use, particularly the integration of the 4-channel PSD. The low-frequency, low-amplitude signal was chosen to emulate typical displacement signals, making this trial a crucial step in qualifying the control electronics before moving to the full optical alignment stage of the SIPS experiment.

CONCLUSION

This paper is focused on the integration and control strategies of the Suspended Interferometer for Ponderomotive Squeezing (SIPS), with the goal of enabling quantum-enhanced performance using the Einstein-Podolsky-Rosen (EPR) technique. The optical configuration, including a Fabry Perot cavity arms and Input Mode Cleaner (IMC), was designed to support squeezed light injection and stable resonance conditions. Simulation studies using the Pound Drever Hall (PDH) method, with both infrared and green beams, demonstrated effective cavity locking across two different modulation frequencies (210 MHz and 130 MHz), confirming that separate EOMs are required for each beam. In parallel, a complete electronic control system was implemented using LabVIEW and PXI hardware, allowing real-time acquisition and feedback through BNC-connected photodetectors. Initial tests using a signal generator (1.21 Hz, 200 mV) validated signal acquisition and processing. This setup was then extended to a 4-channel Position Sensitive Detector (PSD), enabling precise angular and positional feedback using coil-magnet actuators. The custom LabVIEW interface ensured robust control, crucial for maintaining interferometric stability under suspended and low-noise conditions. Overall, the integrated optical and electronic systems developed in this work make a significant contribution to advancing quantum noise suppression through EPR entanglement, paving the way for next-generation gravitational wave detectors, such as the Einstein Telescope.

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