

Demonstrating the velocity response of a table-top EPR speedmeter

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The sensitivity of gravitational wave interferometers is fundamentally limited by quantum noise, as dictated by the Heisenberg uncertainty principle, due to their continuous position measurement of the end mirrors. Speedmeter configurations, which measure mirror velocity rather than position, have been proposed as a means to suppress quantum backaction noise, but practical implementations remain at an early stage. In this work, we present a table-top realization of the Einstein-Podolsky-Rosen (EPR) speedmeter concept, employing an optical readout scheme based on two orthogonal polarization modes that probe the interferometer with different effective bandwidths. Using a triangular cavity, we demonstrate that the differential optical response between the linear p- and s-polarized modes exhibits a speedlike frequency dependence: vanishing at DC and increasing linearly with signal frequency, up to the bandwidth of the slower mode. With this we show that an optical system equivalent to the EPR speedmeter indeed performs a velocity readout of the end mirror.

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I. INTRODUCTION

Second-generation kilometer-scale gravitational wave interferometers, such as Advanced LIGO [1] and Advanced Virgo [2], have successfully detected signals from compact binary coalescences, including merging black holes and neutron stars, during their first three joint observing runs [3–5]. In the ongoing fourth observing run (O4), the cryogenic underground detector KAGRA in Japan [6] has joined the global detector network and more than 200 candidate events have been reported, offering among other things valuable insights into stellar evolution and the population of massive compact objects in the Universe. Although current detectors have not yet reached design sensitivity across the full detection band [7], ongoing upgrades and the development of next-generation observatories such as the Einstein Telescope (ET) [8–10] are expected to push quantum noise to the forefront as the dominant sensitivity limitation across much of the detection bandwidth [11].

Quantum noise arises from fundamental vacuum fluctuations entering the interferometer via its dark port, contributing in two uncorrelated ways [12–14]. First, quantum phase fluctuations manifest as shot noise in the photodetector readout, dominant at high frequencies. Second, quantum amplitude fluctuations couple to the carrier light in the interferometer arms, generating a fluctuating radiation pressure force on the mirrors—so-called backaction noise—which scales inversely with the square of signal frequency, $\sim\Omega^{-2}$, due to the mirrors acting as free test masses. These two noise terms trade off against each other—increasing circulating optical power reduces shot noise but enhances backaction. The frequency at which both contributions become equal defines the standard quantum limit (SQL), beyond which position measurement interferometers with uncorrelated shot and backaction noise cannot surpass without altering their quantum measurement scheme.

Modern gravitational wave detectors already employ squeezed vacuum states to reduce quantum noise [15–18]. This technique exploits quantum correlations to suppress fluctuations in one quadrature (e.g., phase) at the cost of enhancing those in the conjugate quadrature (e.g., amplitude), in accordance with the Heisenberg uncertainty principle [19–21]. Simultaneous broadband suppression of both noise types requires frequency-dependent squeezing, typically achieved using large-scale filter cavities, which has recently been demonstrated in full-scale detectors [22,23].

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An alternative quantum noise mitigation strategy is offered by speedmeter interferometer configurations, first proposed in [24]. In contrast to position meters, speedmeters aim to measure the momentum of the test masses, which is a quantum nondemolition observable. Such observables satisfy the commutation relation $[\hat{\phi}(t), \hat{\phi}(t')] = 0$ for all times t, t' , and can, therefore, in principle, be measured continuously without introducing quantum backaction [25]. A speedmeter achieves this by performing two coherent position measurements with opposite sign in the interaction Hamiltonian and a short delay τ , so that the readout becomes proportional to the average velocity, $\phi_{\text{out}} \propto x(t + \tau) - x(t) \simeq \bar{v}\tau$, and the radiation pressure forces imparted by each measurement partly cancel. Note that velocity is not strictly proportional to the momentum of the free test mass when it is coupled to a meter, so that a speedmeter achieves a significant reduction but not a complete cancellation of backaction noise [21].

Multiple realizations of the speedmeter concept have been proposed over the years [21, 26–34], but none have yet reached the technological maturity required for large-scale implementation. In this paper, we present an experimental demonstration of a table-top Einstein-Podolsky-Rosen (EPR) speedmeter, as proposed in [32]. This approach belongs to the class of polarization-based speedmeters, which employ two orthogonal polarization modes to perform two independent measurements of the test mass position. A key advantage of this scheme is that it does not require major modifications to the core interferometer topology—only additional optical elements at the interferometer output are needed to convert position readout into speed readout.

We implement the EPR speedmeter using a triangular optical cavity with polarization-dependent bandwidths, resulting in different frequency responses acquired by p-polarized and s-polarized modes. We show that the differential optical response between these modes exhibits a speedlike frequency dependence, vanishing at DC and increasing linearly with signal frequency, up to the bandwidth of the slower mode.

The structure of the paper is as follows. Section II outlines the theoretical concept of the EPR speedmeter and its equivalence to a triangular cavity. Section III A describes the experimental setup and measurement procedure. Section III B presents the results, and Sec. IV provides a discussion and outlook.

II. THE TRIANGULAR CAVITY AS AN EPR SPEEDMETER

The EPR speedmeter shown Fig. 1 features a dual-recycled Michelson interferometer with Fabry-Perot arm cavities (purple box) pumped with linearly polarized laser light at polarization angle ϑ set by the orientation of the half-wave plate (HWP) at the interferometer input. The quarter-wave plate (QWP) at the interferometer output is

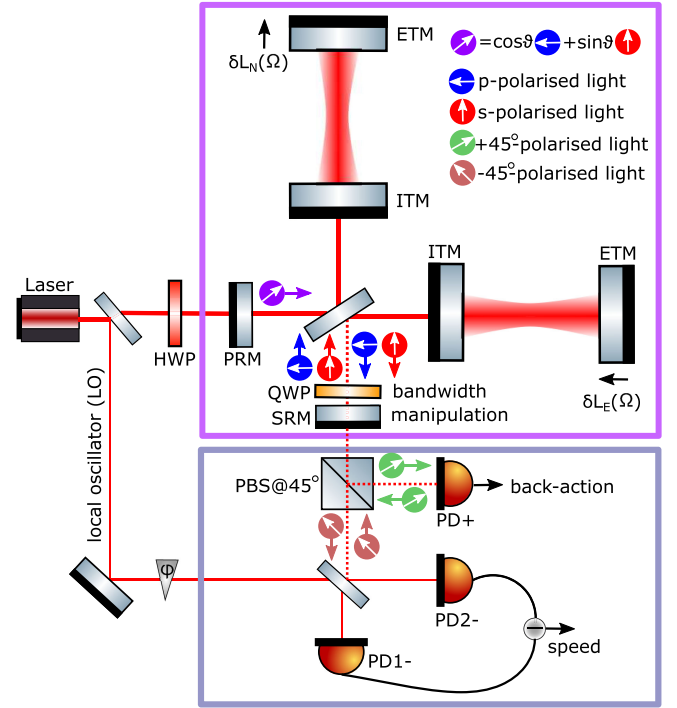


FIG. 1. Optical layout of the EPR speedmeter as a gravitational wave interferometer adapted from [32].

oriented such that it introduces a phase retardation of $\pi/2$ between p-polarized (blue) and s-polarized (red) components of the light used to probe the differential arm length change $\delta L_{\text{darm}}(\Omega) = \delta L_N(\Omega) - \delta L_E(\Omega)$ caused by a passing gravitational wave at frequency Ω . The position of the signal-recycling mirror (SRM) is then tuned such that one polarization mode (e.g., s-pol) is resonant in the signal-recycling cavity formed by the SRM and the input test masses (ITMs) of the two Fabry-Perot arm cavities, while the other one (e.g., p-pol) experiences the resonant sideband extraction configuration of the signal-recycling cavity, resulting in a much larger interferometer bandwidth $\gamma_p \gg \gamma_s$ in accordance with the so-called scaling law [35]. The interferometer bandwidth is inversely proportional to the average storage time of light in the interferometer and can, therefore, be understood as the rate at which position information leaks out of the interferometer. Due to the different bandwidths of the two polarization modes, a recombination at a beam splitter effectively combines position information from different times and, therefore, results in a speed measurement.

In case of the EPR speedmeter, a polarizing beam splitter (PBS) rotated by 45° acts as a 50:50 beam splitter for p-polarized and s-polarized light, splitting the light into $\pm 45^\circ$ linearly polarized beams, where the difference channel (transmission) carries speed information that can be extracted by choosing a suitable local oscillator phase φ . The vacuum entering through the sum port of the PBS creates additional backaction noise but can be removed in

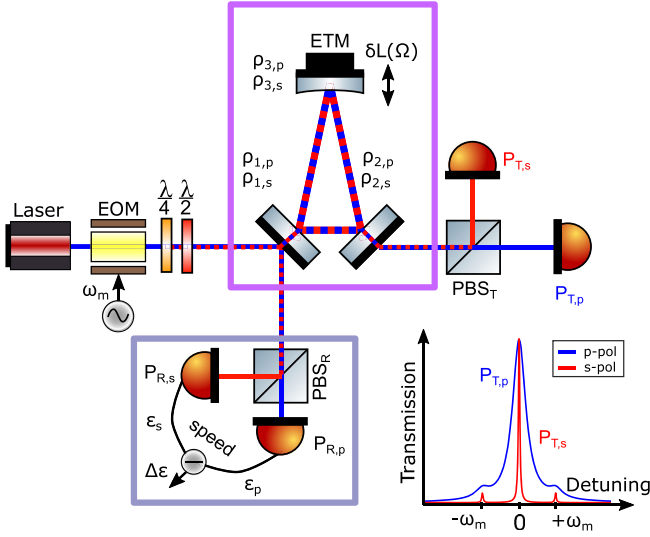


FIG. 2. Conceptual design of the EPR speedometer proof-of-principle experiment with a triangular cavity representing a system with two different bandwidths for two linear polarization modes (purple box) and a speed readout by means of the error signal difference $\Delta\epsilon = \epsilon_p - \epsilon_s$ (grey box).

postprocessing by measuring the amplitude quadrature of the sum channel (PD+). This is possible since the position meter outputs represented by the two polarization modes get entangled when combined on the PBS, which motivated the name of this speedometer configuration after the famous Gedanken experiment by Einstein, Podolsky, and Rosen.

In a nutshell, the EPR speedometer achieves a speed measurement by using two polarization modes with different bandwidths $\gamma_p \gg \gamma_s$, which results in different AC responses of the interferometer. The differential response vanishes at DC and is to leading order proportional to the signal frequency Ω , therefore, it represents speed. A triangular ring cavity, see Fig. 2, similarly realizes a system with two different bandwidths for p-polarized and s-polarized light, since the transmissivity of the input mirror is in general different for the two orthogonal polarization modes under non-normal incidence, as described by Fresnel relations.

The frequency-dependent reflectivity of a triangular ring cavity for each polarization mode $k = p, s$ can be derived as

$$\mathcal{R}_k(\Omega) = \frac{\rho_{1,k} - \rho_{2,k}\rho_{3,k}e^{i\phi_n(\Omega)}}{1 - \rho_{1,k}\rho_{2,k}\rho_{3,k}e^{i\phi_n(\Omega)}}, \quad (1)$$

where $\rho_{j,k} = \sqrt{R_{j,k}}$ is the amplitude reflectivity of each mirror j derived from the power reflectivity $R_{j,k}$ specified by the optics supplier. For lossless mirrors, reflectivity and transmissivity are connected via $\rho_{j,k} = \sqrt{1 - \tau_{j,k}^2}$ due to energy conservation. Assuming a high reflectivity for the piezo-driven end mirror $\rho_{3,k} \approx 1$ for both polarizations,

we define the coupling rates of the two input mirrors $\gamma_{j,k}$ and the complex cavity pole function $\ell_k(\Omega)$ as

$$\gamma_{j,k} = \frac{\tau_{j,k}^2}{2T_{rt}}, \quad \ell_k(\Omega) = \gamma_{1,k} + \gamma_{2,k} - i\Omega, \quad (2)$$

with $T_{rt} = L_{rt}/c$ being the travel time of light for a single pass through the cavity with round-trip length L_{rt} . Using the single-mode approximation with assumptions $\Omega T_{rt} \ll 1$ and $\tau_{j,k}^2 \ll 1$ combined with operation close to resonance, $\phi_{rt} = 2\pi n + \Omega T_{rt}$ (n integer), one can show that

$$\mathcal{R}_k(\Omega) \approx \frac{\gamma_{2,k} - \gamma_{1,k} + i\Omega}{\gamma_{1,k} + \gamma_{2,k} - i\Omega}. \quad (3)$$

A mirror motion $\delta L(\Omega)$ at frequency Ω (signal) creates symmetric sidebands at $\omega_0 \pm \Omega$ around pump frequency $\omega_0 = k_0 c$ of the laser, which we treat as DC at the cavity operating point. These sidebands leak through the input mirror and show up in the reflected field,

$$E_{\text{ref},k}(\Omega) \approx \frac{2ik_0\sqrt{\gamma_{1,k}}}{\ell_k(\Omega)\sqrt{T_{rt}}} E_{\text{in},k} \cdot \delta L(\Omega), \quad (4)$$

$$= H_{\text{opt},k}(\Omega) \cdot \delta L(\Omega), \quad (5)$$

with $E_{\text{in},k}$ input fields to the cavity calculated from the optical power via $P_k = \hbar\omega_0 E_{\text{in},k}^2$.

The optomechanical transfer function $H_{\text{opt},k}$ describes how motion of the mirror couples to the electric field of each polarization k and can be extracted using the error signal $\epsilon_k \propto H_{\text{opt},k}(\Omega) \cdot \delta L(\Omega)$ of the well-established Pound-Drever-Hall (PDH) technique [36]. The input field $E_{\text{in},k}$ contains frequency components of the carrier ω_0 and symmetric sidebands at $\omega_0 \pm \omega_m$ from phase modulation with the electro-optic modulator (EOM) at frequency ω_m . The EOM modulation frequency is chosen large enough such that $\mathcal{R}_k(\omega_0 \pm \omega_m) \approx 1$, which means that the sidebands are reflected from the cavity and, therefore, are not affected by mirror motion, which creates new sidebands at $\omega_0 \pm \Omega$. The optical power reflected from the cavity is separated into p-polarized and s-polarized components by means of a PBS (see Fig. 2) to monitor the reflected power $P_{R,k}$ for both polarizations independently with photodetectors. The PDH error signals ϵ_k for both polarizations are generated by mixing the measured reflection signal with a reference at EOM modulation frequency ω_m and low-pass filtering. This generates signals at $\omega_m \pm \Omega$, one of which beats down to a demodulated signal at Ω .

For a suitable mirror motion amplitude, the difference between the error signals of the two polarizations is

$$\frac{\Delta\epsilon(\Omega)}{\delta L(\Omega)} \propto \frac{2ik_0}{\sqrt{T_{\text{rt}}}} \left(\frac{E_{\text{in,p}}\sqrt{\gamma_{1,\text{p}}}}{\ell_{\text{p}}(\Omega)} - \frac{E_{\text{in,s}}\sqrt{\gamma_{1,\text{s}}}}{\ell_{\text{s}}(\Omega)} \right), \quad (6)$$

$$\stackrel{(*)}{=} \frac{2ik_0}{\sqrt{T_{\text{rt}}}} \frac{E_{\text{in,p}}}{\sqrt{\gamma_{1,\text{p}}}} \frac{i\Omega(\gamma_{1,\text{s}} - \gamma_{1,\text{p}})}{\ell_{\text{p}}(\Omega)\ell_{\text{s}}(\Omega)} \propto i\Omega, \quad (7)$$

where the last equality sign is valid for a critically coupled cavity $\gamma_{1,j} = \gamma_{2,j}$ if the tuning condition $(*)E_{\text{in,p}}/\sqrt{\gamma_{1,\text{p}}} = E_{\text{in,s}}/\sqrt{\gamma_{1,\text{s}}}$ is fulfilled, equivalent to the tuning condition formulated for the EPR speedmeter [21,32]. The above expression is linear in frequency and the system behaves like a speedmeter for $\Omega < \min(\gamma_{1,\text{p}}, \gamma_{1,\text{s}})$ provided that $\gamma_{1,\text{p}} \neq \gamma_{1,\text{s}}$. Considering only optical parameters, the tuning condition is fulfilled by choosing the input polarization angle $\vartheta = \arctan(\gamma_{1,\text{s}}/\gamma_{1,\text{p}})$. Gain differences from other sources such as photodetector response and readout electronics have been omitted in Eq. (6) but need to be taken into account in the real experiment by proper calibration, as detailed in Sec. III A.

In the following, the experimental realization of such a system as a table-top experiment is discussed. We demonstrate a classical speedlike response of the triangular cavity representation of the EPR speedmeter. Note that we do not show backaction suppression in this paper, as this would require a quantum noise limited system, including, among other things, a vacuum system, monolithic suspensions, and a high-power laser with external frequency stabilization.

III. EXPERIMENTAL REALIZATION

A. Setup and control

The optical layout in Fig. 3 shows the realization of the idea described in the previous section and highlighted in Fig. 2. As input to the experiment, 60 mW of laser power at wavelength 1550 nm was used. The input polarization was chosen to be linear by adjusting the QWP and along a polarization angle by adjusting the HWP, such that signals of similar amplitude within range of the two reflection photodetectors were measured. Additionally, phase-modulated sidebands were imprinted by a resonant EOM at 21.2 MHz for both polarization modes to enable PDH lock and signal extraction from the PDH error signal.

For a triangular cavity and any other cavity with an odd number of mirrors, the resonance condition for horizontal modes is shifted by half a free spectral range (FSR) compared to vertical modes. In Jones formalism, this is represented by a sign flip acquired by the s-polarized electric field component at each reflection, which for simplicity is not taken into account in Eq. (1). In order to have the fundamental mode of both polarizations resonant in the cavity at the same time, one of the polarization modes needs to be frequency-shifted by FSR/2 with respect to the other. For this purpose, the two polarization components are split by PBS1 and prepared separately before being recombined by PBS3 and injected into the cavity, see Fig. 3.

By design, the cavity spacer used for the experiment had a round-trip length of 0.42 m, which corresponds to $\text{FSR} = c/L_{\text{rt}} \approx 714$ MHz. An acousto-optical modulator

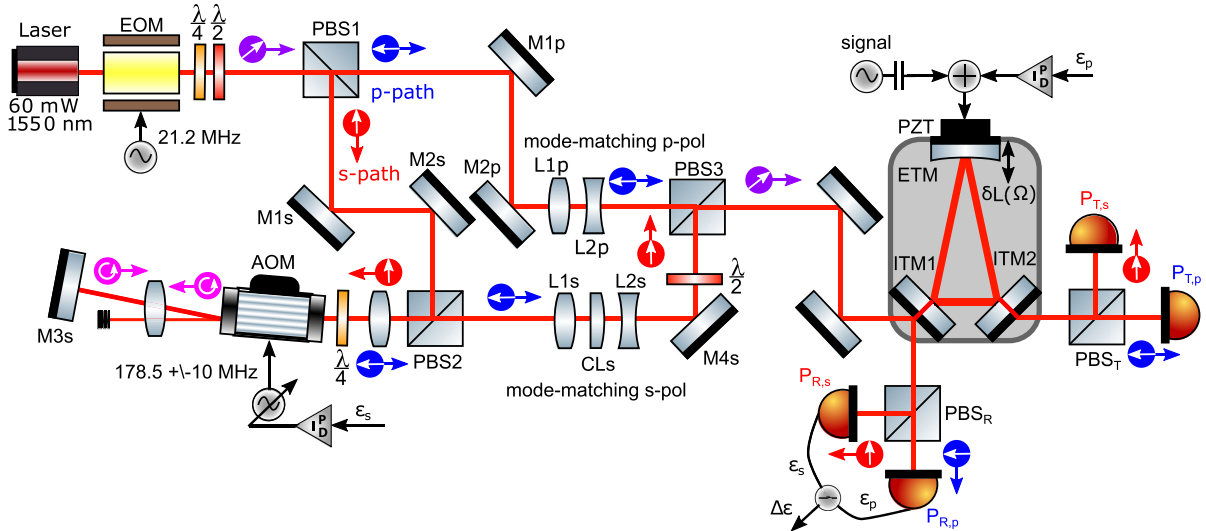


FIG. 3. Practical realization of the triangular cavity version of the EPR speedmeter on an optical bench. Laser light enters from the left and both polarization modes are prepared separately for injection into the optical cavity. The cavity spacer has three mirrors clamped to it, with the input/output couplers (ITM1 and ITM2) featuring different transmissivities for the two polarization modes and the piezo-driven, highly reflective end mirror (ETM) used for locking the cavity length to the p-polarization mode and for signal injection. The speedlike response is measured by recording the differential demodulated error signal $\Delta\epsilon$ in reflection. The transmission signals are used for lock acquisition and optical characterization.

(AOM) with nominal driving frequency 178.5 MHz was used in the double-pass configuration to achieve a total frequency shift of $\text{FSR}/2 \approx 357$ MHz. The AOM allows for frequency modulation of ± 10 MHz by means of an applied DC voltage in the range $\pm 2V_{\text{dc}}$, which is used for PDH lock of the s-polarization mode accounting for FSR differences from manufacturing tolerances and rubber rings between the spacer, piezo, and end mirror.

The direction of the AOM output beam depends on the applied frequency shift. Operation in the double-pass configuration ensures that the beam alignment to the cavity is independent of the frequency shift applied by the AOM, since the mirror M3s retro-reflects the beam independently of its direction. However, the double-pass configuration has the disadvantage of introducing large losses, since only up to 55% of the input power is coupled into the first-order diffracted beam. The orientation of the HWP at the input was, therefore, chosen such that 55 mW of the original 60 mW input power was sent to the s-path. A double pass through the QWP in front of the AOM turns s-polarized light into p-polarized light, which ensures separation of input and output beams from the AOM by means of PBS2. Additionally, the AOM introduces an astigmatism quantified by the ratio of beam waist sizes w_{0i} in two orthogonal directions ($i = x, y$) $w_{0x}/w_{0y} \approx 0.54$, which needs to be compensated by a cylindrical lens in order to avoid further losses from mode mismatch to the cavity.

The triangular cavity itself had flat mirrors with identical specifications for ITM1 and ITM2 with power transmissivities $T_{i,p} \approx 4.3\%$ for p-polarized light and $T_{i,s} \approx 0.35\%$ for s-polarized light, respectively, at an angle of incidence 44° . The piezo-driven cavity end mirror (ETM) was chosen to be highly reflective for both polarizations, $T_{p,s} = 2$ ppm, and with radius of curvature 1 m. In this configuration, the fundamental TEM_{00} (transverse electromagnetic) mode resonant in the triangular cavity had a beam waist of $448 \mu\text{m}$ located in the center between the two ITMs. The positions and focal lengths of the mode-matching telescopes for p-polarized light (lenses L1p and L2p) and s-polarized light (lenses L1s and L2s) were chosen and adjusted to match this condition independently for both polarizations.

The power transmissivities of the two ITMs lead to effective measured bandwidths of $\gamma_p \approx 5.5$ MHz for p-polarized light and $\gamma_s \approx 0.975$ MHz for s-polarized light. The lock of both polarization modes was engaged in a two-step hierarchical process using a digital data acquisition system similar to the one of the large-scale gravitational wave detector Virgo located in Italy [2]. First, the cavity length was controlled to match the resonance condition for p-polarized light by using PDH lock and feeding back the error signal to the piezoelectric transducer connected to the ETM, see Fig. 3. The lowest piezo resonance was observed around 10 kHz and limited the achievable unity-gain frequency (UGF) to maximum $\sim 2\text{--}3$ kHz. Second, the

control loop for the s-polarized light was closed, controlling the AOM frequency to keep s-polarized light resonant in the cavity. The digital control filter of the s-polarization mode was designed so that both polarization modes exhibit a similar open-loop transfer function. Since the piezo motion is common for both polarizations, the control signal of the p-polarized light couples to the s-polarization lock.

The common coupling of the piezo actuation to the error signals of the two polarization modes was used to inject a signal $\delta L(\Omega)$ in a frequency region $\sim 15\text{--}500$ kHz far above the UGF of both control loops. The signal injection was done via a capacitor acting as a high-pass filter at 20 kHz to prevent the signal injection from exciting piezo resonances that could peak through unity gain, and to protect the signal generator from large feedback signals at low frequencies below the UGF.

The frequency response measurement was performed using a MokuLab signal analyzer configured for swept-sine excitation. Separate response functions were recorded simultaneously for the p- and s-polarized beams using the demodulated signals of the photodetectors in reflection. The full measurement range from 15 kHz to 500 kHz was covered by two overlapping frequency bands to optimize the resolution and dynamic range by choosing a higher excitation amplitude for frequencies above 100 kHz, where the response of the piezoelectric transducer was observed to degrade with increasing frequency. This frequency band covers the relevant regime in which the differential signal should experience a speedlike behavior.

B. Data analysis and results

The measured frequency-domain data were imported to Matlab from comma-separated value files. Each dataset contained the excitation frequency, the magnitude response in decibels (dB), and the phase in degrees. These were converted to complex transfer functions for each polarization channel k as follows:

$$H_k(f) = 10^{\frac{m_k(f)}{20}} \cdot e^{i\phi_k(f)}, \quad (8)$$

where $m_k(f)$ is the measured gain in dB and $\phi_k(f)$ is the phase in radian. This conversion yields a frequency-dependent complex response $H_k(f)$ for each polarization, capturing both the amplitude and phase behavior of the system. Additionally, the data were sorted by frequency and concatenated into a single frequency vector with corresponding complex transfer functions for both p- and s-polarization, denoted $H_p(f)$ and $H_s(f)$, respectively.

Since the absolute calibration between the two polarizations may differ due to gain variations, optical path differences, or photodetector responsivity, a real-valued rescaling factor α was estimated to align $H_s(f)$ with $H_p(f)$ using least-squared minimization over all frequency points,

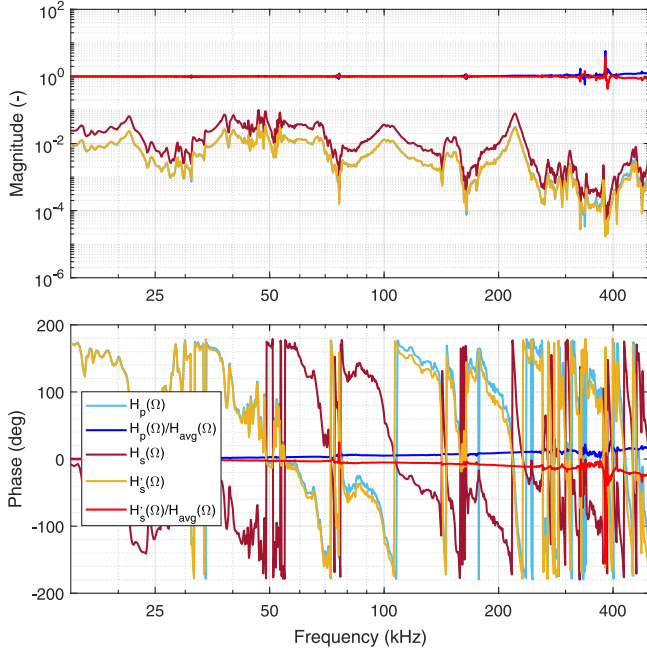


FIG. 4. Raw measured complex frequency response separated into magnitude (top) and phase (bottom) for p-polarization $H_p(f)$ (light blue) and s-polarization $H_s(f)$ (dark red). After rescaling the s-polarization response $H'_s(f) = \alpha H_s(f)$ (orange), the responses of both polarizations overlap. Division by the common mode response $H_k(f)/H_{\text{avg}}(f)$ leads to a more or less flat unity response for both polarization modes (blue and red), as expected within the cavity bandwidth.

$$\alpha = \frac{\mathbf{H}_p^\dagger \mathbf{H}_s}{\mathbf{H}_s^\dagger \mathbf{H}_s}, \quad (9)$$

with $\mathbf{H}_k^\dagger$ denoting the complex conjugate transpose of the complex response vector. The rescaled s-polarization response is then defined as $H'_s(f) = \alpha H_s(f)$. This step minimizes the integrated squared deviation between the two channels and effectively removes any constant gain mismatch. Figure 4 shows the raw measured response for p-polarization (light blue) and s-polarization (dark red) corresponding to $H_p(f)$ and $H_s(f)$, as well as the rescaled s-polarization response $H'_s(f)$ (orange).

Ultimately, we are interested in the optical response of the cavity undisturbed by resonances from the piezoelectric transducer and its clamping mechanism. To quantify the degree to which the optical system responds differently to the two polarizations, we define the common-mode response as

$$H_{\text{avg}}(f) = \frac{1}{2} [H_p(f) + H'_s(f)], \quad (10)$$

and the complex fractional residual as

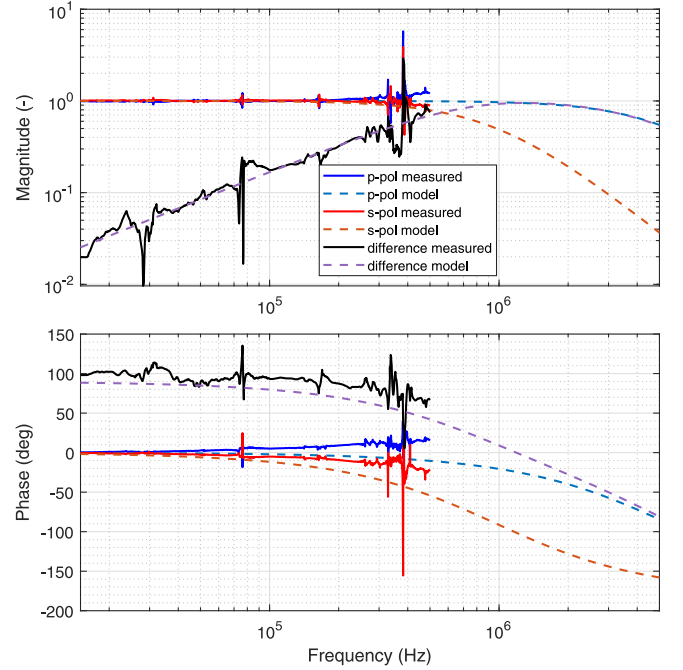


FIG. 5. Comparison of measured frequency responses of individual polarization modes (blue and red) with the analytical model of the optical cavity response (dashed light blue and dashed orange), and differential responses from postprocessing of measurement data (black) with the corresponding model (dashed purple).

$$H_{\text{res}}(f) = \frac{H_p(f) - H'_s(f)}{H_{\text{avg}}(f)}. \quad (11)$$

The residual function represents the polarization-induced asymmetry in the transfer function, normalized to the average system response. Its magnitude and phase provide frequency-resolved insight into how differently the system acts on the two polarization states. Figure 4 shows the common-mode response $H_k(f)/H_{\text{avg}}(f)$ for both p-polarization (blue) and s-polarization (red), which is, apart from some small features, close to the unity response expected for an optical cavity for signal frequencies well within its optical bandwidth.

To interpret the observed response and compare against the expected speedlike behavior, we constructed analytical transfer function models using a zero-pole-gain representation of the system components. Polarization-dependent cavity responses were modeled as second-order low-pass systems with distinct cutoff frequencies given by the different bandwidths for both polarizations. These simple models provided a reference for comparing measured and predicted behaviors of the system. Figure 5 shows an overview of the comparison between the model and measurement. The common mode response $H_k(f)/H_{\text{avg}}(f)$ for p-polarization (blue) and s-polarization (red), respectively, is the same as in Fig. 4 but now compared against the model of the optical

response shown in dashed lines. The measurement was performed up to 500 kHz, limited by the degrading piezo response at higher frequencies. Above 300 kHz, the measured response is deteriorating and coherence with the excitation is reduced, therefore, the cavity pole could not be resolved for either of the polarizations. Below the cavity pole of the s-polarization mode around 975 kHz, the differential mode is expected to behave linearly with frequency, and the measured differential response (black) is in good agreement with the response predicted by the model (dashed purple). With this, we demonstrate the speed measurement characteristic of the EPR speedmeter proof-of-concept experiment.

There are some dips in the measured differential response (black) coinciding with structures in the measured common-mode responses (blue and red). A potential explanation is the capacitive behavior of the piezoelectric transducer, which leads to electromagnetic radiation emitted at certain frequencies characteristic of the piezo at hand. At these frequencies, energy from the excitation is not converted to mirror motion, hence, there is a loss of coherence between the optical response and excitation.

IV. SUMMARY AND DISCUSSION

In this paper, we have presented a table-top proof-of-principle experiment of the EPR speedmeter, a concept proposed to mitigate backaction noise in gravitational wave detectors. The EPR speedmeter features an optical resonator for two polarization modes with different bandwidths, which was realized in the proof-of-principle experiment by a triangular cavity with different input mirror transmissivities for the two polarizations due to non-normal incidence. Readout of the differential response was realized by subtraction of demodulated, gain-matched reflection signals of the impedance-matched cavity with bandwidth 5.5 MHz for p-polarization and bandwidth 975 kHz for s-polarization. The measured differential response to motion of the cavity end mirror driven by a piezoelectric transducer in the frequency range 15 kHz to 500 kHz shows good agreement with the theoretical prediction featuring a vanishing response toward DC and increase of response $\propto i\Omega$ up to the cavity pole of the s-polarization mode.

In the triangular cavity scheme, backscattering from the mirrors can couple otherwise degenerate counterpropagating modes [37]. Such coupling would manifest as resonance splitting, which we do not observe with the current

sensitivity of the experiment. Related work by Korobko *et al.* [38] explores a hybrid configuration, where the traveling wave of a ring resonator is combined with the standing wave component of a Fabry-Perot resonator. Optical coupling introduced by a membrane enables a direct comparison between the optical response of a position meter and a speedmeter.

The current setup could still be improved, for example, by optimizing excitation parameters and longer averaging to yield a smoother speed response. Another aspect to investigate would be a speed readout in real time by implementing an analog electronics circuit for gain matching and signal subtraction. However, this would not change the main outcome of the setup, which was to demonstrate that this optical system indeed realizes a speedmeter with a classical speedlike response to mirror motion. In order to move further toward technical readiness of the speedmeter for implementation as an upgrade of future gravitational wave interferometers, one would have to demonstrate backaction noise suppression experimentally. This requires a quantum noise limited system with suspended mirrors in vacuum.

A natural place to test the EPR speedmeter configuration is prototype facilities, such as the AEI 10 m Prototype in Hannover (Germany), which was designed specifically to test techniques to surpass the SQL [39], or ETpathfinder in Maastricht (Netherlands), which is a cryogenic interferometer under construction with the aim to test technologies for the low-frequency part of the ET [40]. Practical implications of implementing the EPR speedmeter configuration and testing its alleged compatibility with established quantum noise reduction techniques, like squeezing, experimentally in such a prototype facility will be subject to future work.

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DATA AVAILABILITY

The data that support the findings of this study are openly available in [41].

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