PROCEEDINGS OF SCIENCE

Control scheme for the polarization circulation speed meter

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Speed meters are one of the approaches to mitigate the quantum radiation pressure noise in interferometric gravitational wave detectors, which limits the sensitivity at low frequencies. The most recent version of the speed meter concept is the Polarization Circulation Speed Meter (PCSM), which requires only modest modifications to the conventional interferometer design. To implement this design in real large-scale detectors, we need to test it in a table-top experiment to investigate potential difficulties. The primary challenge lies in controlling the length and alignment of the cavity formed by the input test masses and the polarization circulation mirror while maintaining a round-trip phase shift of π. In this proceeding, we introduce the concept of the speed-meter-type interferometer, provide a brief explanation of the control scheme for the PCSM, termed Dual-Retardance Control (Nishino, *et.al.,* 2023, Phys. Rev. **D** 107, 084029), and outline our future plans for conducting a proof-of-concept experiment.

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1. Introduction

The sensitivity of gravitational wave (GW) detectors is fundamentally limited by quantum noise, especially at low frequencies when seismic and thermal noise are well suppressed. At this point, the limitation comes from what is known as *quantum radiation pressure noise*, which gives rise to the standard quantum limit (SQL) in accordance with Heisenberg's uncertainty relation [1]. Techniques to overcome the SQL are called quantum non-demolition (QND) measurements [1, 2].

One of the QND measurements is the speed meter, a concept originally proposed by Braginsky and Khalili [3], which has been investigated in many practical implementations [4–7]. The quantum radiation pressure noise arises due to the amplitude fluctuations of vacuum fields entering the interferometer's anti-symmetric (AS) port, which interact with the pump laser and randomly perturb the mirrors [2]. In speed meters, the vacuum field interacts with the mirror twice with opposite signs, leading to a back-action force on the mirror given by:

$$\hat{F}_{\text{b.a.}}(\Omega) \simeq -i\Omega\tau\frac{2\hat{I}_c(\Omega)}{c}, \tag{1}$$

where $\Omega \ll 1/\tau$ represents low frequencies, $\hat{I}_c$ is the fluctuation part of the circulating laser power resulting from the coupling between vacuum fluctuation and the pump laser, and c is the speed of light. The signal is proportional to the mean velocity ($\bar{v}$) at low frequencies:

$$\phi(t) \propto \hat{x}(t+\tau) - \hat{x}(t) \tag{2}$$

$$\sim \tau\bar{v}, \tag{3}$$

where $\phi(t)$ represents the phase modulation of light, and $x(t)$ is the displacement of the mirrors.

The advantage of speed meters lies in their capability to achieve broadband sensitivity improvement at low frequencies, and when combined with balanced homodyne detection, they can surpass the free mass SQL without requiring frequency-dependent homodyne angles or additional filter cavities [2, 8].

2. Background

2.1 Mechanism of the polarization-circulation speed meter

Figure 1 illustrates the schematic design of the Polarization Circulation Speed Meter (PCSM). The primary interferometer resembles the conventional Fabry-Perot Michelson-type position meter. At the AS port, there are two polarization optics, namely, a quarter-wave plate (QWP) and a polarization beam splitter (PBS), collectively referred to as the polarization circulator (PC). The cavity formed by the polarization circulation mirror (PCM) and the input test masses (ITMs) is called the polarization circulation cavity (PCC).

The polarization circulator works as followings: The p-polarized (p-pol) vacuum fluctuation from the AS port undergoes conversion by the QWP and becomes the left-polarization vacuum (l-pol, represented by $\hat{a}_l$). This left-polarized vacuum couples with the pump laser and causes random perturbations to the mirror. Subsequently, the vacuum field (denoted as $\hat{b}_l$) returns to the

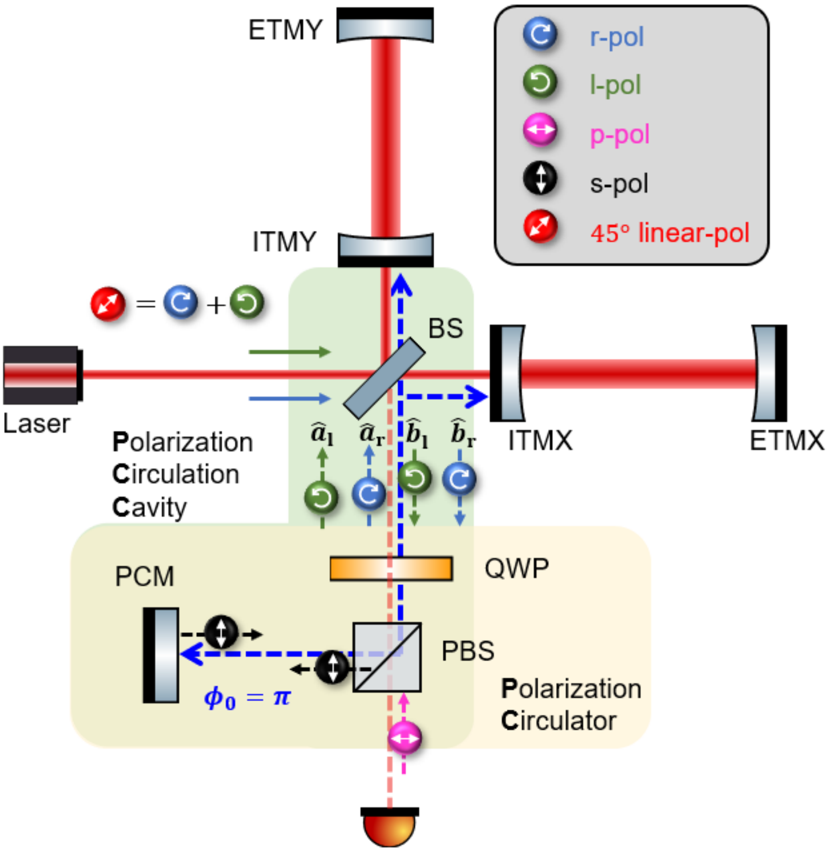

Figure 1: Configuration of the PCSM [6]. The Quarter-Wave Plate (QWP) turns the polarization state of the vacuum, enabling it to interact with the interferometer twice. The Polarization Circulator (PC) comprises the QWP, Polarization Beam Splitter (PBS), and Polarization Circulation Mirror (PCM), while the Polarization Circulation Cavity (PCC) is a cavity formed by the PCM and the Input Test Masses (ITMs) with the QWP and PBS incorporated inside. Here, (E)ITMs represent (end) input test masses.

AS port, where it is transformed into s-polarization (s-pol). The s-pol beam is then reflected by the PBS, completing a round trip to reach the PCM. Here, it gets converted back to right-polarization (r-pol) by the QWP, eventually reaching the beam splitter (BS) as a field denoted by a_r. The r-pol beam perturbs the mirror again, returns to the AS port (denoted as $\hat{b}_r$), and finally passes through the PBS. By ensuring that the round-trip phase shift between the ITMs and PCM remains at π, the radiation pressure forces generated by $\hat{a}_r$ and $\hat{a}_l$ through a bite note with the main carrier exhibit opposite signs and effectively cancel out each other.

The advantage of the PCSM is that one only needs a slight modification to the AS port optics while retaining the structure of the Michelson interferometer intact. Also, by switching the light path in the AS port, the interferometer modes can be switched from the position-meter type to the speed-meter type, and vice versa, corresponding to the situation.

2.2 Difficulty in the control

It is crucial for the PCSM to control the round-trip phase inside the PCC at π. In the current GW detectors, the Pound-Drever-Hall (PDH) method is employed to control the length of a cavity. The PDH method is a scheme to stabilize the distance between two mirrors on a nanometer scale [9]. In the PDH method, the length fluctuation of the cavities is sensed by taking a beat note between the signal sideband generated by the mirror motion and the local-oscillator sideband generated by an electro-optic modulator (EOM).

However, the same PDH locking method cannot be applied to the PCC in the PCSM. The PCC allows the infrared (IR) beam to circulate inside it only twice at most, due to the presence of the QWP and PBS. Consequently, the finesse of the PCC is almost zero, posing a problem as signal sidebands cannot be effectively amplified. For this reason, the traditional PDH method cannot be used for the PCC.

3. Dual-retardance control

To form a cavity with the Polarization Circulation Mirror (PCM) and Input Test Masses (ITMs), it is necessary to have the waveplate retain the polarization state, ensuring that the PBS does not discard any light. This requirement can be fulfilled using a dual-retardance waveplate, which functions as a QWP for the IR light but as a half-wave plate (HWP) for a green (GR) laser. The

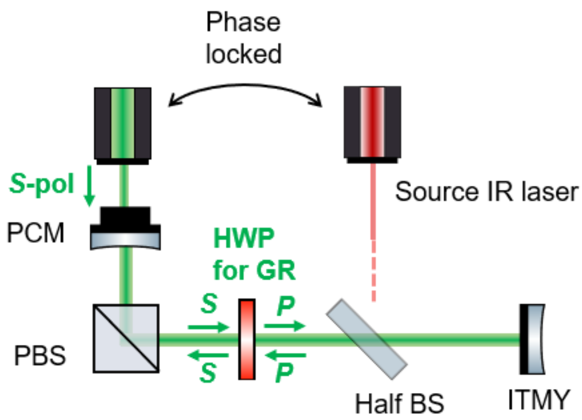

Figure 2: Conceptual illustration of the DRC [10]. We prepare a dual-retardance waveplate that acts as a QWP for the IR and HWP for GR. It turns the polarization from s-pol to p-pol or p-pol to s-pol, but it can be kept to only s-pol between the PCM and the HWP.

retardance of a waveplate can be expressed as:

$$\phi_{\mathrm{ret}} = 2\pi \frac{(n_s - n_f)d}{\lambda}, \tag{4}$$

where n_s and n_f are the refractive indices along the slow and fast axes, respectively, λ is the wavelength of the light, and d is the thickness of the waveplate. When the waveplate operates as a QWP at the wavelength of λ, it should function as a HWP at the wavelength of $\lambda/2$. A HWP maintains the polarization state during round-trip transmission (see Fig. 2). By injecting a laser with half the wavelength of the main interferometer beam from behind the PCM with *s*-polarization, it can resonate inside the PCC. This proposed scheme is referred to as the dual-retardance control (DRC) [10].

The benefit of the DRC is that the mirror-motion sideband is amplified inside the PCC. This amplification enables us to lock the PCC length stably. Also, the DRC allows us to employ the wave-front sensing method for mirror-alignment control, which is commonly used in the current large-scale detectors.

As depicted in Fig. 2, the GR laser frequency should be phase-locked to the main IR frequency with a tunable frequency offset. Additionally, the IR and GR beams must be co-aligned. To achieve this, we necessitate an additional cavity outside the PCC, for instance, a ring cavity can be employed to co-align the paths of the IR and GR light (see Fig.3a).

4. Proof-of-concept experiment

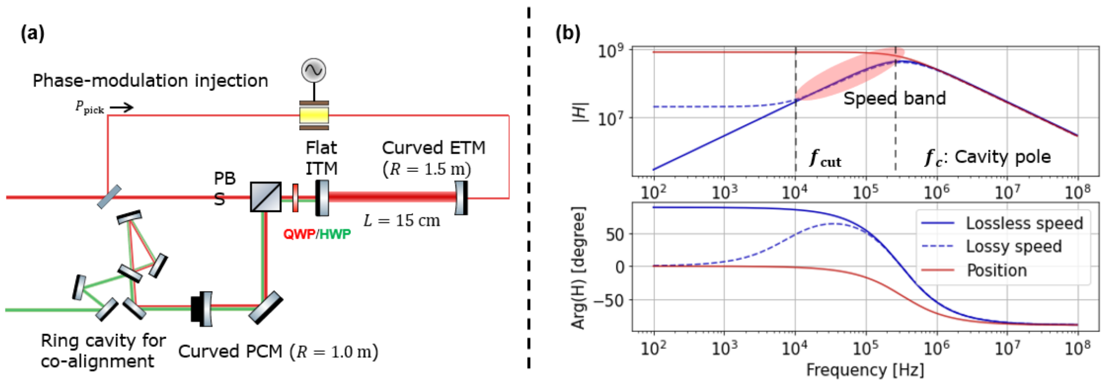

Figure 3: (a) Optical layout of the proof-of-concept experiment. The basic configuration is a 15-cm Fabry-Pérot cavity. The GR laser is injected from behind the PCM. The GR laser phase is locked to the main IR source laser. (b) Expected transfer function. The red curve shows the transfer function of the position-meter type configuration. The blue curve shows the speed-meter-type response in the lossless case and the dashed curve is that when losses are included.

Fig.3a illustrates the experimental setup for demonstrating the DRC. For simplicity, we employ a single optical cavity instead of the Michelson interferometer. The GR laser is generated through the second harmonic generation and phase-locked to the main IR laser. The basic design comprises a 15-cm-long rigid Fabry-Pérot cavity with flat Input Test Mass (ITM) and curved End Test Mass (ETM). The cavity is controlled using the Pound-Drever-Hall (PDH) technique and the error signal of the PCC obtained through the GR PDH technique is fed back to the PCM.

The primary objective of this experiment is to observe the f-proportional structure in the transfer function in the frequency range between $\gamma_{\rm cut}$ and $\gamma_{\rm c}$ as shown in Fig.3b and evaluate the performance of the dual-retardance control. A small portion of the main IR beam is extracted before the PBS and injected from the anti-reflection side of the ETM. This light undergoes phase modulation via another EOM to generate sidebands that simulate pseudo-gravitational wave signals. Considering that the carrier is resonant in the arm cavities, the amplitude reflectivity of a single arm cavity can be expressed as:

$$r(\Omega) \simeq \frac{\gamma_1 - \gamma_2 + i\Omega}{\gamma_1 + \gamma_2 - i\Omega}, \tag{5}$$

where Ω represents the frequency of an audio sideband. γ_1 and γ_2 are defined as:

$$\gamma_1 \equiv \frac{cT_{\mathrm{ITM}}}{4l_{\mathrm{arm}}} \text{ (cavity pole)}, \tag{6}$$

$$\gamma_2 \equiv \frac{c\mathcal{L}_{\mathrm{arm}}}{4l_{\mathrm{arm}}}. \tag{7}$$

and $\gamma = \gamma_1 + \gamma_2$ is the effective bandwidth of the cavity. Here, T_{ITM} denotes the power transmissivity of the input mirror, $\mathcal{L}_{\mathrm{arm}}$ is the round-trip power loss of the arm cavity, with l_{arm} being the length of the arm cavity and c is the speed of light. Indicating the round-trip power loss in the PCC as $\mathcal{L}_{\mathrm{PCC}}$, the transfer function G_{speed} can be written as:

$$\begin{aligned} G_{\mathrm{speed}}(\Omega) &\propto \frac{1 - (1 - \mathcal{L}_{\mathrm{PCC}}) r(\Omega)}{2} \\ &\simeq \frac{\gamma_2 + \mathcal{L}_{\mathrm{PCC}}\gamma_1/2 - i\Omega}{\gamma_1 - i\Omega}, \end{aligned} \tag{8}$$

From this formula, the cutoff generated by internal losses is derived as $\gamma_{\mathrm{cut}} = \gamma_2 + \mathcal{L}_{\mathrm{PCC}}\gamma_1/2$. The transfer function from the phase modulation to the differential arm output is expected to have a zero and pole as depicted in Fig.3b.

5. Summary and prospect

In this study, we summarized the control scheme of the polarization circulation speed meter [10], which is the latest incarnation of the speed-meter-type interferometer. The proposed scheme ensures a stable length control of the polarization circulation cavity, which is a crucial element of the PCSM. Currently, we are in the process of conducting an experimental demonstration using a single Fabry-Pérot cavity, and the setup is currently under construction.

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