Demonstration of a dual-pass differential Fabry–Perot interferometer for future interferometric space gravitational wave antennas

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Abstract

A dual-pass differential Fabry–Perot interferometer (DPDFPI) is one candidate of the interferometer configurations utilized in future Fabry–Perot type space gravitational wave antennas, such as Deci-hertz Interferometer Gravitational wave Observatory. In this paper, the working principle of the DPDFPI has been investigated and necessity to adjust the absolute length of the cavity for the operation of the DPDFPI has been found. In addition, using the 55 cm-long prototype, the operation of the DPDFPI has been demonstrated for the first time and it has been confirmed that the adjustment of the absolute arm length reduces the cavity detuning as expected. This work provides the proof of concept of the DPDFPI for application to the future Fabry–Perot type space gravitational wave antennas.

Keywords: gravitational wave, space mission, laser interferometer, Fabry–Perot cavity, control system

(Some figures may appear in colour only in the online journal)

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1. Introduction

The first detection of the gravitational wave from the black hole binary by the Advanced Laser Interferometer Gravitational-wave Observatory (aLIGO) opened the era of the gravitational wave physics and astronomy [1]. The first detection has been followed by many detections of the gravitational wave from the black hole and neutron star binaries [2, 3]. The gravitational wave detections and its electromagnetic follow-up observations have already provided significant physical and astronomical information [4, 5].

For further expansion of the gravitational wave physics and astronomy, we need to observe manifold classes of the gravitational wave sources. In other words, expanding the observation frequency is required [6–8]. Although stellar-mass objects, ∼1–100 M⊙ (M⊙ is the solar mass), have been observed by aLIGO and Advanced Virgo [9] around 100 Hz, a relatively heavy object, e.g. ∼10³ M⊙ is still an attractive observational target around 0.1 Hz [10, 11].

The upper observable mass bound, i.e. lower limit of the observation frequency range, of aLIGO and the other ground-based detector is mainly limited by ground motion [12, 13]. Thus, in order to observe the heavy objects, space gravitational wave antennas have been proposed, such as laser interferometer space antenna [14], Big Bang Observer [15], TianQin [16], Taiji [17], TianGO [18], and DECi-hertz Interferometer Gravitational Wave Observatory (DECIGO) [19].

Among them, DECIGO and its precursor proposal, B-DECIGO [20], are planning to utilize a Fabry–Perot interferometer to enhance the sensitivity around 0.1 Hz. The Fabry–Perot interferometer gives DECIGO the possibility even to observe a stochastic gravitational wave background generated in the early Universe [21–24]. Therefore, when the Fabry–Perot type space gravitational wave observatory is realized, new gravitational wave physical and astronomical knowledge will be provided by the observation of the astronomical objects that have not been detected.

There are, however, some challenges for the use of the Fabry–Perot cavity in space missions. One of the challenges is how to ensure the redundancy with as a small number of components as possible. In space missions, the total mass of the components is critical since it is strongly restricted by the ability of the launch system. One proposed solution to ensure the redundancy is a dual-pass Fabry–Perot interferometer configuration [19]. In this configuration, the Fabry–Perot cavity is designed to be critically coupled and two lasers from two sources are injected into the cavity from both cavity mirrors. Consequently, the cavity signal can be measured with both lasers. As a result, the redundancy of the interferometer operation is provided by the minimum number of the mirrors.

For further proceedings of the dual-pass Fabry–Perot interferometer concept in the gravitational wave detector, it was necessary to investigate a realistic proposal on the concept. In this paper, we propose a realistic dual-pass Fabry–Perot interferometer configuration, a dual-pass differential Fabry–Perot interferometer (DPDFPI). Figure 1 shows the schematic of the DPDFPI. In the DPDFPI, the gravitational wave signal is mainly obtained with a differential Fabry–Perot interferometer, which is adopted in some ground-based gravitational wave detectors [25, 26]. As another configuration with the dual-pass Fabry–Perot interferometer, a back-linked Fabry–Perot interferometer was also proposed [27]. It uses two laser sources in one satellite for each cavity metrology and the gravitational wave signal is obtained by making two lasers interfere in one satellite. Compared with the back-linked Fabry–Perot interferometer, the DPDFPI requires the relatively simple optical configuration without the back-link interferometer. However, in the DPDFPI shown in figure 1, we need to consider a new control
Figure 1. Schematic view of the DPDFPI considered for DECIGO. PD is a photodetector, EOM is an electro-optic modulator, BS is a beam splitter, and TM is a test mass. Instruments in the dashed circle are placed in one station, i.e. one satellite in the space detector. For decoupling, the frequency of the lasers are shifted from each other and the polarization of the lasers input to one cavity is orthogonalized.

topology among three cavities peculiar to the DPDFPI since the cavity mirrors are shared with each other interferometer. In this paper, we analytically investigate the working principle of the DPDFPI for the first time and show the requirement of the cavity length adjustment for the operation of the DPDFPI. Moreover, we constructed the first experimental prototype of the DPDFPI for its proof of concept.

2. Formalization of the dual-pass differential Fabry–Perot interferometer

We present the working principle of the DPDFPI using the block diagram. Figure 2 shows the block diagram of the DPDFPI shown in figure 1. For the measurement with the Fabry–Perot cavity, we need to make it resonate using, for example, Pound–Drever–Hall technique [28]. Usually, the servo system is used to keep the resonance and even to perform sensitive gravitational wave observation. Notice that the frequency of the lasers in the DPDFPI is shifted from each other for decoupling. The signal flow of the DPDFPI shown in figure 1 is presented in table 1. The length signal, i.e. the resonant frequency, of the cavity C is fed back to the laser 1 and 2. With this feedback system, the frequency of the laser 1 and 2 are controlled at the resonant frequency of the cavity C. Then, the resonant frequency of the cavity A and B are compared with the frequency of the laser 2 and 1, respectively, and are controlled by actuating the position of the mirrors, TM2A and TM1B, respectively. In addition, the length signal of the cavity A is fed back to the laser 3 with the consequence that the frequency of the laser 3 is controlled at the resonant frequency of the cavity A. Thanks to the above feedback system, the laser 1 (2) resonates with the cavity B and C (A and C) and the laser 3 resonates with the cavity A. One consideration is that the length signal measured with the PD3B cannot be fed back to the
length of the cavity B or the frequency of the laser 3 since the feedback paths are occupied by the other signals. Therefore, we need some method to reduce the detuning of the cavity B from the laser 3 as discussed later. If the laser 3 resonates with the cavity B, the obtained signals in the feedback system shown in figure 2 are expressed as,

\[
s_{PD_{1B}} = \frac{1}{1 + G_{2A}^{\nu_2} L_{C}} \left( \frac{G_{2A}}{1 + G_{2A}} L_{C} \Delta x_{C} + \frac{1}{1 + G_{2A}} L_{B} \delta \nu_{1} \right),
\]

\[
s_{PD_{3C}} = \frac{1}{1 + G_{2A}^{\nu_3}} \left( \Delta x_{C} + L_{C} \delta \nu_{1} \right),
\]

\[
s_{PD_{2C}} = \frac{1}{1 + G_{2C}^{\nu_2}} \left( \Delta x_{C} + L_{C} \delta \nu_{2} \right),
\]

\[
s_{PD_{2A}} = \frac{1}{1 + G_{2A}^{\nu_2}} \left( -\frac{G_{2A}}{1 + G_{2A}} L_{C} \Delta x_{C} + \Delta x_{A} + \frac{1}{1 + G_{2A}} L_{A} \delta \nu_{2} \right),
\]

\[
s_{PD_{3A}} = \frac{1}{1 + G_{2A}^{\nu_3}} \left( \frac{G_{2A}}{1 + G_{2A}} L_{C} \Delta x_{C} + \frac{1}{1 + G_{2A}} L_{B} \delta \nu_{3} \right) - \frac{1}{1 + G_{2A}^{\nu_2}} \frac{L_{B}}{L_{C}} \Delta x_{C},
\]

\[
\begin{align}
\frac{1}{1 + G_{2A}^{\nu_2}} \frac{L_{B}}{L_{C}} \Delta x_{C} & - \frac{1}{1 + G_{2A}^{\nu_2}} \frac{L_{B}}{L_{C}} \Delta x_{A} + \frac{1}{1 + G_{2A}^{\nu_2}} \frac{L_{B}}{L_{C}} \Delta x_{B} \\
& - \frac{1}{1 + G_{2A}^{\nu_2}} \frac{G_{2A}}{1 + G_{2A}^{\nu_2}} L_{A} \Delta x_{A} + \frac{1}{1 + G_{2A}^{\nu_2}} \frac{G_{2A}}{1 + G_{2A}^{\nu_2}} L_{B} \Delta x_{B} \\
& - \frac{1}{1 + G_{2A}^{\nu_2}} \frac{G_{2A}}{1 + G_{2A}^{\nu_2}} L_{B} \Delta x_{B} + \frac{1}{1 + G_{2A}^{\nu_2}} \frac{G_{2A}}{1 + G_{2A}^{\nu_2}} L_{B} \Delta x_{A}
\end{align}
\]

where \( \Delta x_{A} \equiv x_{3A} - x_{2A}, \Delta x_{B} \equiv x_{1B} - x_{3B}, \) and \( \Delta x_{C} \equiv x_{2C} - x_{1C} \) are the cavity length fluctuation, \( x_{i0} \) (\( i = 1, 2, 3 \) and \( \alpha = A, B, C \)) are the longitudinal displacement of each test mass, \( \nu_{i} \) are the laser frequency of the laser \( i, \delta \nu_{i} \) are its fluctuation, \( L_{i} \) are the cavity length of the cavity \( \alpha, s_{PD_{\alpha}} \) are the signal obtained with each photodetector, and \( G \) are the open loop gain.

When \( |G_{\nu_1}| \gg 1 \) and \( |G_{\nu_2}| \ll 1 \) (or \( G_{2A} \approx G_{1B} \)), \( s_{PD_{2A}}, s_{PD_{1B}}, \) and \( s_{PD_{1B}}, \) are denoted as

\[
s_{PD_{1B}} = \frac{1}{1 + G_{1B}^{\nu_1}} (-\Delta x_{C} + \Delta x_{B}),
\]

\[
s_{PD_{2A}} = \frac{1}{1 + G_{2A}^{\nu_2}} (-\Delta x_{C} + \Delta x_{A}),
\]

\[
s_{PD_{1B}} = \begin{cases} 
-\Delta x_{A} + \Delta x_{B} & (|G_{1B}| \ll 1, |G_{2A}| \ll 1) \\
\frac{1}{1 + G_{1B}^{\nu_1}} \left( -\Delta x_{A} + \Delta x_{B} \right) & (G_{2A} \approx G_{1B})
\end{cases}
\]

Here, we assume that all arm cavities have almost the same length, \( L \). Equations (7)–(9) indicate that differential signals between two cavities, which include gravitational wave signals, can be obtained in the DPDFFI.

Here, we explain how to reduce the detuning of the cavity B from the laser 3. Let us consider the frequency offset of the laser 2, \( \Delta \nu_{2}, \) from the resonant frequency of the cavity B, \( N_{c}^{x_{2B}} \).
Figure 2. Block diagram of the DPDFPI shown in figure 1. \( x_i \ (i = 1, 2, 3 \text{ and } \alpha = A, B, C) \) are the longitudinal displacement of each test mass, \( \nu_i \) are the laser frequency of the laser \( i \), \( \delta \nu_i \) are its fluctuation, \( L_\alpha \) are the cavity length of the cavity \( \alpha \), \( s_{PD\alpha} \) are the signal obtained with each photodetector, and \( G \) are the open loop gain.

Table 1. Signal flow of the DPDFPI shown in figure 1. The signal obtained with the photodetectors in the first column corresponds to the sensing objects in the second column and is fed back to the controller in the third column.

| Photodetector | Sensing object       | Controller |
|---------------|----------------------|------------|
| PD_{1B}       | Laser 1, cavity B    | TM_{1B}    |
| PD_{1C}       | Laser 1, cavity C    | Laser 1    |
| PD_{2C}       | Laser 2, cavity C    | Laser 2    |
| PD_{2A}       | Laser 2, cavity A    | TM_{2A}    |
| PD_{3A}       | Laser 3, cavity A    | Laser 3    |
| PD_{3B}       | Laser 3, cavity B    | —          |

\( (N \in \mathbb{N}) \). \( \Delta \nu_3 \) is expressed by

\[
\Delta \nu_3 \equiv \nu_3 - N \frac{c}{2L_B},
\]

where \( L_B \) is the length of the cavity B and \( c \) is the speed of light. Since the frequency of the laser 3 is controlled to follow the resonant frequency of the cavity A, \( \nu_3 \) is written as

\[
\nu_3 = N' \frac{c}{2L_A} \quad (N' \in \mathbb{N}),
\]

where \( L_A \) is the length of the cavity A. Hence, \( \Delta \nu_3 \) is denoted as

\[
\Delta \nu_3 = N' \frac{c}{2L_A} - N \frac{c}{2L_B}.
\]
When the length of the cavity A is \( L_A = L_B + \Delta L (|\Delta L| \ll L_B) \), \( \Delta \nu_3 \) is written as
\[
\Delta \nu_3 = \frac{c}{2L_B} \left( \Delta N - N \frac{\Delta L}{L_B} \right),
\]
where \( \Delta N \equiv N' - N \). Since \( \Delta L \) can be measured with non-interferometer sensors mounted in satellites, such as microwave ranging system [29], we can choose \( \Delta N \) to be the proper integer to \(-N \frac{\Delta L}{L_B}\) by adjusting \( \nu_3 \). Consequently, \( \Delta \nu_3 \) is constrained to be within
\[
|\Delta \nu_3| \leq \frac{c|\Delta L|}{2L_B^2}. \tag{14}
\]
This is because, when we change \( \Delta N \rightarrow \Delta N + 1 \) and \( N \rightarrow N + 1 \), \( \Delta \nu_3 \) is changed by the difference of the free spectral range of the cavity A and B as
\[
\left| \frac{c}{2L_A} - \frac{c}{2L_B} \right| = \frac{c|\Delta L|}{2L_B^2}. \tag{15}
\]
Here, we use the fact of \( |\Delta L| \ll L_B \). Equation (14) indicates that the cavity lengths should be adjusted to reduce the cavity detuning.

In order to resonate the cavity B with the laser 3, \( \Delta \nu_3 \) has to be well within the linewidth of the cavity B. For example, in DECIGO and B-DECIGO, the cavity linewidth is 15 Hz [20]. Thus we need to adjust the cavity length to be \( \Delta L \ll 100 \text{ km} \) for DECIGO (\( L = 1000 \text{ km} \)) and \( \Delta L \ll 1 \text{ km} \) for B-DECIGO (\( L = 100 \text{ km} \)) for the operation of the DPDFPI.

For the sensitive gravitational wave observation, it is necessary not only to resonate the cavity but also to reduce the interferometer noise. Specifically, the sensing noise coupled with the laser intensity fluctuation that is proportional to the cavity detuning needs to be reduced. For the reduction of the interferometer noise coupled with the detuning, e.g. laser intensity coupling noise, the requirement for \( \Delta L \) can be strict depending on the sensitivity requirement. For example, if the laser intensity coupling noise is considered, \( \Delta L < \frac{2h_{\text{req}}}{I_{\text{RIN}} \nu_3} \) where \( h_{\text{req}} \) is the sensitivity requirement, and \( I_{\text{RIN}} \) is a relative intensity noise of the input laser.

### 3. Experimental setup for the demonstration of the DPDFPI

Since the DPDFPI is the new interferometer configuration, the experimental demonstration of the DPDFPI is necessary. We perform the experiment to confirm the following two points that are characteristic of the DPDFPI: first, dependence of the laser frequency offset from the cavity resonant frequency on the cavity length difference discussed in the previous section, and, secondly, the operation of the DPDFPI to measure the differential cavity displacement signal. For the experimental demonstration, we construct the prototype of the DPDFPI. Figure 3 shows the schematic of the experiment of the DPDFPI prototype. In the DPDFPI prototype, only two cavities are used since the operation of the DPDFPI can be confirmed by evaluating the correlation of the signals measured with two lasers. Even in this setup, the key feature of the DPDFPI, i.e. the necessity of the cavity length adjustment for the interferometer operation, still remains. Thus, we need to adjust the length of the cavity A against the length of the cavity B to operate the interferometer.

In the experiment, we use two laser sources, Koheras AdjustiK C15 (laser 1) and Koheras BASIK X15 (laser 2), with a wavelength of 1550 nm. The output power of the laser 1 and the laser 2 are 10 mW and 30 mW, respectively. The laser beams are phase modulated with electro-optic modulators for the Pound–Drever–Hall technique [28]. After the electro-optic
modulators, the laser beams are split into two ways. One beam is injected into the main free-space interferometer, i.e. the DPDFPI, and another beam is injected into the fiber-based auxiliary interferometer for the cavity absolute length measurement, which is explained in appendix A. The length of the two cavities is measured to be $0.55340 \pm 0.00001$ m. The length of the cavity A is able to be adjusted using the stage with the movable stage. For the main cavities, the lasers are injected from both sides. The main cavities are composed of the mirrors having the same specification. Their radius of curvature is 2 m and their amplitude reflectivity is 0.992. The reflected and transmitted beams from the cavities are measured with the photodetectors and the cavity longitudinal signals are obtained with the Pound–Drever–Hall technique [28]. The two laser frequencies are shifted by one free spectral range of the cavity A, $c^2/L_A$. The cavity mirrors are placed on the optical bench that is isolated with the rubber stack. The resonant frequency of the optical bench is about 10 Hz.

4. Results and discussions of the demonstration experiment

We investigated the dependence of the frequency difference, $\Delta \nu$, between the frequency of the laser 1 and the resonant frequency of the cavity B on the cavity length difference between the cavity A and B. $\Delta \nu$ corresponds to $\Delta \nu_2$ in the previous discussion in section 2. The measured result is shown in figure 4. Figure 4 shows that $\Delta \nu$ is shifted depending on the cavity length difference. From figure 4, the relation between the frequency offset and the cavity length difference is determined to be $(-5.1 \pm 0.5) \times 10^8$ Hz m$^{-1}$ by linear fitting the measured data. The determined value is consistent with the expected value, $(-4.8976 \pm 0.0002) \times 10^8$ Hz m$^{-1}$, from equation (15) and the measured cavity length within the error ranges. Figure 4 also indicates that the cavity detuning that causes the laser intensity coupling noise discussed in section 2 can be suppressed by reducing the cavity length difference in the DPDFPI.
Figure 4. Measured frequency difference, $\Delta \nu$, between the frequency of the laser 1 and the resonant frequency of the cavity B. The solid line is determined by fitting the measured data.

Figure 5. Calibrated noise spectra of the DPDFPI measured with the PD$_{1B}$ and the PD$_{2B}$.

After the cavity length adjustment, the noise spectra of the interferometer were measured as shown in figure 5. The ‘1B’ and ‘2B’ curves represent the spectra measured with PD$_{1B}$ and PD$_{2B}$, respectively. Below the unity gain frequency of the frequency control loop of the laser 1 and the laser 2, the spectra shown in figure 5 indicate the differential length fluctuations of the cavity A and the cavity B as discussed in section 2. Note that the unity gain frequency of the frequency control loop of the laser 1 and the laser 2 were measured to be 2.9 kHz and 4.0 kHz, respectively. The peak at 50 Hz and its higher harmonics are caused by the power line. The ‘2B’ spectrum was calibrated from the feedback signal of the cavity length control loop using
Figure 6. Measured magnitude-squared amplitude (upper panel) and phase (lower panel) of the coherence between the signals from the PD1B and the PD2B. The dashed line is the significance threshold of the coherence, 0.06 [30].

the measured open loop gain and actuation efficiency. The actuation efficiency was measured by scanning the cavity length.

If the DPDFPI in figure 3 is properly operated, the correlated differential signals between the cavity A and the cavity B are measured with the PD1B and the PD2B. To check the correlation, the coherence between the signals from the PD1B and the PD2B is calculated as shown in figure 6. Figure 6 does not show a full coherence between around 80 and 400 Hz and above 1 kHz. The lack of the coherence is caused by the noises that are not correlated between the signals from the PD1B and the PD2B, for example the laser frequency noise. However, given the average number of 100 for the coherence measurement, the 95% significance threshold of the coherence is 0.06 [30]. Thus, figure 6 indicates that the two signals are coherent below \( \sim 1.5 \text{ kHz} \) as expected from the unity gain frequency of the frequency control loops of the laser 1 and the laser 2. Hence, the DPDFPI is conceived properly operated.

5. Conclusion

In this paper, we presented the working principle of the DPDFPI for the first time. For the operation of the DPDFPI, the absolute length adjustment is necessary. Moreover, using the 55 cm-long DPDFPI prototype, we demonstrated the operation of the DPDFPI and confirmed that adjustment of the absolute arm length reduced the cavity detuning as expected with our formulation. We conclude that the proof of concept of the interferometer sensing scheme that can be applied to the future Fabry–Perot type interferometric space gravitational wave antennas has been demonstrated theoretically and experimentally.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Appendix A. Cavity absolute length measurement

Here, we explain how to measure the absolute length of the cavity in our experiment. We adopt a similar scheme to [31, 32]. In the dual-pass cavity, two different lasers resonate with a cavity. Thus, by measuring the frequency difference between the two lasers, we are able to determine the cavity free spectral range, which is related with the cavity length. For example, in our experimental setup shown in figure 3, the frequency difference of the laser 1 and the laser 2, \( \nu_{\text{diff}} \), is expressed as

\[
\nu_{\text{diff}} = \frac{n c}{2L_A} = \frac{n' c}{2L_B} \quad (n, n' \in \mathbb{N}).
\]

\( (A.1) \)

Note that \( \frac{c}{2L_A} \) and \( \frac{c}{2L_B} \) are the free spectral range of the cavity A and the cavity B, respectively. When we know \( n (n') \), the cavity length \( L_A (L_B) \) can be determined by measuring \( \nu_{\text{diff}} \). \( \nu_{\text{diff}} \) is measured by observing the interference between the two lasers. In this work, \( n \) and \( n' \) are set to be 1 and the interference signal between the laser 1 and the laser 2 is measured with the PDbeat in figure 3.

It is worth noting that, even in the setup shown in figure 1, the cavity length can be measured with almost the same scheme used in figure 3. One difference is using the injected and transmitted laser of the cavity to obtain the interference signal. Although two injected lasers are interfered in this work, it is challenging to do the same thing in the space detectors where two laser sources are placed in the distant satellites.

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