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Displacement noise free interferometory for gravitational wave detection

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Abstract. We have demonstrated displacement- and frequency-noise-free laser interferometry (DFI) by partially implementing a recently proposed optical configuration using bidirectional Mach-Zehnder interferometers (MZIs). This partial implementation, the minimum necessary to be called DFI, has confirmed the essential feature of DFI: the combination of two MZI signals can be carried out in a way that cancels displacement noise of the mirrors and beam splitters while maintaining gravitational-wave signals. The attained maximum displacement noise suppression was 45 dB.

1. Introduction

The effect of gravitational wave (GW) and test mass motion are essentially different. The practical application of this fact to the GW antenna was addressed only recently in the references [1, 2]. As was shown theoretically, when each test mass in an N-test-mass array sends and receives light pulses from all other test masses, and if the array contains enough test masses [$N > (d+2)$, where d is the number of spatial dimensions of the array], then there exist combinations of time delays which do not sense test-mass motions or timing noises, but do sense gravitational waves. We will call configurations that cancel both timing and displacement noises displacement-noise-free interferometry (DFI).

Recently, practical optical designs of DFI using laser interferometry in three dimensions have been proposed [3]. In these configurations, the conventional, equal-arm Mach-Zehnder interferometer (MZI) was used as a building block to eliminate laser noise. Four such MZIs were combined, in such a way that they form two pairs of counterpropagating MZIs. Within each pair, the 2 MZIs share the same beam splitters and folding mirrors; subtraction of their outputs balances out displacement noise from motions of the folding mirrors. The two pairs share the same beam splitters, which allows the elimination of beam splitter displacement noise.

In this paper, we study DFI experimentally using a single pair of counterpropagating MZIs and a single pair of independent MZIs, demonstrating the elimination of folding mirror and beam splitter displacement noise.

2. Partial demonstration of 3-D DFI

As described in reference [3], the full configured 3D DFI is composed of two pairs of counterpropagating MZIs, for a total of four MZIs. MZIs of equal-arm length operated on the midfringe are insensitive to laser frequency noise, and by superimposing two counterpropagating MZIs on the same optical path, the displacements of the folding mirrors are sensed redundantly (once by each direction of the MZI) and can thus be unambiguously removed from the signal. An additional pair of counterpropagating MZIs can then be added, which shares beam splitters with the first pair—this second pair allows redundant sensing of beam splitter displacements. As discussed in [3], the signals from the four MZIs can be combined in such a way as to cancel the displacements of all the optics while retaining sensitivity to gravitational radiation.

For the experiment on folding mirror displacement, we have constructed a partial-DFI composed of a single pair of counterpropagating MZIs to demonstrate the cancellation properties of the DFI. The practical experimental setup is shown in Figure 1. The displacement-noise simulator (EOM1) should be located at the exact center of the arm, so the position of EOM1 was carefully tuned. One of the output ports of MZI 1 (output 1a) was monitored with a dc detector (DCPD) and an error signal created by subtracting a static offset; this signal was fed back to a PZT-actuated folding mirror (FM2) after appropriate filtering to give a midfringe locking control. Once the fringe of the MZI 1 is controlled, that of MZI 2 is also automatically controlled because the two MZIs share common optical paths. Other output beams (output 1b and 2a) were received with high-speed photodetectors to monitor differential optical path length variations. The polarization optics (HWP: half wave plate and PBS: polarizing beam splitter) just in front of both high-speed detectors act as an optical attenuator, which serves as a gain compensator for imbalanced outputs of the two detectors. The signals from high-speed photodetectors HPD1 and HPD2 were summed with a power combiner to produce a DFI output signal, which was then monitored with a network analyzer. The DFI features of bi-directional MZIs were demonstrated with a transfer function measurement from noise simulators to DFI output.

The results for displacement-noise suppression are shown in Figure 2. About 30 dB of suppression of displacement noise was attained in a wide frequency region, while the maximum attained suppression was 45 dB at a particular frequency band, achieved when we tuned for maximum suppression in that region. Any imbalance between the two MZI signals determines the suppression ratio; it is believed that the subtly different frequency response of our two photodetectors, which cannot be compensated by simple optical attenuators or path length tuning, was the limiting factor here.

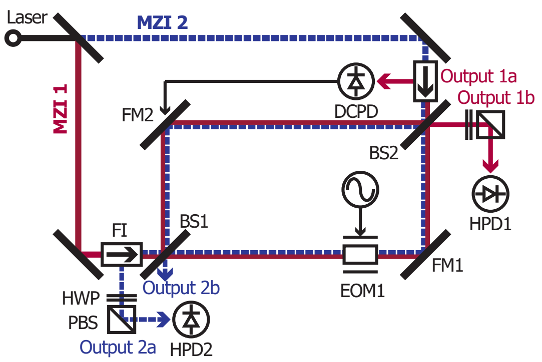

Figure 1. Experimental setup for cancellation of folding mirror displacement.

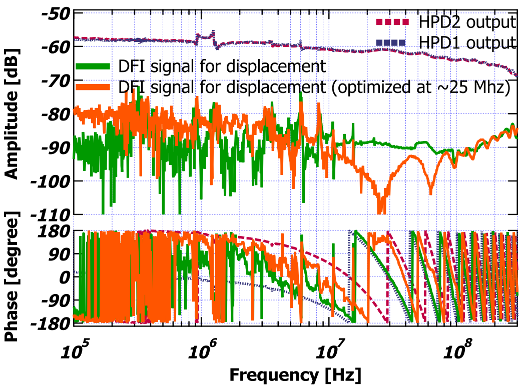

Figure 2. Cancellation of folding mirror displacement.

For the beamsplitter displacement, we have constructed another set of partial-DFI composed of a single pair of MZIs sharing a beamsplitter to demonstrate another cancellation property of the DFI. The practical experimental setup is shown in Figure 3 sharing input beam splitter (BS1). The laser beam is introduced into beamsplitter BS1, then split into two to form independent MZIs. The displacement-noise of the beam splitter was simulated by EOM3, which is located just after BS1. Displacement noise simulation is identical to the previous experiment. One of the output ports of MZI 1 and MZI 2 were monitored with dc detectors (DCPD) and error signals were fed back to a PZT-actuated folding mirrors (FM1 and FM2) independently after appropriate filtering to give midfringe locking control. Other output beams were received with high-speed photodetectors to monitor differential optical path length variations.

The results for displacement-noise suppression are shown in Figure 4. Both amplitude and phase for the two signals were tuned to match each other using optical attenuators and path length adjustments so that the displacement-noise signal disappears in the DFI signal. About 30 dB of suppression of displacement noise was attained in a wide frequency region, while the maximum attained suppression was 45 dB at a particular frequency band, achieved when we tuned for maximum suppression in that region.

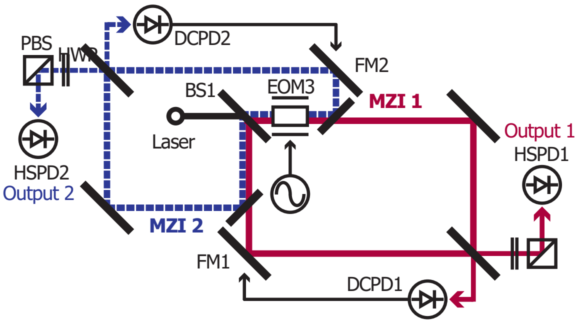

Figure 3. Experimental setup for cancellation of beamsplitter displacement.

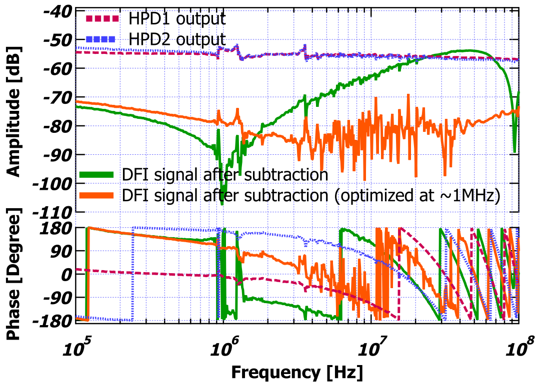

Figure 4. Cancellation of beamsplitter displacement.

3. Summary

We studied DFI experimentally using a single pair of counterpropagating MZIs and a single pair of independent MZIs, demonstrating the elimination of folding mirror and beam splitter displacement noise. The fundamental features of DFI were confirmed with these proof-of-principle experiments. The maximum attained suppression of displacement noise was 45 dB at a particular frequency band; it is believed that the subtly different frequency response of our two photodetectors was the limiting factor.

Acknowledgments

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