Noise cancellation properties of displacement noise free interferometer

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Abstract. We have demonstrated the practical feasibility of a displacement- and frequency-noise-free laser interferometer (DFI) by partially implementing a recently proposed optical configuration using bi-directional Mach-Zehnder interferometers (MZIs). The noise cancellation efficiency was evaluated by comparing the displacement noise spectrum of the MZIs and the DFI, demonstrating up to 50 dB of noise cancellation. In addition, the possible extension of DFI as QND device is explored.

1. Introduction
Gravitational waves (GWs) and test mass displacements have different effects on an interferometer. The idea of displacement noise (and frequency noise) free interferometry (DFI) is based on this fact and uses a network of interferometers to exploit it [1, 2]. DFI was suggested as a potential interferometer topology for third generation GW antennas in 2004. It can in principle cancel the effects displacements of optics (and laser frequency noise) completely in the whole frequency band: this is a frequency independent feature. The distinguishing aspect of this property is that DFI cancellation does not depend on the driving force (disturbance) on the optics. DFI can cancel the optic’s motion driven by any kind of disturbances, even including quantum effects from the light such as quantum radiation pressure noise. This can allow an ultimate sensitivity limited only by the quantum shot-noise. The key challenge is that DFI should have finite response to GW signal at the same time. The effect of GW and test mass displacement are indistinguishable in the low frequency limit, which means that DFI will certainly cancel the GW signal out to some extent in some frequency bands. The key task is to realize a DFI topology with reasonable sensitivity to GWs in the frequency range of our interest, which is still a challenge to work on.

After the invention of a practical topology for DFI using conventional laser interferometry [3], several proof-of-principle experiments were performed to demonstrate the fundamental feature of DFI [4, 5]. In these experiments, the characteristics of noise cancellation and a response to GW signals are confirmed to be as expected using artificial excitations simulating the displacement of optics and GW signals.

In this article, we focus on the cancellation properties of naturally existing displacement noise in the frequency domain by measuring the interferometer sensitivity spectrum. A significant
suppression of displacement noise (presumably seismic disturbances) was observed in the low frequency band, but there still remain some practical noise contributions that cannot be cancelled out with DFI mechanism. These may come from an “asymmetry” of the instrument in a broad sense, which can easily degrade the cancellation efficiency of the DFI. However, once these technical noises have been overcome, the DFI will be limited only by the quantum shot noise. Thus, DFI will have no equivalent of the concept of “standard quantum limit (SQL)” for conventional free mass laser interferometers, and that implies the capability of free mass laser interferometry to go far beyond the SQL. Thus, the idea to use DFI as a QND device is discussed in this article, together with the current status of the experiment.

2. DFI experiments

2.1. Proof-of-principle experiments

Practical optical topologies of DFI using conventional laser interferometry in two and three dimensions have been proposed recently [3]. There are many possible configurations to build a DFI, but the proposed ones are particularly simple. In these configurations, the conventional, equal-arm Mach-Zehnder interferometer was used as a building block to eliminate laser frequency noise. Four such Mach-Zehnder interferometers were combined, in such a way that they form two pairs of counter propagating Mach-Zehnder interferometers. Within each pair, the 2 Mach-Zehnders share the same beam splitters and folding mirrors; subtraction of their outputs eliminates 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. It should be mentioned that DFI configurations work only for nonzero frequencies, because at DC gravitational waves are indistinguishable from relative mirror motions. We started to characterize DFI instruments with a series of proof-of-principle experiments using partial and full three-dimensional DFI topologies [4, 5]. The goal of these experiments was to confirm that DFI topologies work as GW detectors, while being insensitive to displacement noise. The scale of the interferometers was about a meter, so the optimal frequency for maximum response is around a few hundreds of MHz. This is because the frequency depends mainly on the scale of the instruments. The displacement noise and the GW signal were simulated using EOM phase modulators with a bandwidth up to several hundreds of MHz. The transfer function from simulated source to the DFI output gives the cancellation property for displacement noise and the response to simulated-GW signals. Thus, these experiments were performed with an artificial excitation in a relatively high frequency region.

2.2. Demonstration experiments

Following the completion of a series of proof-of-principle experiments, we had moved to a demonstration experiment. Our next interest was to operate a DFI in the terrestrial detector band to see the characteristics of DFI. This is because there are natural displacement noises (mainly driven by seismic and acoustic disturbances) to be suppressed by the DFI mechanism, and because this experiment directly connected the extension of DFI to a QND device, which will be described in a later section 3.

The setup is as simple as in one of the previous experiments, but we now focus on observing a natural displacement noise and its suppression. Thus we now use the noise spectrum instead of the transfer function to assess the performance. The goal of this experiment is to see the suppression of displacement noise to achieve quantum shot noise levels down to the 1 Hz region, in combination with the elimination of other technical noises that are not within the scope of DFI.

For this experiment we have used a partial-DFI composed of a single pair of counter propagating MZIs to demonstrate the cancellation properties of the DFI. The practical experimental setup is shown in Figure 1, which is very similar to that of a previous setup.
Figure 1. The experimental setup for the practical demonstration of DFI. This is one pair of bi-directional MZIs, which is part of a 3D DFI, to confirm the cancellation efficiency for both folding mirrors and the beam splitters.

The laser source is a commercial solid-state Nd:YAG laser (Innolight Mephius) yielding 500 mW at 1064 nm. The output beam is split into two, and each beam enters a MZI after passing through polarizing beamsplitter (PBS), which allow the detection of light exiting the counter propagating MZI. The light paths of both MZIs are carefully adjusted and superposed on each other so that the two MZIs can exactly share the displacement noise. With this setup, the displacement effects from the two folding mirrors should cancel out, while that of the beam splitters will not, because this setup is only one building block of a full DFI. However, some suppression of displacement noise can be expected depending on the scale of the instrument and the frequency of interest. Thus, the arm length of the MZIs affects the cancellation efficiency of the displacement noise; in this experiment, the arm lengths were chosen to be about $l = 10$ cm, to ensure the ideal balance up to $\ell \omega / c \approx 160$ dB around $\omega = 1$ Hz.

Both output ports of MZI 1 (output 1a and 1b) were monitored with two identical dc detectors (DCPD) to provide a differential error signal; this signal was fed back to a PZT-actuated folding mirror (FM2) after appropriate filtering to give a mid-fringe locking control. The control bandwidth was very low, around a few hundred Hz. 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. The other two output ports (output 2a and 2b) were equipped with dc detectors to monitor the differential optical path length variations affecting the MZI 2 sensitivity. The differential error signals from MZI 1 and MZI 2 were subtracted with an instrumentation amplifier to produce the DFI output signal, which was then monitored with a dynamic signal analyzer (Agilent 35670A). The DFI features of the bi-directional MZI setup were confirmed by comparing the spectra of the single MZIs and DFI in the frequency domain.

The results for displacement-noise suppression are shown in Figure 2. The sensitivities of the MZIs are limited by shot noise above 1 kHz corresponding to tens of mW of power on the beam splitter, while presumable seismic noise is dominant at lower frequencies. Proving this, the DFI sensitivity showed a significant reduction of structured noise, which a cancellation of up to 50 dB. The DFI output was shot noise limited down to around 200 Hz, however, there remained some technical noise which the DFI mechanism cannot suppress. It is inferred that any “asymmetry” of the instruments in a broad sense, i.e. optical, mechanical and electronic imbalance, can easily degrade the performance of the DFI. We so far believe that this excess
noise came from such an asymmetry and is thus not a fundamental problem. Therefore making the instrument more symmetric is expected to reduce this excess noise.

3. Extension of DFI to a QND device
DFI is essentially capable of eliminating the displacement information of optics, which is a frequency independent and driving force independent feature. Any noise that appears as motion of optics, even if it arises from the quantum nature of light, will thus be cancelled in principle. Therefore, once technical noise sources have been eliminated, the DFI should be limited only by the quantum shot noise at all frequencies. Thus, DFI will have no analogue to the “standard quantum limit (SQL)” concept for conventional free mass laser interferometers, and this implies that free mass laser interferometers can have a sensitivity far below the SQL. At the same time, a DFI should have a reasonable response to GWs in the frequency band of interest, such that a DFI could be an excellent GW detector. However, the sensitivity to GWs depends on the exact DFI configuration, which is still a challenge to work on, and is beyond the scope of this article. So here we focus on a noise reduction aspect: the possibility to demonstrate sub-SQL measurement of the displacement using DFI.

A sketch of the sensitivity of MZIs is shown in Figure 3, assuming that they are limited by quantum shot noise and radiation pressure noise. When the setup described here is extended to an input-equivalent laser power of 100 W and 10 mg free mass, the sensitivity curve will touch the SQL level of $10^{-16}$ m/√Hz at 10 Hz. Although there is still room to improve the instrument configuration, this is already not so far from a practical design using current technologies.

4. Summary
We studied the practical features of DFI using a single pair of counter-propagating Mach-Zehnder interferometers to see the elimination of folding mirror and beam splitter displacement noise. The fundamental features of DFI were confirmed by a sensitivity spectrum measurement. The maximum attained suppression of displacement noise was 50 dB in a particular frequency band; it is believed that some asymmetry in the instruments was the limiting factor for the cancellation. In addition, the possibility of using DFI as a QND device was discussed. 100 W input laser power...
A sketch of quantum-noise-limited sensitivity of conventional MZIs. With 100 W-equivalent input power and free optics weighing only 10 mg, the sensitivity touches the $10^{-16}$ m/rHz QSL level at 10 Hz. If this sensitivity is reasonably attainable, DFI will be able to show the capability of sub-SQL displacement measurement below 10 Hz.

and 10 mg free mass with the current setup can move the SQL up to an attainable level with current technologies, but there is still room for improving the configuration.

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