Experimental demonstration of a Displacement noise Free Interferometry scheme for gravitational wave detectors showing displacement noise reduction at low frequencies

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Abstract

This paper reports an experimental demonstration of partial displacement noise free laser interferometry in the gravitational wave detection band. The used detuned Fabry-Perot cavity allows the isolation of the mimicked gravitational wave signal from the displacement noise on the cavities input mirror. By properly combining the reflected and transmitted signals from the cavity a reduction of the displacement noise was achieved. Our results represent the first experimental demonstration of this recently proposed displacement noise free laser interferometry scheme. Overall we show that the rejection ratio of the displacement noise to the gravitational wave signal was improved in the frequency range of 10 Hz to 10 kHz with a typical factor of $\sim 60$.

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I. INTRODUCTION TO DISPLACEMENT NOISE FREE INTERFEROMETRY

General Relativity describes gravity as the curvature of space-time. The theory predicts the existence of gravitational waves (GWs) which can be described as ripples of space-time propagating with the speed of light.

The detection of GWs is possible by measuring the variation $\delta l$ of the distance between two free masses but the predicted GW amplitude is so small which renders the detection very difficult. So far no instrument has detected any GW signals directly.

The sensitivity of the current GW detectors is limited by several noise sources. One group, usually referred to as displacement noises (DNs) directly moves the reflective part of the test masses. Current GW detectors are limited by displacement noise such as seismic noise, gravity gradient noise, thermal noise and radiation pressure noise at frequencies below 100 Hz.

The technology development for GW detectors has focused on reducing each of the noise contributions independently, e.g. suspension systems are employed to decouple optical components from the seismic motion of the environment. Several new ideas and concepts are under study to create a new generation of GW detectors with a strongly improved sensitivity [1–4]. In the context of future GW detectors a new idea called displacement and frequency noise free interferometry (DFI) was proposed by S.Kawamura and Y.Chen [5]. DFI is based on the fact that gravitational waves and displacement noise as well as frequency noise affect the light in a different manner and aims at reducing all displacement noises and frequency noise simultaneously. The realization of an experiment with multiple read-out channels where each single channel carries the gravitational wave signal and the noise information differently allows the creation of a channel that is completely free from frequency and displacement noises [6, 7].

The current experimental demonstrations of DFI affected only frequencies above $\sim 1$ MHz [8, 9]. However, the large-baseline gravitational wave detectors do not work in this band. Recently a new DFI scheme has been proposed which works in a low frequency region. A detuned Fabry-Perot (FP) cavity configuration [10] in combination with two lasers is used to partially remove the displacement noise from both cavity mirrors. One laser is used for the input cavity mirror (IM) and one is used for the end cavity mirror (EM) (Double Pumped Fabry-Perot cavity). Such a configuration, although it does not include
the frequency noise aspect of DFI, allows the isolation of GW signal from displacement noise in a wide range of frequencies. Basically for each laser the reflected and transmitted output signals of the detuned FP-cavity carry different GW and displacement noise information, due to the existence of the prompt reflected light. A proper combination of both signals results in the suppression of the displacement noise of the cavity’s input mirror. Here the mechanism of noise cancelation is completely different from the Chen-Kawamura’s mechanism. The latter uses the distributed nature of GW’s which results in different kind of responses. In the long wave approximation \( \lambda_{gw} \gg L \), where \( \lambda_{gw} \) is the GW wavelength and \( L \) is the cavity length, the leading order of the DFI signal for the detuned FP-cavity is \( h(L/\lambda_{gw})^0 \) which is much better than the \( h(L/\lambda_{gw})^2 \) that can be obtained from Chen-Kawamura DFI scheme [7]. Nevertheless the detuned FP-cavity scheme looses the optical resonant gain from the cavity which is in the order of \( c/\gamma L \), where \( \gamma \) is the cavity half bandwidth. Hence, the sensitivity of this scheme concerning GWs is strongly reduced compared to conventional interferometers and the noise performance of auxiliary optics becomes much more important. Hence, our experiment shows partial DFI because it is not completely DN free. Nevertheless we stick to the name DFI throughout this paper to be compatible with previous published papers [10] and address as DFI only the suppression of displacement noise of the cavity mirrors.

In this letter we present the first experimental proof of principle demonstration of the detuned FP cavity based DFI scheme proposed in [10]. We could thus verify the core concept of this new idea which is the basis for new proposed interferometer schemes [11]. We use one laser in combination with two homodyne detectors to strongly suppress the displacement noise of the input mirror of a FP-cavity with respect to a simulated GW signal. As a result we gain a factor of \( \sim 60 \) in the GW signal to displacement noise ratio in the whole frequency range of interest.

II. DFI CONFIGURATION: DETUNED FP-CAVITY

A detuned FP-cavity pumped through one side (see Fig. 1) guarantees the existence of one channel in reflection (S1) and one in transmission (S2) which contain GW and DN information in a different ratio. The difference is due to the existence of the directly reflected light which occurs only on the input cavity mirror. This directly reflected light contains only the information about the position of mirror IM and not the position of mirror EM [10].
The response of the transmitted signal measured in S2 can be written as:

\[ S2 = q_1 (\phi_{GW} + \phi_{EM} - \phi_{IM}) + \phi_{S2}, \]  

where \( q_1 \) represents the resonant gain factor of the cavity, \( \phi_{GW}, \phi_{EM}, \phi_{IM} \) are the phases accumulated in the cavity due respectively to GW signal and the displacements of both the cavity mirrors EM and IM and \( \phi_{S2} \) is the phase induced by the optical elements which the light encounters before it is detected in S2. The response of the reflected signal measured in S1 is written:

\[ S1 = p(\phi_{IM} - \phi_{S1}) + q_2 (\phi_{GW} + \phi_{EM} - \phi_{IM}), \]  

where \( p \) describes the 'prompt' reflected light from the input cavity mirror, \( q_2 \) is the resonant gain factor of the cavity, and \( \phi_{S1} \) describes the phase changes induced by all the auxiliary optical elements the light passes before it is detected in S1. Using only one laser one can find a certain linear combination of the reflected and the transmitted signals which will partially remove the displacement noise fluctuation from mirror IM while the displacement noise of mirror EM and the simulated GW information remain. If a second laser is used and coupled into the cavity through mirror EM simultaneously and another two homodyne detectors are set up, two more output channels are available. Only a proper linear combination S of all four output channels allows to suppress the displacement noise of both mirrors while the GW signal is retained. Using the approximation \( \delta \tau, \gamma \tau \ll 1 \) with \( \tau = L/c \), the DFI response in the latter case for a cavity with two equal mirrors and L length is given by [10]:

\[ S = p(\phi_{GW} + \phi_{S2} - \phi_{S1}) \approx \frac{i\delta}{\gamma - i\delta} (\phi_{GW} + \phi_{S2} - \phi_{S1}), \]  

where \( \delta \) and \( \gamma \) are respectively the cavity detuning and the cavity half bandwidth. It can be noticed that the optimal case of the GW response is given when the \( p \) factor is approximately one which requires a large detuning compared with the cavity half bandwidth \( (\delta \gg \gamma) \).

### III. EXPERIMENTAL SET-UP

Our experimental setup is shown in Fig. 1. The laser source is a commercial solid state Nd:YAG yielding 1W at 1064nm. The light originating from the laser is split into two beams, one to pump the FP cavity and one to provide the two local oscillators (LO) for
FIG. 1: Experimental setup of our DFI experiment using a detuned FP cavity. The laser pumps the cavity through the mirror IM. The reflected light is measured with homodyne detector HD1 while the transmitted light is measured with homodyne detector HD2. The cavity length is 30 cm, the bandwidth $2\gamma$ is 2.4 MHz and the detuning $\delta$ is 12 MHz. The cavity is controlled in its detuned state with the Pound-Drever-Hall technique: The feedback signal is applied to the PZT attached to the input cavity mirror. The two homodyne detectors are controlled using the difference photocurrents $S_1$ and $S_2$ as error signal while the feedback is applied to the phase shifters PS1 and PS2 respectively. $S_1$ and $S_2$ are used for the transfer function measurements of the displacement noise and GW signal as well.

The homodyne detectors HD1 and HD2. The FP cavity is formed by two identical mirrors which are separated by 30 cm. Each mirror has a power reflectivity of 98.5% and a radius of curvature of 1 m resulting in a cavity bandwidth $2\gamma$ of 2.4 MHz.

PD$_{cav}$ is used to detect the reflected light from the cavity and to generate an error signal using the Pound-Drever-Hall (PDH) technique. The electro-optic-modulator EOM1 is used to imprint phase modulation sidebands with a frequency of 12 MHz onto the laser light. The photocurrent produced by PD$_{cav}$ is then demodulated with the same frequency and filtered to generate a PDH like error signal. This error signal is processed and fed back to a PZT being attached to the input cavity mirror to stabilize the cavity in a detuned state, shifted by 12 MHz from the cavity’s resonance.

The reflected and transmitted signals from the cavity are individually sensed with the two homodyne detectors HD1 and HD2. These allow us to measure signals in an arbitrary quadrature in between amplitude and phase quadrature. We used a local oscillator power of 25 mW for each homodyne detector. The power of the reflected signal beam at the cavity is 2 mW whereas the transmitted signal beam through the cavity signal power is 0.1 mW.
Thereby we fulfilled the condition that the LO power has to be much higher than the signal power to ensure that the resulting signal is dominated by the signal on the signal beam and not by noise present on the LO [12].

The difference photocurrent $S_1$ of homodyne detector HD1 as well as the difference photocurrent $S_2$ of homodyne detector HD2 are used to generate individual error signals for the homodyne detectors. Each error signal is fed back to the PZT actuators PS1 and PS2 respectively. Thereby we provide the necessary control to lock both homodyne detectors to phase quadrature. The control bandwidth of the cavity and the homodyne detector control loops are kept as low as possible, around $\sim 70$ Hz, in order to avoid that the control loop affects the DFI response in the low frequency region.

The electro-optic-modulator EOM2 is used to imprint a phase modulation on the light resonating inside the cavity, as would be done by a GW. Hence EOM2 is used to create our simulated GW signal. By injecting a swept-sine signal into EOM2, we can measure a simulated GW transfer function to both homodyne detectors. The original scheme proposed in [10] includes the effects of the GW on the LO paths. Our scheme however represents the case where the LO for HD2 can be provided by an independent laser. The DN rejection ratio between these two schemes can differ at maximum by a factor of two. Hence our experiment shows qualitatively the proof of principle of the originally proposed scheme.

The PZT attached to mirror IM stabilizes the cavity length by applying a feedback signal. Furthermore, our simulated displacement noise signal is imprinted on the light by applying swept-sine signal to this PZT which allows us to measure a displacement noise transfer function to both homodyne detectors. Both transfer functions (DN and simulated GW) are measured using the homodyne outputs $S_1$ and $S_2$, thereby creating the basis for the demonstration of this DFI scheme.

IV. MEASUREMENTS AND RESULTS

To demonstrate the detuned FP cavity based DFI scheme, we measured the displacement noise and simulated-GW responses. The resulting transfer functions are shown in Fig. 2. Both, the signal as well as the noise strength measured in the homodyne detectors depend on the particular quadrature used. Hence, it is important that the quadrature control is stable. In particular we ensured that all of our data obtained with the two homodyne detectors
FIG. 2: Comparison of the measured transfer functions with the two homodyne detectors HD1 and HD2. The two displacement noise transfer functions are represented by trace A and B, whereas trace C and D show the transfer functions for the simulated GW signals. One can see that the two displacement noise transfer functions are in phase almost in the whole frequency range, where the simulated GW signal transfer functions have a relative phase shift of $180^\circ$ to each other.

FIG. 3: The improvement due to the DFI scheme is expressed by the ratio $\rho_i$ between the processed DN rejection factor $\sigma_{DFI}$ and unprocessed DN rejection factors $\sigma_{S1}$ and $\sigma_{S2}$. The two resulting ratios $\rho_{S1} = \sigma_{DFI}/\sigma_{S1}$ (trace E) and $\rho_{S2} = \sigma_{DFI}/\sigma_{S2}$ (trace F) show an improvement of $\sim 60$ in the whole frequency range with a slight advantage for $\rho_{S1}$ compared to $\rho_{S2}$. Trace G shows the expected result for a phase difference between the transfer functions of the two homodyne detectors of $\phi = 1^\circ$, which reduces the maximally achievable DN reduction factor to $\sim 140$.

As one can see the two transfer functions for the displacement noise from the cavity input mirror IM to the two homodyne detectors $S_{1DN}$ and $S_{2DN}$ (trace A and B in Fig. 2) are in phase in almost the entire frequency range. On the other hand the two GW signal transfer functions $S_{1GW}$ and $S_{2GW}$ (trace C and D in Fig. 2) are out of phase by about $180^\circ$. All
transfer functions include phase shifts induced by the optical elements ($\phi_{S1}, \phi_{S2}$) that the reflected and transmitted light from the cavity passes before the detection in the homodyne detectors $S1$ and $S2$ respectively. The decreasing magnitude of all transfer functions towards low frequencies is a result of the cavity servo loop gain which increases at low frequencies thereby suppressing the injected signals more strongly.

The fact that the GW and DN transfer functions have different phase relations can be used to create two new DFI data channels where the GW content is maintained while the DN content will be strongly suppressed. These two new data channels are given by:

\begin{align*}
S_{DN,DFI} & = S_{1DN} - k \cdot S_{2DN}, \\
S_{GW,DFI} & = S_{1GW} - k \cdot S_{2GW}.
\end{align*}

(4)  
(5)

here $k$ represents a fixed scaling factor which minimizes the DN content in channel $S_{DN,DFI}$. In our case we arbitrarily choose $k$ to be the ratio of the DN transfer function magnitude at 50 Hz ($k = S_{1DN}[50 \text{ Hz}]/S_{2DN}[50 \text{ Hz}]$), as changing the frequency for determining $k$ does not dramatically change the results.

The DN rejection factor $\sigma$ of the initial unprocessed data channels of $S1$ and $S2$ are given by $\sigma_{S1} = S_{1GW}/S_{1DN}$ and $\sigma_{S2} = S_{2GW}/S_{2DN}$ and show us how good a GW can be detected with respect to the present DN. For the processed data channels a similar DN rejection factor given by $\sigma_{DFI} = S_{GW,DFI}/S_{DN,DFI}$ can be calculated. To see the enhancement effect of the DFI in our experiment we plot in Figure 3 the ratio $\rho_i$ between the processed and unprocessed DN rejection factors $\rho_{S1} = \sigma_{DFI}/\sigma_{S1}$ (trace A) and $\rho_{S2} = \sigma_{DFI}/\sigma_{S2}$ (trace B) respectively.

The reduction of the DN shown by $\rho_i$ is significant in the frequency range of interest. Overall $\rho_{S1}$ performs a little bit better than $\rho_{S2}$. In the whole frequency range of interest the DN is reduced by a factor of $\sim 60$.

The DFI toy model described in [10] provides a perfect cancelation of displacement noise from the input cavity mirror, which corresponds to an infinite DN rejection. A theoretical description of our experiment using ideal components predicts perfect cancelation only at DC with a $1/f$ frequency dependence. However, realistic rejection ratios must be computed including inevitable asymmetries in the experimental setup. If the transfer functions in Fig. 2 (i.e. the DN transfer functions marked with A and B) show a phase difference $\phi$ the expected improvement factor can be expressed as $\alpha/(e^{i\phi} - 1)$ where $\alpha = |S_{GW,DFI}|/|S_{1GW}|$. 


In particular when $\phi = 0.1^\circ$ the expected improvement factor is $\sim 1500$. Whereas a phase difference of $\phi = 1^\circ$ reduces the improvement factor to $\sim 140$ resulting in trace G shown in Fig. 3. As one can see the overall DN reduction level of trace G corresponds quite well with our experimental result at high frequencies. In addition to this frequency independent phase difference, which we expect from an imperfect setup of the homodyne detectors, we could also identify a frequency dependent asymmetry. This originates from slight differences in the feedback control electronics and lead to different slopes in the phase behaviour at low frequencies. In more detail, traces A and B of Fig. 2 have relatively high phase difference at low frequencies which decreases up to $\sim 100$ Hz while the corresponding amplitudes have flat shapes starting from $\sim 70$ Hz. Less dominant but still present, this effect is visible in traces C and D. Due to this frequency dependent phase difference the resulting DN rejection factor is decreasing towards low frequencies and does not follow the expected behaviour shown by trace G. Furthermore, this type of table-top experiment is subject to mechanical vibrations of optics mounts which create sharp dispersion-like structures in the DN and GW transfer functions at frequencies between 200 Hz and 4 kHz. The phase asymmetries mentioned above convert such dispersion structures in peaks or dips in the DN rejection factor.

V. CONCLUSIONS

In conclusion, we have demonstrated the first experimental proof of principle of the detuned FP cavity based DFI scheme showing a large enhancement of a mimicked GW signal compared to the DN in the gravitational frequency band from 10 Hz-10 kHz. In particular we used a symmetrical and detuned FP cavity in combination with two homodyne detectors to create two data channels each containing information about the simulated GW signal and the DN. We processed the data of these two channels and created one new DFI channel in which the DN of the IM of the FP cavity was strongly suppressed. A detailed analysis of the performance improvement within the GW frequency band showed that at all frequencies the GW signal to DN ratio was improved with a typical factor of $\sim 60$. Although these results are promising the main problem of this detuned FP cavity DFI scheme is that the enhancement from the cavity effect is lost. Hence, the displacement noise of any auxiliary optics becomes more important. Commonly high finesse cavities are used in conventional GW interferometers to enhance the GW signal size and therefore minimize the influence of
the displacement noises of auxiliary optics. The demonstrated DFI scheme however uses a different approach where the cavity finesse is suppressed together with the displacement noise of the cavity mirrors. This can be beneficial to the conventional method if relative displacement of nearby optics is relatively small. A possible solution is presented in [11] where two double pumped cavities with mirrors attached to rigid platforms are described. This idea is currently under investigation.

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