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Comparing interferometry techniques for multi-degree of freedom test mass readout

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Abstract. Laser interferometric readout systems with $1\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ precision over long time scales have successfully been developed for LISA and LISA Pathfinder. Future gravitational physics experiments, for example in the fields of gravitational wave detection and geodesy, will potentially require similar levels of displacement and tilt readouts of multiple test masses in multiple degrees of freedom. In this article we compare currently available classic interferometry schemes with new techniques using phase modulations and complex readout algorithms. Based on a simple example we show that the new techniques have great potential to simplify interferometric readouts.

High precision interferometry with a dynamic range over multiple interference fringes is the core metrology technique for the space-based low-frequency gravitational wave detector LISA [1]. This technology is also well suited as auxiliary readout system for ground-based detectors, for example for suspension point interferometry [2]. One very promising concept is to apply such a readout not only to a single test mass in one direction, but to all degrees of freedom of multiple test masses in an accelerometer or gradiometer configuration. It is expected that this will make it possible to significantly increase the sensitivity of current accelerometers using electrostatic readout [3]. This would be of great benefit for future geodesy missions that aim to improve on the gravity sensing capabilities of GRACE-FO [4] and GOCE [5].

Different techniques are available and currently under investigation that can be used to construct such readout systems. In the following, we will shortly introduce a number of relevant techniques and discuss their advantages and disadvantages on the basis of conceptual sample implementations. In the end we will briefly compare the techniques and determine the most promising candidate for future research.

Classic heterodyne interferometry already achieves the desired performance with kHz beat notes as used in LISA Pathfinder (LPF) [6], or with MHz beat notes as used in LISA [1, 7] and GRACE-FO [4]. The usage of active stabilisation schemes and several post precessing corrections brings the performance down to $1.42\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ at 3 mHz [8].

Deep phase modulation (DPM) interferometry is the first example of a technique that can be classified as sinusoidal phase modulation homodyne interferometry. Only one single-frequency laser is split and in one arm a very deep phase modulation ($m \gtrsim 2\pi$) is applied. The DC photodetector signal therefore decreases and several harmonics of the modulation frequency are detected. By performing an IQ-demodulation the complex amplitudes for all harmonics can be recovered. A sophisticated fit algorithm uses this information to extract the four parameters modulation depth and phase, and interferometric amplitude and phase. Considering an electrical null-measurement, using one optical signal split after the photodiode, a phase performance of $1\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ at $0.1\,\mathrm{mHz}$ could be achieved. This is currently limited by white digitisation noise [9, 10]. DPM can be used to simplify the optical set-ups for the laser preparation which are quite complex in comparable kHz heterodyne interferometers, such as in LPF.

We also introduce two multiplexing techniques, **digitally enhanced heterodyne interferometry (DEHeI)** and **digitally enhanced homodyne interferometry (DEHoI)**. DEHeI combines the classical heterodyne interferometer with a digital pseudo-random noise (PRN) high speed phase modulation. It uses the binary phase shift keying (BPSK) technique, which introduces a phase shift by either zero or π on the optical signal in the interferometer path used for the phase measurement of test masses. The beam is then interfered with a frequency shifted local oscillator. It has been shown with DEHeI that signals reflected from various objects with cm-distance and entering the same photodetector can be distinguished from each other due to their different travel time by using high speed PRN phase modulations. The optical complexity decreases but GHz electronics are required for the modulation and demodulation, the detection and the signal digitisation. High speed DEHeI achieved a phase performance of $3\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ at $10\,\mathrm{Hz}$ using an active clock jitter correction [11, 12]. The DEHoI scheme allows for further simplification by removing the second laser frequency. It uses the quadrature phase shift keying (QPSK) scheme to inject two perpendicular PRN phase modulations onto the light. The achieved displacement measurement noise floor is $3\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ at $4\,\mathrm{Hz}$ [13, 14]. Because of the multiplexing capability both, DEHeI and DEHoI, are promising candidates for multichannel interferometry with easily duplicatable optical heads. Furthermore, digital interferometry (DI) is by design insensitive to stray light which makes it very attractive for multi test mass readouts with small dimensions.

Another sinusoidal phase modulation homodyne interferometry technique is **deep frequency modulation (DFM)**. DFM uses only one laser source which is strongly modulated in its frequency. Assuming that the test mass readout consists of an unequal arm length interferometer, the photodetector monitors an optical power signal which is similar to the typical DPM signal, but here the effective phase modulation depth depends on the strength of the frequency modulation and on the arm length mismatch. The DPM fit algorithm can easily be adopted to read out this new kind of interferometers [15–17]. DFM can be used to simplify the set-ups required for the laser preparation delivering kHz beat note signals and it simplifies the optical heads due to intrinsic self-homodyning. First experimental results indicate that pm level performance is feasible [17], but this remains to be verified.

The requirements for a **multi-degree of freedom readout** of various test masses are: The optical head should be as simple and compact as possible with improved sensitivity in comparison to electro-static readout. The phase measurement should be sensitive to differential wavefront sensing (DWS) such that tilts can be measured as well. An insensitivity to stray and scattered light is always advantageous, because spurious reflections spoil the phase measurement. The set-up should be easily duplicatable.

Fig. 1 shows that the complexity of the optical set-ups can be drastically simplified by new interferometer techniques like DI or DFM interferometry, especially because no local reference interferometer is required that measures the phase fluctuations due to the injection fibers or the laser preparation. The amount of phase stable components and photodiodes is reduced and the need for ultra stable fiber couplers can be removed by using self-homodyning techniques as well. DWS can be used if a local oscillator beam is present in the optical head. This requires either a second laser beam or the interference with the laser beam itself. At this point one should remark that a DWS readout requires quadrant photodetectors which are currently not available

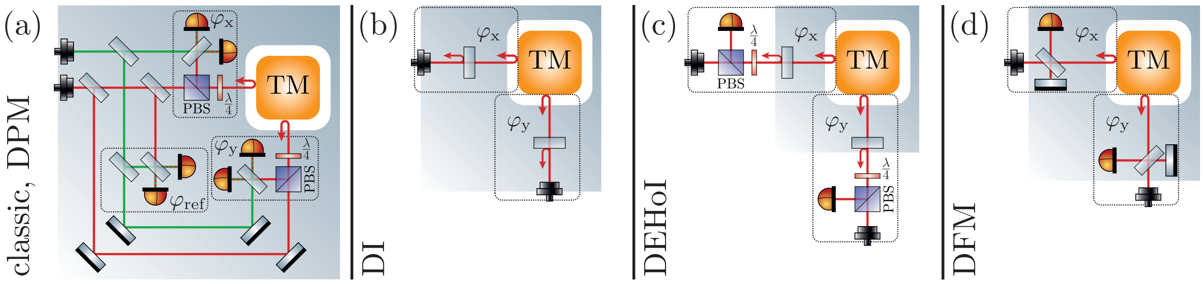

Figure 1. Shown are the optical set-ups for the readout of two longitudinal (and four angular) degrees of freedom of one test mass: Non-multiplexing classic interferometry and also deep phase modulation (DPM) is shown in (a), a possible set-up that can be realised by both digital interferometer (DI) techniques is shown in (b) and two set-ups using the self-homodyning scheme that can be implemented by using digitally enhanced homodyne interferometry (DEHoI) or deep frequency modulation (DFM) interferometry are shown in (c) and (d).

in such small sizes that DEHoI signals with several GHz rates could be detected. Using the alternative DI set-up, the reflections of the test mass and the reference mirrors are interfered with an oscillator beam behind the injection fiber. In this case, multiple signals can be collected by only one photodetector, but DWS cannot be used since the wavefront is destroyed by the fiber coupling. Angular fluctuations could be measured, however, by combining multiple longitudinal degrees of freedom measurements.

Phase modulation interferometer techniques also simplify the set-ups for the laser preparation as shown in Fig. 2. Two acousto-optical modulators (LPF) or two lasers (LISA), can be replaced by one electro-optical modulator and the DPM technique or completely removed by using the DFM technique. This enables a kHz readout without the need for an optical pathlength difference (OPD) stabilisation. However, it remains to be investigated which other stabilisation schemes are required for DPM and DFM. Laser preparation is only needed once, but separate OPD stabilisations are necessary for each pair of fibers feeding light to the optical readout.

Conclusion

Table 1 shows a short comparison of the interferometer techniques and their sensitivities. In terms of optical complexity and excluding GHz electronics and photodiodes the DFM technique might be the most promising candidate for a multi-degree of freedom readout of multiple test

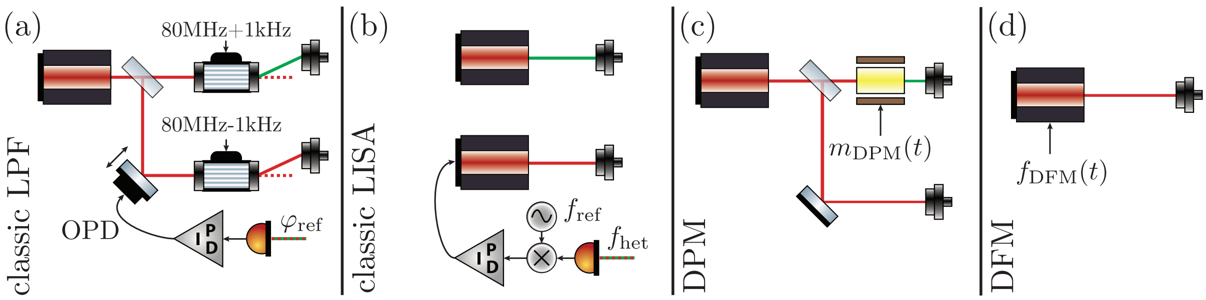

Figure 2. Laser light preparation for various interferometer types. (a) shows the LPF-style modulation for kHz beat notes. The LISA-style laser preparation is used to prepare MHz beat notes and is shown in (b). Inlets (c) and (d) show the application of DFM or DPM to simplify kHz frequency readouts.

masses, even though it does not provide the stray light insensitivity of DI. Further experiments are needed to validate and improve the quoted sensitivities and to determine the set-up complexities of actual implementations. Other potential optical techniques for test mass readout that we have not included here are for example fiber micro-cavity based sensors [18] and optical leaver/shadow sensing [19].

Table 1. Comparison of the new interferometer techniques deep phase modulation (DPM), digital interferometry (DI) and deep frequency modulation (DFM) with the classic heterodyne interferometer. n denotes the number of test masses within a satellite.
[1]based on experimental results, [2]the difference of one optical signal split after photodetector, [3]the difference of one optical signal split before photodetector, *assuming set-ups shown in Fig. 1.

technique	local reference interferometers	electronic bandwidth modulation	readout	DWS capability*	sensitivity [pm/$\sqrt{\mathrm{Hz}}$]
classic	$\geq n$	–	k/MHz	yes	1.4 at 3 mHz[1] [6]
DPM	$\geq n$	kHz	kHz	yes	1.0 at 0.1 mHz[1,2] [10]
DI	0	GHz	GHz	no	3.0 at 10 Hz[1] [12]
DEHoI	0	GHz	homodyne	yes	1.0 at 20 Hz[1] [13]
DFM	0	kHz	kHz	yes	2.5 at 1 Hz[1,3] [17]

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