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SOME NEW CONCEPTS FOR LASER INTERFEROMETER GRAVITATIONAL WAVE DETECTORS

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ABSTRACT

Some new experimental concepts for extending the performance and range of laser interferometers for gravitational wave detection are described. These include the use of holographic diffraction gratings in test mass mirror coatings to permit higher light power and reduced thermal noise, and possibilities for extending interferometer performance to lower gravitational-wave frequencies by use of magnetic levitation and other techniques.

1. Introduction

The sensitivity of laser interferometer gravitational wave detectors is determined by noise of various types, with the noise source which dominates being dependent on the frequency region being considered. At high gravitational-wave frequencies photon shot noise is generally the limiting factor; at low frequencies seismic noise is expected to set the limit until gravitational gradient noise on the earth is encountered, and at intermediate frequencies thermal noise from the test masses and their suspensions is expected to dominate until quantum limits are reached. We discuss here some experimental concepts intended to facilitate pushing these limits down. To reduce photon shot noise we discuss possibilities for interferometers using diffractive, instead of transmissive, coupling to allow operation at higher light powers, and permit choice of test mass material for lower thermal noise. To reduce seismic noise we introduce some concepts involving magnetic levitation, and also discuss some possibilities for coupling the suspensions at the ends of each arm of an interferometer.

2. Diffractive-coupled interferometers

To minimize photon shot noise high circulating light flux is required in the arms of gravitational-wave interferometers: circulating powers as high as 500 KW have been suggested for "advanced" interferometers using power recycling. Heating effects in even low-loss mirror coatings and in transmission through substrates of beamsplitters or through test masses can be limiting factors. These can be reduced by avoiding transmission through materials, and forming low-amplitude diffraction grating patterns in the mirrors or reflecting coatings. Light is then coupled into optical cavities, or divided and recombined at beamsplitters, by diffraction alone.

2.1 *Proposed interferometer configurations*

An example of a simple diffraction-coupled Michelson interferometer is illustrated in Fig. 1. Losses associated with blazed gratings may be avoided by choosing a grating spacing which allows only one order of interference, and by using oblique incidence near the Littrow configuration it can be arranged that all diffracted light appears in one output direction, as indicated.

This oblique-angle diffractive coupling technique can be applied to triangular ring cavities, to folded linear Fabry-Perot cavities where the fold occurs at a diffractive mirror, and to complete interferometers. Some possible configurations have been suggested in an earlier paper (1).

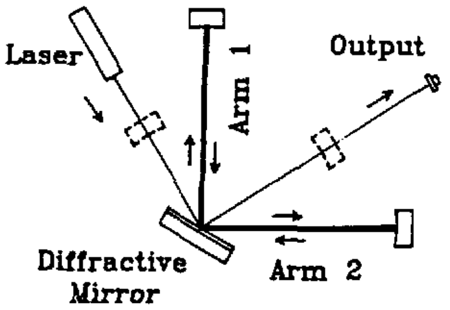

Figure 1

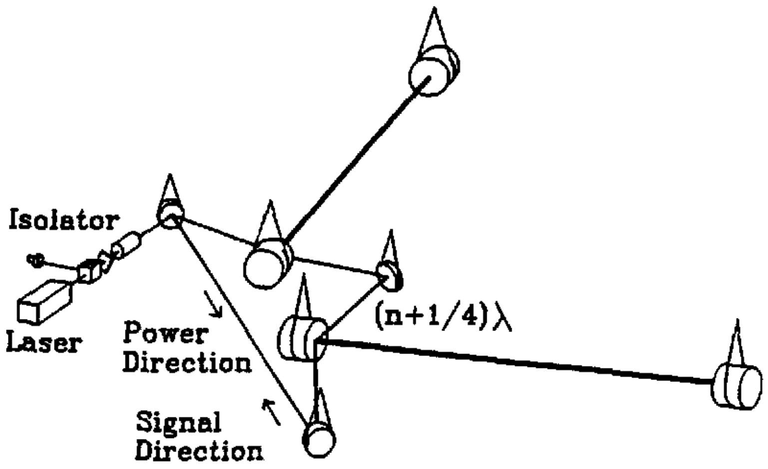

Figure 2

It is possible to use a diffractive mirror at normal incidence, and take advantage of the two symmetrical diffracted beams for input and output coupling. One system of this type is illustrated, in schematic and simplified form, in Fig. 2. Here the two arms of a gravity-wave detector are formed between pairs of suspended non-transmissive test masses, and are coupled via a ring cavity to give some power and signal recycling.

2.2 *Advantages of diffractive systems*

We originally proposed diffractive coupling for gravity-wave detectors with the main aim of avoiding thermal lensing and allowing increased light power. The possibility of using non-transparent test masses can also make it practicable to use single-crystal test masses of very high mechanical quality factor, Q, thus significantly reducing internal thermal noise. Suitable materials may include silicon and sapphire, which also have the advantage of high thermal conductivity. The removal of substrate absorption losses can also reduce total heating, which may eventually contribute to make it practicable to maintain test masses at reduced temperature, where the highest Q-factors are achieved.

2.3 *Considerations on mirror design and manufacture*

The low scattering losses desirable make holographic manufacturing techniques advantageous. Some potentially-applicable techniques have been used for other high-power laser systems. However, further development may be required to minimize scattering losses. Techniques may include making a grating profile on the top layer of a mirror coating stack, making the pattern on the substrate, or possibly generating a pattern of refractive index in the coating material by ion implantation or suitable irradiation.

3. Extension of interferometer performance to lower frequencies

Isolation of the test masses of a gravitational wave detector becomes increasingly difficult as operating frequency is reduced, since it is difficult to achieve sufficiently low mechanical resonances in the stages of a passive isolation system, and seismic motions themselves become larger at low frequency. We propose here the possibility of using magnetic levitation to form test mass suspension and isolation systems with lower resonance frequencies than achieved in simple mechanical systems usually used in this field. We also propose some new coupled isolation concepts.

3.1 Magnetic levitation techniques for test mass suspension

The levitation techniques we are developing are currently all room temperature systems, with the fields generated by permanent magnets. Stabilization of the levitated objects is achieved by sensing vertical position and feeding small control currents to trimming coils around the fixed permanent magnets. Such systems can have negligible power dissipation. We are developing several different magnetic configurations. For test mass suspension it is essential to have very low thermal noise, and correspondingly low dissipative losses. To obtain this, electrically insulating magnetic materials are required, at least in any location where fields depend on the position of the test mass in the direction of the laser beam. Further, coupling to time-varying ambient magnitude fields must be made small enough to avoid introducing significant noise. We propose using one or more pairs of oppositely-oriented magnets on the test mass to cancel dipole and possibly higher-order moments, thus reducing coupling to external fields. An example of a simple 2-magnet configuration we are testing is shown in Fig. 3.

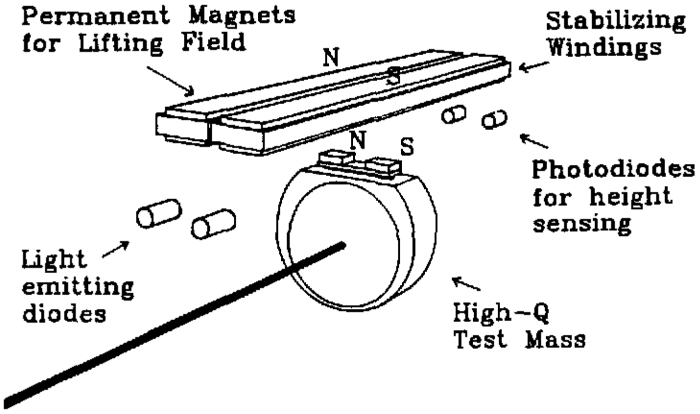

Figure 3

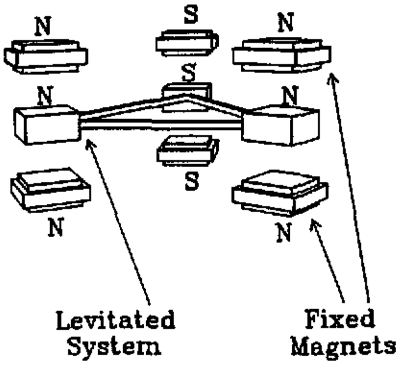

Figure 4

In the version shown, a pair of oppositely-polarized small permanent magnets is attached to a high-Q test mass, via a mechanically-isolating connection to reduce thermal noise. The suspending field is produced by two long, insulating, permanent magnets, with trimming coils. The vertical position of the test mass is sensed by a simple shadow system using two infra-red beams intersecting the top of the test-mass magnets, which control the stabilizing current in the trim coils.

Tests with suspensions of this general type have shown that the period for pendulum-type motion in the direction of the laser beam may be dominated by accidental irregularities in the fields of the suspending magnets. A small trimming permanent magnet (not shown) located to the side of the main magnets may be used to adjust the period. In preliminary experiments, typical periods are around 10 seconds or longer, with relaxation times of several hours.

3.2 *Magnetic levitation seismic isolation stages*

Slightly different considerations apply here, in that eddy-current damping provided by the conductivity of typical rare-earth magnets can be used to advantage. Further, a system providing more isotropic isolation can be useful. A simple configuration used in some preliminary tests is illustrated in Fig. 4. Here three separate levitated "legs" are used, each having a levitated magnet between two fixed field magnets. Each levitated magnet has its own vertical sensing system, for which we have used Hall-effect sensors (not shown) in this case.

3.3 *Tilt-coupled suspensions*

The test-mass suspension shown in Fig. 3 is very sensitive to ground tilt when adjusted for a long period. We have earlier suggested coupling the positions of the suspension points of conventional pendulum-type suspensions at each end of the arms of gravitational wave detectors by auxiliary interferometers, to reduce or monitor differential horizontal ground motion. In long-period systems there may be an advantage in coupling tilt motions at the ends of each arm in a similar way, as illustrated schematically in Fig. 4, for the case of a magnetic suspension system.

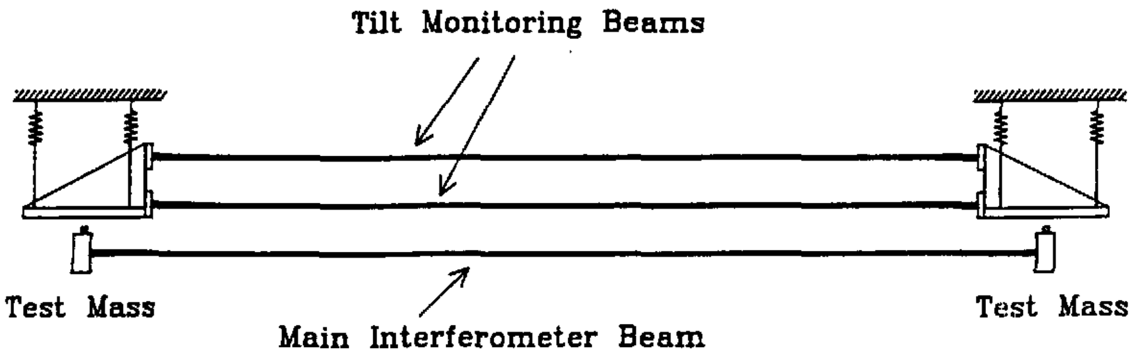

Figure 5

Systems of this general type, whether using magnetic elements or other suspension or isolation techniques seem likely to be useful as a way of improving seismic isolation at very low frequencies.

4. Acknowledgments

I should like to acknowledge the valuable assistance of S. J. Augst, who built and tested several of the magnetic levitation systems investigated. I should also like to thank several colleagues for very helpful discussions, including, in particular, E. W. Cowan, who developed computer models of some of the magnet configurations; and J. L. Hall (JILA) and C. W. Peck for much stimulation and encouragement. The experimental work was supported by the California Institute of Technology.

5. Reference

(1) R.W.P. Drever, in *Proceedings of the Seventh Marcel Grossman Meeting on General Relativity*, Stanford, California, July 1994, eds. M. Keiser and R. T. Jantzen (World Scientific Publishing Co., 1996), p. 1401-1406.