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Review of All-Reflective Optics for the Einstein Telescope

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1 Introduction

The purpose of this note is to review the current status of all-reflective optics research for advanced interferometry as part of the design study for the Einstein Telescope project (ET). Gravitational wave detectors currently operating around the world (LIGO[1], GEO600[2], VIRGO[3] and TAMA[4]) are gathering data and upgrade cycles are underway to improve the sensitivities of these instruments by around an order of magnitude. The aim of the ET design study is to develop a design for advanced 3rd generation gravitational wave detectors capable of providing 10 times better sensitivity than these upgraded instruments. In order to achieve this, high circulating laser power within the instrument (of the order of MW) will be required to improve sensitivity at high frequencies where shot noise is the limiting noise source. The basic idea of all-reflective interferometry is to replace all optical components that are used in transmission by all-reflective devices to avoid absorption based problems that occur when high laser power is transmitted through the bulk material. On the other hand, not being restricted to highly transparent substrate materials, widens the choice of possible candidates for substrate materials in future detectors. In contrast to partly transmissive optics, where some components only need to have a moderate reflectivity (leading to a reduced number of coating layers) every all-reflective component has to have ultra-high reflectivity in order to minimise optical loss. This will result in more coating layers being required and since this is the dominant contribution to the thermal noise budget in existing detectors, this noise source may be even more problematic. Thus, in order to benefit from the advantages of all-reflective interferometry, it is essential that either the coating materials are considerably improved in terms of their thermal noise performance, or the newly developed techniques of grating waveguide mirrors are successfully united with the all-reflective schemes that are discussed in the following sections.

2 All-Reflective Topology Options

Since the aim of using all-reflective optics is to prevent light from having to pass through mirror substrates, the diffractive optics used are reflection gratings and can be included into laser interferometric systems in several ways. There are two types of coupler – four-port couplers as beam-splitter/combiners to replace transmissive beam-splitters in conventional Michelson topologies (see Figure 1), and two- or three-port couplers to replace the cavity input couplers (see Figure 2). Note – these individual elements can be combined to construct many different types of interferometric system [5][6] but for the purposes of this discussion we will consider only the performance of the individual components.

2.1 Beam-splitting/combining

In principle splitting the beam using a reflection grating is very similar to using a conventional beam-splitter. In both scenarios the optic will split the incident field down both interferometer arms and the returning beams can be recombined with appropriate phase difference using conventional sensing techniques. In the conventional Michelson arrangement the geometry of the incident beam remains the same at all ports, while in the case of the four-port reflection grating the beam is diffracted into the 1 st orders, and the diffraction angle and angle of incidence are not equal. Therefore the beam profiles in the interferometer arms differ, because the beam shape of the beam diffracted in the 1st order is altered in the plane of the interferometer.

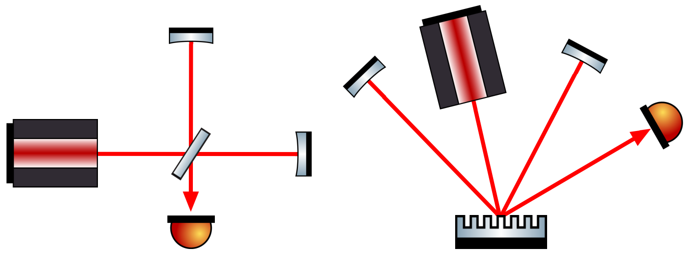

Figure 1: Michelson and reflection grating beam-splitter options. (a) Traditional Michelson interferometer design with 4 port beam-splitter and (b) 4 port, all-reflective beam-splitter configuration.

Geometry effects can be compensated for by careful design of the instrument (arm lengths and end mirror curvatures) and the beam parameter of the incident beam. Such systems have been demonstrated successfully on table-top scales [7] and have been shown to operate as expected with the inclusion of recycling techniques.

It should be noted that the change in geometry, while particularly important in Michelson-type systems in ensuring good interferometer output contrast, will also be present in any diffractive system including those with arm cavities. The initial set-up of such configurations will therefore require more care to be taken with input beam geometry and cavity mode-matching to ensure efficient coupling of light into the interferometric system.

2.2 All-reflective cavities

There are two possible cavity coupling options. The first is the two-port coupler – a reflection grating with an ultra-high 1 st order diffraction efficiency set in the 1 st order Littrow mount configuration. In other words, the grating is arranged such that the 1 st diffraction order is back along the incoming beam while the 0 th order beam is along the cavity axis. This arrangement provides a more direct analogue to traditional mirrors than the three-port option. However, while these cavities have also been demonstrated on a bench-top scale [8] geometrical limitations imposed by the sharp incident angle and potential for high scattering loss from high efficiency gratings mean that three-port gratings offer a more accessible option as cavity couplers.

In the three-port case, a low 1 st order diffraction efficiency grating coupler is mounted in the 2 nd order Littrow configuration with the weak 1 st diffraction order beam aligned to the cavity axis, the 2 nd diffraction order beam directed back along the input path and high reflectivity at normal incidence. The first experimental demonstration of a three-port grating cavity [9] revealed that, due to the additional port of the coupler, the phase relations between input and output ports of the device result in non-symmetric sensing signals [10]. The degree of asymmetry is determined by the relative diffraction efficiencies of the coupler. The implications of these phase relations on cavity behavior have been verified experimentally [11]. It has also been demonstrated that three-port grating cavities are compatible with power-recycling techniques [12][13].

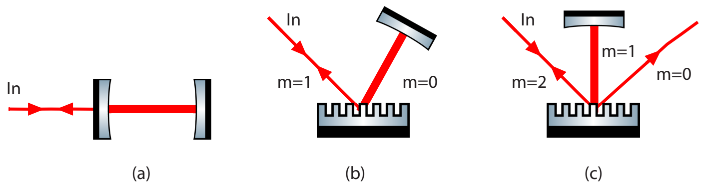

Figure 2: Traditional cavity and reflection grating cavity configuration comparison. (a) Traditional Fabry Perot cavity design with 2 port mirror coupler, (b) 2 port, 1 st order Littrow mount cavity input coupler and (c) 3 port, 2 nd order Littrow mount cavity coupler.

In the past three-port gratings were produced by etching a binary grating structure onto a substrate, and then overcoating with a standard multi-layer dielectric stack to produce the low diffraction efficiencies and high reflectivities required. Additionally, the act of overcoating the grating helps to 'smooth' out any imperfections in the grating structure and thus reduce scattering [14]. Due to the readily reproducible nature of this process most recent experiments have focussed mainly on understanding and controlling systems with three-port cavity couplers.

However, while overcoating leads to a smoothing it also results in distortion of the multi-layer coating stack. This leads to an increase in the transmission of the optic and therefore results in an additional optical loss mechanism for the cavity. More recent work on grating production and lithographic techniques has shown greatly improved performance with low scattering while maintaining low transmission of the coating. Thus all gratings, whether high or low efficiency are now produced by etching on top of the multi-layer coatings stacks.

3 Control

Conventional interferometers utilise multiple control systems to maintain the operating condition required for gravitational wave detection – resonant arm cavities, system held to the dark fringe condition, power and signal recycling length control, alignment sensing, etc. The main method for length sensing and control of interferometric lengths is through extensions of the simple Pound Drever Hall RF sideband approach. These techniques are well understood and a great deal of work has been undertaken to extend them to all-reflective topologies.

The coupling relations for diffractive optics have been modelled and their use has been experimentally verified for each of the topologies mentioned in section 2. In principle, as long as care is taken to account for asymmetries inherent in the diffractive coupling relations, the same techniques used for traditional topologies are viable for the control of all-reflective systems. Tests have been performed on both bench-top and suspended-prototype scales [15], and for length sensing purposes coupling relations of gratings are well understood as optical couplers for gravitational wave detectors.

In terms of cavity alignment, an important feature of all large scale detectors, recent experiments have shown the validity of conventional wavefront sensing techniques as a read-out method for diffractively coupled cavities [16]. With full knowledge of all the length and angular coupling and with viable sensing techniques available, there is nothing to prevent a full, suspended test of diffractive systems.

4 Limits

In broad terms, all-reflective interferometers are very similar to traditional systems – the noise levels associated with optical effects, thermal noise, quantum limits, etc, are still present, but if we consider an ideal grating configuration what additional noise couplings are present in diffractive systems?

As mentioned above, the coupling relations of diffractive elements are non-symmetric and, for example, require careful selection of cavity mirrors and lengths to ensure good optical mode-matching. In other words, the reduced symmetry results in extra coupling of geometry changes of the grating or the incoming beam into alignment and phase changes of the outgoing beam. This coupling takes two forms – increased sensitivity to angular misalignment of the cavity input coupling elements, and noise associated with translational grating motion [17].

The first of these effects is based purely on increased coupling of beam geometry fluctuations into optical phase noise at the gratings. However, the second effect is a feature unique to grating interferometers, whereby translational motion of a diffraction grating induces a phase shift proportional to the diffraction order. If a grating is suspended and free to move then residual translational motion of the suspended optic across the incident beam will manifest as phase noise on the output signal. This effect has been demonstrated experimentally in a fully suspended test system [18].

Initial assessments suggest that the alignment coupling effects will place limits on beam stability and residual suspension angular motion which are several orders of magnitude more stringent than those in existing systems. This would result in the detector sensitivity being limited by alignment noise. More rigourous analysis of the translational coupling effects [19] indicate that some cancellation of the noise is possible depending on grating parameters and choice of readout, but further analysis is required to determine whether these limitations place a hard limit on the performance of all-reflective interferometers or if we can utilise different topological arrangements or other techniques to minimise the noise coupling.

5 Transmission Loss

As previously mentioned, in all-reflective interferometric topologies multi-layer coating stacks are required to maintain low transmissivity through the optic for all diffraction orders. The main reason why transmission in all-reflective topologies such as those discussed above is undesirable is not the thermal problems that arise (the device is not used in transmission so thermal lensing and associated effects are not so critical) but rather that transmission is an optical power loss channel. In contrast to a conventional mirror coupler, the reflectivity of the multi-layer system of the grating should ideally be 100 % for all beams. Essentially, this means the contribution of coating thermal noise will be even more significant with grating couplers because all the optical elements must have a high reflectivity and thus many layers. One possible solution to this issue is waveguide coatings – diffraction gratings with resonant structures, designed to provide ultra-high reflectivities without the need for multiple coating layers [20][21]. These reflection gratings are micro-structured to provide only one (0 th) diffraction order at normal incidence and can be used as direct replacements for conventional mirrors. At this stage the performance of these devices as optical couplers has been experimentally verified [22] and work is continuing on the characterisation of optical and thermal/mechanical performance. Rigourous analysis is also underway with regard to combining the high reflectivity waveguide coatings with the higher diffraction order gratings required for all-reflective optical topologies.

6 Conclusions

In summary, all-reflective optics are undergoing theoretical and experimental testing for potential inclusion in the design of future gravitational wave detectors. In terms of optical design and testing, the theory of light field interaction with grating couplers is well understood and the basic optical elements of advanced interferometry (beam-splitters and cavities) have been experimentally validated in terms of length sensing and control. During the course of these experiments it has been shown that conventional length and alignment sensing techniques can be extended to reliably control all-reflective systems. Analysis of potential noise limitations associated with diffractive systems indicates that the intrinsic asymmetry associated with grating coupling relations will allow greater coupling of alignment noise and beam geometry fluctuations into the gravitational wave detection signal. Additionally, translational phase noise (a noise source not present in traditional interferometers) has been analytically and experimentally verified. These additional noise sources are currently considered to be the most significant barrier to the use of diffractive couplers in large scale interferometric gravitational wave detectors, however more investigation is required to determine if the extra noise couplings can be minimised through careful optical and mechanical design. Work is also underway in the field of micro-structured gratings to produce resonant waveguides as replacements for multi-stack dielectric coatings. Such devices have the potential to give low transmission (and therefore reduced optical power loss) for all diffraction orders on an all-reflective surface and may be required if diffractive optics are to be a viable option for future gravitational wave detectors.

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