

All-Reflective Interferometry For Gravitational-Wave Detection

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Abstract. The circulating power within an interferometric gravitational-wave detector is limited by thermal lensing in transmissive optical elements [1]. All-reflective interferometers have been proposed to overcome this limitation [2,3]. In this paper we discuss the use of a low-efficiency diffraction grating as an input coupler for a high-finesse cavity. Residual thermal effects due to absorption in the high-reflection optical coatings are discussed.

The rapid development of high-power coherent light sources and optical materials with high mechanical quality factor has enabled the design of next generation gravitational-wave detectors operating at the standard quantum limit [4,5] within the measurement band. To reach the proposed sensitivity limit, signal-recycling techniques have to be applied, narrowing the bandwidth of the detector. In an all-reflective interferometer thermal lensing is eliminated making the detector able to handle much higher circulating power and therefore to reach the same sensitivity within a broader measurement bandwidth.

Sun and Byer [6] used the specular order of a reflection grating in Littrow configuration to couple light into a cavity, and the diffracted order to close the cavity. The best high-efficiency multilayer dielectric diffraction gratings today have a first order diffraction efficiency of around 0.96 [7]. This limits the cavity power gain to approximately 25. We suggest here the use of the diffracted order of a weak grating to couple light into a cavity, and the reflected order to close the cavity. This allows a much higher finesse, and therefore a much higher power gain.

Assume a reflection grating coupling 1 percent of the incoming power into the first order at a diffraction angle Φ . The diffracted field is coupled into a ring cavity, which is closed on the reflected order of the grating. The ring cavity is designed so that the return beam is incident on the grating at the same angle Φ , but on the opposite side of the grating normal. Using a symmetric grating 99 percent of the light is used to close the cavity loop.

A weak grating can be written into the top layer of a low-loss mirror. As the cou-

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pling efficiency of the grating is weak, the scatter due to the grating is small. This means that the losses of the cavity are dominated by the output coupling efficiency of the grating, and a high finesse can easily be realized. The power gain in the described system is approximately 100.

Diffracting a light field influences the shape of the beam. A circular Gaussian laser beam becomes elliptical by an amount depending on the difference of Φ and Θ (angle of incidence). However, by using the grating so that $\Phi \approx \Theta$, the effect is small and can be treated as a loss due to non-perfect input coupling.

Although there is no thermal lens effect in this system, residual absorption in the high-reflection coatings results in thermo-elastic deformation of the optical surfaces. *Winkler et al.* [8] give an approximation for the normal surface distortion. The change in the shape of the optics changes the cavity eigenmodes, resulting in less input coupling efficiency, as well as possibly increasing the losses in the cavity. Both effects would reduce the power gain. The amount of surface deformation for a given absorbed optical power depends on material parameters of the substrate. A good indication is the ratio of thermal expansion and thermal conductivity, which should be as small as possible. By far the best of the materials currently under discussion for the test masses of advanced gravitational-wave detectors is Silicon ($\alpha/\kappa = 0.1 \times 10^{-7}$ m/W), followed by Sapphire ($\alpha/\kappa = 2 \times 10^{-7}$ m/W), and Fused Silica ($\alpha/\kappa = 3.4 \times 10^{-7}$ m/W). Assuming coating absorption of 1 ppm, a Silicon cavity as described above can handle circulating light powers of 10 MW without reducing the effective power gain. It should be noted that other material parameters, e.g., the mechanical Q, also influence the choice of the test mass material.

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