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Ultra-low noise meta-mirrors with optical losses below 500 ppm

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Abstract. Interferometric experiments are often limited in sensitivity by the thermal noise of the mirrors. In particular, interferometric gravitational wave detectors and laser stabilization resonators can benefit from reduced mirror noise. We present results of experimental investigations on micro-structured mirrors (meta-mirrors) and hybrid etalon mirrors (meta-etalons) promising particularly low thermal noise. We show the first characterization of meta-etalons scattering and absorption losses, demonstrating optical losses below 500 ppm. This level of optical losses is sufficient for planning direct thermal noise measurement in dedicated optical cavity experiments. These measurements would be very important for validating the thermal noise predictions. We present our development toward the integration of meta-etalons in ultra-stable optical cavities.

1 Introduction

Brownian thermal noise from dielectric mirror coatings limits the performance of ultra-stable optical cavities and gravitational wave detectors [1, 2]. It is proportional to the mechanical losses of the materials used in the alternating high and low index of refraction layers composing the high-reflectivity coatings and to the total thickness of the coating [3]. The quest for lower Brownian thermal noise mirrors has so far been mainly focused on finding materials with lower mechanical losses [4]. We work on an approach based on reducing the thickness. While a Bragg reflector requires many layers to achieve high-reflectivity, micro-structured surfaces exploit resonant light-matter interactions to achieve reflectivity close to unity with only one structured layer (meta-mirrors) [5]. In previous studies, it has been shown that the theoretical thermal noise of these surfaces can be ultra-low with suitable geometry and material selection [6]. Experimental realizations of meta-mirrors however only demonstrated reflectivity as high as 99.8%, mostly limited by fabrication accuracy [7]. By using an etalon composed of a a meta-mirror and a dielectric mirror, see Fig. 1, we demonstrate optical losses below 500 ppm while maintaining the thermal noise advantage.

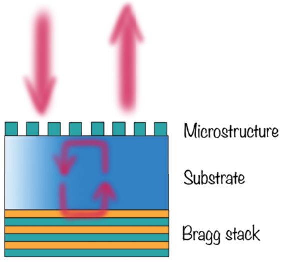

Figure 1. Sketch of the etalon mirror under investigation: The silicon microstructure on the front of the etalon reflects most of the light at ultra-low noise. The Bragg stack on the back then covers the transmitted light, which contributes little to the overall noise due to its low intensity.

2 Optical loss characterization of meta-mirrors

To measure the reflectivity of the meta-mirror with high precision, we use the cavity ringdown method. The experimental setup is shown schematically in Fig. 2: a tunable laser (1450 . . . 1650 nm) is used to scan cavity resonances. Laser light passes through an acousto-optic modulator (AOM), which acts as a fast optical switch. With the help of free-space optics, the light is mode-matched and coupled into the cavity. The photodiode PD2 measures the transmitted power, which increases strongly on a resonance, when a high amount of light power is circulating in the cavity. When the transmitted optical power reaches a chosen threshold, the ring down electronics (RDE) switches off the light incident on the cavity acting on the RF signal driving the AOM. Using an oscilloscope, the exponential decay of the transmitted optical power with time constant τ is recorded as a function of time. Finesse $\mathcal{F}$ is calculated as:

$$\mathcal{F} = \frac{\pi c}{L}\tau, \qquad (1)$$

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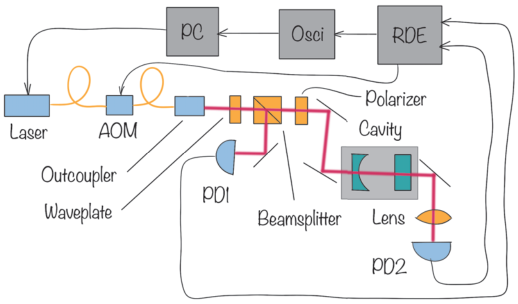

Figure 2. Schematic of reflectivity measurement using cavity ringdown: The acousto-optic modulator (AOM) can quickly switch the light coupled into the cavity. With the help of the out-of-loop photodiode PD1 and the in-loop photodiode PD2, the lifetime of the photons in the cavity can be measured precisely. The ringdown electronics RDE developed in-house switches the AOM.

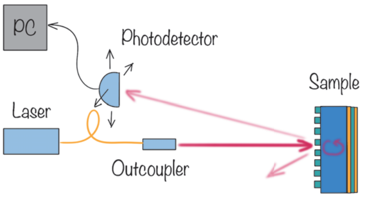

Figure 3. Schematic setup of the scatterometer for measuring scattered light.

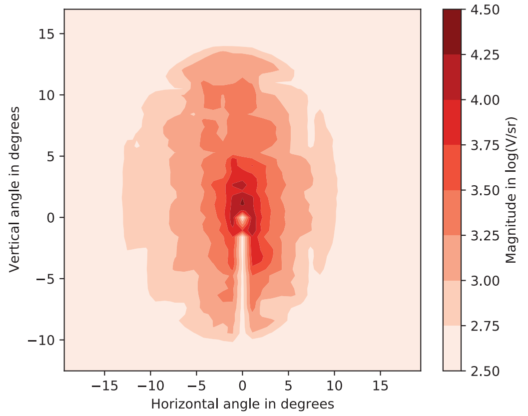

Figure 4. Scattered light measurement at the meta-etalon: The scattered light is shown in logarithmic units. The microstructures are aligned parallel to the horizontal axis.

where c is the speed of light and L the cavity length, respectively. The out-of-loop photodiode (PD1) is used to measure the delay in the setup. Our cavity consists of a meta-etalon and a focusing dielectric Bragg mirror with residual transmission $<$ 10 ppm. We obtained a finesse of $11,665 \pm 330$, from which follows a meta-mirror reflectivity $> 99.95\%$ [8]. We assign the remaining optical losses of less than 500 ppm to residual absorption and scattered light. To assess the scattering, we have set-up a scatterometer (Fig. 3). A tunable laser is directed at the meta-etalon at 0° angle of incidence (AOI). The scattered light is read out as a function of the scattering angles (θ, ϕ) with the help of a photodetector on a movable stage. Our self-developed system offers an angular resolution of 10 mrad and an angular range of $\pm 30°$ in azimuthal and polar angle.

Initial results are shown in Fig. 4: The distribution of the scattered light is shown in logarithmic units. The microstructures are aligned parallel to the horizontal axis. It can be seen that light is mostly scattered at small angles $< 5°$. This points to scattering by structures larger than 18 μm. We will use the knowledge gained to optimise the manufacturing processes of the meta-mirrors and thus achieve even higher reflectivities. In this way, we hope to develop ultra-stable lasers based on the mirrors presented here for record-low thermal noise in the future.

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