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Coating-free mirrors for high precision interferometric experiments

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Thermal noise in mirror optical coatings may not only limit the sensitivity of future gravitational-wave detectors in their most sensitive frequency band but is also a major impediment for experiments that aim to reach the standard quantum limit or cool mechanical systems to their quantum ground state. We present the design and experimental characterisation of a highly reflecting mirror without any optical coating. This coating-free mirror is based on total internal reflection and Brewster angle coupling. In order to characterise its performance the coating-free mirror was incorporated into a triangular ring cavity together with a high quality conventional mirror. The finesse of this cavity was measured using an amplitude transfer function to be about $\mathcal{F} \simeq 4000$. This finesse corresponds to a reflectivity of the coating-free mirror of about $R \simeq 99.89\%$. In addition, the dependence of the reflectivity on rotation was mapped out.

I. INTRODUCTION

The optical quality of mirror coatings has vastly improved over the last decade, driven by high precision optical metrology applications. One such application is the detection of gravitational waves using interferometry. The performance of planned GW detectors in their most sensitive frequency band is, however, predicted to be limited not by optical properties but by mechanical properties responsible for thermal noise in the coatings. For a detailed analysis of thermal noise related to optical coatings see e.g. [1–5].

Coating thermal noise is also a major impediment to experiments aimed to reaching and eventually even surpassing the so called standard quantum limit (SQL) [6]. The SQL is a direct consequence of the Heisenberg uncertainty principle (HUP). The SQL of an interferometric measurement arises from quantum fluctuations in the amplitude and phase quadratures of the interrogating laser field, commonly refered to as radiation-pressure noise and shot noise, respectively.

Due to the different scalings of shot noise and radiation-pressure noise with power, at a given frequency there exists a power level at which the two are equal in magnitude. The sensitivity reached under these conditions is the SQL. Despite the effort of numerous groups the SQL has never been reached for the measurement of a macroscopic object such as the mirror of an interferometer [7–9].

Closely related to SQL experiments are attempts to cool macroscopic objects to their quantum ground state [10, 11] as well as experiments aiming to generate quantum mechanical entanglement between macroscopic objects [12]. Careful analyses show that again coating thermal noise must be greatly reduced in order to observe quantum mechanical phenomena with objects visible to the naked eye.

A possible way to overcome this limitation is to improve the mechanical properties of the optical coatings. This is currently being tried by adding various dopants, e.g. titania, to the coating materials. Another promising approach is to reduce the thickness of the coatings by, for example, using grating waveguide structures. Waveguide coatings are already used as wavelength selctive elements and as broadband mirrors at 1550nm laser wavelength. The demonstration of a highly reflecting grating waveguide coating at 1064nm is, however, still to be done. [13]

Khalili [14] suggested reducing coating thermal noise in a GW detector, by replacing the end mirrors with short Fabry-Perot cavities. By using a front mirror of moderate reflectivity in this Fabry-Perot cavity, a thinner coating can be used, reducing the coating thermal noise by a substantial factor. This approach is, however, impractical for use in other applications.

A more radical approach is to construct highly reflecting mirrors with no optical coatings. In 2004 Braginsky suggested using corner reflectors as end mirrors in advanced gravitational-wave detectors [15]. These corner cubes rely on total internal reflection (TIR) but need an anti-reflection coating on the curved input face. As an anti-reflection coating can be much thinner than a highly reflecting coating its thermal noise should be much smaller than that of a higly reflecting coating. This system is designed for use with large diameter laser beams ($\approx$ 10cm) so that optical loss accompanying reflection off the corner discontinuity will be very small. However, small diameter laser beams as used in SQL and optical cooling type experiments, would read out the discontinuity and suffer unacceptably large optical loss.

In 2005, Giazotto [16] suggested another corner reflector based design. His method relies on the interference of the beam promptly reflected at the front face with the beam being reflected off the rear face of the corner reflector. This is the most complex of the suggested designs as it relies on the front face curvature of the reflector very precisely matching the curvature of the beam's phase fronts as well as on a very high homogeneity of the refractive index of the substrate material to ensure

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constructive phase wrapping at another mirror to form a cavity.

In this article we introduce a coating-free mirror (CFM) also based on a corner reflector using total internal reflection, but without reflection incorporating the discontinuity at the corner. Furthermore, the need for anti reflection coating is avoided by coupling the laser beam in to the corner cube at Brewster angle. In the next section we present a detailed analysis of this design. This is followed by a description and results from an experimental prototype and future outlook.

II. COATING-FREE MIRROR DESIGN

The CFM is shown in Figure 1. We will describe the principle of operation in the context of our objective which was to design a CFM that had a high reflectivity (of the order of 99.9%) and was light enough to be used in SQL and optical cooling experiments. Such experiments aim to use gram scale mirrors. Hence, the CFM was designed to be as small as possible without being limited by diffraction loss. The CFM dimensons were chosen such that each relevant face was at least three times the diameter of the incident laser beam plus some margin to allow for alignment. This consideration and the geometry of the test cavity led to the CFM dimensions shown in Figure 1. The laser beam enters the CFM via Brewster angle, is then reflected twice at the rear faces using TIR. In this way the discontinuity of the corner is avoided. The beam is then coupled out of the CFM via Brewster angle. The sketch shows this main beampath along with the two residual reflections at the front face due to imperfect Brewster-angle coupling. With the given dimensions and a density of Suprasil1 of 2.20g/cm^3 the weight of the CFM was 0.43g.

The angle Θ_c above which TIR occurs satisfies the relation

$$\Theta_c = \sin^{-1}\frac{n_1}{n_2} \qquad \text{for} \quad \mathrm{n}_1 > \mathrm{n}_2 \tag{1}$$

with n_i giving the refractive indices of two media with a common interface. As can be seen from Equation 1 it is evident that TIR can only occur for a reflection at an optically less dense medium. In other words, the laser beam has to hit the TIR faces from inside the CFM substrate. This requires the beam to enter and consequently to leave the substrate, placing two requirements on the CFM: Firstly the internal transmission loss due to absorption and scatter must be small enough and secondly the in- and outcoupling of the beam must be done with small enough residual reflection.

Coupling of the beam into and out of the CFM at Brewster angle allows, in principle, loss-less coupling of the laser. However, due to the cavity geometry (see Figure 2) it was required that the ingoing and outgoing beams meet at about 7cm from the CFM. To accomodate this requirement the corner between the TIR surfaces was made slightly less than 90°. This deviation from a right angle leads to a deviation from perfect Brewster angle at the front face for both the ingoing and outgoing beams. As a consequence, a fraction of the light power is reflected at these two points, as illustrated in Figure 1. By separately adjusting the angle of the input and output beams on the front face of the CFM (that is, putting in a 'kink') one could correct for the deviation and thus minimise the residual reflection. However, the loss due to imperfect Brewster angle coupling is small in our case. Using Snell's law, the refractive index of Suprasil1 of n=1.45, and the angle of incidence of $\theta_{\text{in}} = 54.3°$ for the ingoing and $\theta_{\text{out}} = 35.1°$ for the outgoing beam one obtains a reflection loss of $\alpha_{\text{refl}} = 0.021\%$. Also these two beams can be used for diagnostics.

A further source of loss is the transmission loss of the CFM. With the transmissivity as specified by the manufacturer and 1.5cm optical pathlength inside the CFM the internal transmission loss of the CFM was calculated to be $\alpha_{\text{trans}} = 0.006\%$. Under the assumption that TIR is perfect the overall optical loss of the CFM is thus $\alpha_{\text{CFM}} = 0.027\%$, allowing a theoretical reflectivity of $R \simeq 99.97\%$.

III. EXPERIMENTAL SETUP

Characterisation of the CFM was performed by incorporating it into a cavity. The other cavity mirror was a spherical (radius of curvature R=0.5m) high-quality conventional mirror with a reflectivity of $R = 99.95\%$. Figure 2 shows the setup used. The round trip length of the cavity was 142mm. The incident light power was 4mW.

The cavity was stabilised to the laser frequency using the Pound-Drever-Hall technique [17]. The conventional mirror was mounted on a piezo-electric transducer to enable length control of the cavity. The control signals were derived from the light reflected by the resonator and incident on photodiode PD1. The light from the two residual reflections were used for diagnostics, e.g. to monitor the intra-cavity power.

In order to obtain accurate information about the relevant cavity properties amplitude modulation (AM) transfer functions were recorded. By modulating amplitude sidebands at different Fourier frequencies onto the beam incident on the cavity the frequency and phase response of the cavity can be mapped out. In practice a swept sine was used to sweep through all relevant Fourier frequencies. The transmitted, or intra-cavity, light contains a fraction of the sideband power at a given Fourier frequency according to the cavity response at this particular frequency. By demodulating the signal from photodiode PD2 in Figure 2 with the modulation frequency the intra-cavity sideband power at all Fourier frequencies was determined and normalised to the incident sideband power. The half linewidth (HWHM) of the cavity was determined from the Fourier frequency at which the intra-

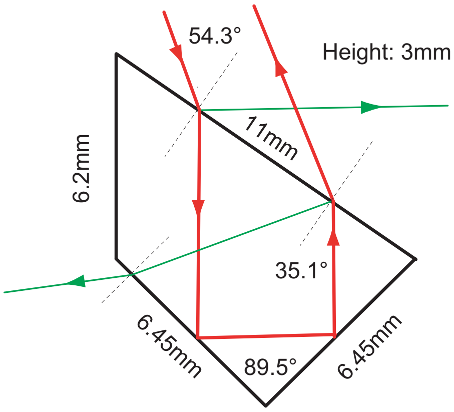

FIG. 1: Left: Sketch of the CFM with all dimensions. Right: Photograph of a coating-free mirror alongside an Australian five cent coin.

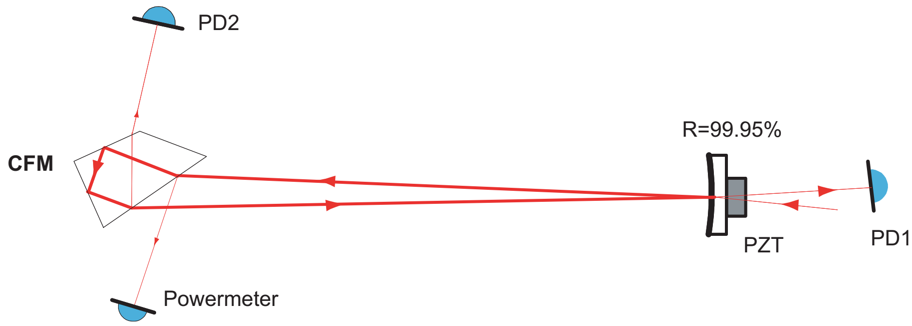

FIG. 2: Setup to characterise the CFM reflectivity (not to scale).

cavity sideband power was down by 3dB, or equivalently the sideband phase lagged by 45°.

From the linewidth of the cavity, its length, and the known reflectivity of the conventional mirror, the reflectivity of the CFM was inferred.

IV. RESULTS

Figure 3 shows the data obtained (solid line) using AM-sideband cavity interrogation for the CFM rotational alignment angle that corresponds to maximum observed CFM reflectivity. The reflectivity of the CFM was used as the only fitting parameter in a least squares fit that is also shown in Figure 3 (dashed line). The 3dB point as well as the corresponding 45° point are highlighted in the graphs. The full cavity linewidth for this rotational alignemt angle of the CFM is FWHM=560kHz. The corresponding cavity finesse is $\mathcal{F} = 3930 \pm 260$. The reflectivity of the CFM as obtained from the least squares fit is $R = 99.89\% \pm 0.01\%$.

Since the theoretical value for the CFM reflectivity differed from the experimental value it is evident that an optical loss mechanism that was previously not taken into account dominates the loss. When switching off the room lights and using an infrared viewer, it was clear that the two TIR surfaces were strong sources of scattered light. The surface of the front and the two TIR faces of the CFM were polished to $\lambda/10$ quality. From the experiment it is evident that this surface quality is not compatible with a reflectivity in excess of 99.9%. A numerical investigation of TIR scattering due to random surface roughness was undertaken in [18], though none of the cases investigated therein provide numerical values for a surface roughness corresponding to that of the polished CFM surfaces. Surface roughness was also attributed to be the main source of loss in a fused silica monolithic TIR resonator investigated in [19]. According to [20, 21] it is possible to reduce the effects of this phenomenon dramatically by super-polishing the reflective surfaces to rms values in the sub-Ångstrom regime, where TIR reflects 99.9999% of the power.

As mentioned above, the coupling of the beam into and out of the CFM was not done exactly at Brewster's angle. When the rotational alignment of the CFM was changed by a small amount then one beam was closer to Brewster angle while the other beam moved farther away from the Brewster angle. This feature led to a rather flat characteristic of the CFM reflectivity when rotated away from optimum alignment. The measurements presented in Figure 4 were obtained via AM transfer function measurements for different rotational alignment angles of the CFM. The solid line is normalised to meet the obtained maximum reflectivity of the CFM. This normalisation

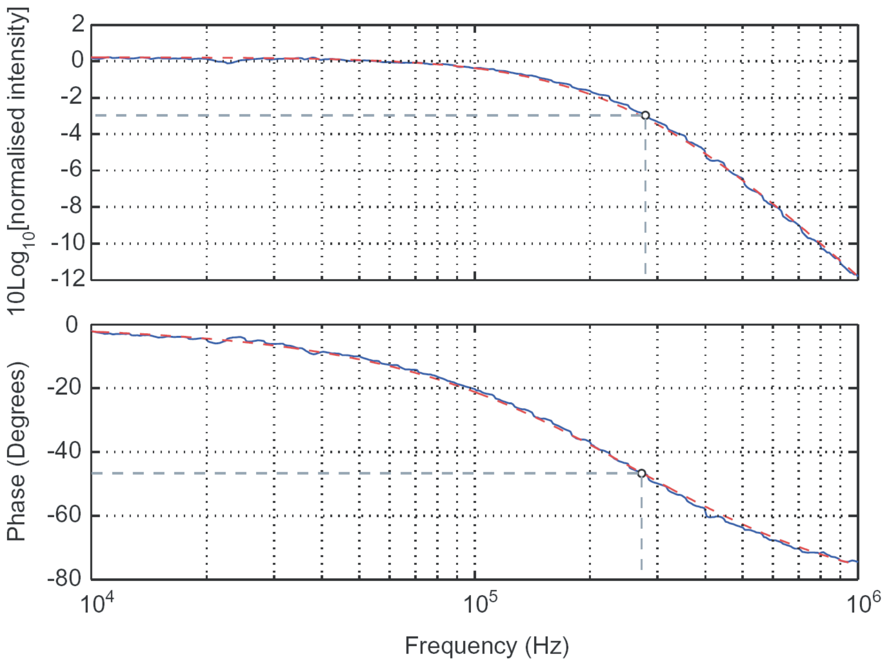

FIG. 3: The measured frequency (top graph) and phase (bottom graph) response of the cavity for the optimum rotational alignment angle of the CFM. The solid line represents the measured data while the dashed line is the result of a least squares fit used to determine the reflectivity of the CFM. The -3dB point, corresponding to half the cavity linewidth (HWHM), of the frequency response is marked along with the equivalent 45° phase point.

had to be done since the the experimentally obtained value of the CFM reflectivity was, as mentioned above, found to be lower than the theoretical value.

It should be noted that the CFM is in principle a retro-reflector and hence, the cavity alignment does, to first order, not suffer from a small rotational misalignment of the CFM. An accurate geometrical analysis revealed, however, that the point at which the ingoing and outgoing beams converge shifts along the cavity axis as the CFM rotates. Hence, the point at which the input and output beams converge is no longer at the surface of the conventional mirror. This results in the respective beam positions being slightly offset at this point, and part of the circulating power does not reproduce as desired. It was evident that this effect caused a reduction in circulating power with CFM rotation in addition to that due to the change in CFM reflectivity. This was investigated by probing the resonant intracavity power with measurements of the beam reflected from the front face of the CFM (the beam hitting the powermeter in Figure 2). This beam gives the cavity power for a given CFM rotation angle, weighted by the rotationally dependent reflectivity of the front face. This is compared in Figure 5 to a calculation of the power this beam would have, if the change in reflectivity of the Brewster window was solely responsible for changes in intracavity power. As such, the difference between this calculated curve and the measured power represent power lost due to misalignment.

V. FUTURE WORK

In follow up experiments we will increase the CFM reflectivity. According to [20] the loss due to scattering at the TIR surfaces can be reduced by reducing the surface roughness via superpolishing. This can provide a reflectivity of 99.9999% from these surfaces [21]. The loss of the beams in- and outcoupled of the CFM can be reduced by altering the front face of the CFM such that both beams are incident without deviating from Brewster angle. By combining these two improvements, the CFM promises to be limited by internal transmission loss only.

Although no photothermal effects were observed in the CFM this can become problematic when operating with higher input powers. If the need arises, a CFM can be made from Suprasil SV311 grade fused silica, which can have an absorption as low as 0.2 ppm/cm, more than one order of magnitude less than Suprasil 1 as used for the CFM described here. The same consideration applies for thermal lensing inside the CFM.

In order to fully benefit from the use of CFMs in SQL and cooling type experiments it would be desirable to create an all coating free cavity. Such a cavity consisting of two CFMs as described in this article would be an unstable plane-plane cavity. A stable cavity could be made, for example, by polishing a curvature into one of the TIR faces of one of the CFMs. However, as this would introduce astigmatism, a corrective cylindrical curvature

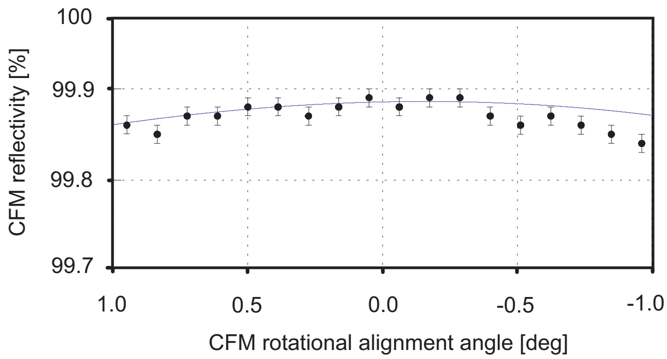

FIG. 4: Reflectivity of the CFM versus its rotational alignment angle. The error bars arise from the relative calibration of the powermeter used. Error bars in the rotational angle are too small to be displayed. The solid line represents the calculated change of reflectivity of the CFM due to deviation from the Brewster angle of the in- and outcoupled beams. The calculated curve is normalised in a way that its maximum coincides with the maximum reflectivity of the CFM as experimentally obtained.

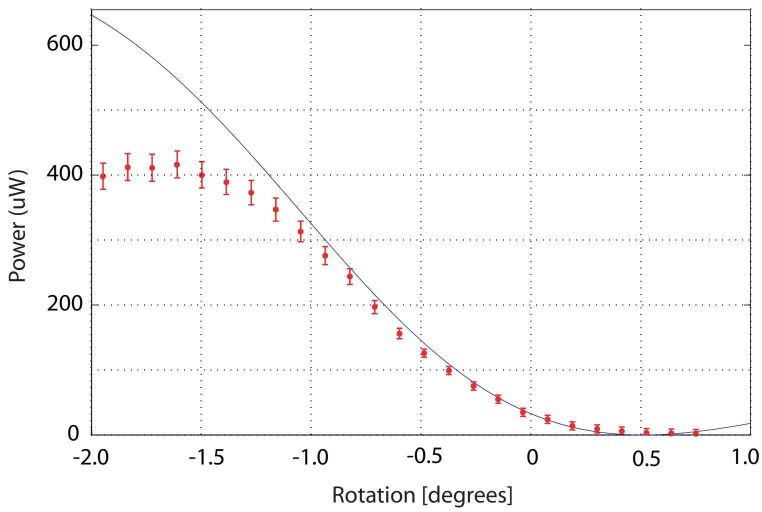

FIG. 5: The power reflected from the front face of the CFM (the beam hitting the powermeter in Figure 2) as a function of rotational alignment. The solid line is derived under the assumption that no cavity mismatch occurs, and changes in intracavity power are caused only by deviations of the beams from the Brewster angle at the CFM front face. Thus, the difference between this curve and the experimental values corresponds to the power lost from the TEM_{00} mode.

would have to be overlaid on the curved surface.

A coating free beamsplitter can be realised using evanescent coupling, or frustrated total internal reflection [22]. This combined with CFMs would then enable the construction of a range of coating free interferometers.

VI. CONCLUSION

We have presented a unique design for a CFM for use in opto-mechanical experiments aimed at reaching quantum limits. The mirror is based on TIR at the rear sides of a low loss subtrate. In contrast to previous suggestions the readout of the discontinuity at the corner of the CFM is avoided by using two reflections. The laser beam is coupled into and out of the CFM via Brewster angle transmission thus avoiding the need for anti-reflection coatings.

To characterise the first prototype mirror of this design it was incorporated into a triangular ring cavity. A finesse $\mathcal{F} \simeq 4000$ was achieved. Due to the resulting deviation of the in- and outcoupled laser beams from Brewster angle the reflectivity of the CFM depends on rotation. This dependence was mapped out and found to be in good agreement with theory for misalignment angles smaller than $\pm 1°$. The maximum reflectivity of the CFM was found to be about $R \simeq 99.89\%$. At an input light power of 4mW no photothermal effects were observed.

VII. ACKNOWLEDGEMENTS

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