Measurement of a low-absorption sample of OH-reduced fused silica

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Abstract. Low-absorption optics made of OH-reduced fused silica are a key technology for future gravitational wave detectors such as Advanced LIGO. We developed a sensitive method to measure the absorption inside the beam splitter of GEO 600, taking advantage of the effect of thermal lensing. Using this method we derived a bulk absorption of less than 0.25 ppm/cm for a piece of Suprasil 311 SV at a wavelength of 1064 nm. This is the lowest value of light absorption inside fused silica reported so far in the literature.

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1. Introduction

The four large-scale laser-interferometric gravitational wave projects, LIGO [1], VIRGO [2], TAMA 300 [3] and GEO 600 [4], have dedicated much effort to commissioning the detectors and improving their sensitivity. Soon the initial projects will have reached a sensitivity limited by fundamental noise sources like, for instance, shot noise. Second generation projects such as Advanced LIGO [5], Advanced VIRGO [6] and GEO HF [7] aiming at strain sensitivities in the region of 10^{-23} to $10^{-24}/\sqrt{\text{Hz}}$ will operate at much higher light powers than the initial detectors, in order to reduce the influence of shot noise. Accordingly, one major problem will be the absorption of laser light in the optical elements like beam splitters and test masses. Even though techniques for thermal correction and compensation have been developed (e.g., [8, 9]), the use of low-absorption materials is a key point of future detector research.

The beam splitter substrate currently installed in GEO 600 was manufactured by Heraeus, Hanau [10] and consists of Suprasil 311 SV which provides extremely low bulk absorption due to an OH-content of less than 50 ppm [11]. Recent measurements of OH-reduced fused silica showed an absorption below 0.5 ppm/cm which was the lowest

absorption of fused silica reported so far [11]. Therefore it is of great interest to obtain a lower absorption value, as presented in this work.

In Section 2 of this paper we will explain the principle of a new method for a more sensitive estimation of the bulk absorption in the beam splitter by using the GEO 600 interferometer itself as a measuring tool. Realization and details of this measurement are described in Section 3 while the result is discussed in Section 4.

2. A new method for measuring bulk absorption

Large Michelson interferometers such as GEO 600 working at high optical powers can be used to measure small effects of thermally induced distortion of their optical elements [12]. One of the most sensitive optical components in GEO 600 is the beam splitter which is placed inside a high-finesse cavity: the power-recycling cavity (Figure 1.1). The absorption of the bulk material causes a weak lens building up inside the beam splitter [13, 14]. This lens disturbs mainly the beam passing through the beam splitter substrate, whereas the beam reflected to the other arm (in case of GEO 600 this is the north arm) is only slightly influenced (Figure 1.3). This means that depending on the strength of the lens we see a change in the interference pattern at the ports of the interferometer. Since GEO 600 is operated on a dark fringe at the output port, this effect can most easily be visualized there, using, for example, a CCD camera.

Due to the fact that the thermal lens does not build up instantaneously, we can compare the beam pattern at the output port for a cold state and a hot state of the beam splitter (as shown in Figure 2). Using GEO 600 parameters we can reproduce the pattern of the cold state using a FINESSE [15] simulation. Now we can add to the simulation an additional lens inside the beam splitter and vary its focal length until it matches the experimentally observed beam pattern for the hot state. If the light power transmitted through the beam splitter is known, an estimate of the bulk absorption can be derived from the focal length of the simulated thermal lens as described below.

Absorption of light power from the transmitted beam heats the substrate non uniformly. Because of the temperature dependence of the index of refraction a path difference δs occurs between a light path measured along the beam axis and a light path measured along the $1/e^2$ point of the intensity distribution [13].

$$\delta s = 1.3 \cdot \frac{\beta}{4\pi\kappa} \cdot p_a \cdot d \cdot P, \tag{1}$$

Here κ is the thermal conductivity, p_a is the absorption per unit length, P is the light power and d is the geometrical path length inside the substrate. The temperature dependence of the index of refraction is given by $\beta = dn/dT$. Expressing δs by the focal length of the thermal lens induced in the beam splitter as $f_{\text{therm}} = w^2/2\delta s$, where w is the beam radius at the beam splitter, Equation (1) transforms to

$$p_a = \frac{4 \cdot \pi}{2.6} \cdot \frac{w^2 \cdot \kappa}{\beta \cdot d \cdot P \cdot f_{\text{therm}}}. \tag{2}$$
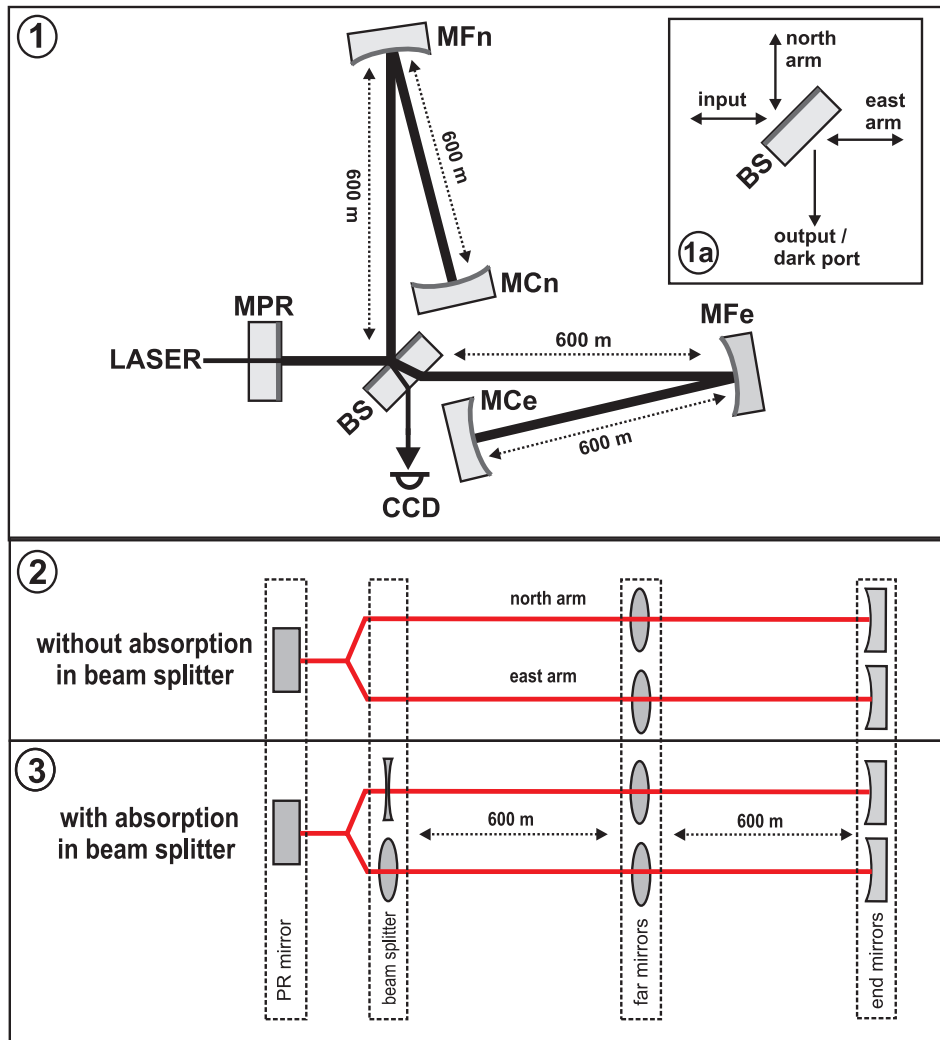
Figure 1. **1**. Simplified optical layout of the GEO 600 main interferometer with folded arms. The Laser beam enters the Michelson interferometer through the power-recycling mirror (MPR), gets split at the beam splitter and transverses the two folded arms, each of 2400 meter round trip length. At the output port of the interferometer the beam pattern is observed using a CCD camera. **2**. Optical imaging inside the interferometer arms expressed in an equivalent lens diagram for the case of no absorption inside the beam splitter substrate. **3**. Bulk absorption inside the beam splitter can be modelled by an additional convex lens inside the east arm (dominant effect) and an concave lens in the north arm.

Up to here we only took absorption inside the beam splitter and the corresponding thermo-refractive effect into account. Of course, in reality the optical imaging in GEO 600 is also slightly influenced by two other effects: the thermal expansion and the absorption of the dielectric coatings. Nevertheless ignoring these two effects still gives a valid upper limit for the bulk absorption of the beam splitter, as we will show in the following sections.

The principle of our absorption measurement relies on the thermally induced change in the difference of the wavefront curvature of the two interferometer arms. Therefore
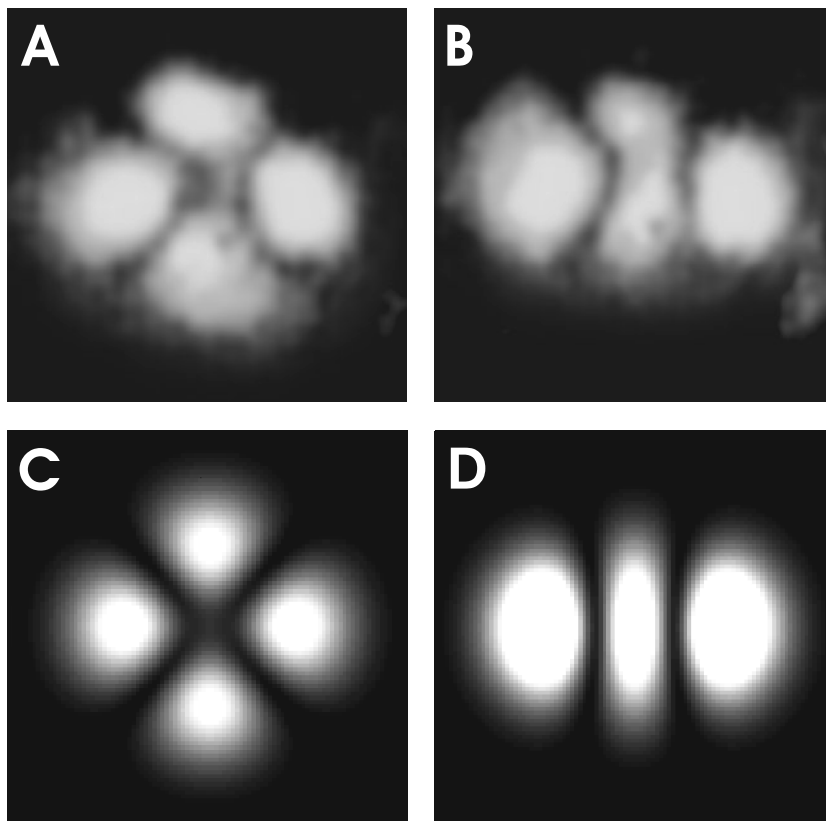
Figure 2. Beam pattern of the GEO 600 dark port for the case of a power-recycled Michelson interferometer. **A**: Observed dark port pattern for a cold beam splitter. **B**: Observed dark port pattern for a hot beam splitter, i.e., thermal lens present. **C**: Corresponding simulation of the cold beam splitter. **D**: Corresponding simulation of the hot beam splitter, i.e., thermal lens present.

we can neglect absorption at any coating of the four main interferometer mirrors (MFe, MFn, MCn and MCe in Figure 1) and the corresponding thermal deformation of the mirror surfaces, because this effect would influence the wavefront curvature similarly in both interferometer arms (assuming symmetric absorption in both arms of the interferometer).

Under this assumption the beam splitter is the only optical component that can change the wavefront curvatures of the two arms differentially. In the case of the bulk absorption it is reasonable to neglect the thermal expansion because it is first of all ten times smaller than the thermo-refractive effect and second would enhance the strength of the thermal lens.

Finally we have to consider light absorption at the two dielectric coatings of the beam splitter and the related thermal effect. For the east arm these effects can be modelled by adding an additional convex lens, while in the north arm we have to insert a concave lens.

All of the effects discussed above would cause a differential change of the two wavefront curvatures, which would increase the strength of the observed thermal lens

and by this lead to a smaller value of the bulk absorption p_a. Hence Equation 2 gives a valid upper limit for the bulk absorption inside the beam splitter.

3. Setting an upper limit for the bulk absorption in the GEO 600 beam splitter

To investigate the thermal lensing of the beam splitter, the GEO 600 detector was used in the configuration of a power-recycled Michelson interferometer. To avoid the influence from mode healing [17], the signal-recycling mirror was misaligned, such that it can just be considered as an attenuator at the dark port. Figure 2A shows the dark port image for a cold state beam splitter, i.e., immediately after lock acquisition. Figure 2C shows the result from a FINESSE simulation for the same configuration using our best estimate of the parameters of the GEO 600 detector.

The cross shape of the dark port image is caused by an astigmatic mismatch of the radii of curvature from the two far mirrors (MFe and MFn in figure 1.1) [8]. Due to this astigmatism the dark port image changes quite strongly with the beam splitter's lensing, which makes it easier to match measurements and simulations. Furthermore this fact also makes our method more accurate in obtaining the focal length of the thermal lens.

Figure 2B shows the dark port image for the hot state of the beam splitter, after the lens has fully developed and the beam splitter is in thermal equilibrium, which takes about 30 minutes. The result of the corresponding simulation is shown in Figure 2D. An additional thermal lens with a focal length of $f_{\text{therm}} = 13\,\text{km}$ best matches the simulation to the observed dark port shape.

The light power inside the beam splitter for this measurement was $P = 1.4$ kW . The beam radius is $w = 0.9\,\text{cm}$ and the geometrical path length inside the beam splitter is $d = 9\,\text{cm}$. Using these parameters and $\beta/\kappa = 10^{-5}\text{m/W}$ for Suprasil [16] Equation (2) gives an upper limit for the bulk absorption of the GEO 600 beam splitter of

$$p_a = 0.25 \pm 0.1\,\text{ppm/cm}. \tag{3}$$

The main contributions to the error budget are uncertainties in the measurement of the radii of curvature of the far mirrors, the intra-cavity power, P, and the beam radius w.

4. Conclusion

A new method was developed to estimate the bulk absorption of beam splitter substrates in a large scale power-recycled Michelson interferometer. Using this method we obtained an upper limit of the bulk absorption of the GEO 600 beam splitter of $p_a = 0.25 \pm 0.1$ ppm/cm. This is, to the knowledge of the authors, the lowest value ever measured for absorption in fused silica at a wavelength of 1064 nm.

Acknowledgments

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