Ottaway, David John; Betzwieser, J.; Ballmer, S.; Waldman, S. J.; Kells, W.
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In situ measurement of absorption in high-power interferometers by using beam diameter measurements

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Received October 27, 2005; accepted November 15, 2005; posted November 16, 2005 (Doc. ID 65637)

We present a simple technique to make *in situ* measurements of the absorption in the optics of high-power laser interferometers. The measurement is particularly useful to those commissioning large-scale high power optical systems. © 2006 Optical Society of America

OCIS codes: 120.3180, 120.6810.

Several large-scale laser interferometers have been constructed to detect gravitational waves. The LIGO interferometers are in the advanced stage of commissioning.[1] The optics in these interferometers require superb surface figure precision to provide the extraordinary displacement sensitivity required for observing a passing gravitational wave. At the same time, high circulating power is required in order to reduce the quantum noise that dominates the performance of these instruments at high frequencies.

It has been shown by a number of researchers that the combination of small amounts of excess absorption and high circulating power can lead to thermal aberrations that significantly degrade the performance of these detectors.[2–6] We have retrofitted the Initial LIGO interferometers with a thermal compensation system (TCS) to correct for these aberrations.[7]

The absorption of laser light in optical coatings and substrates has been extensively studied by using photothermal deformation.[8] Indeed, the coatings and the substrates of Initial LIGO optics were studied prior to installation.[9] Contamination of the LIGO core optics during the assembly and in-vacuum installation is a possibility. Access to the installed in-vacuum LIGO core optics is limited, which prevents us from using more standard methods of measuring the absorption of installed in-vacuum optics. Hence the technique described in this Letter was developed. A complimentary technique that measures the photothermal distortion in the high-reflection surfaces of the optics by using the change in the cavity g parameters has also been developed.[10]

The Initial LIGO interferometers are power-recycled Michelson interferometers with Fabry–Perot cavities in the arms.[1] These interferometers were designed with a deliberate mismatch in the radius of curvature of the recycling mirror to accommodate the expected thermal lensing in the substrates of the input test masses (ITMs). The radius of curvature of the recycling mirror was optimized to match the expected radius of curvature of the thermally lensed ITMs at 6 W of power incident on the interferometer. Initial attempts to reach this operating power on the 4 km instrument at the Hanford Observatory (H1) were clearly limited by thermal absorption. This was because the maximum sideband buildup was achieved on this instrument with only 2.4 W of input power. The combined lensing of the X-arm ITM (ITMX), the Y-arm ITM (ITMY), and the beam spliter (BS) affects the optical buildup of the rf sidebands used to control the interferometer. The strength of the thermal lensing and hence the degradation of performance depends to first order only on the amount of power absorbed in these optics and not on whether it is absorbed within the coating or the substrate.[6] Thermal compensation by using the TCS is necessary to achieve higher powers.[7] The two other LIGO interferometers showed minimal signs of thermal lensing. Clearly a method was required in order to accurately survey the LIGO core optics *in situ* for thermal lensing characteristics.

In this measurement we monitor the change in the spot size of the beam that reflects off the inside of the antireflection (AR) coatings of the aligned ITMX and ITMY after breaking the light buildup condition and misaligning all other optics except the BS. These ghost beams naturally separate from the main beam because of the vertical wedge in the test masses. For example, the optical path for the measurement of ITMX lensing is illustrated in Fig. 1. In normal operation the LIGO interferometers use these beams for interferometer sensing and control.[1] These beams have the advantage of passing through the test mass of interest multiple times and hence are more sensitive to changes in the thermal lens of the optic. The spot size and the phase-front curvature of the incident beams are well known because of the mode-defining properties of transmission through a suspended modecleaner.[1] The thermal lens alters the radius of curvature of the beam reflected from these optics. With the correct selection of optics the change in the wavefront radius of curvature can be converted to a spot size change that is linearly related to the thermal lens power. In order to observe the change in

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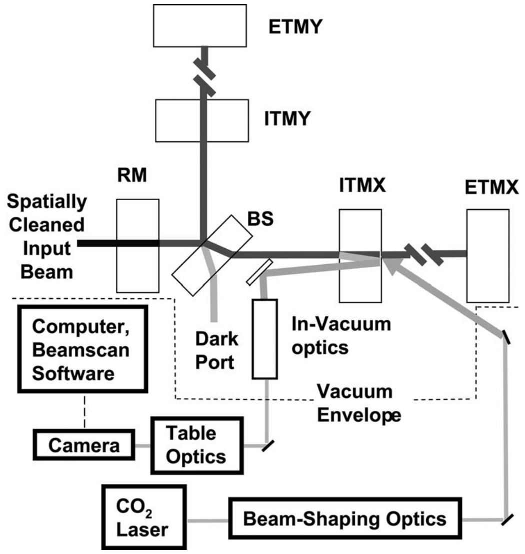

Fig. 1. Schematic of the measurement of the setup used to measure the thermal lensing in the LIGO ITMX. The incident beam is the spatially cleaned input to the interferometer. The RM and the ITMY are misaligned during this experiment. The TCS and BS are also shown. ETMX, end test mass.

the reflected spot size, we use a commercially available beam-analyzing CCD array and its associated diagnostic software.[11] In Fig. 1 the setup used to measure the lensing in the ITMX is shown. This measurement is slightly sensitive to lensing in the BS and the recycling mirror (RM); however, these effects can be shown to be insignificant by analyzing the ghost beam reflected from the inside of the BS AR coating.

The spot size on the CCD array is related to the radius of curvature and the spot size of the beam at the ITM by the following equation:

$$w_{\text{out}}^2 = w_{\text{in}}^2 \left[\left(\frac{B}{R} + A \right)^2 + \left(\frac{\lambda B}{\pi w_{\text{in}}^2} \right)^2 \right], \tag{1}$$

where R is the radius of curvature of the phase front of the incident beam, w_{in} is the spot size of the incident beam at the ITM, and A and B are the matrix elements from the standard 2×2 propagation matrix from the optic under study to the CCD array, namely,

$$\begin{pmatrix} x_{\text{out}} \\ x_{\text{out}}' \end{pmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{pmatrix} x_{\text{in}} \\ x_{\text{in}}' \end{pmatrix}. \tag{2}$$

Here x_{out} and x_{out}' are the transverse position and the slope, respectively, of a ray relative to the optical axis at the CCD array, and x_{in} and x_{in}' are the transverse position and slope, respectively, of a ray leaving the ITM.

The large waist size of the incident beam at the optic under test ensures that the second term in Eq. (1) is negligible. This leaves us with a simple formula for the observed spot size as a function of the curvature,

$$w_{\text{out}} \simeq w_{\text{in}} \left(\frac{B}{R} + A \right). \tag{3}$$

The A and B terms of the output telescope are independent of the thermal lensing present in the ITM, and the input spot size, w_{in}, is determined only by the incident beam. The radius of curvature of the beam leaving the test optic can be written as

$$\frac{1}{R} = \frac{1}{R_{\text{cold}}} + \frac{N}{f_{\text{thermal}}}, \tag{4}$$

where f_{thermal} is the focal length of the thermal lens, N is the number of passes the incident beam takes through the substrate, and R_{cold} is the incident beam phase-front radius of curvature when the optic is cold.

By combining Eqs. (3) and (4), we have an equation that relates the change in the spot size on the camera to the change in thermal lensing in the optics. In practice, we make differential measurements between the measured spot size for the hot and the cold optics, leaving

$$f_{\text{thermal}} = BN \frac{w_{\text{in}}}{w_{\text{hot}} - w_{\text{cold}}}. \tag{5}$$

The only parameters that need to be known accurately are the B parameter of the propagation matrix between the optic and the CCD array and the incident beam spot size at the optic under consideration. The B parameter can be obtained by careful modeling of the optical train between the optic under test and the CCD array. However, in practice we have found it more convenient to measure the B parameter by applying a known tilt to the test mass and observing the resulting transverse motion of the beam on the CCD array.

Care must be taken in the design of the optical system between the optic under test and the CCD array. If the second term in Eq. (1) is too large, the measurement becomes nonlinear and significantly harder to

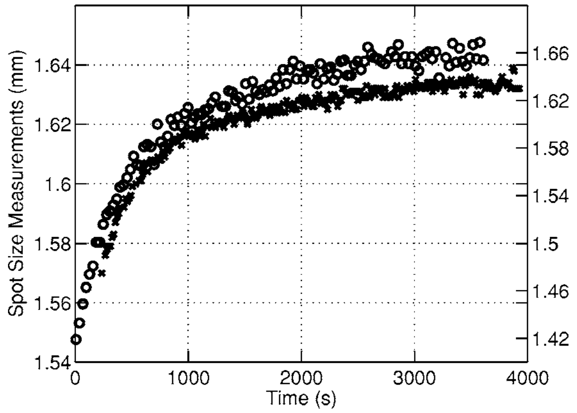

Fig. 2. ITMX cool-down data; two data sets are shown. The crosses and the left axis represent data from the cool down after the interferometer has been run for an hour with 2 W of power incident on the mode cleaner. The circles and the right axis are data from the cool down of the optic when it is heated with 185 mW of power from the TCS.

interpret. In the results presented here, we use an optical system with $A=0.02$ and $B=11.8$ m/rad.

In practice we study LIGO interferometers by running the interferometers at 2 W of input power (4.4 kW of circulating power in the arms) for 2 h, which allows the thermal lens to stabilize. This operating power level was chosen because it is near the highest operating power at which this interferometer can reliably operate without thermal correction from the TCS. Then the interferometer lock is broken (effectively removing the heat source by stopping optical power from being built up in any part of the instrument). All test masses except the BS and the optic under study are misaligned, and the spot size of the beam on the CCD array is monitored during the cool down. The results for the Hanford 4 km interferometer are shown in Fig. 2. Also shown are the results of a cool down, after the the optic is heated with a near-Gaussian beam delivered by the TCS. This beam is of similar spot size to the optical cavity mode at the ITMX. The different spot sizes at the end of the measurements are thought to be due to slight alignment drifts; the optics are known to have slightly spatially dependent radii of curvature, and hence a drift will sample different parts of these static errors of the mirror. Indeed, this is thought to be the main limit to the accuracy of the measurement.

Combining the data shown in Fig. 2 and Eq. (5) shows the thermal lens of the ITMX and ITMY to be 1.0×10^{-5} and 4.7×10^{-6} diopter, respectively, per watt of input power. By comparing the delta spot size for interferometer heating to that of a known absorbed power delivered by the TCS, we found the absorption of the ITMX and the ITMY to be 34 ± 4 and 12.6 ± 1.6 mW, respectively, per watt of input power. If this absorption is assumed to be dominated by the absorption in the high-reflecting surfaces, then the relative absorptions for the ITMX and the ITMY surfaces are 15 and 5.7 ppm (parts in 10^6). Since the ITMX was found to have anomalously high absorption, it was decided to vent the LIGO vacuum system and replace it. These measurements were repeated on the new ITMX, and an upper limit of 1.3 ppm was set on its absorption by using this method. This significantly reduced the load on the TCS system, allowing high-power operation of the interferometer to be achieved.

We have found that the technique can resolve thermal lensing power as small as 10^{-6} diopter. This corresponds to a surface error of $\lambda/700$ over the radius of the beam in the LIGO test masses.

In conclusion, we have demonstrated a simple technique that allows an accurate survey of the *in situ* absorption characteristics of optics in large-scale high-power interferometers. The technique is simple to apply and requires minimal specialized equipment. The technique is particularly useful in the commissioning of large-scale high-power optical devices where optical absorption is likely to be an issue.

This work is supported by the National Science Foundation under Cooperative Agreement PHY-0107417, LIGO Internal DCC LIGO-P050028-01-R. The authors gratefully acknowledge helpful discussions with Keita Kawabe, Fred Raab, and Rick Savage. D. J. Ottaway's e-mail address is ottaway@ligo.mit.edu.

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