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Active correction of thermal lensing through external radiative thermal actuation

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Absorption of laser beam power in optical elements induces thermal gradients that may cause unwanted phase aberrations. In precision measurement applications, such as laser interferometric gravitational-wave detection, corrective measures that require mechanical contact with or attachments to the optics are precluded by noise considerations. We describe a radiative thermal corrector that can counteract thermal lensing and (or) thermoelastic deformation induced by coating and substrate absorption of collimated Gaussian beams. This radiative system can correct anticipated distortions to a high accuracy, at the cost of an increase in the average temperature of the optic. A quantitative analysis and parameter optimization is supported by results from a simplified proof-of-principle experiment, demonstrating the method's feasibility for our intended application.

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Optical aberrations caused by thermal lensing and (or) thermoelastic deformation are a common limitation on the performance of high-power optical systems. A particular example can be found in the design of the second generation of large-scale gravitational-wave detectors now being proposed.[1,2] In brief, these instruments are intended to detect weak gravitational disturbances emanating from astrophysical events by interferometrically monitoring the motions of carefully isolated test bodies separated by kilometer-scale baselines. The test bodies are configured as the end mirrors of passive Fabry–Perot resonant cavities, which are suspended in vacuum. To attain the necessary displacement sensitivity to detect anticipated gravitational-wave disturbances ($<10^{-19}$ m over periods of 10^{-1}–10^{-4} s), it is anticipated that approximately 1 MW of circulating optical power must be stored in these Fabry–Perot cavities to reduce the effect of Poisson (shot) noise on fringe detection. Thermal distortions induced by absorption in the mirror substrates and coatings will severely limit the sensitivity of the instrument if uncorrected.[3–5] At the same time the extremely small displacement noise that can be tolerated for these isolated, suspended optics precludes mechanical interaction or direct attachments.

We present here an active, radiative thermal compensator that significantly reduces such aberrations without compromising the mechanical isolation of the optics and that will facilitate the interferometer's optimal function at a wide range of operating powers.

Optical absorption in a thermally isolated cylindrical optic induces aberrations in two ways: (1) Radial spatial variation of the beam intensity profile (here Gaussian) causes a spatially nonuniform absorbed energy distribution, and (2) radiative heat loss through the sides of the optic produces a net radial heat flow. Both effects contribute to radial temperature gradients, causing two predominant forms of optical aberrations: thermal variations in the material refractive index, and optical surface distortion through thermoelastic expansion effects. For interferometers such as those planned for the Advanced Laser Interferometer Gravitational Wave Observatory (LIGO), transmissive errors are the dominant concern, and our experiment here concentrates on this effect. Our model is, however, fully general and treats both transmissive and reflective aberrations.

The proposed compensation scheme is illustrated in Fig. 1. A ring of Nichrome wire radiatively heats the peripheral region on one face of the optic. Added heat at the edge flattens the radial profile of absorption, compensating for the centrally peaked beam heating. This alleviates the radial component of the thermal gradient at the cost of an increase in the mean temperature of the optic. A low-emissivity radiation shield is provided around the cylindrical periphery of the optic as a radial insulator to further discourage radial heat flow. A cylindrical passive radiation shield

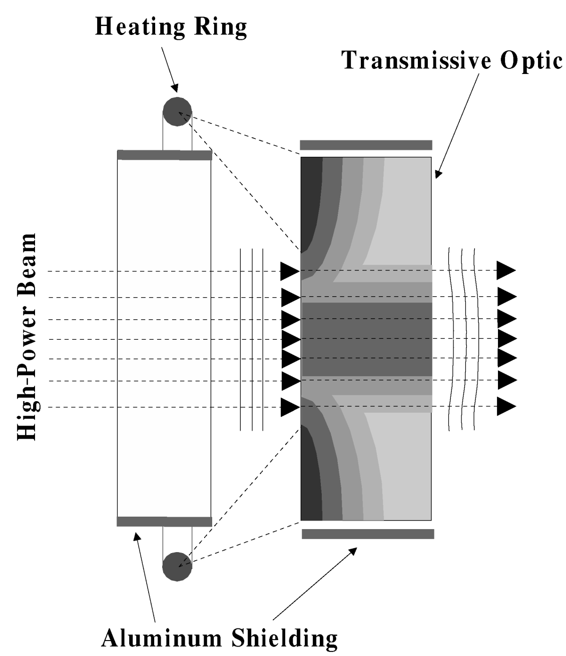

Fig. 1. Cross-sectional view of shielded heating ring thermal compensation of absorption-induced aberrations in a transmissive optical element.

is installed to protect the center of the optic from the heater's radiation, which is otherwise undirected.

This shielded, insulated ring geometry, as well as configurations with and without the shield and (or) insulation, was modeled with finite-element methods to solve the heat transfer equation under radiative boundary conditions, as well as the stress–strain relations under the resulting thermomechanical loads. Axial symmetry was utilized to reduce the model to two dimensions (thus significantly reducing computation time and speeding the process of optimization), and the results were verified against analytical results for simple limiting cases.[6,7] Optimization of the degrees of freedom within a given heater geometry (i.e., intrageometry optimization) is achieved by maximizing the correction quality over the relevant degrees of freedom of the geometry (e.g., for the simple ring, these are the ring's power, radius, and axial position relative to the optic's face). "Quality" here refers to the degree to which deleterious phase distortions induced by unit absorbed beam power can be corrected by compensation. Quantitatively, this is the residual fractional power scattered from the TEM_{00} Gaussian mode (defined as the circulating eigenmode within the proposed interferometer, thus also the source term for the aberration). Properly optimized solutions for all the modeled geometries show a potential reduction of TEM_{00} scatter by a factor of 100 or more.

Any of these corrections comes at the price of an increased temperature of the optic. Although, in principle, many optical materials can withstand extreme temperatures, in our application the instrument's ultimate sensitivity is partly limited by the Brownian thermal noise of the mirrors. This imposes a relatively soft limit on the allowable temperature rise, of the order of 30 K above ambient. As such, as an intergeometry figure of merit, we examine each optimized geometry's efficiency in compensation: the mean temperature increase of the optic per unit absorbed power that is compensated. Although the simple ring and shielded ring exhibit similar degrees of correction quality, the simple ring is found to be a factor of 100 less efficient than the shielded ring (because the simple ring deposits some amount of heat in the optic's center, thus exacerbating the original distortion we wish to compensate). The properly optimized solution for the shielded, insulated heater geometry shows an efficiency of

$$20\ ^{\circ}\mathrm{K/W}\left(\frac{0.05\ \mathrm{m}}{w}\right)^2, \tag{1}$$

where w is the $1/e^2$ radius of the absorbed Gaussian beam, and will thus allow compensation upward of 1-W total optical absorption in the optics of the Advanced LIGO. The inverse-square dependence on heating beam size is a reflection of the fact that steeper thermal gradients require proportionately more compensator power to counteract (hence a larger temperature increase in the optic).

To experimentally test the feasibility of this form of thermal compensation and the reliability of our model, we performed a small-scale benchtop experiment inside a high-vacuum chamber. A schematic of the experiment is shown in Fig. 2. The test optic is a cylindrical flat–flat fused-silica optic 10 cm in diameter and 8 cm thick, with a 1° wedge. An initial thermal distortion is artificially induced by a Gaussian-profiled pump beam from a CO_2 laser operating at 10.6 μm, a wavelength strongly absorbed by the test optic. The pump beam is set to a radius of $w = 1.5$ cm at the surface of the optic to match the approximate ratio of beam to optic diameter in the Advanced LIGO. The absorbed pump power is set to 50 mW, which is chosen to replicate the magnitude of the radial thermal gradients, hence the optic's resulting temperature increase under compensation, that would be seen for 0.5 W of beam power absorbed from a 5-cm-radius beam on a much larger optic [recall expression (1)].

To measure the aberrations on the optic, a commercially available Shack–Hartmann sensor is used (Wavefront Sciences CLAS-2D), with an active area of 22 × 22 lenslets. A low-power fiber-coupled diode laser is used as a probe light source; its beam is expanded with a collimator and double-passed through this optic, reflecting internally from the far face. On retracing its path through the collimator the light is diverted to the Shack–Hartmann sensor by a polarization circulator. Differences are taken between wave-front slopes measured with no active sources, with the pump beam alone, and with the pump beam and compensator both active to remove the effects of static aberrations in the collimator and test optic.

The heater comprises a 5-mm-thick torus of thin Nichrome wire, shaped around a 13.4-cm-diameter circular core of ceramic fish-spine beads on a steel wire frame. Supported in four places, it is electrically and thermally insulated from the optical table and the test optic mount. The ring plane is located 11.9 cm from the optic's face. A coaxial shield obstructs the heater's radiation from the center of the optic. The shield has an inner diameter of 10.1 cm and an outer diameter of 11.4 cm and is located 8.5 cm from the optic face. The ring is powered by an adjustable 100-W dc power supply, whose current and voltage are monitored to control the total power emitted from the ring. After the current is switched on, the optic takes approximately 20 min to radiatively and conductively equilibrate.

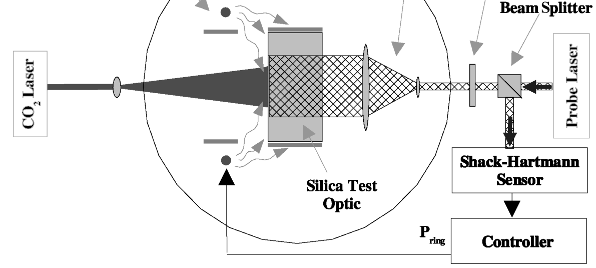

Fig. 2. Setup of the heating ring experiment. The probe examines the test optic in transmission, and the pump shines on the far optical surface.

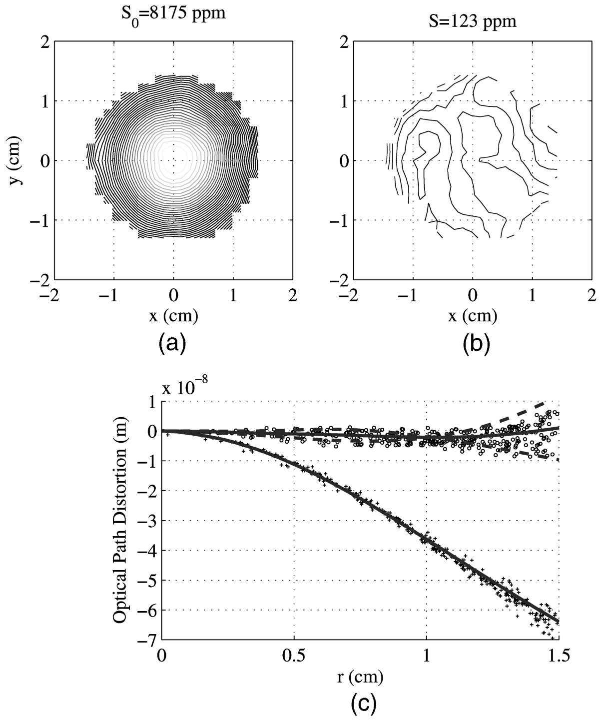

Fig. 3. Results of the shielded heating ring test. (a) Raw pump-induced optical path distortion due to 50 mW of 10.6-μm pump power delivered in a Gaussian profile of 1.5-cm radius. (b) Residual optical path distortion after optimization of the heater current. The contour interval in both plots is 2 nm. The calculated scattered power from a 1.06-μm-wavelength TEM_{00} Gaussian beam of 1.5-cm radius is given at the top of each diagram. (c) Points from both maps are replotted as a function of radial coordinate and superimposed on our model's prediction (solid curve). The dashed curves show the envelope of the predicted result if the heating ring is an ellipse with eccentricity 0.2.

Figure 3(a) shows the observed effect of the pump beam alone. A peak optical path distortion of 70 nm is observed with respect to the unpumped control case. Such a distortion would scatter 8200 parts in 10^6 (ppm) of power out of the TEM_{00} mode power.

Figure 3(b) shows the residual distortion with the shielded heating ring correction applied with 100 W of electrical input power. The compensated distortion is less than 20 nm peak to valley over the sampled aperture and is calculated to scatter only 120 ppm into higher-order modes, i.e., effective TEM_{00} scatter is reduced by a factor of 70 over the uncompensated case. The astigmatic residual distortion is attributed to a slight ellipticity in the heater ring, a known artifact of its fabrication. Improved engineering will mitigate this defect. However, this also serves to highlight a potential limitation of our method; if the optic's absorption is substantially inhomogeneous or nonaxisymmetric (as might arise, for example, from localized concentrations or macroscopic gradients in impurity content), the achievable correction will be limited, and a more complex, spatially directed compensation method must be considered.[4,5,8]

To reach this optimum, 100 W of electrical power was delivered to the heater ring, although the expected power requirement was 70 W. The discrepancy was resolved by noting that the ring glowed visibly, indicating that some electrical power was converted into radiative wavelengths at which the test optic was transparent. Although no independent measurement was made of the test optic's final temperature, system performance was examined at multiple compensator powers and an estimated correction derived by integrating an idealized fused-silica absorption spectrum against the ring's predicted blackbody emission gave approximate consistency with our observations.

In conclusion, we have designed and demonstrated a noninvasive, noncontact compensator for beam-induced thermal optical path distortions in an isolated transmissive optic. Although this specific geometry is designed to address the problems associated with high-power optical cavity systems in next-generation gravitational-wave interferometers, this technique of correction is readily generalized to include beam-induced transmissive and reflective distortions of all kinds. The method is both straightforward to optimize for particular applications of interest and inexpensive to implement. Under expected operating conditions, this technique promises to allow an increase of an order of magnitude or more in the circulating power within gravitational-wave interferometers constrained by optical absorption.

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