Adaptive control of laser modal properties

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An adaptive optical system for precise control of a laser beam's mode structure has been developed. The system uses a dynamic lens based on controlled optical path deformation in a dichroic optical element that is heated with an auxiliary laser. Our method is essentially aberration free, has high dynamic range, and can be implemented with high average power laser beams where other adaptive optics methods fail. A quantitative model agrees well with our experimental data and demonstrates the potential of our method as a mode-matching and beam-shaping element for future large-scale gravitational wave detectors. © 2006 Optical Society of America

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Adaptive optics plays a key role in optical systems such as astronomical telescopes and high-average-power laser systems. The primary roles of an adaptive optical system are to correct aberrations associated with propagation and to maintain or restore the phase front of the light, typically by using deformable mirrors. For situations where correction must be applied directly to high-average-power laser beams, alternative methods are needed because the deformable mirror materials typically have low damage thresholds. Several methods have been reported that compensate for thermal aberrations, using compensating materials with opposite temperature derivatives of the refractive index,[1,2] and external radiative thermal actuation.[3–5]

Large-scale gravitational wave interferometers[6] have particularly restrictive requirements on the ways in which the corrective phase can be applied. Average circulating powers of as much as 800 kW are envisioned in the Fabry–Perot cavities of the Advanced Laser Interferometer Gravitational Wave Observatory (AdvLIGO),[7] and minute levels of absorption in optical coatings and substrates result in significant changes to the power recycling cavity and arm cavity mode structures, thus requiring adaptive correction. These changes manifest themselves as changes in the effective radii of curvature of the mirror surfaces and the focal power of the substrates, changing the fundamental arm cavity and power recycling modes and reducing coupled power. In physical environments, where repositioning of large telescopic optical components is prohibitively difficult, high-power adaptive methods are needed to control the laser beam mode.

In this Letter, we present a method for precisely shaping the mode structure of a laser beam based on the auxiliary heating of a color-glass filter. Using an additional laser operating at a wavelength heavily absorbed by a substrate (shown schematically in the left inset of Fig. 1), an aberration-free parabolic lens can be created, provided that the heating beam mode is substantially larger than the transmitted beam mode. The resulting focal length varies inversely with the heating laser power. This idea forms the basis for an adaptive optical telescope.

To model this concept, we first solve the thermal diffusion equation in the absorber to compute the optical path difference. The absorption of the Gaussian-shaped heating beam with radius w heats the dichroic substrate and generates a nonuniform temperature distribution. The steady-state solution of the temperature change T on a cylindrical substrate thickness L and radius R can be calculated using the thermal diffusion equation,

$$\nabla^2 T(r,z) = -\frac{2\alpha P}{\pi K w^2}\exp\left(-2\frac{r^2}{w^2}\right)\exp(-\alpha z), \qquad (1)$$

where α is the absorption coefficient for the heating beam, K is the thermal conductivity, and P is the heating beam incident power. An exact solution can be found using the boundary conditions appropriate to the experiment (the substrate is mounted with its rim in good contact with a heat sink that itself is in thermal contact with the optical table), namely, $T(R,z)=T_0$ on the rim of the cylindrical substrate and $\partial T/\partial z=0$ on the faces $z=0,L$, since the heat flow from the faces of the substrate is much smaller than the radial heat flow. We neglect the effect of Stefan–Boltzmann radiation (as its effect is small compared with the energy absorbed by the heat sink). This approach leads to

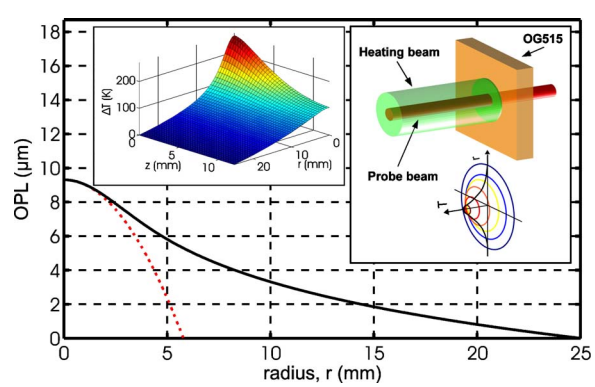

Fig. 1. (Color online) Calculated radial dependence of the optical path difference assuming 4 W of heating power in a 7.2 mm diameter beam. The solid curve results from an exact solution of the thermal diffusion equation; the dotted curve displays the OPL assuming a parabolic lens. Right inset, schematic view of laser adaptive mode control. Left inset, spatial dependence of the temperature profile $\Delta T(r,z)$.

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$$T(r,z) = -\sum_{n=1}^{\infty} \frac{4\alpha P}{\pi K R^2 w^2} \frac{\int_0^R \exp\left(-2\frac{r'^2}{w^2}\right) J_0\left(k_n \frac{r'}{R}\right) r' \mathrm{d}r'}{[J_0(k_n)]^2} \times J_0\left(k_n \frac{r}{R}\right) f_n(z) + T_0, \quad (2)$$

where $f_n(z)$ is given, with $p_k = e^{k_n L/R}$ and $p_\alpha = e^{\alpha L}$, by

$$f_n = \frac{\frac{\alpha R}{k_n}\left[\frac{p_k/p_\alpha - 1}{p_k^2 - 1} e^{(k_n/R)z} - \frac{p_\alpha/p_k - 1}{p_\alpha^2 - 1} e^{(-k_n/R)z}\right] + e^{-\alpha z}}{\alpha^2 - (k_n/R)^2}. \quad (3)$$

Equation (2) is evaluated numerically on a computational grid with 460 steps in the radial direction and 1000 steps in the z direction (right-hand inset of Fig. 1). The temperature gradient modifies the optical path through the filter through the temperature dependences of the index of refraction, the thermal expansion, and the thermally dependent photoelastic effect.[8] Of these, thermal expansion is the dominant term, with some contribution from $\mathrm{d}n/\mathrm{d}T$ for Schott OG515, the material we use in our experiments.[9] The integrated optical path length (OPL) change can be written as

$$P(r) = \left[\frac{\mathrm{d}n}{\mathrm{d}T} + \alpha_T(n-1)\right] \int_0^L \Delta T(r,z) \mathrm{d}z, \quad (4)$$

where α_T is the coefficient of thermal expansion, n is the index of refraction, and $\Delta T(r,z) = T(r,z) - T_0$. A TEM_{00} probe beam $u_\mathrm{p}(r,z)$ propagating through the filter experiences a phase shift from the OPL change given by

$$u_\mathrm{o}(r,z) = u_\mathrm{p}(r,z)\exp[-ikP(r)] = u_\mathrm{p}(r,z)\exp\{-ik[P(0) + P''(0)(r^2/2) + O(r^4)]\}, \quad (5)$$

where we have expanded P in a Taylor series $\sim r=0$ omitting odd powers of r because of the axial symmetry of $P(r)$. Comparing this with propagating a beam through an ideal thin lens,[10] $u_\mathrm{prop}(r,z) = u_\mathrm{p}(r,z)\exp[ik(r^2/2)(1/f)]$, one immediately sees that the focal length of a lens corresponding to the given OPL profile is given by $f_P = -1/P''(0)$. The key result of this analysis is that, provided the beam diameter of the probe beam is sufficiently small that terms of order r^4 and higher can be neglected, the probe beam experiences a perfect lens whose focal length can be adjusted in a continuous manner by changing the heating beam power.

Figure 1 shows the OPL calculated by using Eqs. (3) and (4) (solid curve) assuming a 7.2 mm heating beam diameter with a power of 4 W impinging on a Schott color-glass filter OG515 (Ref. 9) with a radial dimension of 25 mm and a length of 12 mm. The length of the filter and its transmission characteristics are selected to provide complete absorption of the heating beam and complete internal transmission of the probe beam. The dotted curve corresponds to the OPL change of an ideal thin lens with a focal length of 1.69 m. Provided that the probe beam has a radius less than approximately 1 mm, it is evident that the central part of the thermal lens satisfies the approximations that were necessary to obtain that relation.

Our experiments use up to 6 W of a multiline argon-ion laser as the heating beam and a 200 mW, 1064 nm single-mode nonplanar ring resonator (NPRO) Nd:YAG laser as the readout beam. The transverse mode of the NPRO is spatially cleaned by using a single-mode fiber. The Gaussian mode parameters of each beam are prepared separately, and the beams are combined by using a dichroic beam splitter and are focused onto the OG515 color-glass filter. The OG515 is mounted in a heat sink so that it is cooled at its rim; it also is placed in a small chamber to eliminate convection. The Nd:YAG waist is kept much smaller than the heating beam waist at the filter; this arrangement ensures that the Nd:YAG beam samples only the parabolic part of the thermal lens. Typically, the probe beam has a 500 μm diameter waist located 0.3 m in front of the OG515. The changes of the probe beam mode properties are analyzed using a Dataray Inc. WinCamD beam analyzer by measuring the divergence angle (and thus the focal length) as pump power is varied.

Figure 2 displays the experimentally measured lens power (in diopters) as a function of the pump power of the heating beam, clearly demonstrating that the inverse focal length is proportional to the heating beam power. The solid line in Fig. 2 shows the calculated lens power for the parameters used in this experiment, based on the theory presented above. It is important to emphasize that within the limits of the known physical, thermomechanical, and optical parameters for the OG515, no free parameters were used to generate the theory curve. The inset shows the measured beam parameters used to calculate the focal length. The experiment finds thermal lenses that are in good agreement with the computed values. The calculated error bars take into account the uncertainty in the measured beam

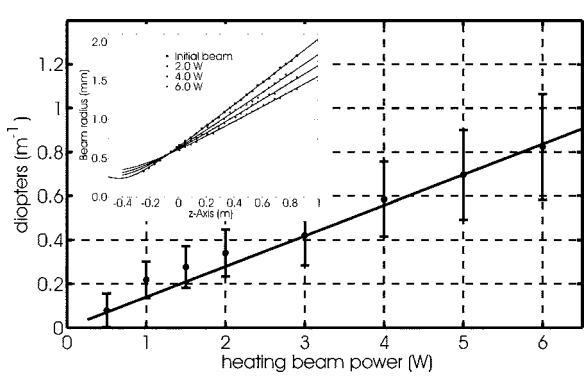

Fig. 2. Measured lens power in diopters (circles) as a function of heating beam power. The solid line is the theoretically computed lens power for the parameters used in this experiment. Inset, raw divergence angle data along the y axis used to compute the lens power. For clarity only a reduced set of measurements is shown.

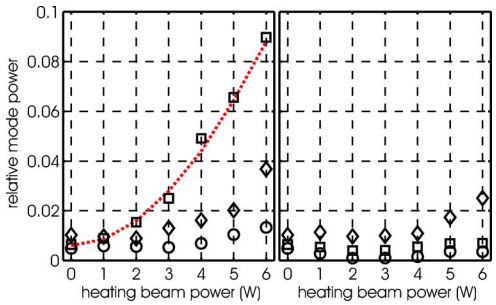

Fig. 3. (Color online) Left, Experimentally measured mode content as a function of heating laser power, starting with optimal mode matching at 0 W. Right, Experimentally measured mode content as a function of laser power after changing the lens position to reoptimize the mode matching at each power setting. The squares, circles, and diamonds correspond to the experimentally measured bull's-eye modes, first-order Hermite–Gauss modes (HG_{01} and HG_{10}) and the sum of all other higher-order modes.

parameters for the probe as well as the uncertainty in the power and the diameter of the pump beam.

To assess the aberrations introduced by the adaptive lens and to quantitatively measure the higher mode content as a function of laser power, two lenses were placed after the OG515, providing optimal mode matching into a 16 cm long analyzer cavity at zero pump power. Figure 3 (left) displays the mode content of the bull's-eye mode, i.e., the first Laguerre–Gauss (LG1) mode in the cavity mode base system (depicted by the square symbols) starting from optimal mode matching. As the laser power increases, the LG1 mode increases parabolically, consistent with a change in the waist position and size with respect to the cavity basis.[11] The dotted curve is the theoretical prediction of the mode content of the LG1 mode obtained by calculating the overlap integral with the fundamental cavity mode after propagating the probe beam through the variable thermal OG515 lens and the cavity-mode-matching telescope. The calculated focal lens is in good agreement with the measured value, and again there are no free parameters used in the theory. The circular symbols and diamonds correspond, respectively, to the experimentally measured first-order Hermite–Gauss modes (HG_{01} and HG_{10}) and to the sum of all other higher-order modes. Figure 3 (right) shows similar data, but in this case the mode-matching lenses were reoptimized after each change in the heating power. From these plots several features are worth noting. First, essentially no aberrations are introduced for heating powers up to 4 W. Although the higher-order mode power increases above 2 W in Fig. 3, this is attributable to the substantial change in the laser mode with respect to the cavity mode. When the mode is reoptimized (Fig. 3, right) by using a lens, the higher-order mode content is driven to a very low value, indicating that the thermal lens introduces a purely parabolic phase shift. Above 4 W (corresponding to $f \sim 1.6$ m), spherical aberration becomes evident, as is seen from the increase in higher-order modes in Fig. 3 (right). Second, the constancy of the $HG_{01,10}$ modes over the range 0–4 W in Fig. 3 shows that the thermal lens introduces no tilt or steering in the beam at those heating power levels. We also experimentally varied the ratio of the heating beam waist to readout beam waist. Provided the ratio of the heating beam waist to the probe waist is at least 6, the resulting thermal lens is aberration free.

Although the experiment was conducted in a nonevacuated environment, nothing prevents the use of this technique in vacuum. For implementation in large-scale gravitational wave detectors using high-power lasers, several other considerations are important. Self-absorption of the probe beam can induce a thermal lens that produces higher-order aberrations. For high-power applications, this may require the use of alternative substrate materials and heating lasers, such as fused silica and carbon dioxide lasers.[4] Also, proper shaping of the heating beam in conjunction with special substrates may allow for more sophisticated phase profiles within the substrate for generating super-Gaussian or mesa beams.[12]

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