Adhesive-free, high optical quality deformable mirror

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Abstract: Mode control is crucial for the high-precision interferometry such as gravitational-wave detectors. We report here the design and characterisation of a linear, high dynamic range, spherically deformable, adaptive mirror that is adhesive-free and low cost. © 2020 The Author(s).

1. Introduction

Recent detections of numerous gravitational-wave sources have been enabled by the continuous increase in the sensitivity of the Advanced Laser Interferometer Gravitational-Wave Observatory (aLIGO) [1]. The sensitivity of these detectors is limited currently by optical quantum noise in the form of radiation pressure noise at low frequency and shot noise at high frequency [2]. The use of squeezed states of light to reduce quantum shot noise has been successfully demonstrated at aLIGO detectors [3] and in future upgrades, frequency-dependent squeezing will be implemented to reduce both shot noise and radiation pressure noise [4]. The efficacy of squeezed light injection is however limited by optical losses [5], including loss caused mode-mismatch between the optical cavities. Deformable mirrors provide a solution to reduce this loss. However, most commercially available technologies use thin substrates to achieve large actuation range and thus compromise surface quality [6,7]. Compatibility with aLIGO's vacuum system further limits the choice of mirrors [8]. Recently developed thermally actuated bimorph mirrors offer a solution, but their actuation range is limited by the shear strength of the adhesive used [9]. We present here a low-cost, high dynamic range, adhesive free, thermally actuated deformable mirror that use LIGO-vacuum-compatible materials and can be easily adapted to off-the-shelf mirrors.

2. Thermally-actuated compression fit mirror (CFM)

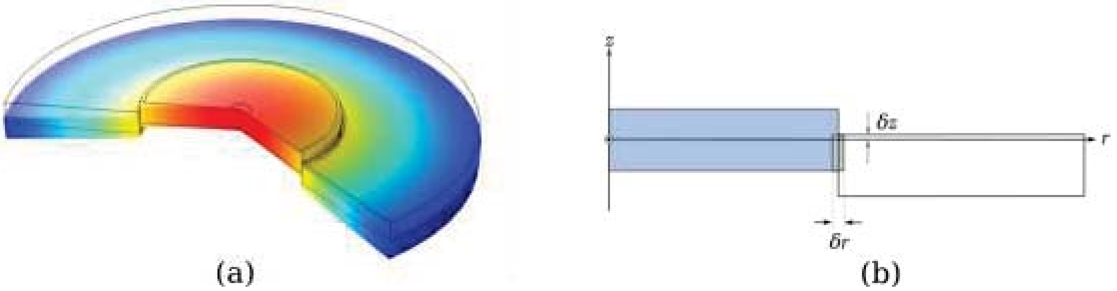

Fig. 1. Schematic of the CFM: (a) 3D-rendering of the deformation of a CFM at room-temperature; (b) Radial section of a CFM, showing the mirror (shaded) and the annular aluminium ring, the front surface of which is a distance δz above the neutral plane of the mirror. At room temperature and before assembly, the inner diameter of the aluminium is $2\delta r$ smaller than the outer diameter of the mirror.

The CFM exploits the difference between the thermal expansion coefficients of fused silica and aluminium to thermally control the mirror curvature. The mirror is captured within the aluminium annular ring, as shown in Fig. 1, by uniformly heating the components until the mirror fits within the aluminium ring and then slowly cooling. As it cools, a compressive stress is applied to the mirror, causing its top (front) surface to become (more) convex. Tuning the curvature of the mirror is accomplished by heating the assembly. This shrink-fitting produces a compression-bias stress within the mirror, which reduces significantly the tensile stress at the top surface compared to a bimorph mirror [9].

We report here a CFM that uses a 2"-diameter 6mm-thick flat mirror, a 6mm-thick Al ring with an outer diameter of 120mm, a nominal $\delta r = 35\mu\text{m}$ and $\delta z = 0$, for which we used a 125°C assembly temperature. Finite-element analysis (FEA) predicts that the maximum tensile stress at the front surface is 15 MPa, a factor of 3 less than the tensile yield stress of fused silica, and the deformation of the top surface should be purely spherical.

10.1364/CLEOPR.2020.C5G_3

3. Results

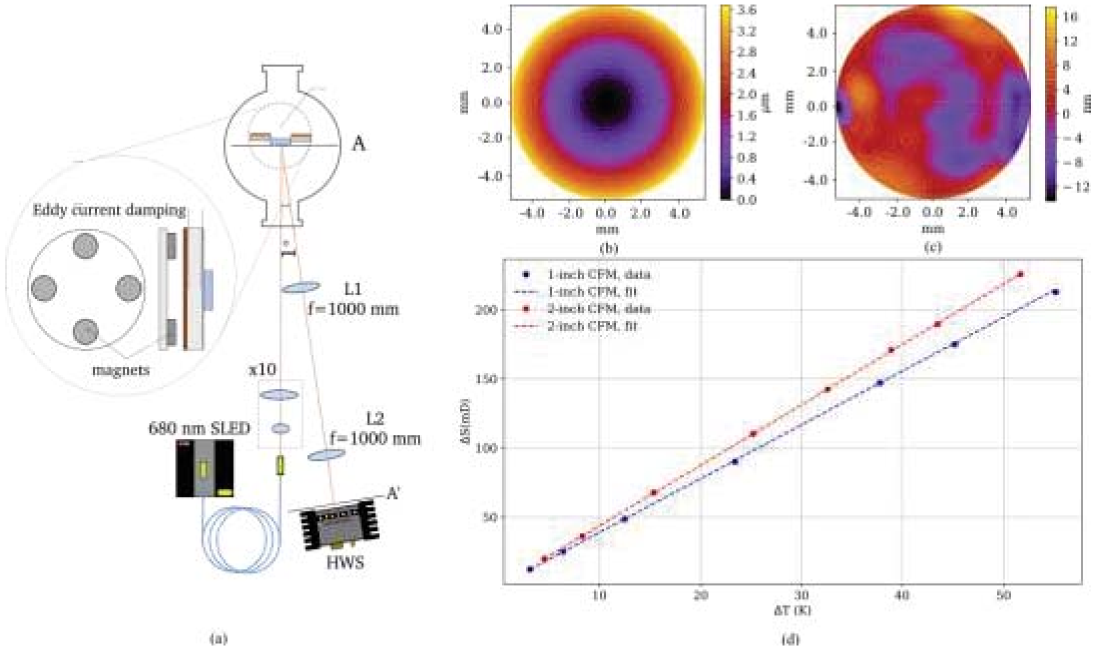

Fig. 2. (a): Experimental layout to test mirror response to change in temperature: the CFM is suspended from fused-silica fibers inside vacuum. A 680 nm superluminescent probe beam is reflected by the CFM and imaged onto a Hartmann wavefront sensor. (HWS). (b) Change in reflected wavefront compared to the mirror's cold state for a temperature increase of 49°C. (c) Residual wavefront after subtraction of quadratic component from (b). (d): Change in spherical power as a function of temperature for the 2" mirror, and a 1" mirror with similar parameters.

The deformation of the mirror was measured using a high-precision Hartmann wavefront sensor (HWS) [10], as shown in Fig. 2(a). The gradient field produced by the HWS is numerically integrated to yield the wavefront change, as shown in Fig. 2(b).

The measured static spherical power of the mirror at room temperature (20°C) was -314±6 mD, which compares favourably with the -316 mD predicted by the FEA. Changing the temperature of the mirror by 49°C resulted in the largely quadratic wavefront change shown in Fig 2(b), with the non-quadratic component shown in Fig 2(c). This non-quadratic deformation would lead to a maximum scatter $< 0.26\%$ for an incident Gaussian beam with a spot diameter ≤ 2.6mm. The change in spherical power, ΔS, as a function of temperature for both the 2" and 1" mirrors is plotted in Fig. 2(d), showing that the response is highly linear.

4. Conclusion

We have described an adhesive-free thermally-actuated adaptive optic that has a large spherical-power dynamic range with very low higher-order aberrations and low tensile stress. The dynamic range surpasses that available in a thermally-actuated bimorph adaptive optic [9]. Additionally, it is simple and can easily be adapted to off-the-shelf mirrors. We believe the CFM will play an important role in optimising the sensitivity of ground-based gravitational-wave detectors.

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