

Nonuniform birefringence in highly reflective substrate-transferred GaAs/Al_{0.92}Ga_{0.08}As coatings at 1064 nm

Andri M. Gretarsson ^{*}, Ambroise L. M. Juston , Benjamin Nicolai, Naomi Borg , and Breck N. Meagher 
Department of Physics, Embry-Riddle Aeronautical University, 3700 Willow Creek Road, Prescott, Arizona 86301, USA

Garrett D. Cole 
Wyant College of Optical Science, University of Arizona, 1630 E. University Boulevard, Tucson, Arizona 85721, USA

GariLynn Billingsley  and Camille N. Makarem 
LIGO Laboratory, California Institute of Technology, 1200 E. California Boulevard, California 91225, USA

Elizabeth M. Gretarsson 
*Departments of Physics and Aerospace Engineering, Embry-Riddle Aeronautical University,
 3700 Willow Creek Road, Prescott, Arizona 86301, USA*

Gregory M. Harry 
Department of Physics, American University, 4400 Massachusetts Avenue NW, Washington, DC 20016, USA

Steven D. Penn 
*Department of Physics, Syracuse University, 900 South Crouse Avenue, Syracuse, New York 13244, USA
 and Department of Physics, Hobart and William Smith Colleges, 300 Pulteney Street, Geneva, New York 14456, USA*



(Received 31 October 2025; accepted 31 December 2025; published 29 January 2026)

Using a custom-built scanning system, we generated maps of birefringence on reflection at $\lambda = 1064$ nm from single-crystal GaAs/Al_{0.92}Ga_{0.08}As Bragg reflectors (henceforth “AlGaAs coatings”). Ten coatings were bonded to fused silica substrates and one remained on the epitaxial growth wafer. The average phase difference on reflection between beams polarized along the fast and slow axes of the coating was found to be $\psi = 1.09 \pm 0.18$ mrad, consistent with values observed in high-finesse optical reference cavities using similar AlGaAs coatings. Scans of substrate-transferred coatings with diameters between 18 and 194 mm showed birefringence nonuniformity at a median level of 0.1 mrad. A similar epitaxial multilayer that was not substrate transferred, but remained on the growth wafer, had by far the least birefringence nonuniformity of all mirrors tested at 0.02 mrad. On the other hand, the average birefringence of the epi-on-wafer coating and substrate-transferred coatings was indistinguishable. Excluding nonuniformity found at the location of crystal and bonding defects, we conclude that the observed nonuniformity was imparted during the substrate transfer process, likely during bonding. Quantifying the impact on the scatter loss in a LIGO (Laser Interferometer Gravitational wave Observatory) interferometer, we find that birefringence nonuniformity at the levels seen here is unlikely to have a significant impact on performance. Nonetheless, future efforts will focus on improved process control to minimize and ultimately eliminate the observed nonuniformity.

DOI: [10.1103/xtsf-t8y4](https://doi.org/10.1103/xtsf-t8y4)

I. INTRODUCTION

Epitaxial GaAs-based optical interference coatings were first demonstrated by researchers at Bell Labs in the mid-1970s [1] and are now routinely integrated as mirrors in

vertical-cavity surface-emitting lasers, the most widely manufactured class of semiconductor laser diodes [2]. Building on developments in compound-semiconductor micromechanical devices [3], optomechanical resonators fabricated from suspended GaAs/AlGaAs Bragg mirrors were found to exhibit simultaneously low optical and mechanical losses [4]. Owing to their potential for use as low-noise reflectors in ultrastable interferometry [5], a substrate-transfer process was developed using direct bonding to apply AlGaAs coatings to arbitrary optical substrates. Employing a cavity-stabilized laser system locked to an optical reference cavity with AlGaAs coatings, it was shown that the coating elastic loss was reduced by a factor of 10 compared to amorphous oxide coatings [6]. Over the last

^{*}Contact author: greta9a1@erau.edu

Published by the American Physical Society under the terms of the [Creative Commons Attribution 4.0 International](https://creativecommons.org/licenses/by/4.0/) license. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI.

decade, continuous refinements have led to the demonstration of “semiconductor supermirrors” with exceptionally low levels of optical loss in the near and mid infrared, with cavity finesse routinely exceeding 300 000 at wavelengths between 1 and 5 μm [7,8]. AlGaAs coatings are now used in the highest-performance ultracoherent laser systems for optical atomic clocks [9] and are expected to improve the astrophysical reach of gravitational-wave detectors [10,11].

First measurements of high-finesse cavities with AlGaAs mirrors showed nonzero static birefringence [6]. This was unexpected given the orientation of the material (100) and the cubic symmetry of the crystal. More recent results in cryogenic cavities have also shown the presence of a noise-like fluctuating birefringence at a similar level as other fundamental noise sources [12,13]. While this unwanted polarization noise can be minimized by simultaneous locking to and averaging of orthogonal eigenmodes (coherent cancellation of the birefringence fluctuations), it remains a nuisance in cavity-stabilized lasers and may be a technical obstacle to implementation in future gravitational-wave detectors.

There are two primary concerns with the use of AlGaAs coatings in applications such as gravitational-wave detection that require large beam sizes and high optical intensity:

(1) Noise-inducing interaction between the optical field and the crystal structure and/or other mechanisms for birefringence fluctuation [12–15].

(2) Static birefringence in the mirror is both ubiquitous and shows significant spatial variation.

Here, we report on the latter, with particular emphasis on birefringence nonuniformity, in small (18 mm diameter) through large (194 mm diameter) substrate transferred AlGaAs coatings. We also consider the implications of the observed birefringence nonuniformity for gravitational wave detection.

II. EXPERIMENT DESIGN

We mapped the birefringence in AlGaAs coatings using a single-reflection setup shown in Fig. 1. Circular polarized light with wavelength 1064 nm is reflected at near-normal incidence from the highly reflective, AlGaAs-coated sample. If the AlGaAs coating is birefringent, the reflected polarization becomes slightly elliptical. This ellipticity is detected with a polarizing beam splitter (the “analyzer”), where the relative power difference in the two polarizations is proportional to the coating birefringence. In order to produce spatial maps of the birefringence, the AlGaAs-coated sample is mounted on a rastering stage that moves the sample under the interrogating beam. Note that the angle of incidence deviates slightly from normal to allow the output beam to pass by the “D-shaped” half mirror to the analyzer. This deviation from normal was always less than a degree and had a negligible effect on the measured birefringence. (For example, effective birefringence due to the differential phase of reflected s - and p -polarizations would be less than 10^{-6} rad for angles of incidence below 1° .)

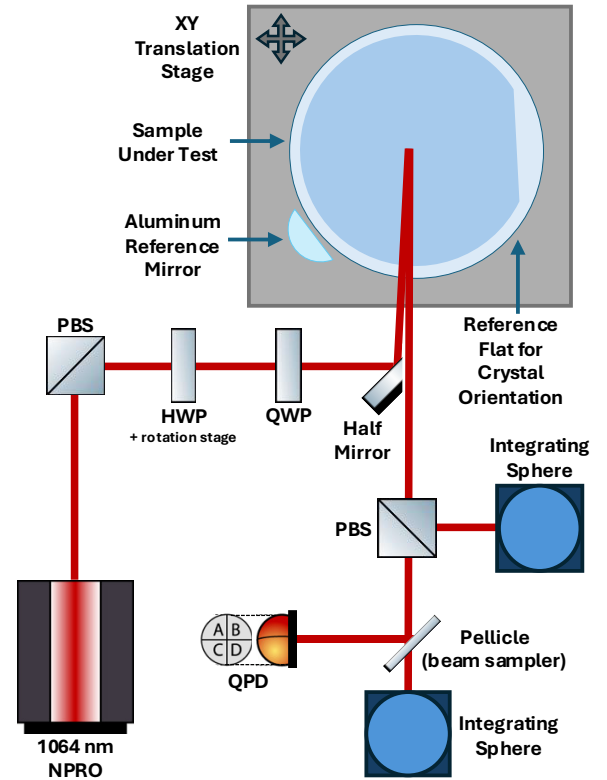


FIG. 1. Simplified diagram of the setup for measuring birefringence on reflection. (Not shown: Power monitoring pick-off, collimating/focusing optics, steering mirrors, and active beam-steering actuators.) The beam interrogates the sample at approximately normal incidence. The orientation of the sample is indicated by the “flat” (chord) next to the aluminum reference mirror. This was varied, but was typically $\pm 45^\circ$, or $\pm 135^\circ$ with respect to the analyzer s polarization, as shown in the top view here.

The Jones matrix formalism is convenient for calculating the relationship between the power in the two output polarizations and the mirror birefringence ψ . Here, ψ is the difference in the reflected phase due to birefringence for light polarized along the fast axis compared to light polarized along the slow axis. We take the fast axis of the sample to be at an angle θ relative to s polarization as defined at the splitting surface of the analyzer. When the beam is traveling parallel to the table surface, s -polarization corresponds to the electric field being oriented vertically. The Jones vector corresponding to this input state, immediately before the half-wave plate, is s polarized:

$$\vec{J}_0 \equiv \begin{pmatrix} J_p \\ J_s \end{pmatrix} = \begin{pmatrix} 0 \\ 1 \end{pmatrix}. \quad (1)$$

We multiply this input polarization by the Jones matrices corresponding to the half-wave plate, the quarter-wave plate, and the reflective coating, which we treat as a wave plate with retardation ψ and orientation θ . This gives the polarization state immediately before the analyzer as

$$\vec{J} = \begin{pmatrix} \frac{1}{\sqrt{2}}(e^{i\frac{\psi}{2}} \cos^2 \theta + e^{-i\frac{\psi}{2}} \sin^2 \theta) - \sqrt{2} \sin \frac{\psi}{2} \cos \theta \sin \theta \\ \frac{i}{\sqrt{2}}(e^{-i\frac{\psi}{2}} \cos^2 \theta + e^{i\frac{\psi}{2}} \sin^2 \theta) + i\sqrt{2} \sin \frac{\psi}{2} \cos \theta \sin \theta \end{pmatrix}. \quad (2)$$

TABLE I. List of high-reflective AlGaAs mirrors whose birefringence was mapped. Entries with dashes (–) correspond to values that are unknown or not measured for technical reasons. Apart from occasional crystal defects and minor edge damage from the substrate-transfer process, these coatings appear flawless to the naked eye.

Sample description	S/N	Coating dia (mm)	Substr. dia (mm)	Avg ^a (mrad) ± 0.17	Peak-to-valley ^b (mrad) ± 0.05
Semicircular	FS/PL-9102	23	25.4	1.4	–
Standard 1 in.	TCS-FS-PL-12264	18	25.4	–	0.09
70 mm, thin	3in-TO-Opt/WP	70	76	–	0.06
100 mm, thin	132979 004 S	89	100	–	0.11
100 mm, thin, on epi	132979 013 S	98	100	0.96	0.02
100 mm, thick (-02)	E1800006-02	93	100	1.09	0.26
100 mm, thick (-03)	E1800006-03	86	100	1.13	0.15
100 mm, thick (-04)	E1800006-04	86	100	–	0.10
200 mm, thin (A)	H8435-068FeF2	194	200	–	1.6
200 mm, thin (B)	1623993-B	194	200	–	0.46
200 mm, thin (C)	P0788-006FEF0	194	200 ^c	–	–

^aAverage birefringence over the central reference area compared with a low birefringence control (Protected aluminum first-surface mirror).

^bThe peaks/ridges and valleys of the pattern were traced by eye and marked. The corresponding data were extracted, and the mean difference between the high and low regions was calculated. For the purposes of this table, we avoided crystal defects and regions along the very edge of the coating.

^cThis sample was broken during manufacture along a straight chord 46 mm from the center.

The power in the p and s polarizations, respectively, are given by $P_p = J_p^* J_p$ and $P_s = J_s^* J_s$, respectively. With some algebra, we find

$$\frac{P_s - P_p}{P_s + P_p} = \psi \sin 2\theta. \quad (3)$$

The left-hand side is the signal we record as a function of position on the coating. Rotating the sample to reveal the sinusoidal dependence of the signal on θ gives the orientation of the birefringence fast axis. We are primarily interested in maps of nonuniformity, so most measurements are made at $\theta = \pm 45^\circ$ to maximize the signal.

A significant portion of the development time was devoted to reducing systematic errors in the readout. The main issue was rastering-stage-induced beam motion on the photodiodes and in the beamsplitter. We need to measure relative power changes between the two polarizations on the order of 1×10^{-4} . Since even good-quality photodiodes typically vary by 1% or more over their face [16], beam motion on the photodiodes induces a strong spurious signal. We added integrating spheres to eliminate this otherwise dominant systematic [17]. To reduce the effect of birefringence in other parts of the optics chain, we actively steer the output beam to keep it in the same position in the optics chain. Coarse and fine actuators steer the final mirror before the sample to correct for beam deviation due to sample curvature or rastering stage tilt. (It should be noted that since actuators are steering the final mirror, the exact position of the beam on the sample is slightly affected by steering. This leads to radial stretching of the image of at most 1%.) These modifications gave sufficient accuracy to measure the spatially averaged birefringence when a nonbirefringent, aluminum-coated reference mirror was used as a control.

However, we were still limited by instrumental artifacts when mapping nonuniformity. To remove these artifacts, we perform each raster line twice, once with left-circular polarization interrogating the sample, and once with right-circular polarization. This changes sign of the right-hand side of

Eq. (3), so subtracting doubles the signal while removing common-mode noise. (The switch in polarization is achieved by rotating the half-wave plate by 45° .) Finally, to remove artifacts from presumed gain drift in the photodiode amplifiers, we fit and removed parabolic features from the individual raster lines. This is roughly equivalent to applying a high-pass filter along the raster lines with a characteristic high-pass length on the order of half the sample size. In other words, our method would not be sensitive to birefringence nonuniformity with lower spatial frequency than about half the sample size that occurs only in the direction of the raster lines. In practice, though, this is not a problem because we can check for such nonuniformity by rotating the sample through 90° and comparing maps.

It is worth noting that we also tested the use of a Mach-Zehnder interferometer as a way to read out the phase difference of the two polarizations directly. However, we found that this gave no advantage. Operating midfringe, where both output ports pass the same power, the sensitivity to the phase difference ϕ between the arms is [18]

$$\frac{P_s - P_p}{P_s + P_p} = \phi. \quad (4)$$

Since the phase difference between the arms induced by the birefringence is just $\phi = \psi \sin 2\theta$, the Mach-Zehnder has the same basic sensitivity as the simpler readout we ended up using.

Table I lists the samples measured. They consist of small and large samples, and one coating that has not been removed from the epitaxial wafer. All the coatings used were grown in the [100] direction. After transfer to the fused silica substrate, the outward normal is $[\bar{1}00]$. Some coatings were produced with a straight chord along the edge indicating crystal orientation. This chord corresponds to the intersection of the $(1\bar{1}0)$ cleavage plane and the coating surface $(\bar{1}00)$.

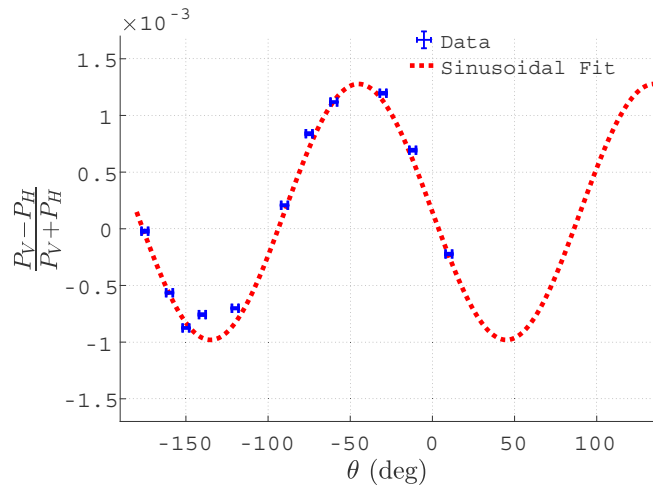


FIG. 2. Average birefringence of a 93-mm diameter AlGaAs mirror on 10-mm thick silica (S/N: E1800006-02). The magnitude of the birefringence obtained from this data is 1.13 ± 0.10 mrad.

III. UNIFORM BIREFRINGENCE

We measured the spatially averaged birefringence in four samples. To do this, we performed multiple scans per sample, rotating the sample about its axis of symmetry between scans. We placed a nonbirefringent, Al-coated, protected first-surface mirror next to our sample to act as a control. Figure 2 shows an example of the data for one of our 100 mm $\times$ 10 mm samples (S/N: E1800006-02), exhibiting the sinusoidal dependence expected from Eq. (3). The clean sinusoidal nature of the data implies that this measurement of the absolute level of average birefringence is robust against systematic errors such as amplifier gain and offset bias drift. Figure 3 shows a similar 100 mm $\times$ 10 mm sample (S/N: E1800006-03) mounted in the apparatus. Substrate-transferred coatings and the coating that remained attached to the epitaxial growth medium had similar average birefringence.

We compared the average birefringence measured in our samples to the birefringence measured in various cavity experiments at 1.0 and 1.5 μ m wavelengths. Figure 4 shows our measurements and the birefringence obtained from mode

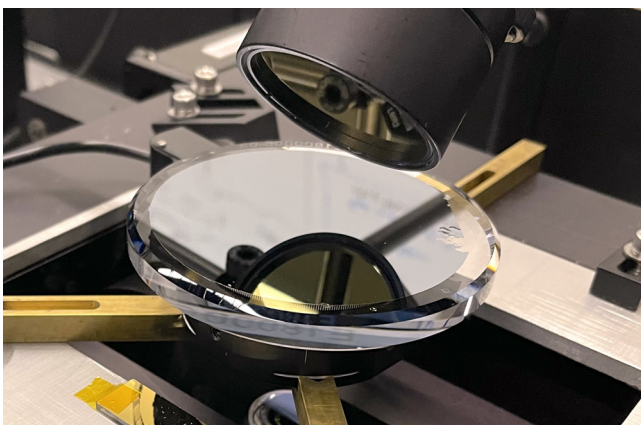


FIG. 3. A 100 mm $\times$ 10 mm sample (S/N: E1800006-03) mounted on the rastering stage.

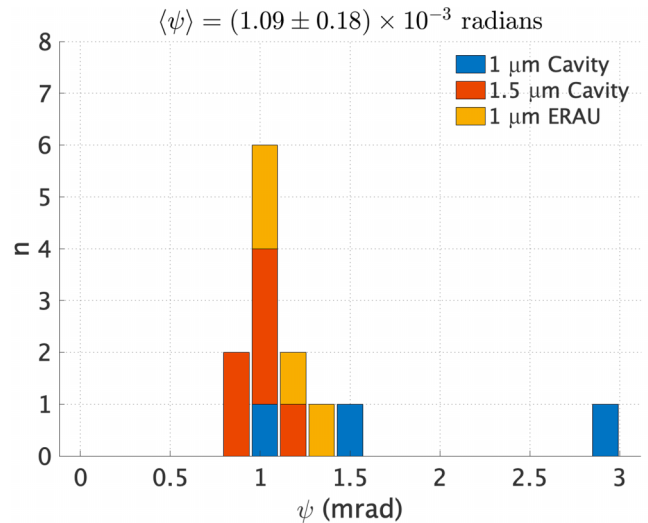


FIG. 4. Birefringence measured in various cavity experiments compared to the average birefringence measured in our samples. The average birefringence and the rms deviation from the mean is shown at the top of the figure.

splitting in several different cavities (collated by one of the authors, G.C.). This figure shows how the results of average birefringence made in our system, which is conceptually simpler and involves no optical cavity, compare to prior measurements with optical cavities. The fact that the measurements from different methods agree gives us confidence in the overall result because the major sources of systematic error are different between the two methods. The spread of the cavity results is not fully explained, but some of the variation may be attributable to the fact that cavity measurements interrogate only a single location on the coating, making them susceptible to random sampling of the nonuniform birefringence we discovered and describe in the following section.

The source of this measured, nonzero, spatially averaged birefringence in AlGaAs coatings is not known. It may be associated with internal stress from the 0.2% lattice mismatch between $\text{Al}_{0.92}\text{Ga}_{0.08}\text{As}$ and GaAs. However, since the coating material is nominally a pure cubic system, the in-plane strains should be isotropic, precluding strain-induced birefringence. So, if the birefringence is indeed strain induced, a source of strain anisotropy must be present. In addition to birefringence, Winkler *et al.* saw polarization dependence of absorption at 4.54 μ m [19]. They proposed nonuniform strain relaxation in the as-grown epitaxial multilayer as a source of anisotropy (previously seen in InGaP-based materials [20]). Another candidate for strain anisotropy is long-range ordering [21–23], which could also affect the index directly.

There may be a way to reduce the built-in compressive stress and any associated birefringence by modifying the production method slightly. The full elasticity calculation required to obtain the stress tensor from the lattice mismatch is beyond the scope of this paper, but the following arguments illustrate why the stress is present, that the level should be about 100 MPa averaged over the coating, and largely confined to the $\text{Al}_{0.92}\text{Ga}_{0.08}\text{As}$ layers. To form a continuous crystal, the denser GaAs lattice must stretch, and/or the AlGaAs lattice

must compress. During bonding, the thinned remnant GaAs substrate is still much thicker ($\geq 100\mu\text{m}$) than the coating ($\leq 5\mu\text{m}$). Therefore, the coating is constrained by the GaAs, and it is primarily the $\text{Al}_{0.92}\text{Ga}_{0.08}\text{As}$ layers that will be compressed to match the GaAs lattice. The remnant GaAs substrate is not etched off until after transfer and bonding to the final substrate, so the coating never relaxes. The constraining tension is just passed from the epitaxial wafer to the final substrate. (When the substrate is thin, the compressive strain in the coating is evident by significant bowing of the substrate.) In any case, we expect compressive strains on the order of $\epsilon_i \sim 2 \times 10^{-3}$ in the AlGaAs layers, where ϵ_i are the first three components of the strain in Voigt notation. Using the inverse of the stiffness tensor for orthotropic materials [24], and ignoring Poisson's ratios, it is straightforward to see that the corresponding stresses will have order of magnitude $\sigma_i = E_i \epsilon_i$ (no summation implied), where E_i are the Young's moduli in the coordinate directions in the plane of the coating, assumed to be aligned with the cubic crystal structure. E_i are on the order of 100 GPa [25], so we expect compressive stresses on the order of 200 MPa in the $\text{Al}_{0.92}\text{Ga}_{0.08}\text{As}$ layers only. The average stress in the coating is about half that, 100 MPa, since the GaAs layers constitute roughly half of the coating thickness.

Based on this, it might be possible to reduce the stress in the AlGaAs layers by about a factor of 2 by releasing the coating from the growth wafer prior to bonding. This would transfer some of the stress to the GaAs layers but with the opposite sign. If the coating were free from the GaAs growth wafer, each layer material would have a strain corresponding to approximately half of the lattice mismatch since the elastic moduli of GaAs and $\text{Al}_{0.92}\text{Ga}_{0.08}\text{As}$ are similar. The opposing strains in alternating layers could lead to partial cancellation of the average birefringence. Further reduction may be possible through careful coating design.

IV. NONUNIFORM BIREFRINGENCE

The main motivation for the measurements described in this article was to look for the presence of nonuniform birefringence in AlGaAs coatings. Methods for reducing the effect of *uniform* birefringence in optical cavities— 90° relative rotation of the cavity mirrors' fast axis, and/or careful alignment of the optical polarization with an axis of the birefringence—may not be effective for nonuniform birefringence. Therefore, we must characterize the amount of nonuniform birefringence and estimate its effects.

We mapped the birefringence variation in 11 coatings of various sizes between 18 and 194 mm in diameter. Since coatings for future gravitational-wave detectors will need to be at least 300 mm in diameter, we are particularly interested in large coatings. Figure 5 shows typical birefringence variation in a large coating (S/N: E1800006-02). For this measurement, the fast axis of the average birefringence is at 45° to the analyzer's s -polarization. Clearly, there is a nonrandom structure to the variation. The level of the peak-to-peak birefringence variation in the center of the sample is on the order of 0.1 mrad, which is about 10% of the average birefringence discussed in the previous section. In this sample, the variation

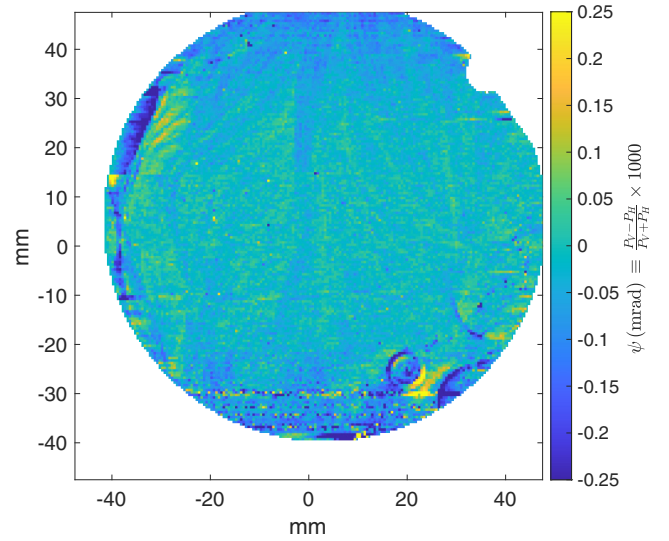


FIG. 5. Birefringence variation in a 93-mm AlGaAs coating on 100 mm diameter by 10-mm thick fused silica substrate (S/N: E1800006-02). Fast axis of the average birefringence is at 45° to the analyzer.

increases by a factor of approximately 2 toward the edge of the sample.

Rotating the sample by 45° so that the fast axis of the birefringence is aligned with the analyzer (Fig. 6), we see that the structure almost disappears. The nonuniform birefringence is therefore a modulation in the amplitude of the average birefringence, but does not seem to affect the direction of the fast/slow axes much. Exceptions occur near crystal defects like the “craterlike” defect seen at the top-right in Fig. 5 and mid-right in Fig. 6. It does not disappear like the more distributed pattern, suggesting that the orientation of the

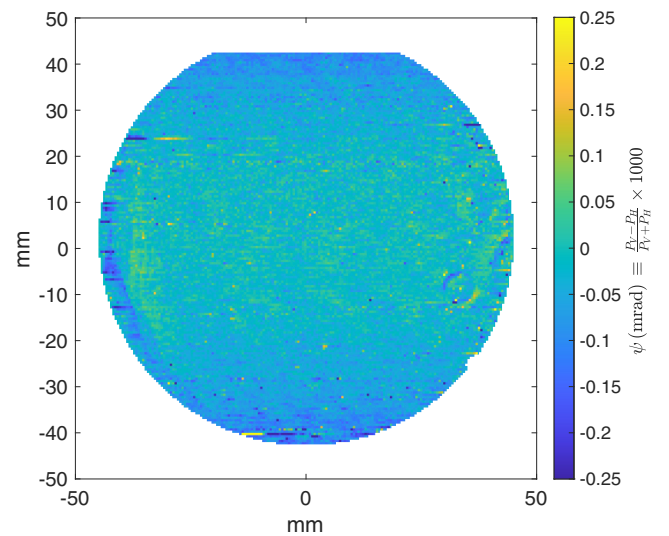


FIG. 6. In this measurement, the sample (S/N: E1800006-02) has been rotated so that the fast axis of the average birefringence is parallel to the analyzer (s -polarization). The birefringence variation has largely disappeared, showing that the variation and the average birefringence are similarly oriented.

birefringence induced by the defect is different from that of the average birefringence.

Since the nonuniformity is usually a small signal against the significantly larger average birefringence, nonuniformity measurements can be sensitive to gain and offset drift in the signal chain. As discussed above, such sources of noise form artifacts aligned with the raster pattern, and are therefore easily recognizable. However, even after efforts to remove these artifacts, some remain, and the required filtering adds occasional filtering artifacts as well. Filtering artifacts are recognizable as noiselike horizontal lines aligned with the raster pattern. We found that the presence of these raster-line artifacts, and the fairly high level of pixel-to-pixel noise, made the straightforward calculation of pixel-to-pixel rms an unreliable measure of the birefringence nonuniformity. Since the pattern of nonuniformity is clearly visible by eye, typically a striated pattern unrelated to the raster, we can identify the peaks and nearby valleys in the pattern. The level of nonuniform birefringence reported here is therefore the peak-to-valley difference, averaged over the relevant sample or sample region. In our case, the identification of peaks and valleys was done by hand in order to safely avoid features associated with raster lines. With this approach, the uncertainty in the peak-to-valley birefringence, estimated by repeated analysis, is approximately 0.05 mrad.

To check whether the birefringence was the same on both sides of the coating, we repeated some measurements with the sample placed upside down, with the coating side on the translation stage and the laser entering from the substrate side. Because the silica substrate is transparent to the laser, we can measure the back side of the coating. We found the same pattern of spatial variation on both sides of the coating, which is consistent with a coating-strain-induced birefringence variation.

To check whether the birefringence was due to the substrate transfer process, we compared the birefringence variation between a substrate-transferred coating and a similar coating that was never removed from the epitaxial growth wafer. (See Fig. 7). The coating that remained on the growth wafer showed an average birefringence of $\psi = 0.96 \pm 0.1$ mrad, similar to the average birefringence in substrate transferred coatings. However, the coating attached to the growth wafer showed completely uniform birefringence within our sensitivity, except at the locations of a few small defects (possibly dust contamination). We conclude that except near crystal defects, birefringence nonuniformity seen in AlGaAs coatings is due to the substrate transfer and bonding process.

Figure 8 shows the birefringence variation in a 194-mm diameter AlGaAs coating (SN: H8435-068FeF2). To maximize the signal, the sample is oriented so that the fast axis of the average birefringence is at 45° to the analyzer. The average birefringence has been filtered out, leaving only the variation. This 200 mm sample exhibits relatively large birefringence variations in places, on the same order of magnitude as the average birefringence. We assume that, like the average birefringence, the birefringence variations are strain related. As in other samples, there appear to be two sources of strain variation: variation due to bonding and variation associated with a large crystal defect slightly below and left of center.

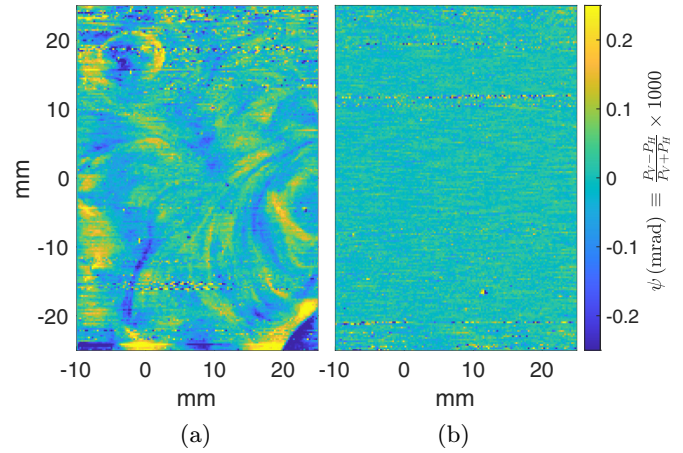


FIG. 7. Central regions of two similar ~ 100 mm coatings. The coating on the left (S/N 132979 004 S) has been transferred to a silica substrate, whereas the one on the right (S/N 132979 013 S) remains on the epitaxial growth wafer (a) Substrate transferred and (b) Still on epi wafer.

During bonding, the bond is initiated at one location, often the center of the coating, and travels in a “bond wave” across the sample until the coating is fully attached. (In everyday life, we may see a similar bond wave when installing a glass cell phone screen protector.) To obtain a strain-free coating, the bond wave must contact the substrate in the same way as a rolling rigid cylinder. Since the coating bonds on contact, and cannot slip to even out in-plane stresses, stress is incorporated into the coating whenever it does not roll on

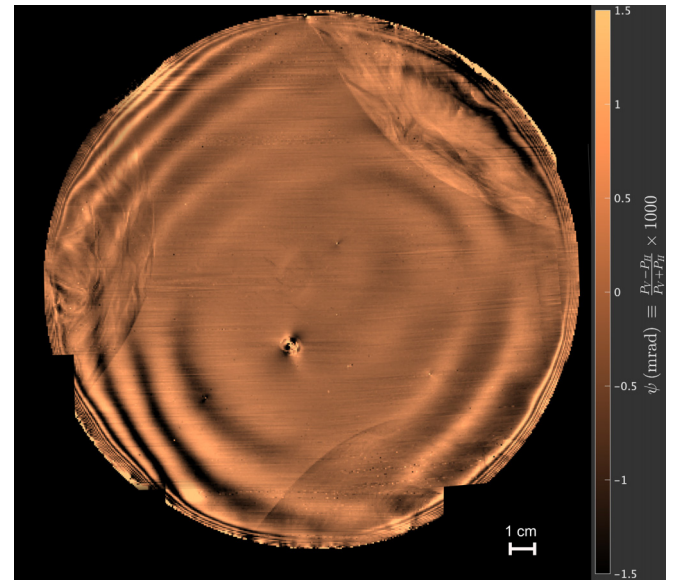


FIG. 8. A diameter of 194 mm AlGaAs on 200 mm substrate exhibiting three types of birefringence nonuniformity: a crystal defect just below and left of center, three mandorla-shaped regions of rapidly varying birefringence, and large concentric rings. This is a composite map made by combining maps of individual subregions. (Due to limited xy -stage range, the 200-mm diameter sample could not be mapped in one step.)

smoothly. For example, the three mandorla-shaped regions around the edge of the sample shown in Fig. 8 exhibit rapid strain variation that is “frozen in.” The mandorla shape is presumed to be caused by slight drooping of the coating as it hangs between three support tabs (“separation flags”) in the commercial wafer bonding tool). As the bond-wave approaches from the center, the coating—drooping between the supports—is not the correct shape to roll on like a rigid cylinder, leaving a characteristic pattern of rapidly varying strain. A similar bond-induced nonuniformity is evident in the irregular rings centered on the middle of the coating. There is a faint “puddlelike” region just to the left of center where the coating appears to have first made contact with the substrate. The bond wave most likely traveled outward from there in an expanding ring. The ringlike “ripples” are presumably due to the inability of the coating to relax from the slightly stretched sagging shape to the final, flat configuration. Interestingly, these rings were absent (or at least greatly reduced in amplitude) in two more 200 mm AlGaAs coatings. In at least one of them, the bond was known to have initiated along an edge. All of these coatings were supported by three tabs and, as a consequence, showed the mandorla shapes. The last of the three 194 mm coatings (P0788-006FEF0) had the flags pulled out as the bond wave approached the edge, which served to reduce the amplitude and spatial frequency of the variations in the mandorla-shaped regions.

The strain pattern induced by bonding can be expected to vary according to the precise support method, location of initial contact, and consequent progression of the bond wave. We see this quite clearly in the difference between the birefringence variation induced in different regions of the 194 mm samples and in the differences between the large and smaller samples. Regardless, birefringence nonuniformity was apparent in *all* the substrate-transferred AlGaAs coatings we mapped.

The smallest sample was sent to the LIGO Laboratory at Caltech for surface metrology measurements (performed by one of the authors, C.M.). The results showed a clear correlation between the birefringence variation and suboptical surface height variations (see Fig. 9). The rms surface height variation was approximately 0.2 nm everywhere except for the very central region, where there is a small defect. The strain variation is assumed to deform the coating slightly during the bonding process, resulting in increased bulging, ridges, etc. The congruence between the surface height and birefringence patterns supports the assumption that strain variation is the cause of the birefringence nonuniformity.

V. OPTICAL LOSS IN THE LIGO A[#] ARM CAVITIES

AlGaAs coatings are a candidate for a future upgrade to the current LIGO detectors, such as LIGO A[#] [26]. Therefore, the effects of birefringence on the detector operation must be understood and factored into the design. Uniform birefringence may lead to increased phase noise through any mechanism that drives temporal fluctuations in the birefringence. Examples include mechanical vibrations, coupling with a thermodynamic Langevin force, piezoelectric coupling to fluctuating electric fields, fluctuations due to optical driving of free carriers, etc. These potential noise couplings are

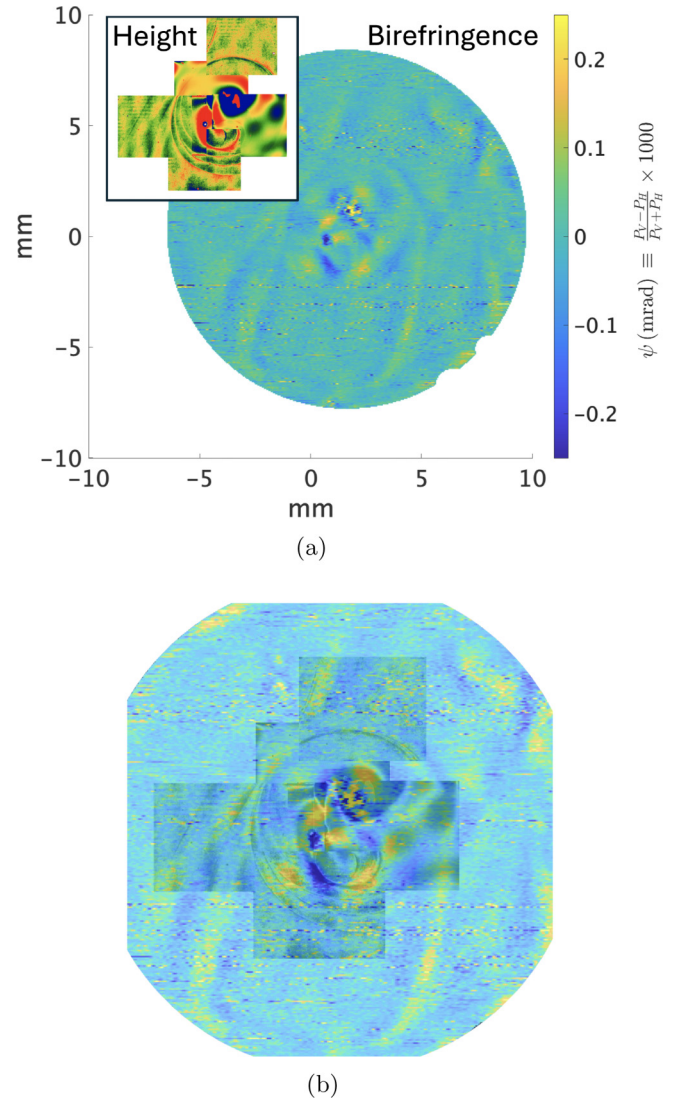


FIG. 9. Comparison between surface height measurements and birefringence for the 18-mm diameter sample, TCS-FS-PL-12264. (a) Background image shows birefringence. Foreground image, inset, shows a height map of the central region. The RMS height variation is ~ 0.2 - 0.6 nm (except for a defect in the center of the coating). The color bar on the right indicates the birefringence variation of the background image. (b) Overlay of the two data sets. The geometrical features of the two maps are similar. To make features in both data sets visible, the height map's color was desaturated and the birefringence map was made partially transparent. The image is zoomed slightly to show the region of congruence.

currently being explored by several groups, analytically, through numerical simulations, and experimentally [12,15,27–30].

Here, we use the nonuniform birefringence data presented above to estimate the expected optical loss in a LIGO arm cavity. This assumes no improvement beyond the non-uniformity seen in current AlGaAs coatings. The method only captures the effect of phase variations associated with anisotropic index variation—i.e., associated with birefringence—but not from the isotropic index variations. Therefore, this approximation is useful insofar as we assume that isotropic variations of the

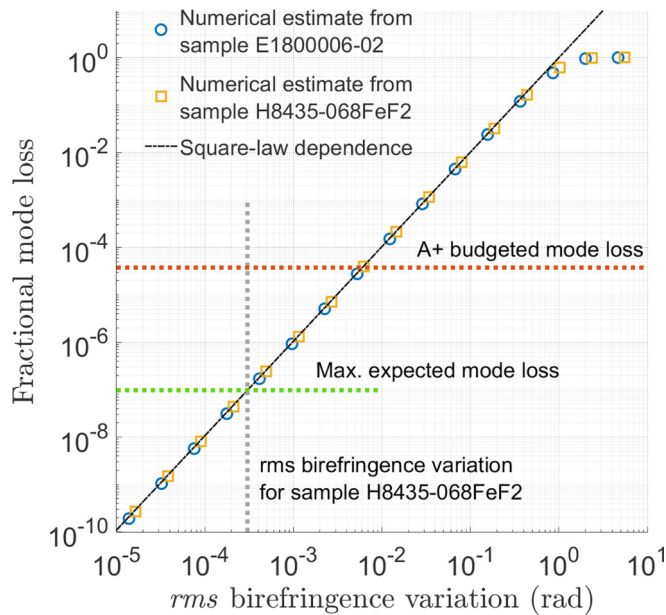


FIG. 10. Power lost from the fundamental mode of the LIGO A+ arm cavity as a function of rms birefringence variation. Birefringence maps for tiling onto a plane were taken from samples E1800006-02 and H8435-068FeF2. In the worst-case scenario, using the map from H8435-068FeF2, the estimated mode loss is about 2 orders of magnitude below the total mode loss budgeted for A+. The rms level of birefringence nonuniformity for this sample is shown by the vertical, dashed grey line.

index are similar to, or smaller than, the anisotropic variations we detect via birefringence.

The LIGO test-mass mirrors are significantly larger than the coatings measured here. We mimicked a larger coating by tiling a plane with the data from a central 50 mm $\times$ 50 mm region of the 93-mm diameter coating (S/N: E1800006-02) shown in Fig. 5. The tiled plane was made sufficiently large (10 $\times$ 10 tiles, 500 mm $\times$ 500 mm) that the amount of power in the beam tails falling outside the tiled region was negligible compared to the loss from scatter due to birefringence variation. The power lost to the fundamental mode was calculated by numerically evaluating the overlap integral between the TEM_{00} mode of the cavity and the perturbed mode with the phase variation impressed upon it by a single reflection. To check for numerical accuracy, we multiplied the birefringence map by a varying factor and found that the mode loss fraction had the expected square dependence on the amplitude of the birefringence (see, e.g., Eq. (49) in Ref. [31]). The process was repeated for a similar 60 mm $\times$ 60 mm region near the lower left portion of the 194 mm coating (S/N: H8435-068FeF2) shown in Fig. 8. Figure 10 shows the result

of the calculation. The mode loss is presented as a function of the rms amplitude of the birefringence and the results from both birefringence maps are included on the same graph. For rms birefringence under 1 mrad, which is satisfied by all the samples we measured, the power lost from the fundamental mode per reflection is at least 1 order of magnitude below the total optical loss per reflection budgeted for the upcoming LIGO A+ detector [32].

VI. CONCLUSIONS

Our single-reflection method for measuring birefringence in large AlGaAs coatings has sufficient sensitivity to reveal spatial variations of less than 0.1 mrad.

The average birefringence measured by our method was consistent with the birefringence measured from resonance-peak splitting in optical cavities, together giving a birefringence $\psi = (1.09 \pm 0.18)$ mrad for a single reflection. The average birefringence is likely due to the $\text{Al}_{0.92}\text{Ga}_{0.08}\text{As}$ layers, which are under compression from the lattice mismatch.

Birefringence nonuniformity is primarily due to the bonding process. The bonding process leads to birefringence variation due to the inability of the coating to slide on the substrate as it bonds. It cannot relax from an initial curved state to the final flat state. To improve this, we need to ensure that the coating rolls onto the substrate in the manner of a rigid cylinder. Crystal defects also cause spatial variations in the birefringence, but are limited to a small area around the defect. Nonuniform birefringence is associated with very small surface-height changes in the coating.

Optical scatter from a LIGO arm cavity due to the nonuniform birefringence seen in our measurements would cause single-reflection loss well under 1 ppm. Optical loss from nonuniform birefringence is therefore unlikely to contribute significantly to the total optical loss budget of a LIGO upgrade using AlGaAs coatings.

ACKNOWLEDGMENTS

This work was performed under National Science Foundation Grants No. NSF2110598 and No. NSF2409602. The authors would like to take the opportunity to thank Thorlabs Crystalline Solutions for their ongoing collaboration and support.

DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

- [1] J. P. van der Ziel and M. Hegems, Multilayer GaAs-Al_{0.3}Ga_{0.7}As dielectric quarter wave stacks grown by molecular beam epitaxy, *Appl. Opt.* **14**, 2627 (1975).
- [2] in *VCSELs*, edited by R. Michalzik, 2013th ed. Springer Series in Optical Sciences (Springer, Berlin, 2012), 2013th ed.

- [3] K. Hjort, J. Soderkvist, and J.-A. Schweitz, Gallium Arsenide as a mechanical material, *J. Micromech. Microeng.* **4**, 1 (1994).
- [4] G. D. Cole, S. Gröblacher, K. Gugler, S. Gigan, and M. Aspelmeyer, Monocrystalline Al_xGa_{1-x} as heterostructures for

- high-reflectivity high- Q micromechanical resonators in the megahertz regime, *Appl. Phys. Lett.* **92**, 261108 (2008).
- [5] *Optical Coatings and Thermal Noise in Precision Measurement*, edited by G. M. Harry, T. P. Bodiya, and R. DeSalvo (Cambridge University Press, Cambridge, 2012).
- [6] G. Cole, W. Zhang, M. Martin, J. Ye, and M. Aspelmeyer, Tenfold reduction of Brownian noise in high-reflectivity optical coatings, *Nat. Photonics* **7**, 644 (2013).
- [7] G. D. Cole, W. Zhang, B. J. Bjork, D. Follman, P. Heu, C. Deutsch, L. Sonderhouse, J. Robinson, C. Franz, A. Alexandrovski, M. Notcutt, O. H. Heckl, J. Ye, and M. Aspelmeyer, High-performance near- and mid-infrared crystalline coatings, *Optica* **3**, 647 (2016).
- [8] G.-W. Truong, L. W. Perner, D. M. Bailey, G. Winkler, S. B. Cataño-Lopez, V. J. Wittwer, T. Südmeyer, C. Nguyen, D. Follman, A. J. Fleisher, O. H. Heckl, and G. D. Cole, Mid-infrared supermirrors with finesse exceeding 400 000, *Nat. Commun.* **14**, 7846 (2023).
- [9] D. Lee, Z. Z. Hu, B. Lewis, A. Aeppli, K. Kim, Z. Yao, T. Legero, D. Nicolodi, F. Riehle, U. Sterr, and Jun Ye, Frequency stability of 2.5×10^{17} in a Si cavity with AlGaAs crystalline mirrors, *arXiv:2509.13503*.
- [10] P. Fritschel, K. Kuns, J. Driggers, A. Effler, B. Lantz, D. Ottaway, S. Ballmer, K. Dooley, R. Adhikari, M. Evans, B. Farr, G. Gonzalez, P. Schmidt, and S. Raja, Report of the LSC post-O5 study group, 2022, <https://dcc.ligo.org/LIGO-T2200287/public>.
- [11] G. D. Cole, S. W. Ballmer, G. Billingsley, S. B. Cataño-Lopez, M. Fejer, P. Fritschel, A. M. Gretarsson, G. M. Harry, D. Kedar, T. Legero, C. Makarem, S. D. Penn, D. H. Reitze, J. Steinlechner, U. Sterr, S. Tanioka, G.-W. Truong, J. Ye, and J. Yu, Substrate-transferred gaas/algaas crystalline coatings for gravitational-wave detectors, *Appl. Phys. Lett.* **122**, 110502 (2023).
- [12] J. Yu, S. Häfner, T. Legero, S. Herbers, D. Nicolodi, C. Y. Ma, F. Riehle, U. Sterr, D. Kedar, J. M. Robinson, E. Oelker, and J. Ye, Excess noise and photoinduced effects in highly reflective crystalline mirror coatings, *Phys. Rev. X* **13**, 041002 (2023).
- [13] D. Kedar, J. Yu, E. Oelker, A. Staron, W. R. Milner, J. M. Robinson, T. Legero, F. Riehle, U. Sterr, and J. Ye, Frequency stability of cryogenic silicon cavities with semiconductor crystalline coatings, *Optica* **10**, 464 (2023).
- [14] C. Ma, J. Yu, T. Legero, S. Herbers, D. Nicolodi, M. Kempkes, F. Riehle, D. Kedar, J. Robinson, J. Ye, and U. Sterr, Ultrastable lasers: Investigations of crystalline mirrors and closed cycle cooling at 124 k, *J. Phys.: Conf. Ser.* **2889**, 012055 (2024).
- [15] S. Kryhin, E. Hall, and V. Sudhir, Thermorefringent noise in crystalline optical materials, *Phys. Rev. D* **107**, 022001 (2023).
- [16] T. C. Larason and S. S. Bruce, Spatial uniformity of responsivity for silicon, gallium nitride, germanium, and indium gallium arsenide photodiodes, *Metrologia* **35**, 491 (1998).
- [17] Thanks to Prof. Marty Fejer of Stanford University for suggesting this modification.
- [18] A. M. Gretarsson, *A First Course in Laboratory Optics* (Cambridge University Press, Cambridge, 2021), Chap. 5.
- [19] G. Winkler, L. W. Perner, G.-W. Truong, G. Zhao, D. Bachmann, A. S. Mayer, J. Fellingner, D. Follman, P. Heu, C. Deutsch, D. M. Bailey, H. Peelaers, S. Puchegger, A. J. Fleisher, G. D. Cole, and O. H. Heckl, Mid-infrared interference coatings with excess optical loss below 10 ppm, *Optica* **8**, 686 (2021).
- [20] M. Bückle, V. C. Hauber, G. D. Cole, C. Gärtner, U. Zeimer, J. Grenzer, and E. M. Weig, Stress control of tensile-strained in $1-x$ Ga $_x$ P nanomechanical string resonators, *Appl. Phys. Lett.* **113**, 201903 (2018).
- [21] T. S. Kuan, T. F. Kuech, W. I. Wang, and E. L. Wilkie, Long-range order in $al_xga_{1-x}As$, *Phys. Rev. Lett.* **54**, 201 (1985).
- [22] A. van Niftrik, G. Bauhuis, J. Schermer, H. Kim, M. Voncken, P. Mulder, and P. Larsen, Quantitative analysis of variant III CuAu-I-type ordering of Al_xGa_{1-x} as on (110), (111)A and (001) GaAs substrates using x-ray diffraction, *J. Cryst. Growth* **289**, 48 (2006).
- [23] A. Pradhan, T. Maitra, S. Mukherjee, S. Mukherjee, A. Nayak, and S. Bhunia, Effect of spontaneous superlattice ordering on the luminescence properties of the MOVPE grown Al-GaAs/GaAs (100) heterostructure, *Opt. Mater. (Amsterdam)* **150**, 115156 (2024).
- [24] A. P. Borelli, R. J. Schmidt, and O. M. Sidebottom, *Advanced Mechanics of Materials* (John Wiley and Sons, Brisbane, QLD, Australia, 1993), 5th ed.
- [25] S. Adachi, GaAs, AlAs, and Al_xGa_{1-x} as: Material parameters for use in research and device applications, *J. Appl. Phys.* **58**, R1 (1985).
- [26] P. Fritschel, K. Kuns, J. Driggers, A. Effler, B. Lantz, D. Ottaway, S. Ballmer, K. Dooley, R. Adhikari, M. Evans, B. Farr, G. Gonzalez, P. Schmidt, and S. Raja, Report of the LSC post-O5 Study group, Technical Report (LIGO Scientific Collaboration, 2023), <https://dcc.ligo.org/LIGO-T2200287/public>.
- [27] W. Winkler, A. Rüdiger, R. Schilling, K. Strain, and K. Danzmann, Birefringence-induced losses in interferometers, *Opt. Commun.* **112**, 245 (1994).
- [28] Y.-P. Zhang, S.-X. Yang, W.-H. Tan, C.-G. Shao, Y. Ma, and S.-Q. Yang, Brownian thermal birefringent noise due to the nondiagonal anisotropic photoelastic effect in multilayer coated mirrors, *Phys. Rev. D* **110**, 022009 (2024).
- [29] B. Wu, S. Goswami, S. Tanioka, and S. Ballmer, Birefringence of AlGaAs/GaAs coatings under above-band-gap illumination, GR noise and photo-optic transfer function, *arXiv:2512.00594*.
- [30] A. Gretarsson, G. Cole, G. Harry, and S. Penn, AlGaAs mirror noise scalings, “Dawn VII 2024”, University of British Columbia, June 12 – June 13, 2024 (2024), <https://dcc.ligo.org/LIGO-G2401190/public>.
- [31] Y. Michimura, H. Wang, F. Salces-Carcoba, C. Wipf, A. Brooks, K. Arai, and R. X. Adhikari, Effects of mirror birefringence and its fluctuations to laser interferometric gravitational wave detectors, *Phys. Rev. D* **109**, 022009 (2024).
- [32] L. Barsotti, L. McCuller, M. Evans, and P. Fritschel, The A+ design curve, Technical Report (LIGO Scientific Collaboration, 2018), <https://dcc.ligo.org/LIGO-T1800042/public>.