Ultrafast laser strain generation for nanometer-precision alignment of optical components

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ABSTRACT

Optical systems such as X-ray telescopes or micro-optical systems can require alignment of optical components with nanometer-level tolerances, and often with stringent volume and mass requirements. We propose fabricating, bonding, and subsequently adjusting length of glass spacers using ultrafast lasers. Ultrafast laser processing has been industrialized over the last decade for micron-accuracy glass cutting with complex shapes, and for glass-to-glass and glass-to-metal welding. In this paper, we will show experimental results demonstrating the ability to generate stable strain in Corning® Eagle XG® glass samples, which causes permanent nanometer-scale length changes. We demonstrate a total strain of ~$10^{-3}$, or microns of displacement per millimeter length of laser-modified glass. We also measure stability in laser-modified samples and find that the length changes are nanometer-stable. We also show how this process may be applied for alignment of X-ray mirrors by combining industrialized ultrafast laser processes for glass cutting and glass-to-glass welding with strain generation and control. This powerful and flexible process may enable compact, lightweight set-and-forget alignment of optical systems with nanometer tolerances.

Keywords: Ultrafast lasers, strain, optical alignment, X-ray optics

1. INTRODUCTION

A constant push for ever-larger and higher-resolution X-ray telescopes [1–4], will continue to enable scientific discoveries but requires ultralightweight yet extremely accurate optical assemblies comprising many accurate thin mirrors aligned and bonded together and launched into space. For the Lynx X-ray Observatory concept (Lynx) [2], which was studied as one of four flagship mission concepts for the 2020 NASA Astrophysics Decadal Survey, the 0.4 arcsecond half-power diameter (HPD) point spread function (PSF) requirement results in an alignment tolerance allocation of around 0.2 arcsec [5]. This allocation would be entirely consumed by pitch misalignments due to random ~10 nm height errors over each 100 mm-long mirror segment. Around 40,000 mirror segments must be aligned to within this tolerance and remain stable through launch and the subsequent 5+ years of operation.

In addition to aligning thin high-resolution X-ray telescope mirrors, there is a need for nanometer-level set-and-forget alignment for coupling single-mode optical fibers to photonic chips [6–8] and tuning the static resonant frequency of Fabry-Perot filters [9], or microring resonators [10,11]. These applications often require sub-micron or even several-nanometer alignment tolerances in one or more degrees of freedom (DOFs). In demanding alignment applications, active adjustment after bonding components in place is feasible but adds complexity and cost. Set-and-forget alignment at micron tolerances can be achieved through active alignment, or by laborious iterative component fabrication, prior to bonding. This requires stiff optical components and extremely stable and low-shrinkage bonds. Piezoelectric set-and-forget adjustable shims are commercially available and provide compact stable adjustment at the nanometer scale [12] but have limited geometry and material options.

In this paper, we present a set-and-forget adjustable alignment approach that leverages ultrafast laser-induced strain in glass materials to provide nanometer-to-micron stable displacements. Similar optical re-alignment schemes have been developed [13,14], and here we present an approach that is specific to aligning multiple optical components relative to one another. This technique is also compatible with ultrafast laser welding [15–17] and cutting [18–23] to allow integration into a wide variety of applications. In Section 2, we present a concept to realign X-ray telescope optics using adjustable glass spacers, and we enumerate some of the requirements. In Section 3, we present optomechanical simulation results showing that realignment of X-ray mirror segments is feasible with sufficiently small degradation of the point-spread function. In Section 4, we describe our early experiments that demonstrate nanometer-precision and micron-range displacement of glass spacers modified using a femtosecond laser. Section 5 lays out a path forward for this technique.
2. ADJUSTABLE HEIGHT SPACERS CONCEPT FOR X-RAY TELESCOPE MIRRORS

A typical Wolter Type 1 X-ray mirror assembly, illustrated in Fig. 1, consists of primary and secondary mirror shells all coaligned to the optical axis, and X-rays reflect off each surface near grazing incidence (typical graze angles of $\alpha \approx 1^\circ$) to focus on a focal plane array. These mirrors typically have at most microns of departure from a perfect cone. The mirror shells can be monolithic [24, 25] or segmented into azimuthal sections [5, 26]. Whereas the Chandra Observatory [3] achieved 0.5 arcsecond HPD using four centimeters-thick monolithic mirror shells, Lynx requires the same resolution but 30x larger effective area, and so requires hundreds of mirror shells that are each at least 10x thinner. The optical assembly for Lynx requires a similar ~0.05 arcsec RMS axial slope error from each shell (roughly, 1 arcsec RMS axial slope error on each mirror corresponds to $2\times\sqrt{2}\times1.36$ arcsec HPD to account for 2 uncorrelated reflections and conversion of RMSD to HPD of a Gaussian PSF), with contributions from mirror fabrication, coating, alignment, bonding, and gravity release.

Figure 1. X-ray telescope mirror assembly, with approximate dimensions for Lynx.

Figure 2. Mounting strategies to align mirrors (grey) using spacers (blue), shown from a side view of a mirror stack. The optical axis is horizontal. a) Kinematic mount, such as a four-post mount [27], which is accurate but has limited bond area. b) Over-constraint, which has large bond area but is less accurate. c) Over-constraint with adjustable-height spacers.
Thin segmented mirrors, with thickness of 0.5 – 1 mm are particularly challenging to align and bond while maintaining surface figure because they are compliant. Furthermore, any approach to alignment and bonding must survive launch, so bonds must have sufficient area and strength. A recently developed and successful approach mounts a conical mirror on 4 points to define 4 DOFs [27] (pitch, yaw, and decenter) and uses adhesive bonds between the posts and mirror to constrain the remaining 2 DOFs with minimal over-constraint. This quasi-kinematic mounting scheme is excellent for preserving mirror figure and has been used to successfully demonstrate 1.2 arcsec HPD resolution from a pair of silicon mirror segments [5], but it is inherently non-redundant and exhibits very small bonding area leading to expected challenges from launch [28]. Our alternative approach, illustrated in Fig. 2, is to over-constrain the mirrors using many spacers to provide large bonding area, then adjust the spacer heights after bonding. Under normal circumstances, this over-constraint would severely deform the mirror surfaces because each spacer could not be made to the proper height within a ~5 nm tolerance. However, if we can adjust the spacer thickness to nanometer-resolution, such an over-constrained approach may simultaneously provide both accuracy and strength for X-ray mirror assemblies.

The height adjustment could be achieved using strain generated by an ultrashort pulsed (USP) laser, as illustrated in Fig. 3. A focused USP laser creates strained inclusions within glass materials, and the laser processing or writing parameters can control the magnitude and locations of the strain. The process of re-aligning mirrors would entail: (1) assembling and bonding the mirror, (2) measuring the alignment using Hartmann testing [27] for example, and (3) adjusting the height of the appropriate spacers. This process would be iteratively applied until the required alignment tolerance is met. This process is compatible with either adhesive bonding (with or without spacer beads), catalysis bonding [29], or USP laser welding [15].

There are potential challenges with this approach, and our simulations (Section 2) and experiments (Section 3) are aimed at evaluating the viability of this approach for bonding and aligning X-ray mirrors. We investigated whether micron-scale adjustments to alignment are theoretically possible without severely degrading the PSF, whether we can experimentally demonstrate the required length adjustments, and whether those length adjustments are stable.

![Figure 3](https://www.spiedigitallibrary.org/conference-proceedings-of-spie)

**Figure 3.** One potential implementation of adjustable height spacers for aligning X-ray optics: a) Focus a USP laser to change the height of glass spacers at controllable locations. b) Adjust the spacer heights of the topmost mirror in a stack, to align it to the rest of the mirrors. c) Structural modifications in the glass generate internal strain that causes the height change $\delta$.

### 3. SIMULATIONS

The adjustable height spacers must serve several functions: (1) Create a large bond area to provide strength for launch, (2) provide a volume to generate strain to cause displacement of the mirror surfaces, and (3) provide a sufficiently stiff and strong connection between mirrors to survive launch and mitigate deformation from gravity release or other errors. At the same time, the spacers cannot be too stiff because adjusting their heights will then bend the mirror they are attached to. A finite element (FE) model coupled with ray tracing is necessary to evaluate whether a particular spacer design meets the functional requirements. An example FE mesh and one possible spacer design is illustrated in Fig. 3.
The two most important re-alignments for X-ray telescope performance are pitch (rotation about the y-axis in Fig. 3a) and yaw (rotation about the x-axis). While it is clear we can adjust pitch, roll (rotation about the z-axis), and decenter in the x-direction by adjusting spacer heights, it is less clear that adjusting yaw or y-decenter is possible with this method. Adjusting focus (translation along the z-axis) is less problematic because of the small graze angles of X-ray mirrors but is not adjustable using adjustable-height spacers. To understand how yaw and y-decenter may be adjusted by changing spacer heights alone, consider that there is an imaginary ideal surface, and we are trying to match our real X-ray mirror to the ideal surface. If the X-ray mirror has a small yaw error (~1 mrad) but is otherwise perfect, the distance between the ideal surface and the misaligned surface (measured along the radial direction of the ideal surface) will follow a shape illustrated in Fig. 5a. While a physical yaw of the mirror could of course correct the error, bending the mirror opposite of the height map in Fig. 5a would also approximately correct the alignment error. In a similar manner, a y-decenter error can be seen as almost identical to a roll error about the mirror center.

![Figure 4. a) Finite element mesh, with a mirror composed of shell elements and the spacers composed of solid elements. b) The glass spacer design used in the simulation, showing the regions where the spacers are bonded to the mirror, and where the height adjustment occurs.](image)

Our simulations focused on correcting a yaw error because this is the most challenging error to correct by spacer height adjustment since it requires bending the mirror. We performed these simulations using the commercial finite element analysis (FEA) software ADINA [30] coupled with our custom X-ray mirror ray tracing code [31]. We simulated a silicon primary mirror segment with a shell radius of $R_0 = 500$ mm (measured at the intersection of the primary and secondary mirrors), segment length $L_m = 100$ mm, segment chord-width of 75 mm, and thickness of 0.5 mm. For modeling simplicity, the mirror was approximated as a conical shell with cone angle 0.7°, corresponding to this shell radius and a telescope focal length of 10 m. The glass spacers we simulated are illustrated in Fig. 3b and were made of Corning® Eagle XG® glass (to match the coefficient of thermal expansion of silicon). The model contained 25 pairs of spacer posts (blue areas in Fig. 3b) on each side of the mirror. The spacers were all within planes parallel to the yz-plane. Our finite element mesh of the mirror contained 2400 9-node shell elements, and the spacers were composed of 20-node 3D solid elements. All materials were linear elastic isotropic (rather than incorporating the orthotropic properties of silicon with a particular crystal orientation for this simulation, we used elastic properties for a <100> wafer [32] and assumed isotropy). Spacer heights were adjusted by imposing uniaxial strain with chosen magnitude in each spacer.

We simulated the primary mirror deformation and assumed the secondary mirror was perfect. The imperfect primary mirror and perfect secondary mirror were then ray-traced to determine the effect on the PSF. We did not account for diffraction but in many cases, this would produce a PSF size far larger than the PSF degradation we found (the effective aperture of X-ray telescope mirror segments that are not phased to one another is an arc-shaped slit with slit-width approximately equal to $L_m \tan \alpha$. Different shells are usually mutually incoherent). We did not account for any other errors such as pre-bonding surface figure errors, gravity sag, coating error, or others.
Fig. 5a shows the error expected for a 50 arcsec yaw misalignment. This produces approximately ±1 µm amplitude distance between the ideal and misaligned surfaces as discussed above. This can be approximately corrected by adjusting the heights of each spacer to flatten the edges, thereby bending the mirror. This creates undesired mirror deformation as well, the magnitude of which depends on the lateral stiffness of the spacers. For the spacer design of Fig. 4b, Fig. 5b shows the residual radial height error after adjusting the spacer heights to correct the misalignment. The ray trace results (Fig. 5c) of the misaligned and re-aligned mirror show 60× improvement and minimal degradation of the PSF.

![Figure 5](image)

**Figure 5.** Preliminary results of mirror alignment simulation: a) the radial height error of the primary mirror caused by a 50 arcsec yaw misalignment, b) the residual radial height error after aligning by adjusting spacer heights, and c) the spot diagram (2000 rays each) for the misaligned and aligned primary mirror, showing 60× improvement.

We find significantly better results for pitch misalignment: a 4.2 arcsec pitch misalignment (producing ±1 µm height error) and subsequent re-alignment reduces the PSF from 16.8 arcsec HPD to 0.04 arcsec HPD. We find that stiffer spacers degrade the PSF, and for this application the spacer stiffness and corresponding alignment accuracy must be traded against strength, resonant frequency, and other survival concerns. With the spacers of Fig. 3a, we found gravity sag (gravity vector oriented along the y-direction) to result in a PSF with 0.02 arcsec HPD. As expected, a larger re-alignment amplitude results in an approximately linear increase in the HPD. It may also be possible to intentionally bend the spacers with the USP laser to correct yaw misalignment, but we did not simulate this.

It is clear from these simulations that it is possible to generate the desired re-alignment DOFs in X-ray mirrors using adjustable-height spacers without significant degradation of the PSF. Carefully designing the spacer stiffness is important. Fabricating these spacers with height accuracy of ~1 µm is critical to achieve the required re-alignment accuracy for yaw especially. This may be achieved using a commonly-used process of USP laser cutting and subsequent chemical etching [23,33,34]. Achieving micron accuracy may require additional processing such as USP laser ablation.

### 4. EXPERIMENTS

A focused USP laser has high intensity (~10¹⁷ W/cm²) to cause nonlinear absorption in transparent materials (which are transparent because linear absorption is negligible) through multiphoton absorption and tunneling ionization [35]. Using a USP laser, we can deposit controlled quantities of energy into specific volumetric regions within a transparent material such as a glass spacer. One effect of this energy deposition is to generate strain up to ~10⁻³ – 10⁻² in fused silica under some processing conditions [36,37]. In other words, for a 1 mm-long spacer, we can expect up to 10 µm dimensional change. We conducted experiments to test whether the dimensions of glass spacers (Corning® Eagle XG®, to match the CTE of silicon X-ray mirrors) can be adjusted using a USP laser. We used two lasers: a borrowed Ti:Sapphire laser, and more recently a Yb-doped fiber laser we installed in our lab. As a more convenient proxy for spacers, we used glass cantilevers, and we measured the change in length resulting from translating the sample under a focused USP laser beam.

#### 4.1 Initial experiments using Ti:Sapphire laser

We conducted initial experiments using a Ti:Sapphire laser with λc = 800 nm 100 fs pulse duration, 80 MHz repetition rate, and average power of 3 W measured immediately out of the laser. With losses through a beam expander, 10 mirrors and an objective (NA = 0.5), we estimate the pulse energy to be around 25 nJ. We used a shutter (response time 10 ms) to block the laser when not writing in a sample. Figure 6 shows the experimental setup. The samples used in this experiment...
were Corning® Eagle XG® cantilevers and we wrote lines in the sample with the laser while measuring the change in length of the cantilever using interferometer probes (Attocube IDS with F2.8 sensor heads) focused on the end face of the cantilever. Since we aimed to measure nanometer-scale displacements, we measured two identical samples simultaneously: a test sample that we wrote lines in with the laser, and a control sample that remained unmodified throughout the experiment. The primary error is expected to be thermal expansion. An environmental monitor measured temperature, barometric pressure, and humidity throughout these experiments.

We wrote lines in the sample oriented along the x-direction at a speed of 5 mm/s, and at various y- and z-coordinates. A “bar” consists of a set of 6 lines (each line written along the x-direction) at 6 different z-coordinates (see Fig. 6 inset for cross-section microscope image). We wrote multiple bars, pausing after each bar to let the sample cool back to room temperature. Repeating this for 30 bars spaced 67 μm apart (total modified length 2 mm), we acquired data on the total strain induced as well as the repeatability of strain from each bar. We chose the z-coordinates of the lines within bars to minimize bending of the sample, as this can introduce displacement measurement errors if the sample tip is not perfectly square.

![Figure 6. Photograph of experimental apparatus. Two identical interferometer probes measure two identical samples (labeled control and test) located side-by-side. The test sample is laser-modified in the region indicated. The objective position is fixed and the sample is translated in X to write lines at various Y and Z positions. Inset: a phase-contrast microscope image of laser-modified lines, viewed from the side sample edge. A bar comprises a stack of 6 lines, with Z-positions chosen to minimize undesirable sample bending. The laser is focused from the top down.](image)

Figure 7a shows the displacement (the difference between measured the test and control sample displacements) measured over the 90-minute experiment. Most of the time in this experiment was occupied by waiting for the sample to cool after each bar. Each line only takes 1 second to write, and all 180 lines here could in principle take < 4 minutes. The sample became shorter due to the laser writing, and the total displacement was 2.5 μm over 2 mm of modification, or a shrinkage strain of 0.13%. Each bar introduced an average of 85 nm of displacement with a standard deviation of 12 nm. The displacement data of Fig. 7a exhibits both permanent strain as well as strain from temperature variations. The inset of Fig. 7a shows a close-up of the displacement while writing a single bar, showing 6 thermally induced cycles. We only had discrete control over the laser in this experiment at the millisecond time scale, so we were only able to write continuous lines, which limits the resolution to about 85 nm.

After creating the 2.5 μm shrinkage, we monitored the test and control samples over a period of 6 days. The measured displacement (again, the difference between the test and control samples) over these 6 days is shown in Fig. 7b alongside the temperature measured by the environmental monitor (See Fig. 6). There is clearly some temperature-correlated displacement, possibly due to a slight mismatch in where the test and control samples are held by the clips. Furthermore, the sign of this displacement indicates increased shrinkage over time, which would be counter to a relaxation of the laser-
induced strain. After the initial temperature rise of 0.4 °C, the temperature and displacement both settled, and displacements remained within ±5 nm. These data strongly suggest there is no appreciable relaxation of the laser-induced strain.

![Figure 7](image-url) a) Measured displacement $d$ of the end of a glass sample during laser modification, showing 2.5 μm displacement. $d > 0$ indicates a shrinking sample. Red circles mark the steady-state $d$ after writing each bar (stack of 6 lines), and $\Delta d$ is the displacement contributed by each bar, and each line therefore contributes about 14 nm shrinkage. The writing procedure is described in the text. b) Displacement of this sample after modification, measured over 6 days, plotted alongside temperature. This data does not indicate relaxation of the laser-induced strain.

4.2 Preliminary experiments using Yb-doped fiber laser

We conducted preliminary experiments using a recently-installed Yb-doped fiber laser (Trumpf TruMicro 2030-FU10) with many improved capabilities over the Ti:Sapphire laser. With this laser, we can electronically control pulse energy (0-100 μJ), pulse duration (350 – 20,000 fs), pulse repetition rate (100 – 2000 kHz), and bursts-pulses (1 – 8 sub-pulses per burst, with 25 ns intra-burst period). Furthermore, our stage can demand individual pulses (picked from the 40 MHz seed pulse train then amplified to the desired pulse energy) at rates up to 1 MHz, enabling precise pulse positioning. We have built software to integrate the laser, stage, and other electro-optical components to allow easy control over pulse parameters and positions. Using this laser, we conducted similar experiments as with the Ti:Sapphire laser.

We conducted three experiments to measure the linear displacement of the sample, varying one parameter per experiment: pulse energy $E_p$, distance between pulses $\Delta x_p$, and number of burst sub-pulses $N_b$. In each experiment, the laser repetition rate was held fixed at 1 MHz and the translation stage speed was modulated to achieve the desired value of $\Delta x_p$. The pulse energy and number of burst sub-pulses were each commanded to the laser directly (pulse energy was subsequently cut using a half waveplate and Glan-polarizer that remained at a fixed setting throughout the experimental campaign). The laser pulses were written in segments of 45 μm length spaced every 50 μm (i.e., 90% duty cycle) to provide discretization for future experiments. As with the Ti:Sapphire laser experiments, we wrote bars of lines and multiple bars. In these experiments, each bar comprised 8 lines, and lines were spaced 20 μm apart along the y-direction. These dimensions are smaller than in the Ti:Sapphire experiments because the modification regions are smaller with this laser. The objective lens in these experiments had 0.4 NA and the beam profile had quality factor $M^2=1.2$. As with the Ti:Sapphire experiments, we measured the cantilever tip deflection and found < 2 μm deflection in all cases. We have not yet measured stability of these samples.

In the first experiment, we varied the pulse energy $E_p$ while maintaining constant distance between pulses $\Delta x_p = 22.5$ nm and number of burst sub-pulses $N_b = 2$. The resulting strain is plotted (Fig. 8a, dashed line) against volumetric energy density, $E_d$, which is the total laser energy that illuminated the laser-modified region, divided by the volume of that region. We did not account for the absorbed fraction of the laser energy within the glass in this calculation, and this fraction may differ between the Ti:Sapphire laser and the Yb-doped fiber laser due to different pulse duration, laser wavelength, and objective NA. For this experiment, we were only able to collect 3 data points because $E_p > 1300$ nJ caused damage to the glass with these parameters. We do not yet understand the cause of the nonlinear relationship between pulse energy and the measured strain. In all cases the strain is lower than with the Ti:Sapphire laser.
In the second experiment, we varied the distance between pulses $\Delta x_p$ while maintaining constant pulse energy $E_p = 843$ nJ and number of burst sub-pulses $N_b = 2$. The laser repetition rate was held fixed at 1 MHz and the translation stage speed was modulated to achieve the desired value of $\Delta x_p$. The measured strain is plotted as a function of the energy density (Fig. 8a, solid line). Since the slope decreases with increasing $E_p$, this indicates densely-packed pulses each contribute less total strain (but there are more pulses, so total strain does increase), possibly because there is more interaction with already-modified material. There are two separate data points at $E_d = 26$ nJ/µm$^3$, each taken during Experiments 1 and 2, illustrating the repeatability of the measured strain.

![Graph](image)

**Figure 8.** Measured strain using a Yb-doped fiber laser with 350 fs pulse duration, as a function of a) volumetric energy density by varying pulse energy (Experiment 1) or pulse spacing (Experiment 2), and b) number of burst sub-pulses (Experiment 3).

In the third experiment, we varied the number of burst sub-pulses $N_b$ while maintaining constant pulse energy $E_p = 1263$ nJ and distance between pulses $\Delta x_p = 20$ nm, with the results shown in Fig. 8b. Note that the energy of each sub-pulse is $E_p/N_b$, so the total burst energy is $E_p$. The number of burst sub-pulses impacts the measured strain, suggesting the observed strain is not simply due to melting and quenching effects. Unfortunately, we changed the spacing of lines throughout the glass thickness for this experiment, which we believe resulted in significantly lower strain than the energy density alone would suggest. This is still under investigation.

All displacements, just like in the Ti:Sapphire experiment, indicated shrinkage of the glass. The appearance of written lines is similar to the Ti:Sapphire laser, both in top-down and cross-section views, and suggests significant melting and quenching effects. We found that increased pulse energy and decreased pulse spacing led to increased displacement, as expected, but at sufficiently high values of either can cause damage (voids and cracking). Fewer burst sub-pulses generally led to higher strain, and the cause of this is still under investigation. In all cases we tested, the measured strain was not as high as the Ti:Sapphire laser, potentially due to differences in pulse duration or repetition rate. There are many parameters we have not yet varied, such as pulse repetition rate, pulse duration, polarization, and spatial focus shaping (e.g., Bessel beams, anamorphic beams). All of these are readily variable with our current system.

### 5. CONCLUSIONS AND FUTURE WORK

We have presented a method of adjusting spacers between optical components that is particularly suitable for correcting alignment errors in X-ray telescope mirrors. We have simulated the effects on figure and PSF of exemplary X-ray mirror pairs using FEA coupled with ray tracing. We found that for small misalignments with corresponding radial height errors on the order of 1-2 µm, the PSF degradation can be acceptably small with the spacer design we simulated. The stiffness of the spacer design can impact the alignment range and accuracy as well as launch survival and gravity release error.

We presented experimental results demonstrating that two different USP lasers can produce strains in Corning® Eagle XG® glass on the order of $10^{-3}$ within the parameter spaces we tested. This data provides an estimate of the achievable displacement for a given geometry for optical alignment applications. We also tested stability of samples modified using a Ti:Sapphire laser, and we found that the laser-induced strain is stable over 6 days to within at least 10 nm. We found
some small differences between the magnitude of strain generated by the Ti:Sapphire laser and the Yb-doped fiber laser, but the general behavior and appearance of the laser-modified glass is similar. We presented data outlining some of the basic trends with the Yb-doped fiber laser parameter space.

In addition to further exploring the parameter space available with Eagle XG, future work will include testing other materials such as fused silica, sapphire, or ULE. These materials may be more applicable to certain applications, and we expect them to exhibit different strain-generation mechanisms. Since our laser can produce much higher pulse energy than we currently use, we plan to measure strain generated by a Bessel beam, which can create uniform intensity throughout the entire cantilever depth at once, since it may provide more uniform strain generation than our current optical system. Finally, we plan to develop an improved approach to measuring stability that can be monitored over much longer time scales. While Eagle XG modified by the Ti:Sapphire laser is stable, other materials or modifications created with other parameters may not be.

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