

Laser welding of crystalline sapphire for use in future generation gravitational wave detector suspensions

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Since the first direct detection of a gravitational wave signal in 2015, advancements in technology have resulted in incremental improvements to the current detector network. Future detectors will exploit new technologies to deliver an order of magnitude improvement in performance by increasing their scale and directly targeting thermal and other noise sources. With many next-generation gravitational wave detectors planning to implement crystalline materials as replacements for fused silica, there is an increasing need for novel techniques in suspension jointing. This work will report on the development and characterisation of a repeatable and repairable laser welding technique for crystalline sapphire. Utilizing a CO₂ laser within a crystal growth machine, specifically designed for laser-heated pedestal growth, we established a reliable method for laser welding sapphire stock pieces of various millimetre scale diameters. Experimental characterisation revealed an upper limit of the weld region to be ≤ 200 μm , and no measurable detriment to the thermal conductivity or tensile strength due to a welded joint. A thermal conductivity of $4587 \text{ Wm}^{-1} \text{ K}^{-1}$ at 20 K and a minimum unbroken tensile strength of 1.1 GPa were measured on a welded sample. In addition, cryogenic mechanical loss measurements produced a lowest loss of 3.2×10^{-7} at 14 K, allowing a weld loss estimate of 5.1×10^{-6} . These initial findings indicate significant potential for sapphire welding as a viable concept in next-generation cryogenic detector suspensions and provide a strong justification for further development of this jointing method.

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I. INTRODUCTION

The current gravitational wave detector (GWD) network utilizes long baseline interferometry to sense the displacement of suspended mirrors caused by spacetime perturbations. The mirrors are suspended to isolate them from the effects of seismic noise which would interfere with detections [1]. Thermal displacement noise, $x(\omega)$, is a dominant noise source in these suspension systems, due to thermal energy causing motion which is related to mechanical dissipation $\phi(\omega)$, via the fluctuation dissipation theorem [2],

$$x(\omega) = \sqrt{\frac{4k_b T}{\omega m} \left(\frac{\omega_0^2 \phi(\omega)}{\omega_0^4 \phi(\omega)^2 + (\omega_0^2 - \omega^2)^2} \right)}, \quad (1)$$

where k_b is Boltzmann's constant, T is operating temperature, m is the mass of the mirror, and ω_0 is the angular resonant frequency of interest. The selection of low-dissipation suspension materials is key to reducing this noise, which is particularly dominant in the low-frequency range of GWDs [3].

Fused silica has very low mechanical loss at room temperature and as such is used in the optics and suspension systems in the Advanced LIGO (aLIGO) [4] and Advanced Virgo [5] detectors. This allows for an extremely low-noise performance, contributing to the high-sensitivity detector network which confirmed the existence of gravitational waves and has observed hundreds of such signals [6]. However, thermal noise is still a major limitation to sensitivity in the 1–100 Hz frequency band. Therefore cryogenic cooling is planned to be used in future GWDs,

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such as the Einstein Telescope (ET) [7], to reduce thermal noise, directly exploiting the temperature dependence of thermal noise. It is hoped that this upgrade, amongst others, will result in over an order of magnitude increase in sensitivity [8]. If the planned scientific potential of ET is achieved, an unprecedented insight to the astrophysical sources of gravitational waves will be realized.

A. Sapphire as a suspension material

For low operating temperatures, such as 20 K, fused silica is no longer a viable material due to increased dissipation at low temperatures [9,10]. Crystalline alternatives such as sapphire and silicon are under consideration as potential replacements due to their favourable properties at cryogenic temperatures. Both have a high thermal conductivity at ~ 20 K [11], which is required to extract heat from the test mass, as well as a low mechanical loss at cryogenic temperatures [12]. Sapphire has a higher tensile strength of 400 MPa [13,14], compared to that of silicon [133–210 MPa [15]], which is desirable as it would allow for the use of thinner suspension fibers to support the test mass, which would decrease their thermal noise contributions. The use of sapphire as a suspension material is currently being used in the KAGRA detector [16] which has a targeted operating temperature of 22 K with the aim to significantly reduce thermal noise.

Looking to future cryogenic detectors, the development of low mechanical loss test masses with good optical quality and low dissipation suspensions is crucial. The technology for the growth of sapphire fibers up to 1 mm has been previously demonstrated [17], and further development into growing larger diameter fibers is ongoing [18]. Silicon fiber growth technology over a range of fiber diameters is currently under development at IKZ Berlin [19], though silicon does not respond well to laser heating and so alternative methods, such as rf heating, are being implemented. The optical properties of silicon, such as absorption and birefringence [20], are more promising than that of sapphire. Therefore, a multimaterial detector, with silicon optics and sapphire suspensions, may be an approach which best exploits the required properties of both materials.

The development of such crystalline fibers has revealed various challenges to overcome in order to realize their full potential in a suspension system. Specifically, the development of novel low-loss and practically feasible jointing techniques is required to reliably attach the fibers to the test mass. Laser welding of fused-silica has been successfully utilized in aLIGO [21,22] as the method of joining fibers to the silica side prisms, or “ears”, which are hydroxy-catalysis (HC) bonded [23] onto the test masses, resulting in extremely low thermal noise. The use of welding also allows for broken fibers to be replaced without any damage to the ears, which are challenging to remove from the test mass once bonded. The

mechanical loss of fused silica at room temperature is extremely low [24], allowing for the thermal noise to be sufficiently low. However, the mechanical loss of the HC bonds is typically a factor of $\sim 10^5$ worse [25]. This higher loss can be mitigated by thickening the ends of the fibers and implementing welding to join them to the ears, keeping the energy in the suspension away from the high loss bond region. The ability to engineer properties like the violin mode frequency through geometry choice, shaping the fiber ends to minimize thermoelastic loss and using a CO₂ laser to polish the fiber surface and hence maximizing strength has resulted in the extremely low thermal noise suspension in use today [22]. Additionally, the length of the fibers can be altered once welded through a “destressing” process, which allows for pitch correction and tuning of the violin modes.

The success of welding in aLIGO motivated this development of an analogous method for the laser welding of crystalline sapphire, as explored in this paper.

II. WELDING METHOD

Fused silica is a favorable material for laser welding due to its high viscosity when molten, and its low thermal conductivity. The viscosity allows for control of the shape of the mechanically unsupported molten zone and weld area. Whereas, for sapphire, there is a more defined solid-liquid transition where the molten material is immediately of a low-viscosity, creating an almost instantaneous balled molten zone, which relies on the careful balancing of surface tension and gravity to form a joint. However, this did not present a great challenge when welding, as the low viscosity allowed for immediate contact with almost no resistance to occur when in contact a solid sapphire interface. The low thermal conductivity of silica allows for the heat to be contained close to the weld region, and away from surrounding mechanical or electrical components. In addition, this is advantageous for achieving molten material as the laser power is minimally extracted. Furthermore, in this process, fused silica can tolerate large temperature gradients, which in crystalline materials such as sapphire, can result in cracking due to thermal stresses. Sapphire has a high thermal conductivity, an advantageous property for cryogenic suspension materials, as will be discussed. However, this presents some challenges when welding, as temperature gradients must be managed, and can cause difficulty with heat extraction, particularly when welding to larger masses. While there is still development to be carried out in order to overcome some of these obstacles, a successful method for welding similar diameter pieces was developed. The procedure below describes the method of welding 1 mm to 1 mm diameter rods which were used in the characterisation tests. However, samples of 425 μm to 425 μm , and 1.6 mm to 1.6 mm diameter rods were also produced by using the same method, and adjusting the power level accordingly.

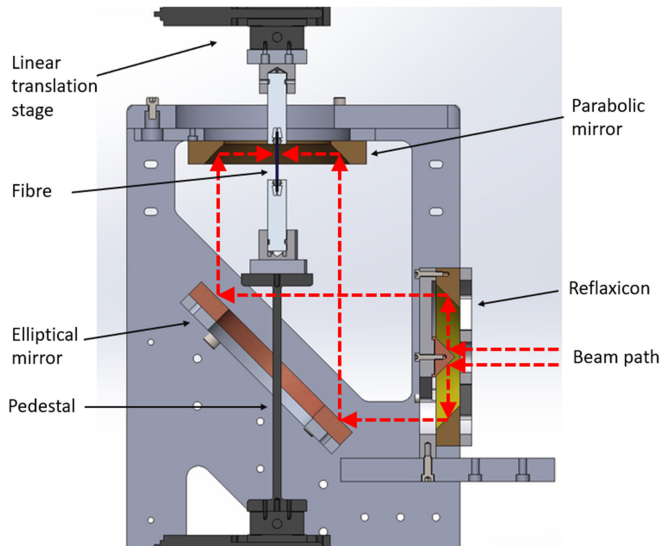


FIG. 1. Inner optical system of the crystal growth machine used to undertake the welding work.

The sapphire welding procedure was carried out using a crystal growth machine (CGM) which was designed for crystalline fiber growth using the laser-heated pedestal growth method [26]. A 200 W rated $10.6\ \mu\text{m}$ CO_2 laser was directed through the optical system as detailed in Fig. 1. The beam path is directed to an optical configuration known as a reflexicon [17], consisting of an inner cone which reflects the beam to an mounted outer conical mirror, resulting in a hollow cylindrical beam, as detailed in Fig. 2. The beam then reaches a 45° elliptical mirror which directs it towards a final parabolic mirror which focuses the beam down on the stock surface. The parabolic mirror enables a tighter focusing than achieved by use of lenses alone. This allowed for a beam $\sim 1.5\ \text{mm}$ in waist to focus on the tip of a $1\ \text{mm}$ sapphire stock piece, which was viewable on two perpendicularly mounted cameras fitted with appropriate neutral density filters to allow clear viewing of heating region.

To begin a weld, the tip of the lower stock piece is melted until a fully liquid ball formed, typically requiring 12%

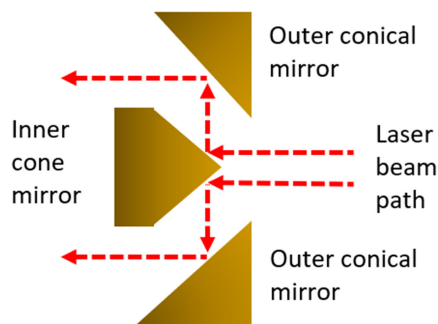


FIG. 2. Illustration of a side cross-sectional view of the reflexicon.

laser power, dependent on alignment accuracy and beam width. The upper stock piece is then slowly lowered until contact is made with the lower molten zone, after which the movement is immediately ceased, allowing a column of molten material to connect the two stock pieces. The laser power is then increased incrementally, to allow for sufficient heating of both stock pieces. The two pieces are believed to be fully joined when no shadows are present in the molten material, as viewed in the two camera feeds. The laser power is then slowly decreased to zero while the beam is simultaneously being translated up and down the welded area at a rate of $1.7\ \text{mm/min}$, avoiding rapid temperature changes in the material. It is important that the laser does not remain stationary on the stock piece for more than a period of $\sim 30\ \text{s}$, as it was found that this risks cutting into the material, resulting in an uneven weld profile.

Images from the two cameras detailing the key steps of the welding process as viewed in a LabVIEW program can be viewed in Fig. 3. An example of a welded sample with annotated key steps is shown in Fig. 4.

Sapphire has been found to be susceptible to thermal shocks with rapid temperature changes in previous studies [18,27], which was confirmed in initial exploratory work. It was found that when the laser power was instantaneously

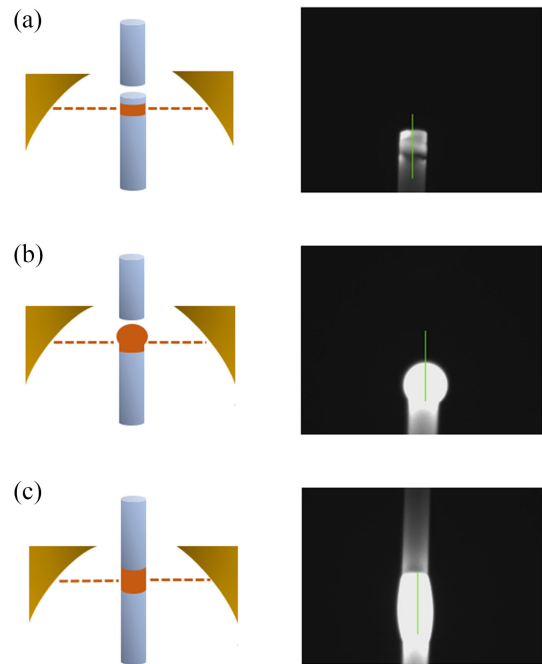


FIG. 3. Illustration (left) and accompanying example screenshots (right) of the key stages of the weld process. (a) The laser is aligned on the lower stock and the laser power is then increased. (b) The power is increased on the lower molten zone until completely melted, and the upper stock is lowered into this. (c) The two stocks have joined and a column of molten material has formed, a short polishing phase is carried out over this region to fully fuse the molten-solid boundaries, and then controlled removal of the laser power begins.

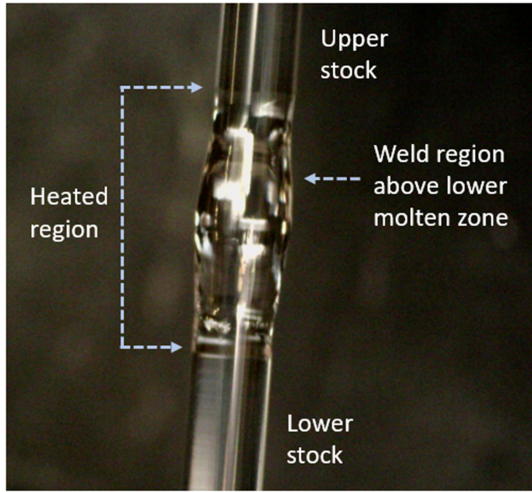


FIG. 4. Annotated 1 mm diameter welded sample of mechanically polished stock.

removed, the sapphire in the heated region solidified to a cloudy appearance, as shown in Fig. 5. Viewing this under a scanning electron microscope (SEM) revealed numerous voids between crystal structures, shown in Fig. 6. These samples were also observed to be very weak, breaking during removal from the CGM. To avoid this, changes in power level were carried out gradually, at approximately 0.5% per second. However, it should be noted that both the opaque material and any cracking could be remedied by remelting with properly controlled heat removal, as detailed in Fig. 5.

Using this successful welding method, three sets of welded sapphire samples were produced for characterization, each consisting of twelve welded samples. The c-axis grown 1 mm diameter sapphire rods used to produce these welded samples were manufactured by American Elements [29], and were of two different surface finishes: ground and mechanically polished. As detailed in Sec. IV, these two

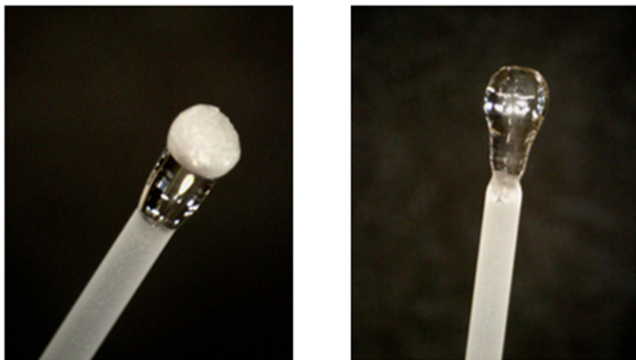


FIG. 5. Sapphire sample which underwent rapid heat removal, resulting in an opaque ball forming from the molten zone (left). The same sample was then melted again and treated with a controlled heat removal, resulted in a clear material once solid (right).

surface finishes were found to have lower strength than the welded area, and so a laser polished sample set was also produced with the aim of increasing the tensile strength of the whole sample.

III. CRYSTALLOGRAPHY

Due to the way in which the two sapphire stock pieces are joined during a weld, it was assumed that there would be at least two crystal orientations present in the sample. However, it was unknown what the crystal orientation of the weld region would be, or whether many disjoint orientations would be present. A polycrystalline joint could be anticipated to have higher loss, lower thermal conductivity, and lower tensile strength. Furthermore, the physical properties of sapphire are dependent on the crystal axes. For instance, the thermal conductivity is slightly lower along the c-axis when compared to the a-axis [30], whereas, tensile strength has been found to be higher along the c-axis [31]. Therefore, when comparing the different properties of sapphire, it is essential to know the axes of the sample. This was achieved by the use of X-ray diffraction (XRD) analysis.

A. X-ray diffraction measurements

Using XRD, a series of measurements from a ~ 30 mm section of a welded sample from each sample set was taken by diffracting x-rays ($\lambda = 0.71073$ Å Mo K α) of beam diameter ~ 200 μ m. The samples were mounted in such a way that 360° rotation (about an axis coincident with the fiber length) was allowed during the measurements. Measurements of the crystallographic axes along each sample length were taken in 100–200 μ m increments, allowing any changes in orientation to be monitored. These measurements were also verified against the expected unit cell for Al₂O₃.

In addition to one sample from each sample set, two additional samples were also analysed to investigate the crystal nature of the cloudy material resultant from rapid cooling.

B. X-ray diffraction results

Analysis of the cloudy samples formed from rapid heat removal confirmed that this material is still single-crystalline, but with domains of off-axis reflections. This implies that the material was unable to recrystallize fully when cooling, highlighting the significance of proper heat removal, and concurring with the SEM image in Fig. 6. This emphasizes the significance of proper heat removal during the welding process.

All three measured welded samples were shown to be a single crystal on either side of the weld with the c-axis coincident with the fiber length in all cases. The orientation of the a and b axes was found to change at the weld and were related by an arbitrary rotation about the c-axis.

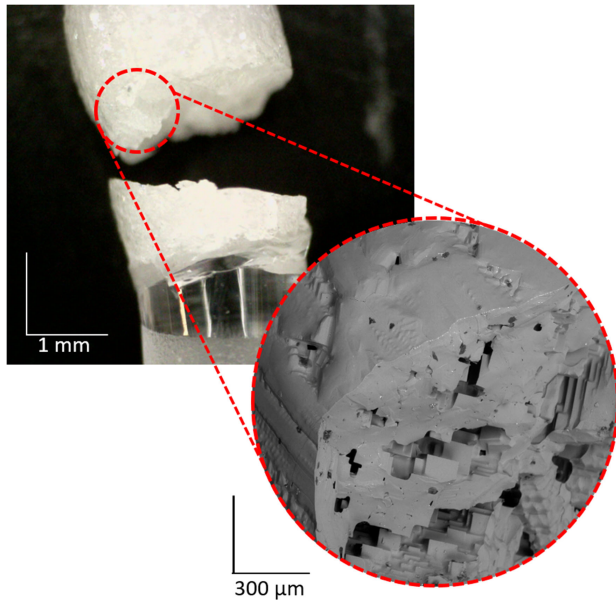


FIG. 6. Welded sample which underwent rapid heat removal and separated due to extreme cracking, with an SEM image [28], revealing voids in the crystalline structure.

This is illustrated in Fig. 7, and is thought to be the result of the manner in which the stock pieces are joined together and maintained once welded. No intermediate orientations were visible, indicating a clean transition.

Through these measurements, the thickness of the weld material was determined to be within a 200 μm region above the lower molten zone. The exact size of this weld region can only be limited to at most 200 μm , as this is the width of the x-ray beam. To further constrain this, measurements using a narrower beam would be required. However, an upper limit of 200 μm indicates that the weld region is small, meaning the mechanical loss associated with the weld will have less impact. In comparison, the weld region in aLIGO fibers is considered to be 2 mm [22], a factor of ten greater. Therefore, the small size of this weld area has promising implications for the joint loss contribution of welded sapphire.

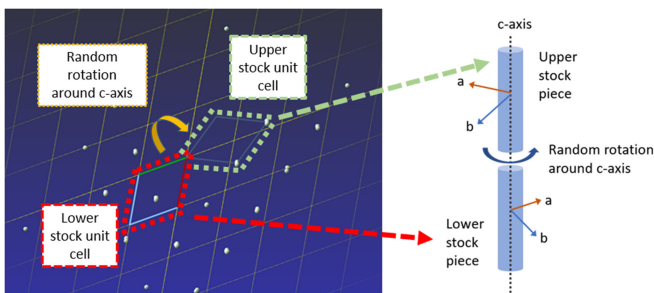


FIG. 7. Measured reflections in the reciprocal space for a welded sample (left), revealing two c-axis unit cell orientations present in the weld region. The two orientations are the result of the stocks being misaligned when joined, as illustrated (right).

IV. STRENGTH TESTING

The commonly used literature value of the tensile strength of base sapphire is 400 MPa [13,14], but this can vary due to factors such as crystal orientation [32], purity level [33], and surface quality [34]. Grown sapphire fibers have been recently found to have tensile strengths of at least 792 MPa [18], this higher value is thought to be a result of a high quality surface due to laser treatment. In addition, a study of four-point bending of bulk sapphire samples has shown strengths ranging from 1019 to 2605 MPa [35], although it is currently unknown how accurately four-point bending represents the tensile load on a suspended fiber.

Currently for sapphire in ET, it is planned that the test mass will be 211 kg suspended by 2.3 mm diameter fibers [7]. This would require a working stress of 373 MPa on each of the four fibers, with an assumed safety factor of three. This safety factor was chosen as this results in the highest stresses, which is beneficial for the thermal noise [36]. However, to optimize thermal noise performance, it is important to have flexibility in the diameter of the fibers, as many factors need to be considered. To reduce thermal noise via dissipation dilution [37], the fiber should be as thin as strength allows. In addition, for cryogenic detectors, a diameter for sufficient heat extraction through the fibers must be accounted for [38,39]. Therefore, the final diameter of the fiber should be the result of a careful balance of these factors, and achieving a higher tensile strength would allow for more range in possible diameters.

To assess the effect of welding on the tensile strength, an initial investigation of the room temperature tensile strength of the three different sample sets was conducted. The ground and mechanically polished stock pieces were used to produce the first two sample sets which were strength tested. However, as surface quality directly correlates to tensile strength, these samples failed at low stress values with no observed failure of the weld. In an attempt to increase the strength of the surrounding stock material to increase the chances of breaking the welds, a laser polishing method was developed by tuning the power level and polishing rate, as this is known to greatly improve the tensile strength of fibers in aLIGO [34]. The laser polishing method involved running the laser over the entire welded sample at a power level of 24 W and a rate of 0.5 mm/min. An example of a laser polished weld can be viewed in Fig. 8.

A. Tensile strength measurements

The strength testing apparatus consisted of two clamps, which self-tighten as an increasing load is applied on the sample. To avoid surface damage imparted by mechanically clamping the samples, cardboard pieces were attached to each end of the sample using epoxy [34,40]. These pieces sandwiched the ends of the sample, allowing the

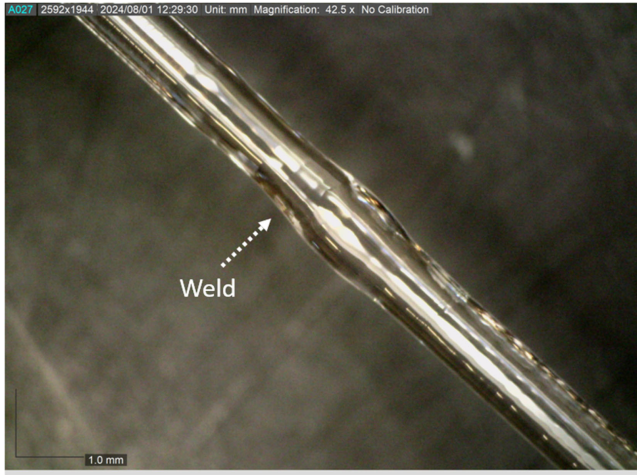


FIG. 8. Laser polished 1 mm diameter welded sample.

self-tightening clamp to grip this without damaging the sample end. To improve the contact between the cardboard and clamp, corrugated copper pieces were affixed onto each cardboard face. The samples were then inserted into the strength testing apparatus, as shown in Fig. 9, and an increasing force was then applied until failure.

The applied force was controlled and linearly increased via a worm drive connected to the bottom clamp, and measured by a load cell with a readout for live recording. The breakage was recorded with a high speed (20,000 + fps) camera. This allowed the breakage location to be determined,

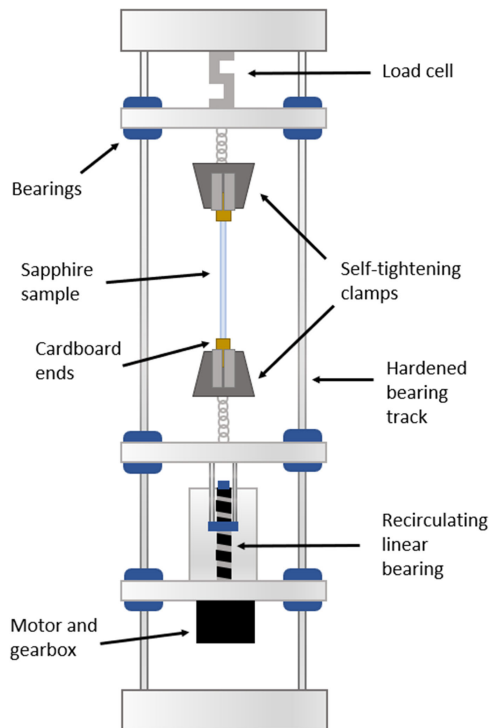


FIG. 9. Strength testing apparatus used to study the tensile strength of the sapphire samples.

and monitoring of the introduction of any angles that may affect the breaking load.

B. Tensile strength results

As the welding process introduced slight diameter variations, all samples underwent diameter profiling using a fiber profiler machine developed for aLIGO fiber characterization [41]. This provided accurate measurements of the diameter profile along the sample length and weld area, allowing for the stress, σ , to be calculated using

$$\sigma = \frac{F}{A}, \quad (2)$$

where F is the applied force at failure, and A is the cross-sectional area. The maximum stress applied to the sample was calculated using the minimum diameter of the sample, while the actual breaking stress was calculated using the diameter of the breaking point.

In addition, to estimate the stress withstood by the weld area, the diameter of the estimated weld point was taken. Although the XRD measurements were able to locate a weld region, it was not possible to mark this location on each sample, and so a region of 1 mm around where the curve of the lower molten zone flattens out into the upper stock piece was taken.

Figure 10 shows the estimated weld stress experienced in the weld region. All measured samples broke in the surrounding stock with the weld area remaining intact.

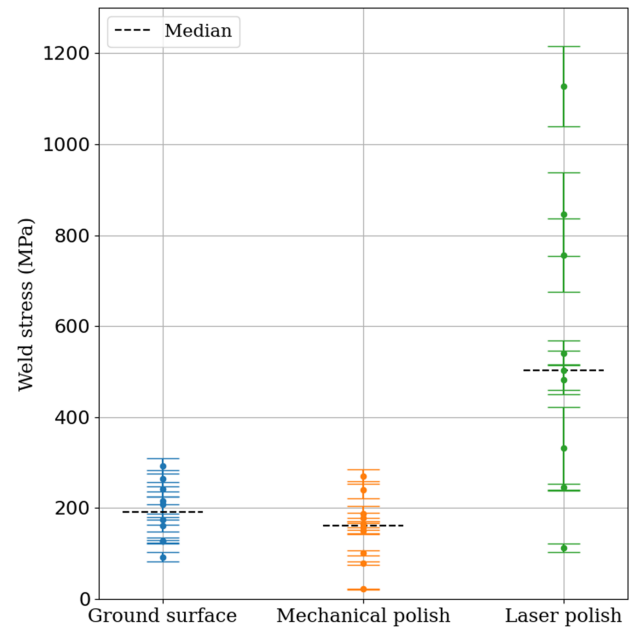


FIG. 10. Estimated stress experienced by the welded sapphire samples using ground surface stock pieces (blue), mechanically polished surface pieces (orange), and laser polished stock pieces (green).

It was found that the laser polished samples had the highest stress values, with a larger spread in values. The laser polished samples with the five highest stress values did not break, and instead began to slip out of the clamps. This spread is thought to be due to the limitations of the set up, causing some failure at lower values. It is thought that an alignment issue was present with the latter half of this sample set, as the samples were seen to bend, resulting in a higher stress concentration in the bending region, resulting in the sample failing at a lower observed load.

The highest stress value which was experienced at a weld joint before the sample slipped out the clamp was observed to be 1.1 GPa. This demonstrates the potential for ultrahigh strength joints, well above the stress requirement for Einstein Telescope Low-Frequency (ET-LF). While further investigation is required to determine the ultimate tensile strength of these welded sapphire joints, it is clear that these measured strengths well exceed the requirements, with the actual weld strength likely being higher than recorded here.

V. THERMAL CONDUCTIVITY

The thermal conductivity of sapphire is known to be high at cryogenic temperatures [11], which is required for heat extraction via fibers in cryogenic detectors [42]. At temperatures around 10–20 K, the proposed operating temperature range for ET-LF [7], radiative cooling will be insufficient for extraction of the heat imparted by the laser and the environment. Therefore, the suspension fibers need to have a sufficiently high thermal conductivity to remove this excess heat from the test mass [42]. As previously discussed, the thermal conductivity requirement sets a lower limit on the fiber diameter, and it is advantageous to have thinner fibers for thermal noise purposes. Therefore, any reduction to the thermal conductivity caused by the introduction of a welded joint would be detrimental to the performance of the suspension fibers.

It has been demonstrated [43] that at temperatures below 50 K, the thermal conductivity of sapphire is dominated by phonon-phonon interactions, and therefore limited by the crystalline quality. In crystalline materials, point defects and impurities cause phonon scattering which reduces the thermal conductivity [11]. With this in mind, it seems logical to assume that welding could potentially reduce the thermal conductivity due to the two crystal orientations present in the weld area, as observed in the XRD analysis.

The thermal conductivity, κ , can be calculated using the following expression:

$$\kappa = \frac{P\Delta x}{A\Delta T}, \quad (3)$$

where P is the applied power, A is the cross-sectional area, and ΔT is the temperature gradient along a length, Δx .

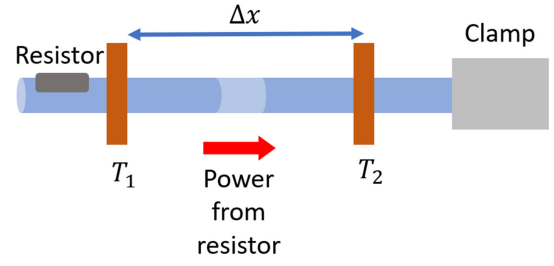


FIG. 11. Schematic of the setup used to measure the thermal conductivity via the steady state method. The temperature from T_1 and T_2 over the separation Δx is used with the power applied by the resistor to calculate the thermal conductivity.

A. Thermal conductivity measurements

A schematic of the absolute steady state method used to obtain the thermal conductivity measurements can be viewed in Fig. 11. The thermal conductivity setup was operated in a cryostat to allow measurements over a range of cryogenic temperatures under a vacuum of $\sim 10^{-6}$ mbar. Figure 12 shows a photograph of one sapphire sample in the thermal conductivity measurement setup. Two temperature sensors, T_1 and T_2 , are affixed to copper bars with indium lining at the sample interface to provide a good thermal contact with the sample. The sensors are separated by a measured distance, Δx . Heat flow is applied to the sample via a 400 Ω resistor, H_1 , which is attached using cryogenic safe varnish to the tip of the sample.

At one end, the sample is thermally and mechanically connected to a clamp with control (from heater H_2) and measurement (by sensor T_3) of the global temperature of the experiment.

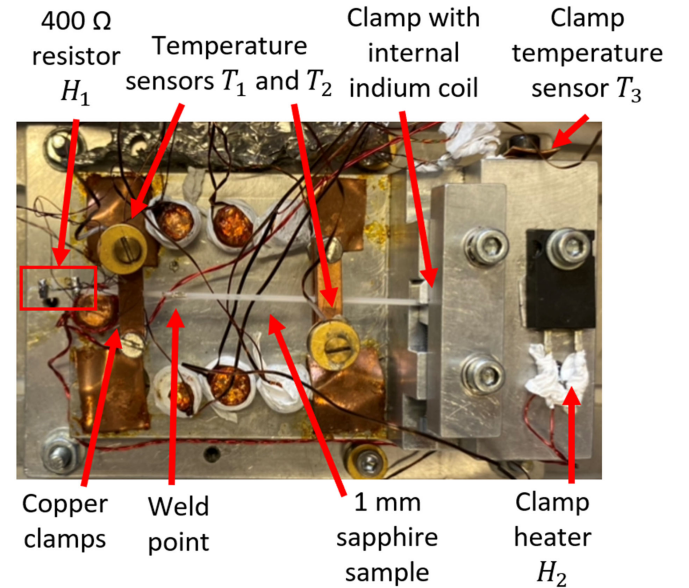


FIG. 12. Clamp used in the thermal conductivity experiment, with a ground surface welded sapphire sample.

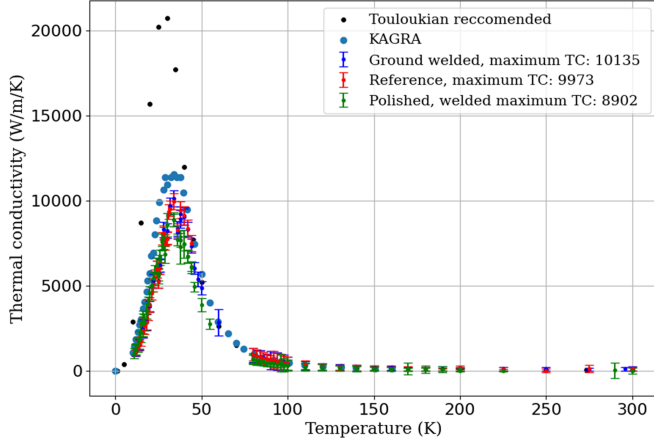


FIG. 13. Measured thermal conductivities of three different sapphire samples, compared to the recommended Touloukian curve [11], and measurements of 1.6 mm diameter fibers from KAGRA [44]. The 1 mm diameter sapphire samples are as follows: a welded ground surface (blue), a ground surface reference sample (red), and a laser polished welded sample (green).

This method was used to investigate the thermal conductivity of three sapphire samples: one welded using ground surface rods, one welded and laser polished, and one ground surface sample with no weld as a reference. Measurements were taken from 12 to 300 K for each sample.

B. Thermal conductivity results

The measured thermal conductivities of all three samples can be viewed in Fig. 13, with Fig. 14 showing the lower temperature data. The conductivities of all three samples were found to have largely overlapping values, within the error bars, which demonstrates that there is no observed appreciable reduction in thermal conductivity due to the welded joint.

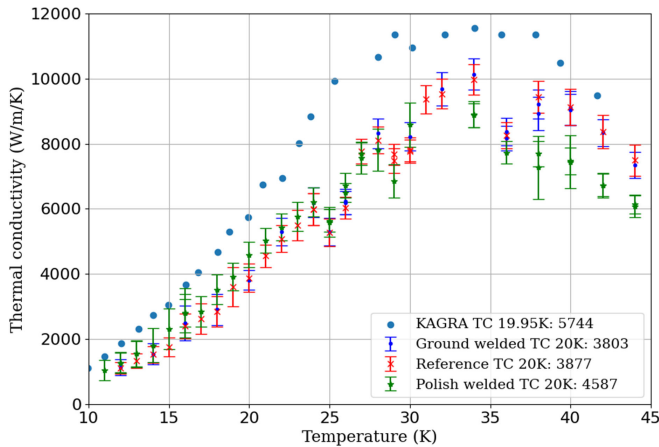


FIG. 14. Lower temperature end of the conductivity data presented in Fig. 13, with 20 K data indicated.

To determine if scattering effects were present, the phonon free path for each sample was calculated by [32]

$$l = \frac{3\kappa}{C_v\nu}, \quad (4)$$

where C_v is the volumetric heat capacity and ν is the phonon sound speed calculated by $\nu = \sqrt{\frac{E}{\rho}}$, where E is the Young's modulus and ρ is the density.

Calculating the phonon free path for each sample using the measured thermal conductivities shows that the samples may have been affected by phonon scattering at the edges of the sample in the lower temperature range, which could be reducing the measured conductivity. For example, the phonon free path for the laser polished welded sample is 0.48 mm at 20 K, which is approaching the 1 mm diameter of the sample. In addition, it can also be assumed that the discrepancy between the thermal conductivities measured here and in KAGRA [44] or in the recommended Touloukian curve [11] may also be due to the quality of the base sapphire used to produce these samples, and are not limited by the welded joint, as demonstrated by the conductivity of the reference sample.

VI. MECHANICAL LOSS

As shown in the crystallography measurements, the welded samples present two crystal orientations at the weld interface, both with the c-axis along the fiber. While this crystal boundary which we consider to be the weld region was limited to $\leq 200 \mu\text{m}$, the impact of this weld area on the mechanical loss still had to be verified. Crystal lattice orientations are known to affect the bulk loss [45], and the welded silica fibers in aLIGO experience a weld loss over a molten region of 2 mm [22,25]. This motivated the cryogenic mechanical loss measurements taken of a welded sample.

The mechanical loss (ϕ_{total}) of a welded fiber is believed to be comprised of the thermoelastic loss (ϕ_{TED}), the surface loss (ϕ_{surface}), the clamping loss (ϕ_{clamping}), the bulk loss (ϕ_{bulk}), and the loss associated with the weld area known as the “weld loss” (ϕ_{weld}). The sum of these losses can be represented by the following expression:

$$\phi_{\text{total}} = \phi_{\text{TED}} + \phi_{\text{surface}} + \phi_{\text{clamping}} + \phi_{\text{bulk}} + \phi_{\text{weld}}. \quad (5)$$

Thermoelastic loss, ϕ_{TED} , in the case of unsuspended fibers, can be calculated by the following equation [21]:

$$\phi_{\text{TED}} = \frac{Y\alpha^2 T}{\rho C} \frac{\omega\tau}{1 + \omega^2\tau^2}, \quad (6)$$

where Y is Young's modulus, $\alpha = \frac{1}{l} \frac{dl}{dT}$ is the coefficient of thermal expansion, ρ is the density, and C is the specific

heat capacity. The characteristic time for heat to conduct across a circular fiber, τ , can be calculated by

$$\tau = \frac{\rho C d^2}{13.55\kappa}, \quad (7)$$

where d is the fiber diameter, and κ is the thermal conductivity.

The surface loss, ϕ_{surface} can be calculated using the following equation:

$$\phi_{\text{surface}} = \frac{8h\phi_s}{2r}, \quad (8)$$

where ϕ_s is the intrinsic mechanical loss of a material's surface, and h is the depth to which these mechanisms are believed to occur, and r is the radius. The ϕ_s and h terms cannot be decoupled easily and so their product is often quoted as one term.

The bulk loss can be found in literature [46], and is assumed to be negligible for fibers of this diameter, due to the high surface to volume ratio. In general, the clamp loss can be minimized by clamping thick stock which is welded to a thinner fiber piece, as the bending is less likely to occur in the clamp. This approach was utilized with the aim to reduce the motion and stress, and thereby the dissipation, in the clamping region. With this in mind, the sample welded for this measurement comprises of a 50 mm long, 1 mm diameter, mechanically polished stock piece with a welded 91 mm long fiber of 425 μm diameter, as shown in Fig. 15.

A. Mechanical loss measurements

For an accurate measure of mechanical loss, ringdowns of the resonant modes of this fiber were measured under vacuum pressures of $\sim 10^{-6}$ mbar to minimize loss due to gas damping [47], in the mechanical loss measurement setup used in multiple studies [48,49]. Precision silicon

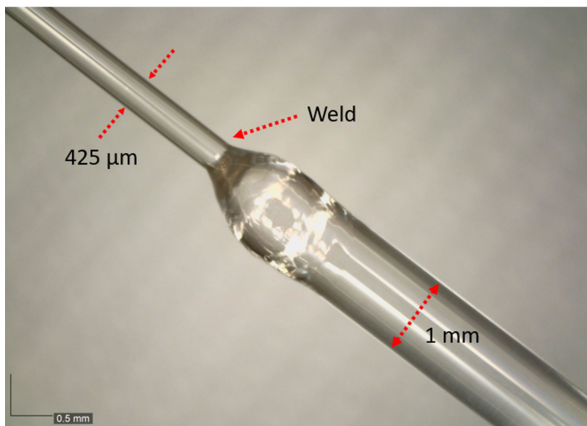


FIG. 15. Welded 425 μm sapphire fiber used in the mechanical loss measurements.

diode temperature sensors [50] were used to measure the temperature of the base plate, and the clamp. The temperature at the clamp was taken as the temperature of the fiber for each measurement step, as they were known to be well thermally connected from previous experiments using this apparatus [49].

The fiber was clamped between two stainless steel blocks, as shown in Fig. 16, which were mounted to raise the sample to be in line with the laser beam, while maintaining thermal contact with the base plate. The polished stock piece was clamped so that the weld point was close to the clamp without being clamped itself, and the fiber was held ~ 1 mm above a high voltage excitation plate. The excitation plate was connected to a high voltage amplifier, and resonant modes of the sample were excited by applying a high voltage signal at the required mode frequency to the exciter plate.

The amplitude of oscillation was recorded using a shadow sensing method, with a laser illuminating the sample and a quadrant photodiode used to record the time evolution of the ringdown decay.

B. Mechanical loss results

For each of the first six resonant frequencies, measurements of multiple ringdowns at each temperature step were attempted. However, this was not always possible due to effects such as alignment drifts, temperature instability, or excess noise.

An excited resonant mode will decay with damped harmonic motion which can be expressed as

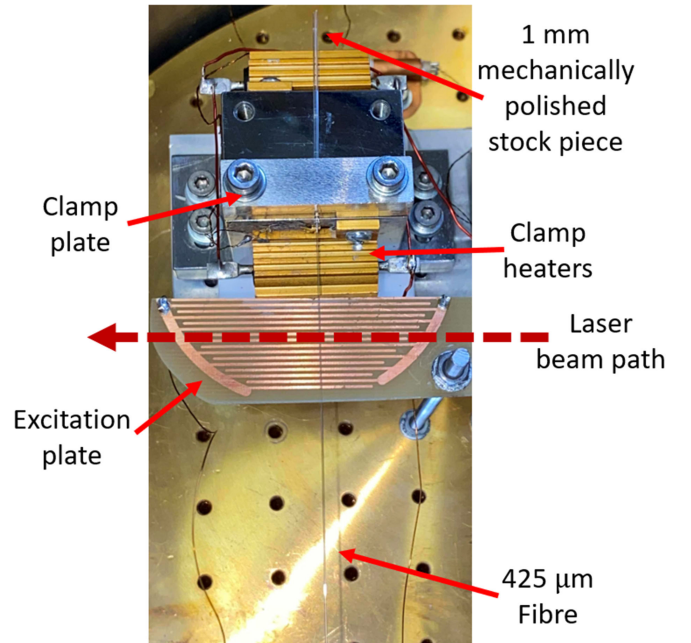


FIG. 16. Welded 425 μm sapphire fiber clamped in the mechanical loss measurement setup.

$$A(t) = A_0 e^{-\frac{\phi \omega_0 t}{2}} \quad (9)$$

for a resonant frequency $f_0 = \frac{\omega_0}{2\pi}$ where $A(t)$ is the amplitude as a function of time, and A_0 is the initial amplitude at time $t = 0$. A fit to the envelope of this ringdown was integrated into a LabVIEW program as detailed in [51], allowing for the mechanical loss, ϕ , to be calculated at each temperature step for the six resonant modes.

The mechanical loss of the first six modes of the fiber was measured between 13 K and 300 K at ~ 5 K intervals. In the majority of cases, multiple ringdowns were obtained at each temperature, and used to obtain an average loss and a standard deviation, with the latter being used as an estimate of the uncertainty in the average loss. At some temperatures, particularly in the < 60 K range, multiple ringdowns per temperature step were not obtained, and so averages over data points within 5 K were taken. However, if there were no data points at similar temperatures, an average could not be taken, and so these points do not have an associated error from the spread of repeated measurements. It is very likely that the error on these points would be similar to errors found at nearby temperatures.

The theoretical thermoelastic loss of this fiber was also calculated, using Eq. (6), as this was thought to be the dominant loss contribution for the upper temperature range. The lowest measured losses were observed in the second mode, as shown in Fig. 17. The remaining resonant modes in Fig. 21 can be viewed in the

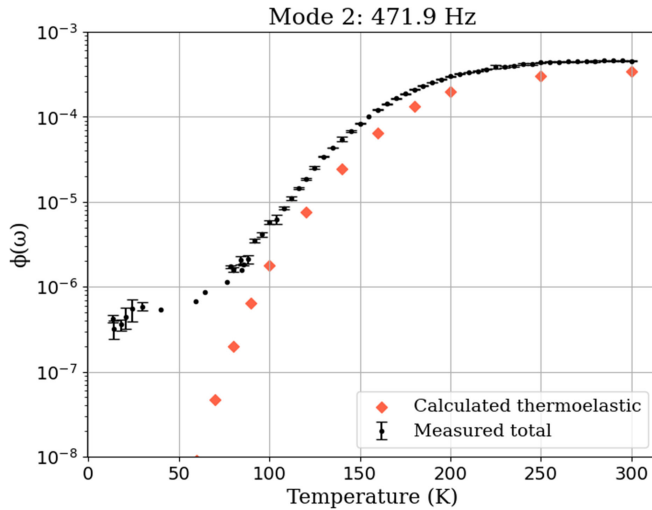


FIG. 17. Measured total mechanical loss (black points) of a welded 425 μm sapphire fiber with the theoretical thermoelastic loss curve (red diamonds) at the second resonant mode. Data points with an error bar represent the average loss over similar temperature points, with the standard deviation being the error. Data points with no error bar represent single measurements, which could not be assigned an error.

Appendix. The increase in loss at higher mode frequencies may be explained by losses associated with the clamp, as more bending energy will be present in the clamping point.

From these plots, it is shown that the measured combined mechanical loss closely follows the calculated thermoelastic trend, with some offset thought to be the result of other loss contributions, such as surface, and differences in the material properties used. The loss begins to flatten off below 50 K where thermoelastic effects are minimal. The major contributing loss mechanisms in this region are thought to be a combination of weld and surface loss. In reality, prior studies [22] have shown that weld and surface loss are not easily decoupled.

As an initial attempt to estimate the respective contributions of the weld and surface losses, the ratio of surface to weld loss from Q-measurements in aLIGO [22], which is determined to be approximately 18:1, was used. Though the different material properties could possibly result in a different loss ratio for sapphire, the fiber geometries are similar, so this is thought to be a suitable initial approximation until further decoupling can be achieved. By modeling the welded fiber sample using Finite Element Analysis (FEA), the amount of energy in the 200 μm weld region for the second mode was found to be 0.078% of the energy of the whole system. To simplify, at temperatures below ~ 60 K, it was assumed that the remaining loss terms are negligible and that the remaining energy, 99.22%, is in the fiber surface. This results in the following expression:

$$E_1 \phi_{\text{surface}} + E_2 \phi_{\text{weld}} = \phi_{\text{min}}, \quad (10)$$

where E_1 and E_2 are the respective energy ratios. Using the same surface to weld loss ratio found in aLIGO, the surface loss can be expressed in terms of ϕ_{weld} as $\phi_{\text{surface}} \approx 18\phi_{\text{weld}}$. This can then be substituted into Eq. (10). The value for ϕ_{min} was taken as the lowest observed average loss value, as this would be the maximum value for combined surface and weld losses. In mode two, the lowest average is taken over five ringdowns at ~ 14 K, to be $3.2 \times 10^{-7} \pm 0.8 \times 10^{-7}$. Using this value in Eq. (10), the surface loss was found to be $2.8 \times 10^{-7} \pm 0.7 \times 10^{-7}$, providing an $h\phi_s$ value of $1.5 \times 10^{-11} \pm 0.4 \times 10^{-11}$ m, and a weld loss of $5.1 \times 10^{-6} \pm 1.3 \times 10^{-6}$.

Previous measurements in KAGRA [52] have allowed a worst-case $h\phi_s$ estimate of 2×10^{-10} m [53]. The measurements here demonstrate that the surface loss of sapphire is likely to be at least an order of magnitude lower. In future studies, loss measurements of laser polished samples are expected to decrease this value further due to increased surface quality.

To obtain exact values of surface and weld loss a sample of the same geometry without a weld would be required, which is an area of ongoing study. While the ratio of surface to weld loss in crystalline materials would likely be different to that of fused silica, this current approximation was determined to be the best method of extracting the two loss terms for this study. However, this weld loss value is already significantly lower than HC bonding loss, and, as will be demonstrated, is approaching an acceptably low level for a real suspension.

VII. THERMAL NOISE MODELING

To fully assess the suitability of welded sapphire suspensions in future GWDs, such as ET, the single test mass displacement noise was modeled and compared to the current ET design curve [54].

To determine which parameters to use when modeling the thermal displacement noise, the loss contributions and fiber diameter were considered. As the fiber diameter is primarily limited by tensile strength and heat extraction, both of these cases were considered to determine the minimum allowed fiber diameter.

The minimum cross-sectional area of a fiber, A_{fiber} , required to extract a heat flow, H , along four fibers of length, L , was determined using the following equation [38],

$$A_{\text{fiber}} = \frac{HL}{4 \int_{T_1}^{T_2} \kappa(T) dT}, \quad (11)$$

where $\int_{T_1}^{T_2} \kappa(T) dT$ refers to the varying thermal conductivity between the temperature of the upper stage, T_1 , and test mass, T_2 . The required heat extraction for all four fibers was taken to be 0.1 W [54], a combination of environmental effects and heating due to absorption of the interferometer laser beam in the test mass. Other estimates [39] place the heat extraction requirement of the entire suspension system to be 0.5 W, including thermal links. So it is assumed 0.1 W is a suitable estimate for the heat extraction of the four suspension fibers alone. Currently, it is thought that the test mass should maintain an operating temperature in the range of 10–20 K [54]. The temperature gradient between the test mass and upper stage is yet to be definitively defined. For this case, a conservative value of 5 K with the test mass at 20 K and the upper stage at 15 K was used to ensure diameter used is an upper limit. Of the samples measured in Sec. V, the best thermal conductivities in this temperature range were found in the laser polished welded sample. These values were used in Eq. (11) to determine a heat extraction limited diameter of 1.52 mm. Note that as it is believed that the thermal conductivities measured may be limited by the crystal quality of the base material, this value could be an overestimate.

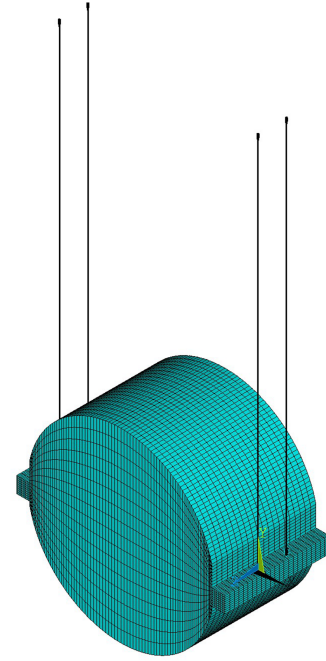


FIG. 18. FEA model of a 211 kg mass with four sapphire fibers welded to ear-like blocks.

This calculated diameter value for the heat extraction case is higher than the strength limited fiber diameter of 1.3 mm, obtained from using the highest stress observed in a weld from the tensile measurements, 1.1 GPa, using a safety factor of three. Therefore, this heat extraction limited diameter of 1.52 mm was used as the fiber diameter in the thermal displacement noise model.

To determine the energy in the weld region in a full four-fiber ET suspension scenario, a preliminary model of an ET-LF style suspension was also constructed in FEA, as shown in Figs. 18 and 19. This model contains a 211 kg silicon test mass with earlike blocks on each side,

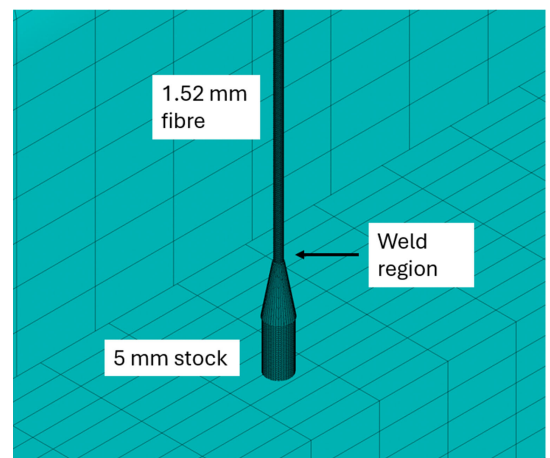


FIG. 19. Close up of one of the 1.52 mm diameter fibers with a 5 mm stock end.

with 1.2 m long sapphire fibers of 1.52 mm diameter welded to 5 mm stock pieces. In aLIGO, the fiber shape is optimized to control the bending energy so that the loss contributions are minimized [21]. Careful analysis of multiple suspension scenarios and fiber profiles are required to fully determine the optimum shaping of the fiber and ear elements to minimize noise, which is outside the scope of this work but an area of future research. Therefore, we have selected this fiber to stock ratio as an initial optimization. This allowed the energy in the weld region to be reduced to 0.115% of the total energy in the system in the pendulum mode, significantly reducing the weld loss contribution. Shaping of grown sapphire fibers is an area of ongoing research in Glasgow, so it is believed that some level of fiber profile optimization will be achievable in the future.

The thermoelastic noise in a suspension system can be calculated using the modified version of Eq. (6), as follows:

$$\phi(\omega) = \frac{YT}{\rho C} \frac{\omega\tau}{1 + \omega^2\tau^2} \left(\alpha - \frac{\beta\sigma_o}{Y} \right)^2, \quad (12)$$

where σ_o is the static stress on the fiber due to the suspended load, and $\beta = \frac{1}{Y} \frac{dY}{dT}$ is the thermoelastic coefficient [55].

The mechanical and thermal energy in the detector will excite modes in the fibers. Some of these modes couple into the detector displacement noise, and so, need to be considered when discussing the overall thermal displacement noise. A simple pendulum system will have a longitudinal, vertical, and multiple violin modes.

The use of a pendulum system allows for an effect known as dissipation dilution to further reduce the mechanical loss contributions [37,56]. The longitudinal mode dilution factor, D_l , can be written as

$$D_l = \frac{2mgL}{n\beta_n\sqrt{FYI}}, \quad (13)$$

where the β_n term refers to the amount of bending on the fibers; for fibers that bend only at one point, $\beta_n = 1$, whereas bending at the top and bottom of the fiber results in $\beta_n = 2$. As the second area moment of inertia, which can be expressed as $I = \frac{\pi r^4}{4}$, depends on the fiber diameter, it then follows that reducing the fiber diameter will increase the dissipation dilution, hence reducing the thermal noise in the suspension system.

In the case of the bounce mode, we can assume pure vertical motion with no longitudinal movement of the test mass, and so the dissipation dilution factor of this mode D_b can be expressed as

$$D_b = 1. \quad (14)$$

For the violin modes, the dilution factor is approximately half [38] the dilution factor of the longitudinal mode:

$$D_v \approx \frac{1}{2} D_l. \quad (15)$$

As previously discussed, the thermal displacement noise can be modeled via the fluctuation-dissipation theorem in Eq. (1). The thermal displacement noise for each mode, pendulum, vertical and violin, can be obtained using this equation, and then added in quadrature to determine the total noise. This method of modal analysis was used as it is a standard approach for low frequency suspension thermal noise estimates which are on and near resonance [21,38,54,57].

The displacement noise, $x_l(\omega)$, caused by the longitudinal mode can be calculated using Eq. (1) like so,

$$x_l(\omega) = \sqrt{\frac{4k_b T}{m\omega} \left(\frac{\omega_o^2 \phi_l(\omega)}{\omega_o^4 \phi_l(\omega)^2 + (\omega_o^2 - \omega^2)^2} \right)}, \quad (16)$$

where ϕ_l is the combined loss for this mode.

The displacement noise of the bounce mode takes the horizontal cross-coupling into consideration. In aLIGO, this is estimated to be $\sim 0.1\%$ [38]. Therefore the $x_b(\omega)$ can be expressed as

$$x_b(\omega) = 0.001 \sqrt{\frac{4k_b T}{m\omega} \left(\frac{\omega_b^2 \phi_b(\omega)}{\omega_b^4 \phi_b(\omega)^2 + (\omega_b^2 - \omega^2)^2} \right)}, \quad (17)$$

where $\phi_b(\omega)$ is the combined loss of the bounce mode.

The oscillation of the violin modes will result in a longitudinal motion of the test mass. This effect is described by the mass coupling factor, c_{mass} , which can be defined as [38]

$$c_{\text{mass}} = \sqrt{\frac{2m_f}{\pi^2 m v^2}}, \quad (18)$$

where $m_f = \rho\pi r^2 L$ is the fiber mass, and v is the violin mode number. The mass coupling is factored into the displacement noise due to the violin modes as such,

$$x_v(\omega) = \sqrt{c_{\text{mass}} \times \frac{4k_b T}{m\omega} \left(\frac{\omega_v^2 \phi_v(\omega)}{\omega_v^4 \phi_v(\omega)^2 + (\omega_v^2 - \omega^2)^2} \right)}. \quad (19)$$

Hence, the total single test mass displacement noise can be modeled using the following expression:

$$x_{\text{total}}(\omega) = \sqrt{(x_l(\omega))^2 + (x_b(\omega))^2 + (x_v(\omega))^2}. \quad (20)$$

TABLE I. Various parameters used in the sapphire suspension thermal noise model. Note that the measured values of tensile strength and thermal conductivity are obtained from the laser polished and welded samples, as it is believed that these are the highest quality of the three sample sets.

Parameter	Value
m (kg)	211 [54]
L_{fiber} (m)	1.2 [54]
r_{fiber} (mm)	1.52 (measured)
T (K)	20 [54]
ϕ_{weld}	0.115% of 5.1×10^{-6} (measured)
ϕ_{bulk}	3×10^{-9} [39]
$h\phi_s$ (m)	1.5×10^{-11} (measured)
σ_{max} (GPa)	1.1 (measured)
E (GPa)	400 [58]
$\kappa(T)$ ($\text{Wm}^{-1} \text{K}^{-1}$)	4587 (measured)
$C_p(T)$ ($\text{Jkg}^{-1} \text{K}^{-1}$)	0.72 [59]
$\alpha(T)$ (K^{-1})	4×10^{-9} [11]
β (K^{-1})	-4.4×10^{-6} [60]
ρ (kg m^{-3})	3980 [61]

This equation and the parameters in Table I were used to model the thermal noise induced by the sapphire suspension, as shown in Fig. 20. The temperature of the test mass was chosen to be 20 K, as an upper estimate of the range of possible operating temperatures proposed. The current ET design curve [54] of the low-frequency detector is highlighted in this plot. It was found that

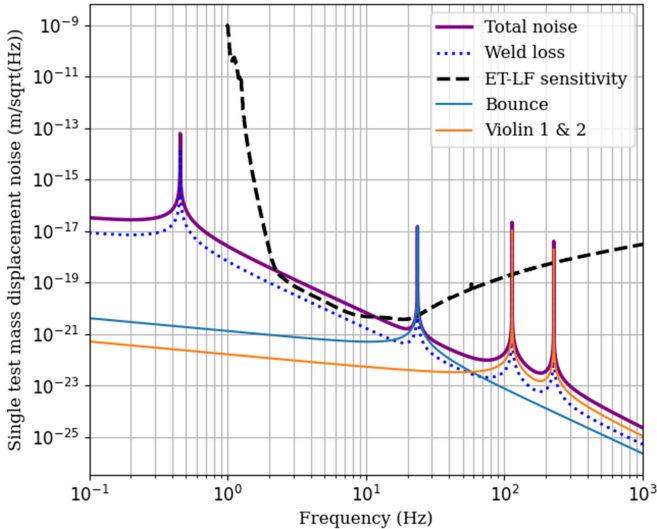


FIG. 20. Single test mass displacement noise modeled in an ET-like suspension with 1.52 mm sapphire fibers and a weld loss of 5.1×10^{-6} with a 0.115% energy contribution, and a surface loss of 7.84×10^{-8} . The current ET design curve [54] is shown in orange for comparison.

the total noise of the sapphire suspension with the conservative weld and surface loss numbers demonstrated in this paper is already approaching this design curve. This is an initial promising result. The conservative measurements of weld loss and thermal conductivity will likely be improved with measurements of different samples which are less limited by effects such as clamp loss and crystal quality, and the fiber profile will be further optimized which will significantly reduce the thermal noise contribution. This demonstrates that laser welding sapphire is a credible possible future cryogenic suspension construction method.

VIII. CONCLUSION

Through experimental characterization, it was found that welding sapphire fibers together had no measurable effect on their thermal conductivity or tensile strength, essential parameters for cryogenic suspensions. Crystallography analysis revealed a small joint area limited to $\leq 200 \mu\text{m}$, with the c-axis orientation (coincident with the fiber length) maintained from the original crystals. Mechanical loss measurements demonstrated loss levels typically expected of sapphire fibers, closely following the thermoelastic trend with reducing temperature until an expected plateau. FEA modeling allowed a weld loss estimate of 5.1×10^{-6} , and a $h\phi_s$ estimate of 1.5×10^{-11} m, which will be constrained further with future measurements. An FEA model of a hypothetical ET-style suspension scenario with welded joints informed a thermal displacement noise model, which included the measured loss of a welded sapphire fiber. This showed that the thermal noise level was promising, with conservative values for weld loss and thermal conductivity. In addition, laser polishing was shown to produce a far superior surface quality than the available machined sapphire samples, indicating that the surface loss of sapphire may not be a dominant hindrance to the thermal noise performance.

The next key step to assess the validity of sapphire laser welding in GWDs is the welding of fibers to larger volume earlike pieces to develop sapphire suspension assembly procedures. As sapphire has a high thermal conductivity and susceptibility to thermal shocks, this could prove challenging, and would benefit from analysis of tolerable temperature gradients and ideal ear geometries. Once welding to ear geometries has been developed, this would then lead on to demonstrating a full crystalline suspension prototype using welded sapphire fibers in the Glasgow 10 m cryogenic prototype interferometer [62].

This work demonstrates the promise of laser welding and polishing sapphire fibers for use in future gravitational wave detectors. The tensile strengths were found to

be significantly higher than the ET requirements, and only represents a minimum value for the weld tensile strength as no welded joints were able to be broken. With this higher tensile strength, sapphire fibers could be much smaller in diameter than originally anticipated, providing an increase in dissipation dilution, which would only be limited by the conductive cooling requirement. This work was proven to be repeatable over the course of multiple sample sets and over 75 welded samples of various diameters, demonstrating the potential of sapphire laser welding as a suspension construction technique for future gravitational wave detectors.

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DATA AVAILABILITY

The data that support the findings of this article are openly available [63].

APPENDIX: MECHANICAL LOSS PLOTS

The mechanical loss of the remaining measured modes can be viewed in Fig. 21.

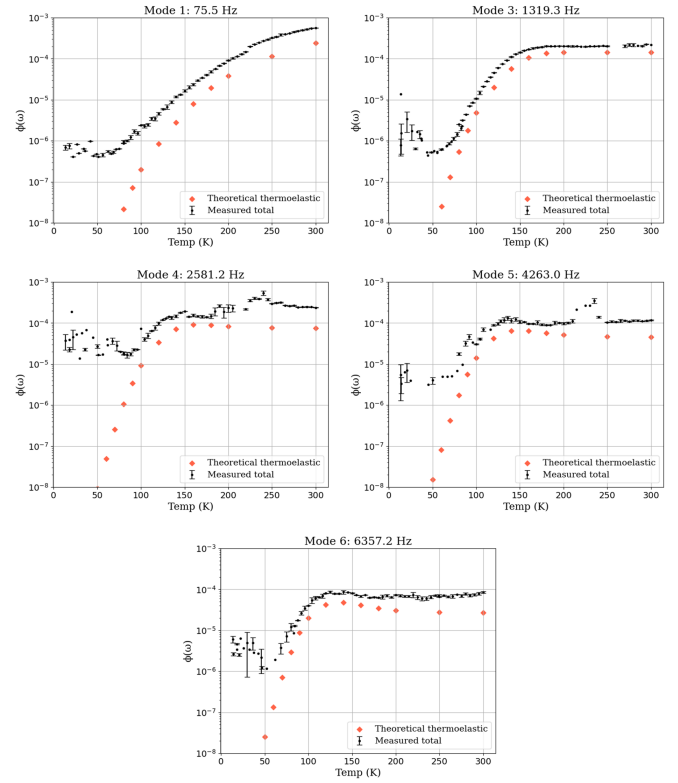


FIG. 21. Measured total mechanical loss (black points) of a welded 425 μm sapphire fiber with the theoretical thermoelastic loss curve (red diamonds) for five of the six resonant modes.

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