Thermal Conductivity of Grinded Monolithic Sapphire Fibers for KAGRA

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The second-generation gravitational wave interferometer, KAGRA, which is to begin taking data in 2018, will have cryogenic suspensions which will significantly reduce the effects of thermal noise. KAGRA will use sapphire fibers that have high thermal conductivity because the heat from the suspended mirrors will be extracted upward through the fibers. However, the fibers' thermal conductivity strongly depends on several manufacturing factors including polishing procedures, how the head is attached to the rod, and even the diameter of the crystal. Hence, the thermal conductivity of all candidate sapphire fibers must be measured in order to determine which is most suitable for suspensions in KAGRA. Our results indicate that grinded monolithic sapphire fibers have a thermal conductivity peak value of 9012 ± 305 $\frac{W}{mK}$ at about 36 K and meet the KAGRA requirement of $\kappa \geq 5000$ $\frac{W}{mK}$ at 20 K.

I. INTRODUCTION

The LIGO and Virgo interferometers, based in the US and Italy, respectively, have the impressive ability of detecting a gravitational wave strain amplitude as small as 10^{-21} [1]. Although the advanced stages of LIGO and Virgo are expected to be ten times more sensitive, the strain sensitivity will continue to be limited by thermal noise. To reduce this thermal noise, as well as the mirror deformation caused by the 180 W laser, the second-generation gravitational wave interferometer, KAGRA, will perform at cryogenic temperatures. KAGRA is currently being built in the Kamioka mine, located 220 km west of Tokyo, and is expected to be operational by 2018 [2]. KAGRA's underground location will also isolate the detector from many of the seismic sources of noise that impact LIGO and Virgo.

KAGRA's initial test masses (IMT) and end test masses (EMT) will operate at temperatures below 20 K [3]. Because of these cryogenic conditions, fused silica fibers, which are used for mirror suspensions in both LIGO and Virgo, will not be suitable for KAGRA because of their low thermal conductivity. KAGRA requires a fiber with high thermal conductivity since the heat from the mirrors will be extracted upward through the fibers. The heat cannot be extracted directly from the mirrors because operating a cryocooler near the mirrors would add significant amounts of mechanical noise to the system. In order to extract all of the heat that needs to be removed from the mirrors, the sapphire fibers must have a thermal conductivity that is greater than 5000 $\frac{W}{mK}$ at 20 K [4].

KAGRA will use sapphire fibers that are 300 millimeters in length and 1.6 millimeters in diameter [3]. The fibers will have two heads; one will be used to attach the fiber to the test masses and the second will be fixed to the upper stages of the suspension. Although the size specifications of the fibers have already been determined based on the amount of heat that the fibers will need to extract, there is still debate about which manufacturing technique will produce the most effective fiber. Currently, grinded monolithic sapphire fibers are a promising candidate for mirror suspensions in KAGRA. These fibers are grown from a single crystal and grinded into the shape seen in Fig. 1. This fiber has a diameter of 1.6 mm and the grinding process produces a rough surface with a peak-to-peak variation of 3.28 microns.

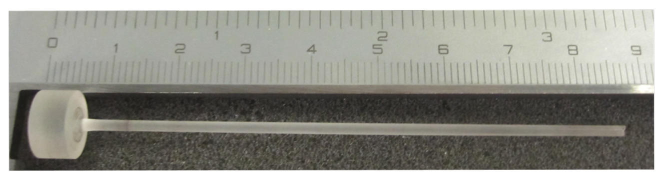

FIG. 1. Grinded monolithic sapphire fiber. One of the fiber's heads broke during a trial because the fiber was not firmly attached to the cryostat.

II. METHODS

The thermal conductivity of the grinded monolithic sapphire fiber was obtained by measuring the thermal gradient along the fiber after one end had been heated. The heater, which was a a 30W, 1kΩ resistor, could only be attached to the rod because one of the heads broke during one of the initial trials. The head that was still intact was used to secure the fiber to the cryostat. As a result, the thermal conductivity was only measured along the rod, and the head-to-rod conductivity could not be obtained.

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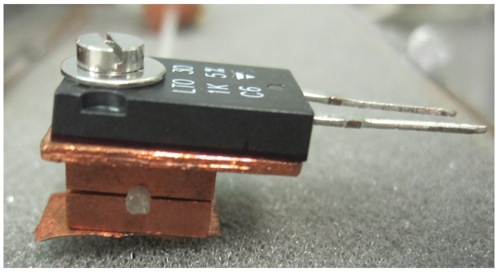

FIG. 2. The image above illustrates how the resistor was attached to the fiber. The resistor was also connected to an ISO Tech IPS2302A DC power supply, which was used to apply a voltage and current across the resistor, allowing it to heat up.

Fig. 2. shows how the resistor was attached to the fiber. Around the fiber were two copper blocks, which were held together by screws. On one side of the copper blocks was a very thin copper sheet, which was gently bent in order to hold the thermometers in place. On the other side of the blocks, was another copper sheet, which had been cut and filed into the same shape and size as the resistor. The resistor was placed on top of this copper sheet so that it was in good thermal contact with the copper blocks, and therefore also with the fiber. It should be noted that copper has a much higher thermal conductivity than sapphire, therefore, all of the copper pieces did not interfere with the measurement.

In addition to the resistor, there were two thermometers attached to both ends of the fiber that are shown in Fig. 3. These thermometers were 1 mm in diameter and very accurate at cryogenic temperatures. They were attached to the fiber using the same copper blocks, which can be seen in Fig. 4, and were kept in place by the gently bent copper sheets.

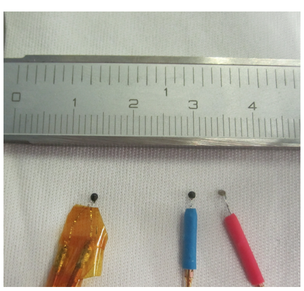

FIG. 3. figure
The thermometers used to measure the temperature at each end of the fiber.

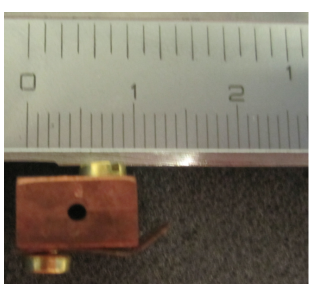

FIG. 4. figure
The copper blocks and bent sheet that attached the thermometers to the fiber.

The sapphire fiber was held in place by a large copper holder, the top of which is shown in Fig. 5. This copper holder was shaped in such a way that the fiber could be slid into position and firmly held in place by the three bolts. After one of the heads broke as a result of improperly mounting the fiber in the copper holder, special spring-like washers were used so that the bolts could be firmly tightened without damaging the fiber.

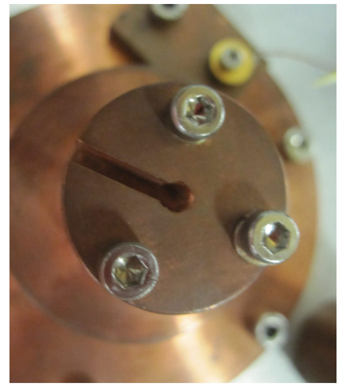

FIG. 5. Copper holder which acted as a heat sink. For the initial trial, during which one of the fiber heads was broken, the fiber was not pushed all the way into the circular opening. As the sample was cooled to cryogenic temperatures, the copper contracted and crushed off the head.

Once the fiber was properly positioned and the thermometers and resistor were attached as shown in Fig. 6, the vacuum chamber was closed, the vacuum pump was turned on, and the sample was allowed to begin cooling. The vacuum pump reduced the pressure to an order

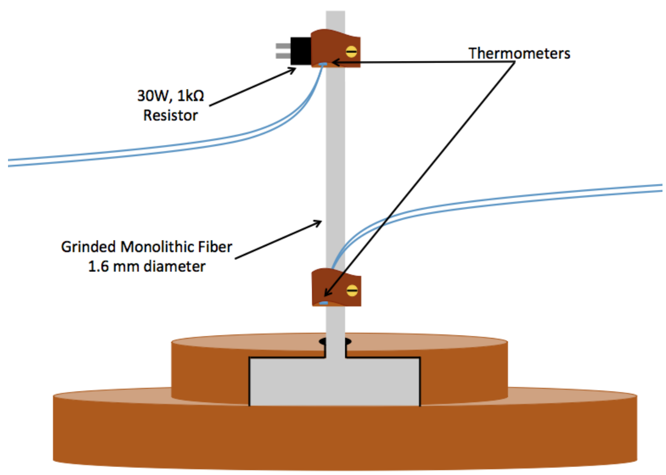

FIG. 6. Schematic of the setup used to measure thermal conductivity.

of 10^{-4} millibars, and the cryocooler cooled the sample to approximately 5 K. When the sample was sufficiently cooled, a small voltage and current were applied across the resistor using the DC power supply. This caused the resistor to heat up, which created a thermal gradient along the fiber. The temperature across the fiber was then allowed to equilibrate and settle over a timespan of 30 minutes, after which the two thermometer readings, the voltage, and the current were recorded. The temperatures were read by a LakeShore 218 Temperature monitor and automatically recorded in 60 second increments using a LabView program. The current was measured by a Hewlett-Packard 3468A Multimeter, and the voltage was obtained using an Agilent 3458A Digit Multimeter. The voltage and current readings were both recorded by hand. After the thermal gradient had equilibrated and the measurements were recorded, the voltage and current were increased and the same process was repeated.

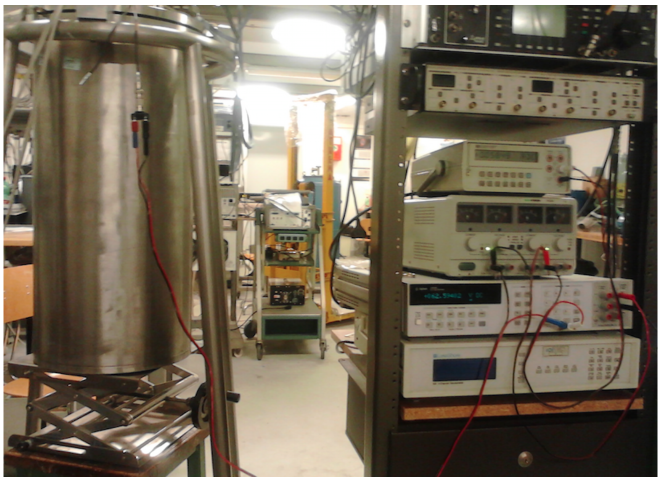

FIG. 7. Image showing how the DC power supply and the resistor were connected. The power supply was hooked up in series so a total of 64 V, instead of 32 V, could be applied to the resistor.

In order to find the thermal conductivity, the amount of power that was applied to the resistor was first obtained using Ohm's Law:

$$P = IV \tag{1}$$

where I is the current, and V is the voltage. The thermal conductivity, κ, can then be determined using Eq. 2.

$$\kappa = \frac{PL}{\Delta T A} \tag{2}$$

where L is the distance between the two thermometers, A is the surface area of the rod and ΔT is the temperature difference between the two thermometers. To account for the difference between the two thermometer readings at equilibrium, a couple measurements of the temperature were recorded when no voltage was applied. These measurements were then averaged, and the average temperature difference at $P = 0$ was subtracted from all ΔT measurements.

III. RESULTS

The two sets of data were recorded on different days. The green curve consists of 24 measurements and the blue curve consists of 35.

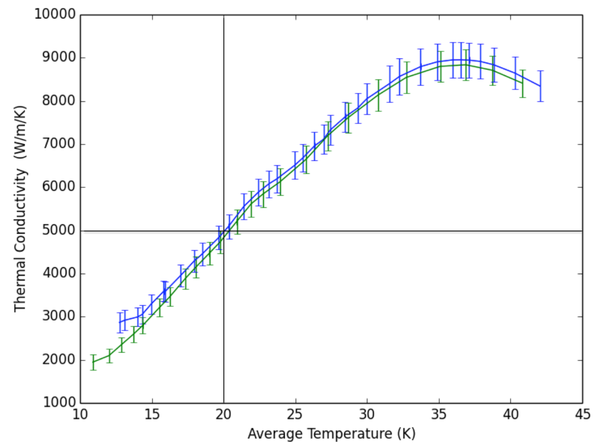

FIG. 8. Results from two individual runs.

From Fig. 8, it can be seen that both trials indicate that the grinded monolithic fiber meets the KAGRA thermal conductivity requirement, which is indicated by the black lines. The fiber has a thermal conductivity peak of approximately $9012 \pm 305 \ \frac{W}{mK}$.

IV. DISCUSSION

The results show an unexpected phenomenon at about 23 K. At this temperature, a small peak in the thermal conductivity can be seen in Fig. 8. This small peak occurs at the same temperature as a strange behavior that is present in two trials for which the sapphire fiber

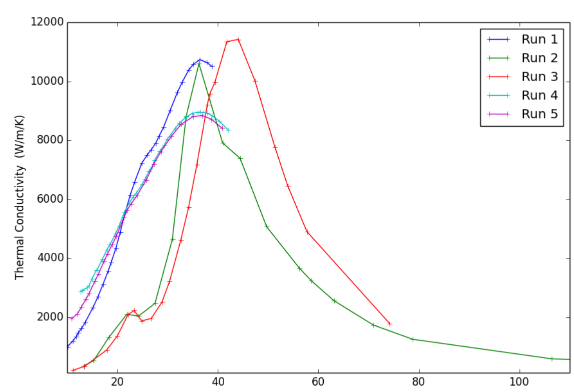

FIG. 9. For run 1, the resistor was not in good contact with the copper blocks, which caused most of the heat from the resistor to be dissipated. For runs 2 and 3, the fiber was not properly attached to the heat sink. Runs 4 and 5 are shown and explained in the Results section.

was not properly attached to the copper base. These trials are shown in Fig. 9 and are labeled run 2 and run 3. Because the copper base acted as heat sink for the fiber, the average temperature measurements for these runs was much higher than that of other trials. Without a heat sink, the heat could not be dissipated into the surrounding environment.

Although the second and third runs show different results, they both exhibit strange behavior around 23 K. It is possible that the small peak in runs 4 and 5 is also caused by an improper contact with the heat sink. Of course, the fiber was in much better contact with the heat sink during runs 4 and 5 than it was during runs 2 and 3, which is why this behavior is much more evident for the green and red curves in Fig. 9. This phenomenon needs to be further investigated to find the true cause of this strange behavior.

Although it is clear that runs 1, 2, and 3 were not taken under good conditions, the average temperature vs. temperature difference plots further confirm that the data for these trials is skewed. It can be seen that the

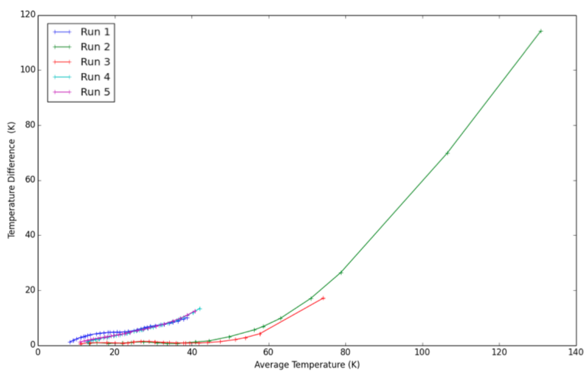

FIG. 10. Temperature difference as a function of the average temperature for all of the runs.

temperature difference and average temperature do not have a linear relation for any of the first, second, and third runs, which means that most of the measurements above 60 K are inaccurate.

In comparison, the temperature difference and average temperature have a much more linear relation for the fourth and fifth runs. Fig. 11 shows that the average temperature and temperature difference have a fairly linear relation. However, as the average temperature approaches 40 K, the relation appears to become nonlinear. This means that measurements above 40 K are not as accurate as those below 40 K. The nonlinear relation could be a side effect of thermal radiation. This would suggest that further work needs to be completed to obtain more accurate results at temperatures above 40 K.

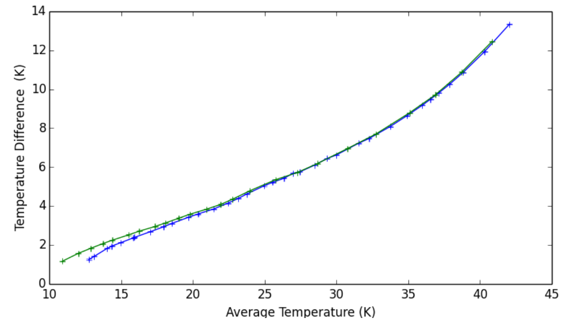

FIG. 11. Temperature difference as a function of the average temperature.

A. Run 1: Resistor attachment

During the first run, the resistor was not in good thermal contact with the fiber. From Fig. 9, it can be seen that for this run, the thermal conductivity peak was much higher than it was for runs 4 and 5, which are the good runs. This is because the power was increasing, but the fiber was not being heated. There was not a large change in the temperature readings of the two thermometers because the thermometer at the top was not being heated as much as the power reading would have suggested. As a result, when calculating the thermal conductivity, there was a large power and a small temperature difference. This caused the thermal conductivity calculation to be higher than it should have been.

Fig. 10 also shows that for this run, the relation between the temperature difference and the average temperature is nonlinear. This strange behavior is most probably a result of thermal radiation because a lot of the heat from the resistor was dissipated. Therefore, the thermal radiation for this trial must have been significant.

B. Run 2 and Run 3: Fiber attachment

Run 2 and run 3 were performed under the same conditions except for the thermometer calibration. The calibration curve for the thermometer at the bottom of the fiber was altered to see how a different calibration curve would impact the results. Run 3 is the only trial that uses a different calibration curve. For the second and third runs, the sapphire fiber was not firmly attached to the copper base, which was a heat sink. As a result, instead of being extracted through the copper holder, the heat remained in the fiber and could not be dissipated. Fig. 9 shows that runs 2 and 3 reached a significantly higher average temperature. This is because the heat did not leave the fiber through the heat sink, but instead kept heating the fiber. As a result, the average temperature was much higher than expected.

The behavior shown in Fig. 10 is also extremely interesting. Up to about 40 K, the temperature difference between the two thermometer readings is very low for both trials. Above 40 K, the relation seems to become almost exponential. It is possible that this behavior is due to thermal radiation. Perhaps, there is some strange property that causes this drastic change in the temperature difference. Although the fiber was not properly attached for these trials, this behavior should be further investigated to understand how the thermal conductivity behaves when the fiber is not attached to a heat sink.

V. CONCLUSION

In summary, the results from this experiment show that grinded monolithic sapphire fibers meet the KAGRA requirements. Based on the results, grinded monolithic fibers have a thermal conductivity of about 4941 $\pm$ 272 $\frac{W}{mK}$ at 20 K, which is within error of the required conductivity. This is a strong indication that these fibers are good candidates for mirror suspensions at cryogenic temperatures. However, other properties, such as the fibers' quality factor and breaking strength must also be considered before they can be used in KAGRA.

To further investigate the thermal conductivity of grinded monolithic sapphire fibers, the resistor should be heated to higher temperatures so that the behavior of the thermal conductivity at higher temperatures can be examined. At higher temperatures, all sapphire fibers, regardless of their surface treatments and fabrication techniques, should have thermal conductivities that are very similar to the thermal conductivity of bulk sapphire. This would be a good indication if the methods described above yielded accurate results.

Furthermore, the thermal radiation could be reduced by placing a shield over the fiber and copper holder. This would reduce the effects of thermal radiation and perhaps eliminate the strange behavior that is exhibited in the first, second, and third runs.

VI. ACKNOWLEDGEMENTS

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