Ultra High Temperature Strain Gauge

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Fig. 1. Jet Engine Test Rig [1]

***Abstract*— Ultra High temperature strain sensors give engineers the capability to directly measure strain in locations which were previously inaccessible. We demonstrate the technical feasibility of using copper and platinum electromagnetic targets for remotely sensing strain in ultra high temperature environments. Despite limitations on both the available design resources and equipment, we show measurable responses to strain which remain consistent as temperature increases. Finally, we propose future steps for mitigating existing challenges in target design and material characteristics and improving the test setup.**

I. INTRODUCTION

A. Motivation

The integrity and performance of materials at high temperatures are crucial in fields like aerospace, automotive, and energy. This highlights the need for accurate and reliable methods to monitor the structural health of materials under extreme conditions. Traditional methods, like electrical strain gauges, often don't work well in these tough environments because high temperatures can damage the materials and electronics in these devices.

In response to these issues, this study looks at using electromagnetic (EM) waves, specifically RF waves, to measure strain without touching the material at high temperatures. Using EM waves is beneficial because they can work through harsh conditions without directly contacting the material being tested, which avoids problems related to physically attaching sensors and the degradation of materials. Additionally, methods based on EM waves could be more durable, repeatable, and possibly more accurate, especially in situations where temperatures change quickly and are extremely high.

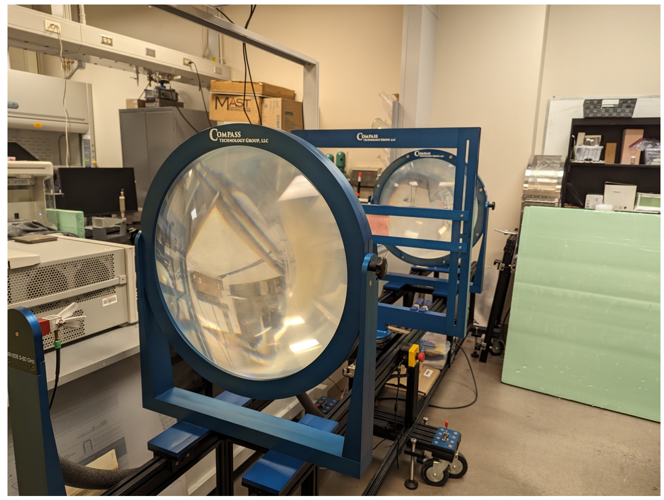


Fig. 2. CTG High Frequency EM Analyzer

This research aims to create a way to measure strain from a distance at high temperatures, which is a big improvement over traditional methods that need direct contact and often fail under such harsh conditions. Traditional strain gauges not only break down in these environments but also can give incorrect readings due to the materials they are attached to expanding from the heat. By improving techniques that use EM waves, we hope to tackle these issues and provide a more reliable and precise way to measure high-temperature strain.

B. Background

RF strain sensors operate by monitoring changes in the resonant frequency of a structure. When the structure is subjected to strain, its resonant frequency shifts due to changes in its stiffness. This frequency shift is directly proportional to the strain applied, enabling the determination of strain by analyzing these frequency variations. This research is committed to advancing high-temperature strain gauge technology, focusing specifically on enhancing and optimizing the use of electromagnetic waves for this purpose.

For our experiments, we utilized Continuous Transverse Gradient (CTG) 2 equipment located in Dr. Xu's lab, which allowed for precise application and measurement of strain under controlled conditions. The results from these experiments were analyzed using a Precision Network Analyzer (PNA), which is crucial for evaluating the electromagnetic response of the tested materials.

An integral part of our analysis was measuring the S parameter, which is critical in both our simulations and physical testing. The S parameter, or scattering parameter, represents the ratio of reflected and transmitted power at various frequencies, providing insight into how much of the EM wave is absorbed versus reflected by the material. This parameter is key in understanding the electromagnetic properties of the materials under strain and is used to assess their performance and suitability for high-temperature applications.

This research is dedicated to enhancing high-temperature strain gauge technology, with a focus on refining and optimizing methods that employ electromagnetic waves.

II. Budget

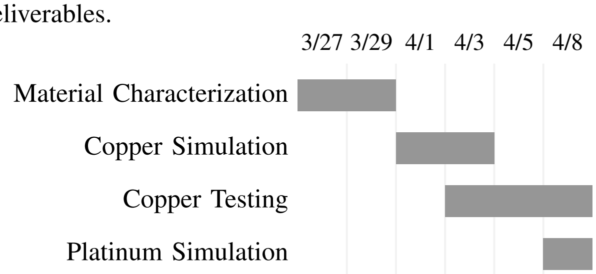
The table below details the essential materials required for this project. For low-temperature testing, we employed copper foil tape, while platinum foil tape was utilized for high-temperature testing; the latter was generously provided by Dr. Xue's laboratory. Additionally, flue tape was used to affix samples to the apparatus during measurements, owing to its suitability for high-temperature conditions. This selection of materials ensured accurate adherence to the testing protocols across varying thermal environments.

TABLE I
Breakdown of the Project Budget

Item	Quantity	Cost (USD)	Vendor
Copper Foil Tape	1	$5.98	Amazon
Flue Tape	1	$6.88	Amazon

III. Timeline

In the report section detailing our project's progression, the Gantt chart below provides a visual timeline and sequence of key tasks, clearly outlining the project's schedule and critical milestones for efficient tracking of our objectives and deliverables.



IV. Methodology

A. Ceramic Mat

Ceramic mats were selected for this experiment from those provided by 3M to Dr. Xu's lab. The ceramic mat was required to be able to withstand temperatures in excess of 1,200 degrees Celsius. Additionally, the more samples available, the better. This was to ensure that in the event that a mat became damaged or was otherwise unusable, there would be a replacement available. The ceramic mat selected was Nextel 440 [2] which is capable of withstanding temperatures up to 1,800 degrees Celsius before melting. The

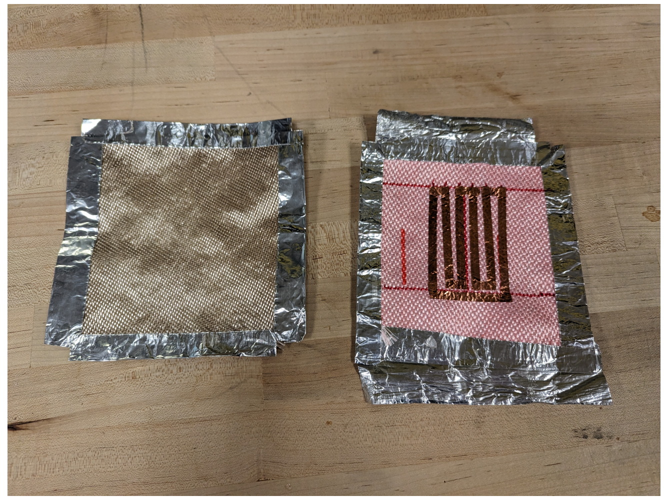


Fig. 3. Color Change of Ceramic Mat After Baking

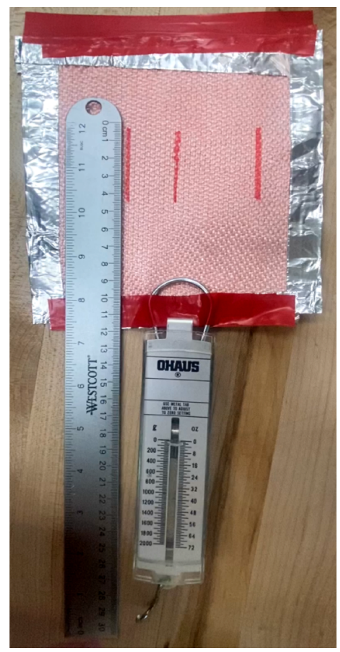


Fig. 4. Characterizing the Stress/Strain Curve of Nextel 440

selected mats were then reinforced around the edges with aluminum flu tape [3] to reduce fraying. In preparation for high temperature testing, one mat was baked at 260 degrees Celsius to remove its binder coating. This was done to prevent the binder from burning off during high temperature testing, which could result in the target loosing its adherence to the ceramic mat. This process changed the color of the mat from red to a light brown as shown in 3. Before measuring the frequency response and S curves of the targets, it was necessary to determine the stress strain curve and the relative permittivity of the ceramic mat. The former was accomplished by applying a load using a fish scale to one end of a ceramic mat, and recording the displacement of multiple points along the mat as shown in 4. This test was conducted in the orientation the mat was to be stressed for physical

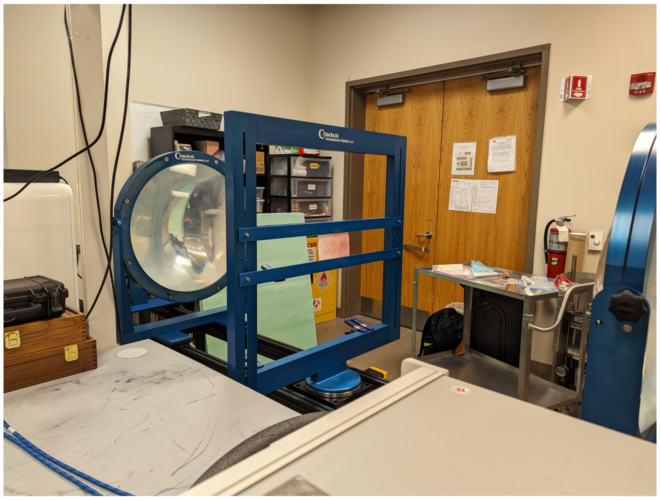


Fig. 5. Duel Antenna Array

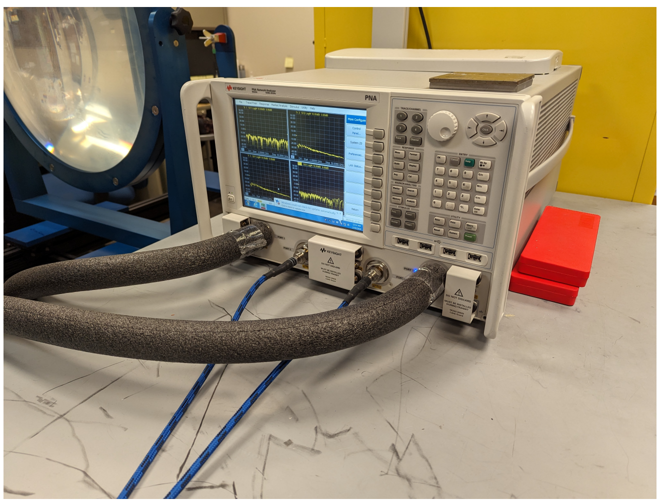


Fig. 6. Vector Network Analyzer

testing. The latter was done using a duel antenna array as seen in Figure 5 connected to the vector network analyzer (VNA) shown in Figure 6 to measure the S parameters of the ceramic mat.

B. Target Fabrication

One target was fabricated. The first was constructed using copper tape in a roughly two inch by three inch rectangular pattern shown in Figure 7. The copper traces were setup to be directional, similar to a standard strain gauge [4] so that deformation of the target vertically would affect the natural frequency and electromagnet absorption characteristics of the target more than deformation in the horizontal direction. A second target was planed using platinum paste. A 3D printed stencil was created in of the same pattern as the copper target. The stencil would have been placed on a ceramic mat and the platinum paste was brushed onto the mat.

C. Simulation

Simulation work was conducted in ANSYS High Frequency Simulation Software (HFSS) [5]. The solution sweep

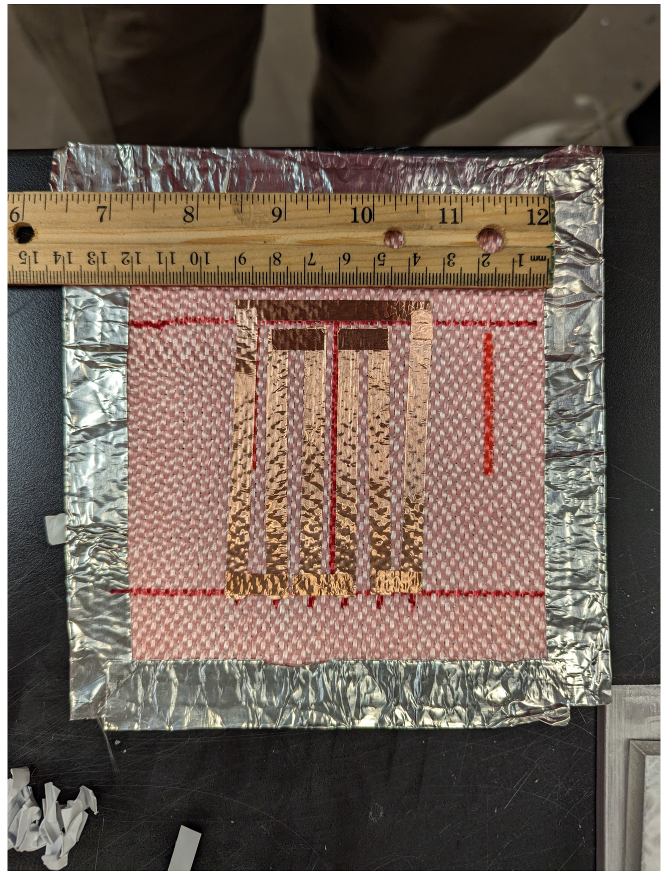


Fig. 7. Copper Target

was set to go from 500 MHz to 40 GHz in 500 MHz increments. The simulation was run with the default 1 V/m electric field applied uniformly to the top surface. Both platinum and copper targets were tested in simulation. The simulation included the ceramic mat, the target, and the aluminum flu tape. The default HFSS material library was used for the mat, copper, platinum, and aluminum flu tape. The ceramic mat was setup using a custom material based on its measured relative permittivity.

D. Physical Testing

Physical testing was conducted using the same VNA and duel antenna array used to measure the S parameters of the ceramic mat. First, the device was calibrated. First, a blank test was conducted. This fired the antennas at the test fixture without a sample present. This result would later be subtracted from the actual measured values to remove the effects of the test fixture. Second, a metal plate shown in Figure 8 the same size as our ceramic mat was tested. This set the threshold for a perfectly reflective target. After calibration, the target was placed in the test fixture. This measurement was used as the baseline for the target before stress was applied. Next, the parallel beams in the fixture were pulled apart to apply strain to the target, as seen in Figure 9 and another reading was taken. Finally, the target was heated using a heat gun, and another measurement was

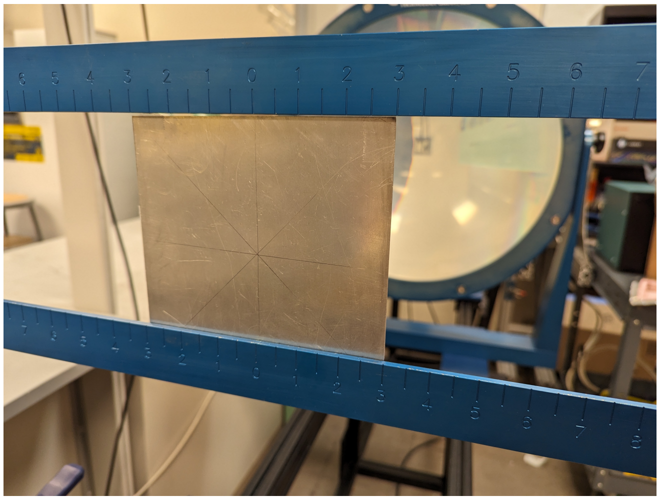


Fig. 8. Metal Plate

Fig. 9. Strain Applied to Target

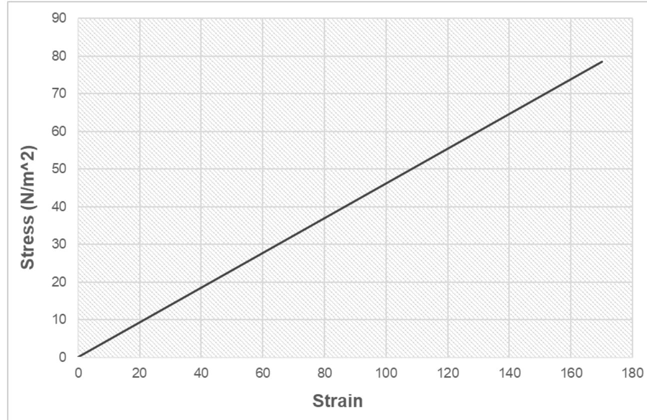


Fig. 10. Stress Strain Curve of Nextel 440

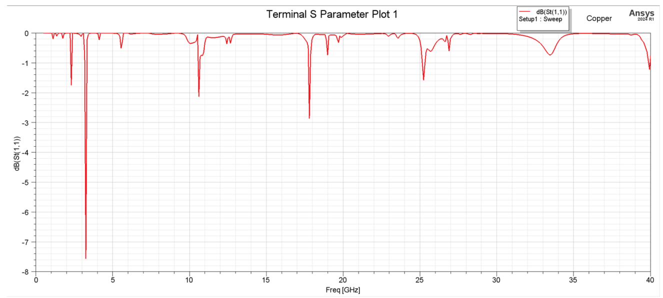


Fig. 11. Copper Simulation Results

taken. However, since the test fixture had been moved when strain was applied, an additional blank test was conducted. This new blank was then subtracted from both the heated readings, and the readings taken after strain was applied.

V. Results

A. Strain Testing

The stress strain curve measured of Nextel 440 is shown above in Figure 10. The material did not experience fatigue or failure during testing, so the curve remained linear. It should be noted that the material displayed an-isotropic behavior due to the weave of the ceramic fibers. When pulled in the direction of the weave, the weave was inflexible, and strain was directly transferred to the ceramic fibers. However, when stress is applied at a 45 degree angle to the weave, the fibers were able to slide past each other, and the material underwent deformation as the weave pulled taught before the fibers began to experience stress.

B. Simulation

Simulations were completed in Ansys High Frequency Simulation Software (HFSS). The first round of copper simulations was conducted with a full model of the ceramic target including both the copper traces, and flu tape. It indicated absorption at approximately 3, 10.5, 18, and 25 GHz as shown in Figure 11 above. This indicated that the miniature emitter which caps out at 14 GHz would be in-sufficient for physical testing. The second copper simulation

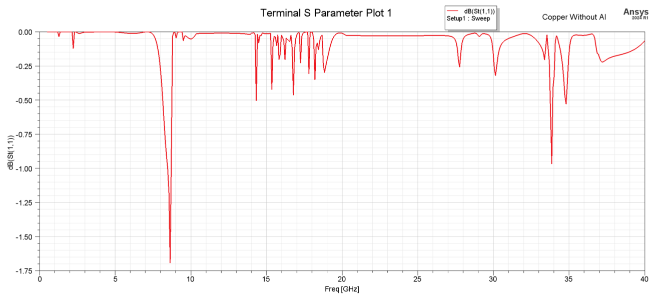


Fig. 12. Copper Without Flu Tape Simulation Results

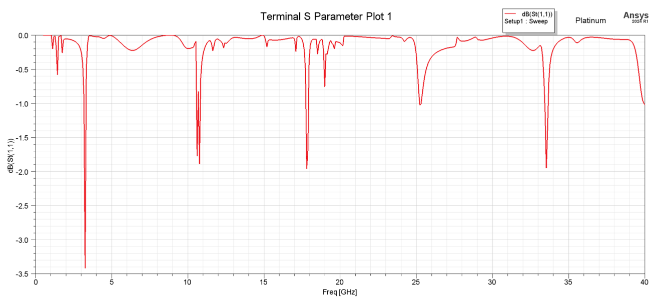


Fig. 13. Platinum Simulation Results

was conducted without the aluminum flu tape. It indicated absorption at 8.5 and 34 GHz along with bands of absorption between 14 and 19 GHz and 32 and 15 GHz. The full S parameter results are shown above in Figure 12. The platinum simulation was conducted with the full model of the ceramic target including both the platinum traces, and flu tape. It indicated absorption at 3, 10.5, 18, 25, and 33.5 GHz as shown in Figure 13 above. The frequency response is very similar to the first copper simulation, however the platinum simulation did not absorb the emissions as well, capping out at approximately -3.4 dB compared to the almost -8 dB of the copper simulation.

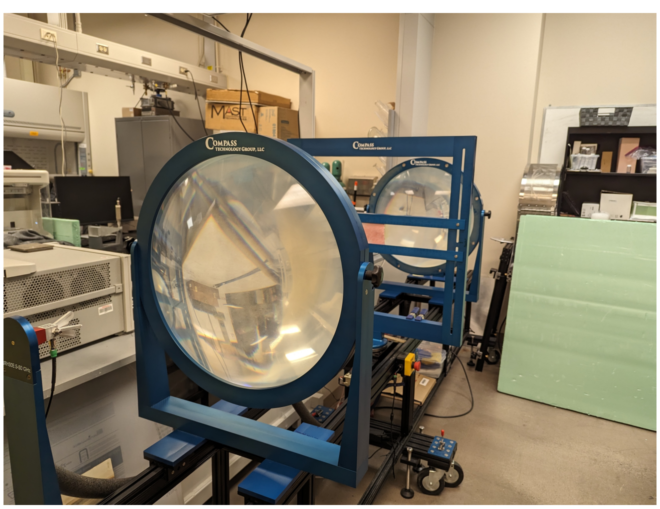


Fig. 14. CTG High Frequency EM Analyzer

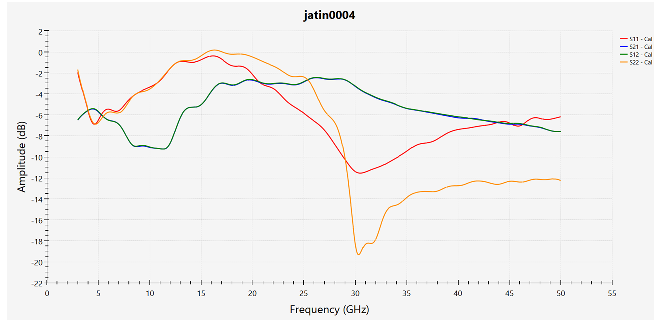


Fig. 15. Copper Physical Test

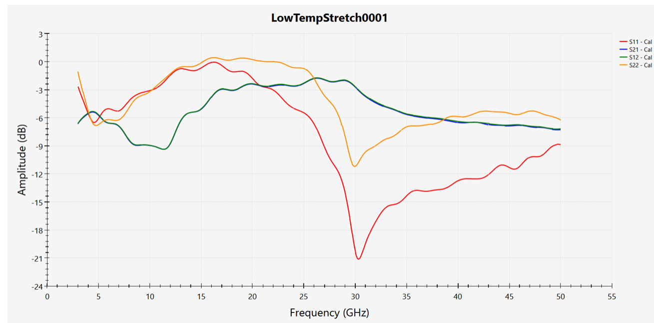


Fig. 16. Copper Strain Test

C. Testing

Physical testing was restricted to the copper target due to test fixture scheduling limitations. The tests were completed in the large high frequency electromagnetic spectrum analyzer shown above in Figue 14. This setup recorded data from two emitters, each on either side of the target. Both emitters also acted as antennas. Results are reported for four sets of data: S11, S21, S22, S12. The first number in the set indicates the emitter, and the second number indicates the receiver. For example, S11 is the reflection detected by emitter one after it transmitted. S12 is the signal which passed through the target from emitter one to emitter two. The first test conducted was with the copper target without strain or external heat. The results are shown above in Figure 15. The most significant response is shown in S22 at 30.25 GHz. There is also a dip in S11 at the same 30.25 GHz. Both dips are significantly lower than the simulated results, dropping a whole -19 dB in S22. When strain was applied, there was a notable shift in both the S11 and S22 curves shown above in 16. The maximum absorption in the S11 curve shifted slightly higher in frequency to 30.5 GHz, and dipped significantly lower to -21 dB. The S22 curve shifted to a lower frequency of 29.78 GHz but the maximum absorption was not as deep, only reaching -11.5 dB. The sample was then heated using a heat gun to approximately 200 degrees Celsius as measured by the thermal camera image shown in Figure 18. The results shown in Figure 17 indicates no change between the strain test and the strain test at temperature, resulting in the same absorption at 30.5 GHz and 29.78 GHz.

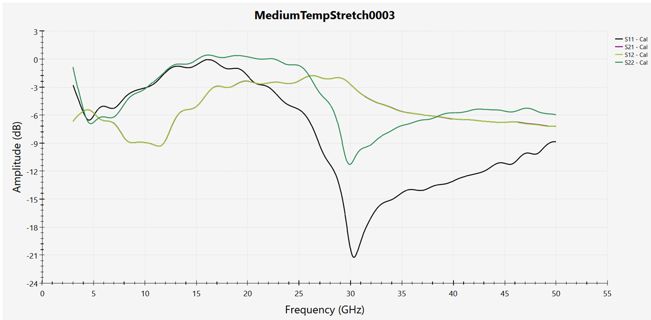


Fig. 17. Copper Strain Test at Temperature

Fig. 18. Thermal Image of the Copper Being Heated

VI. Discussion

The results indicate two significant findings. First, the principle of measuring strain remotely through the use of ceramic fiber mats with target patterns placed on them is viable. The change in strain present in the material corresponded to a measurable shift in the frequencies absorbed by the target. This was observed in both the reflected and pass through signals of antenna one. This is important because in practice, it is likely that only antenna one would be present. This would mean that only S11 from the data collected in the physical experiments would actually be read. Second, the test conducted at 200 degrees Celsius did not show a significant change in the S curve response. This indicates

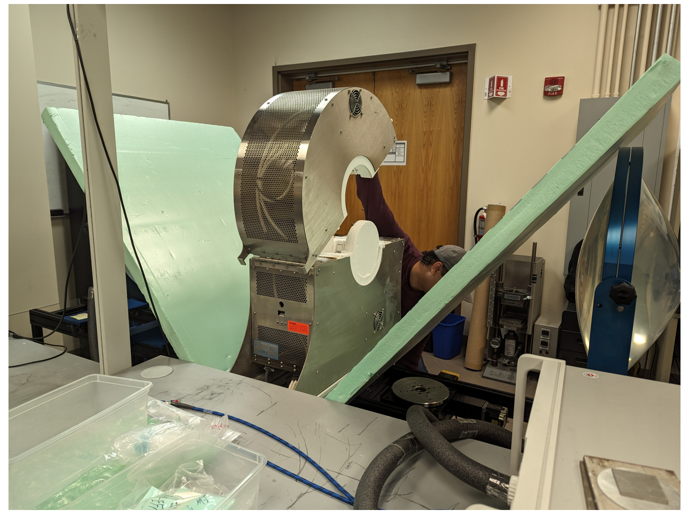


Fig. 19. The Antenna Array Becomes Unavailable

that the target did not undergo changes unrelated to the strain being experienced by its ceramic substrate that would have altered the results or invalidated calibration of the device at high temperatures.

VII. Challenges

A. Test Setup

The test setup selected had two primary drawbacks. The first was the visibility of the metal bars to the antennas. While the antennas are capable of taking a blank reading as mentioned in the Methodology section, repositioning the metal bars invalidated this calibration and required a new calibration to be taken each time this occurred. Additionally, the metal bars partially blocked the antennas from the aluminum tape around the edges of the ceramic mats. This likely contributed to some of the discrepancy between the simulations and actual results. The second was the test setup's schedule. The test setup became suddenly unavailable during the planned platinum tests. This resulted in the platinum tests being cancelled. Ideally a reduction in the frequency of the absorption dips to below 14 GHz would allow for the use of the smaller antenna array which was still available.

B. Ceramic Mats

The ceramic mats provided by 3M presented four distinct challenges. The first and most immediately evident was their propensity for fraying. Until a layer of tape was applied to the edges, a trail of red and white snow would follow the mats wherever they went. The layer of tape solved the fraying problem, but introduced the second one: the tape is conductive. This is due to the requirement that the tape and its adhesive be able to withstand the high temperatures expected of the ceramic mat. The conductive tape altered the absorbance of the mats, and definitely affected the results of the tests. The third challenge was the an-isotropic stress/strain curve of the mats. As previously mentioned, the weave of the mats is far more flexible at a 45 degree angle to the weave than it is parallel to the weave. This caused forces

Fig. 20. Stencil for platinum paste

which were not perfectly parallel to the weave to deform the mats more than anticipated. The fourth challenge was the mat thickness. While this was not directly observed during testing, it was determined that between four and six mats would likely be required to block a metal substrate they were being used to measure. Without completely blocking the substrate, any measurements taken would detect the metal substrate rather than the strain target placed on the mats. This could limit their use in applications with space constraints or fluid flows.

VIII. Future Work

The research conducted so far has laid a solid foundation for high-temperature strain measurement using RF wave-based strain gauges. However, to further the capabilities of this technology, here's some future work that has been identified.

Construction of dedicated strain test setup to minimize external variability and provide a controlled environment for accurate strain application and measurement should be one of the goals. The design will aim to reduce signal interference from external components and maximize the accuracy of the strain readings. Additionally, this setup will facilitate repeated calibration and testing procedures, thereby improving the repeatability of our experiments.

Another critical area of future work will be the testing on platinum at ultra high temperatures. The previously unseen scheduling limitations that led to the cancellation of platinum testing represent a significant opportunity for further research. A stencil was also designed 20 and 3D printed for creating a pattern similar to the copper pattern which will facilitate a direct comparison of material.

References

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