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Experimental Studies of an All-Silicon Carbide Hybrid Wireless-Wired Optics Temperature Sensor for Extreme Environments in Turbines

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ABSTRACT

Shown for the first time is the fabricated all-Single crystal Silicon Carbide (SiC) temperature probe and interface assembly designed for extreme environment temperature sensing in a gas turbine test rig. Preliminary probe test results are described regarding SiC chip temporal response, optical beam stability, and near vacuum sealing.

Keywords: Optical sensors, temperature sensor, soot, extreme environments

1. INTRODUCTION

The sensor community is being challenged to provide robust sensor solutions for the extreme conditions of next generation power plants. Recently proposed is a hybrid optics approach that exploits both the fiber-based remoting capability and the minimally invasive nature of laser targeted light beams incident on a single crystal Silicon Carbide (SiC) chip [1]. Progress has been reported on this theme to enable harsh environment temperature and pressure sensing [2-11]. The focus of this paper is to report on recent experimental data of the proposed hybrid theme for temperature sensing in the 1000 ºC range in the context of a novel industrial probe design for insertion into a turbine engine.

2. SILICON CARBIDE CHIP THERMAL TEMPORAL RESPONSE STUDIES

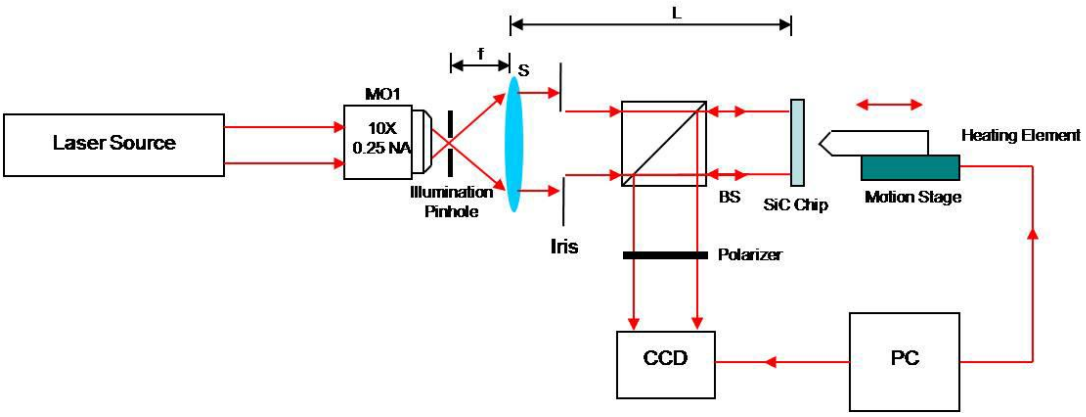


Fig. 1. Optical system design used for measuring the temporal response of the SiC chip as its temperature is changed using a conducting thermal step function induced by a pointed heating element moved by a computer controlled actuator. MO: Micro-objective, S: Spherical lens, BS: Beam Splitter.

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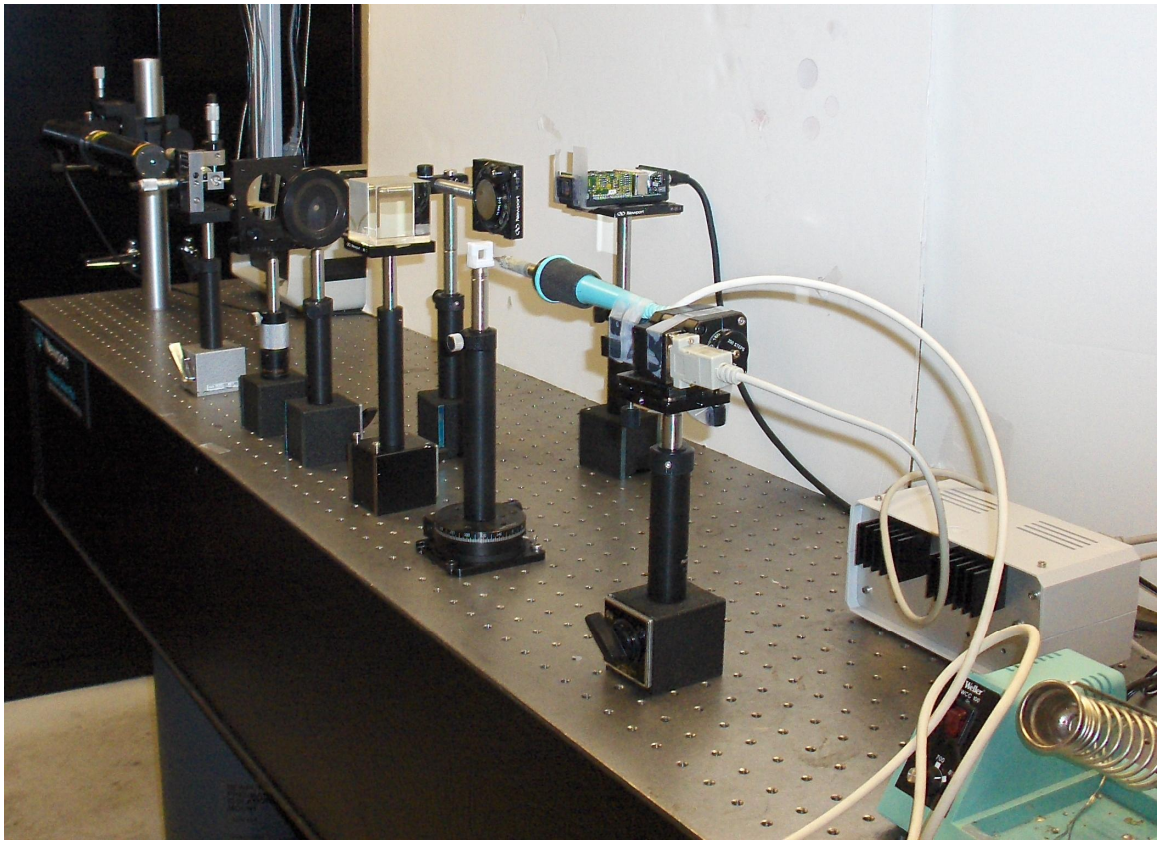


Fig. 2. Experimental arrangement used in the lab to measure the temporal response of the SiC chip to an applied thermal step function.

The heating element is mounted on a motorized digital-step translational stage. Computer based control allows the heating element to move in a digital step so as to make a one step physical contact with the SiC chip when computer actuated. One continuously monitors the interferogram on the CCD. The captured frames at 1/30 s intervals are shown in Fig. 3 (a) – (f) just after the heating element at 90 ^{o}C is brought in contact with the chip. The figures show that the fringes in the interferogram start moving in less than 1/30 th of a second while it takes almost 16 s for the SiC chip to reach the temperature of the heating element when the fringes are observed to stop moving (see Figs. 3 (g)-(l)). Next, the heating element is withdrawn from the chip using the PC actuator control and the fringes are again observed to move, but this time in the opposite direction. Again, the fringes start to move in less than 1/30 th of a second once the heating element is withdrawn and it takes almost 17 s for the chip to cool down to room temperature and for the fringes to stop moving. Note that in this case, heating of the SiC chip is a conductive process while the cooling is a radiative and convection-based process. The temperature of the SiC chip as a function of time is shown in Fig. 4 and shows similar heating and cool-down curves.

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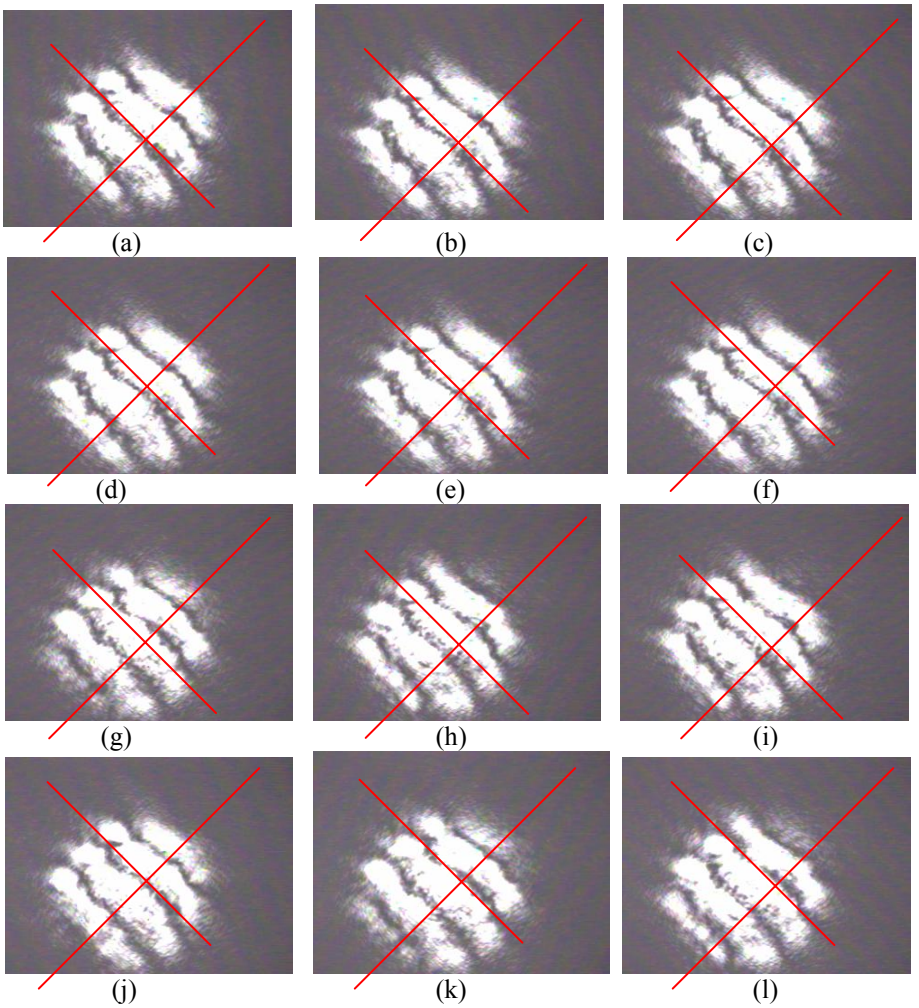


Fig. 3. Observed chip interferograms at time intervals of (a) 0, (b) 1/30, (c) 2/30, (d) 3/30, (e) 4/30, (f) 5/30, (g) 2, (h) 4, (i) 4.5, (j) 8, (k) 12, and (l) 16 seconds after heating element is brought in contact with the SiC chip

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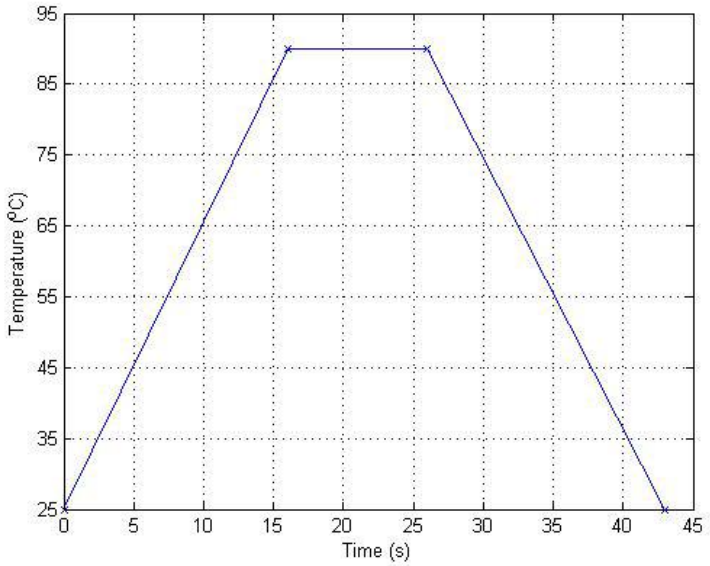


Fig.4 The plot of SiC chip temperature vs time elapsed after placing the chip in contact with the heating element acting as a thermal step function which is at a stepped temperature of 90 ^{o}C.

Fig.5 shows the movement of the fringes from the time the heating element touches the chip till the time the heating element is removed and the steady state under room conditions is reached. When the heating element is placed in contact with the chip, the fringes start to move and the fringe pattern moves by ~ 1.5 fringes till a steady transient state is reached. No fringe movement is seen once this steady state has been reached. Then the heating element is removed from contact with the chip. The chip starts to cool under the influence of the room temperature and the fringe movement is the opposite direction is observed again by ~1.5 fringes such that the original fringe pattern is seen when the steady state after cooling is observed. In Fig.6, the front view and the side view of the chip holder is shown. The dimensions of the chip holder as well as the exposed area of the SiC chip are shown. Only 0.8cm X 0.8cm area out of a 1cm X 1cm area of the silicon carbide chip remains exposed to the air when it is slid into the holder.

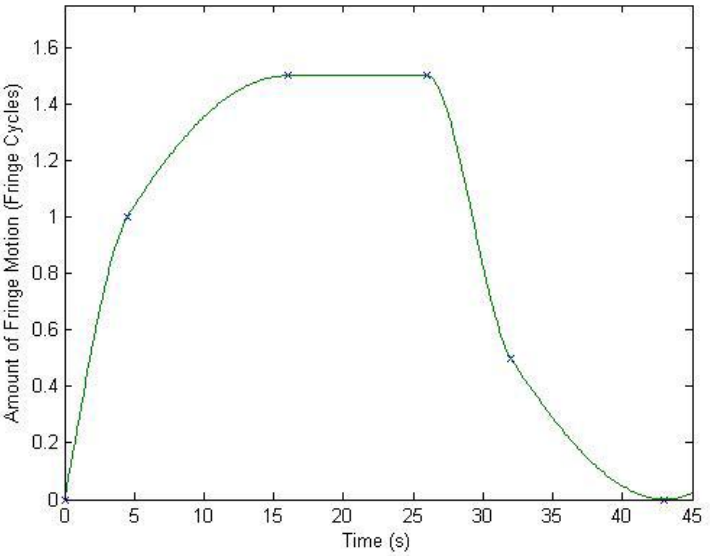


Fig.5 Plot depicting the fringe movement with time elapsed after the SiC chip was placed in contact with the heating element acting as a thermal step function.

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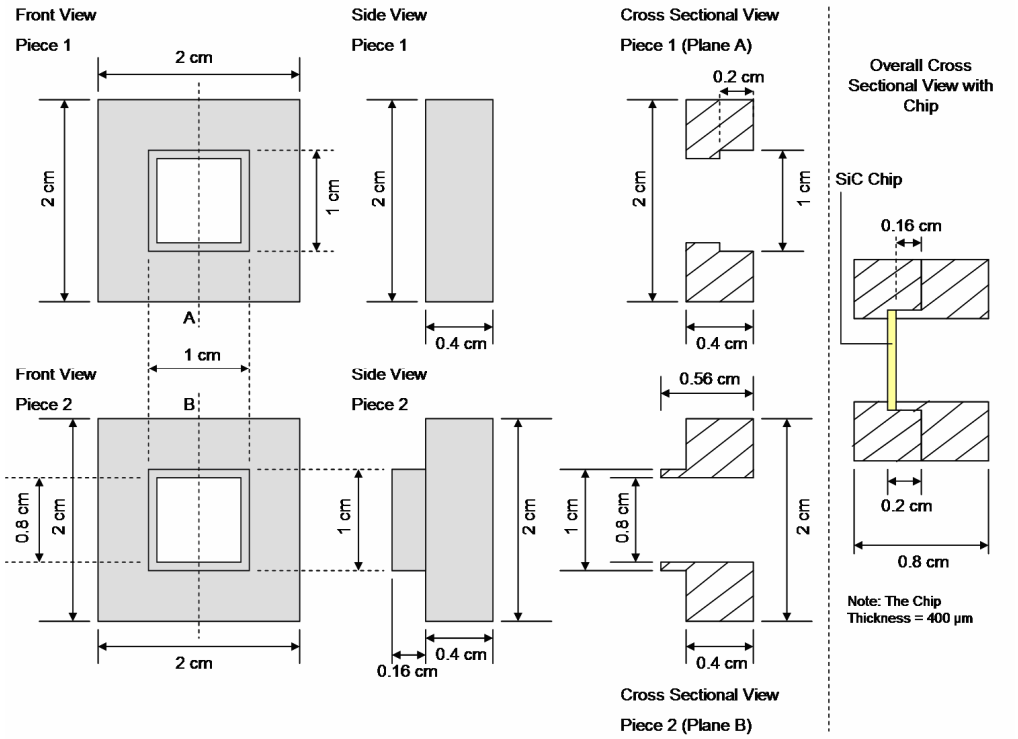


Fig.6 The front, side and rear views of the SiC thermally insulating chip holder with the chip residing inside it.

Newly conducted experiments and calculations show that the instantaneous temporal response of a 400 micron thick 1 cm x 1 cm square single crystal SiC chip when subjected to a conductive temperature step function of 90 deg-C peak value is under 1/30 seconds. Given the 1 mm diameter conductive heat tip placed on the chip, ~ 16 seconds are required to reach the steady state 90 deg-C temperature of the heat tip from the 25 deg-C room temperature setting. Approximately the same time (~ 17 seconds) is required for the chip to cool down to steady state room temperature by simply using convection cooling, indicating a reversible and repeatable heat/cool refractive index change process for the observed temperature range.

3. ALL-SILICON CARBIDE TEMPERATURE PROBE ASSEMBLY

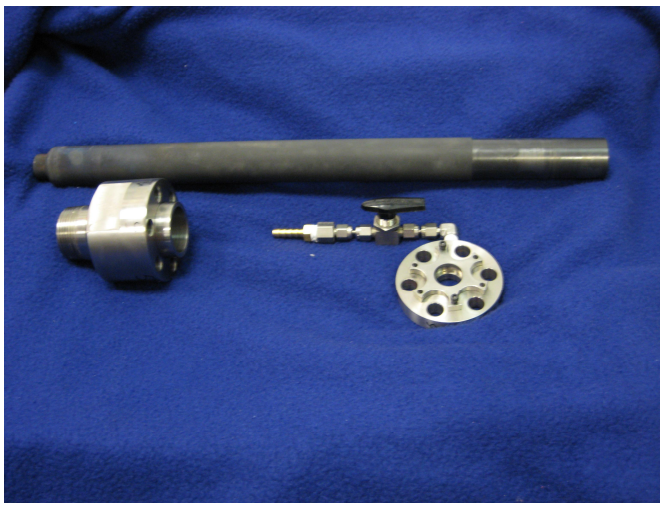


Fig.7. SiC temperature probe shown in an unassembled fashion.

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Figure 7 shows the Nuonics, Inc. provided SiC temperature probe shown in an unassembled fashion. The point to note is the harsh environment frontend probe assembly consists of three parts, namely, (a) the all-in-one SiC probe consisting of sintered SiC tube assembly with an embedded single crystal SiC chip, (b) Pressure sealed connector housing that the tube is inserted in to form an interface with pressurized turbine chamber, and (c) the connector flange that when correctly tightened seals the tube to the connector. The housing/flange also contains an optical window to near vacuum seal the tube. The connector also contains a valve and fittings for vacuum controls. Fig.8 shows the Nuonics probe in an assembled fashion.

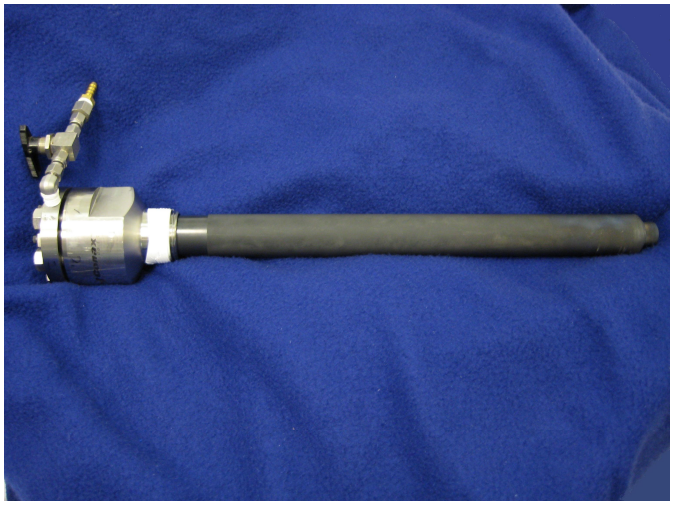
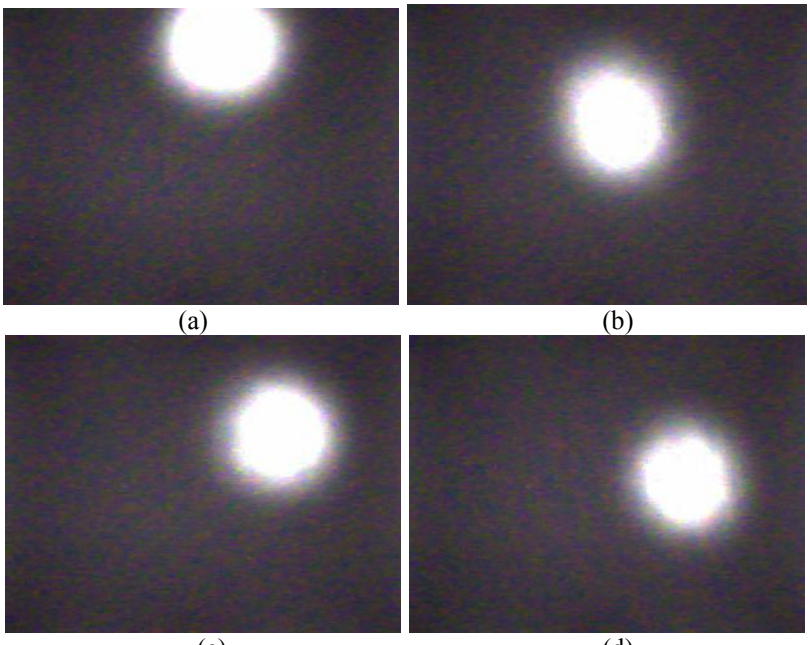


Fig.8. SiC temperature probe shown assembled.



(a) (b)

(c) (d)

Fig. 9. Reflected 1550 nm laser beam motion due to convection currents when the probe is open at one end as seen at 1 s intervals at a temperature of ~1000 deg-C. Camera view of 8.8 mm (horizontal) by 6.6 mm vertical.

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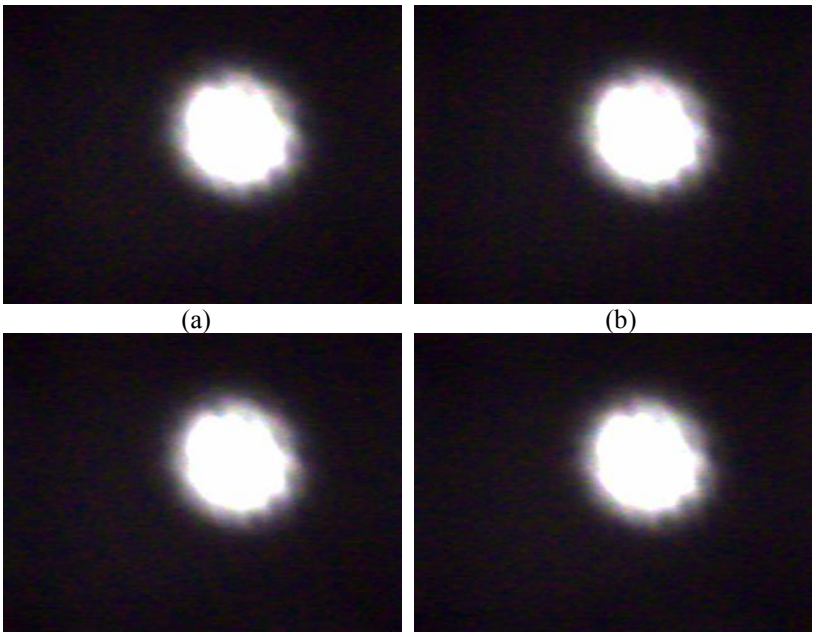


Fig. 10. Reflected 1550 nm laser beam motion when the probe is closed and near vacuum sealed as seen at 1 s intervals at a temperature of ~1000 deg-C. Camera view of 8.8 mm (horizontal) by 6.6 mm vertical.

Fig. 9 shows reflected 1550 nm infrared laser beam movement at temperatures close to 1000 deg-C when the probe is open to external air currents. On the other hand, Fig. 10 shows the reflected 1550 nm infrared laser beam movement at temperatures close to 1000 deg-C when the probe is closed using the optical window and near vacuum-sealed. These figures clearly show that when the probe is open, the laser beam is moving around very rapidly due to convection currents in air whereas when it is closed and vacuum-sealed, the laser beam becomes stable and maintains its location for effective detection by a 2-D camera or large area point detector.

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4. PROBE TURBINE TEST SYSTEM DESIGN

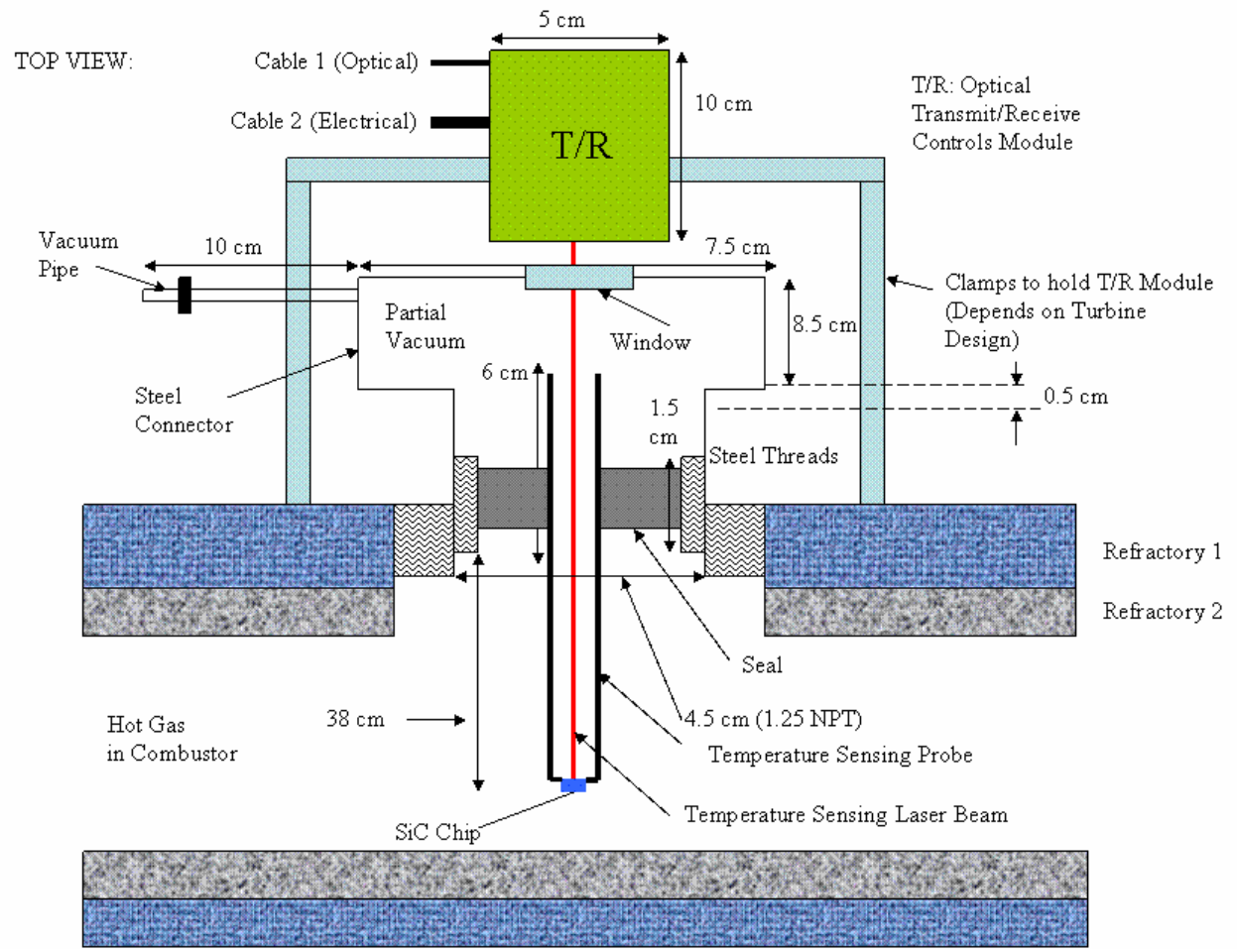


Fig.11. Shown is a typical engagement of the proposed temperature probe with a gas turbine. Figure is not to scale and shows example dimensions.

The developed SiC probe is designed to measure gas temperature in the hottest section of the gas turbine, namely, the combustor where temperature will reach 1500 deg-C. Fig.11 shows a typical engagement of the proposed temperature probe with a gas turbine. Figure 11 is not to scale and shows example dimensions of probe and fittings. The key points to note is that the probe is designed to maintain some partial vacuum and deploys an optical window to restrict beam motion in probe due to air turbulence. This type of system design is expected to be deployed for final tests of this SiC probe technology in a turbine test rig.

5. PROBE ROBUSTNESS ISSUES

It is well known that SiC oxidizes at high temperatures (> 1000 deg-C) and high pressures (> 10 atm) in the presence of water vapor [12]. What is more important to note is that this oxidation rate is about two orders of magnitude smaller for single crystal SiC than for amorphous SiC [13]. As the probe sensing tip is made from single crystal SiC while the optically non-interrogated probe assembly tube is made from an amorphous sintered form of SiC, the probe is expected to adequately handle oxidizing effects in an oxygen present turbine environment with a rich mixture of gases. It is also important to note that the probe uses a thick or about 400 microns single crystal SiC chip and not a thin-film (a few microns) of single crystal SiC that would have a large fraction of its bulk material

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used in the long-term oxidization process (i.e., conversion of silicon atoms in the Silicon-Carbon bond to silicon dioxide layer) that in-turn effects the bulk refractive index and thickness properties of the sensing SIC chip. In the case of a thick SiC chip, the oxidation effect is proportionately smaller and hence its effect on the thick SiC chip sensing parameters (bulk refractive index and bulk thickness) is also negligible given certain plant operational life-times. Furthermore, the wavelength tuned signal processing incorporated in the proposed temperature probe can be used to calibrate for these slow changes in bulk optical parameters over time as real-time sensor signal processing can be used to track the very slow changes in chip thickness and refractive index due to oxidation.

It is also well known that SiC sublimes (changes from bulk to gas form) at high temperatures. Generally, this temperature is between 2000 to 2300 deg-C, so one can expect the proposed probe to function correctly under 2000 deg-C.

Oven tests of the probe have been conducted with 30 heat/cool cycles from ~ 25 deg-C to ~1100 deg-C. The heat cycle is ~ 4.5 hours long while the natural convection cool cycle is conducted over night time (e.g., > 10 hours) in the laboratory as the oven is turned off. These tests show the probe optical and mechanical performance to be unchanged. The probe has also been tested to hold a partial vacuum of 25 inch Hg (~ 85 kpa). Initial tests show a drop to about 20 inch Hg in a 21 hours time frame, indicating the probe vacuum holding capability. During this 21 hour test period, the probe did experience one ~ 1075 deg-C thermal cycle over a 6 hour period.

6. CONCLUSION

The continuing studies and experimental progress for the proposed SiC temperature sensing technology has been presented. Issues highlighted include thermal temporal response of the SiC chip, assembly of the engineering probe, design of the sensor system engaged with the combustor section of a gas turbine, and SiC robustness given its oxidation and sublimation effects. Future works will detail results from turbine rig tests of this new technology.

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