Title	Wireless temperature sensors using single crystal silicon carbide: an industrial feasibility and design study
Author(s)	Riza, Nabeel A.; Sheikh, Mumtaz A.; Perez, Frank
Publication date	2007-05-16
Original citation	Riza, N. A., Sheikh, M. A. and Perez, F. (2007) 'Wireless temperature sensors using single crystal silicon carbide: an industrial feasibility and design study', Proceedings of SPIE, 6585, Optical Sensing Technology and Applications, 65850J, International Congress on Optics and Optoelectronics, 2007, Prague, Czech Republic, 16 May. doi: 10.1117/12.722636
Type of publication	Conference item
Link to publisher's version	http://dx.doi.org/10.1117/12.722636 Access to the full text of the published version may require a subscription.
Rights	**© 2007 Society of Photo-Optical Instrumentation Engineers (SPIE). One print or electronic copy may be made for personal use only. Systematic reproduction and distribution, duplication of any material in this paper for a fee or for commercial purposes, or modification of the content of the paper are prohibited.**
Item downloaded from	http://hdl.handle.net/10468/10103

PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

Wireless temperature sensors using single crystal silicon carbide: an industrial feasibility and design study

Riza, Nabeel, Sheikh, Mumtaz, Perez, Frank

Nabeel A. Riza, Mumtaz Sheikh, Frank Perez, "Wireless temperature sensors using single crystal silicon carbide: an industrial feasibility and design study," Proc. SPIE 6585, Optical Sensing Technology and Applications, 65850J (16 May 2007); doi: 10.1117/12.722636

Event: International Congress on Optics and Optoelectronics, 2007, Prague, Czech Republic

Wireless Temperature Sensors using Single Crystal Silicon Carbide – An Industrial Feasibility and Design Study

Nabeel A. Riza [1,2], Mumtaz Sheikh [2], and Frank Perez [1]
[1] Nuonics, Inc.
1025 S. Semoran Blvd., Suite 1093, Winter Park, FL 32792, USA.
[2] College of Optics-CREOL, University of Central Florida
4000 Central Florida Blvd., Orlando, FL 32816-2700

ABSTRACT

Single crystal Silicon Carbide (SiC) chip operations for a proposed wireless temperature sensor are evaluated for various power plant industrial conditions such as soot levels, chemical exposure, and changes in polarization.
Keywords: Optical sensors, temperature sensor, soot, extreme environments

1. INTRODUCTION

Sensors for harsh environments such as coal-fired power plants are extremely important control system elements that optimize plant efficiency and operations. Advanced combined-cycle power plant designs are requiring higher operational temperatures and pressures to realize cleaner greener power generation systems. Here temperature and pressures in excess of 1400 ºC and 50 atmospheres (atms) are expected. Hence, the sensor community is being challenged to provide robust sensor solutions for these extreme conditions of next generation clean power plants.

Recently, a hybrid fiber-freespace optics approach to solving this sensing problem was put forth that exploits both the fiber-based remoting capability and the minimally invasive nature of laser targeted light beams incident on single crystal Silicon Carbide (SiC) chips [1]. Under US. Department of Energy sponsorship, much progress has been reported by us on this theme to enable harsh environment temperature and pressure sensing [2-8]. In particular, experimental results have been reported for temperature sensing up-to 1000 ºC and pressure sensing up-to 50 atms. Even cold temperature sensing can be achieved with the proposed SiC hybrid optical sensors [9].

The focus of this paper is to report, for the first time, advances of the proposed hybrid theme for temperature sensing in the context of a novel industrial probe design. Specifically, key industrial issues will be described in this paper including fabricated SiC chip quality control studies and robustness of sensor operations due to infrared light polarization changes, presence of harsh acidic chemicals, and exposure to high temperature heat soaking. In addition, experimental results will be described showing the strong operation of the temperature sensor for various levels of power plant industrial soot exposure including light, moderate, and high soot levels on the exposed SiC chip. In conclusion, the paper will give an assessment of the wireless SiC-based temperature probe sensor technology materials versatility for fossil-fuel based power plant applications.

2. FABRICATED SIC CHIPS LIGHT-BASED TEMPERATURE SENSING QUALITY

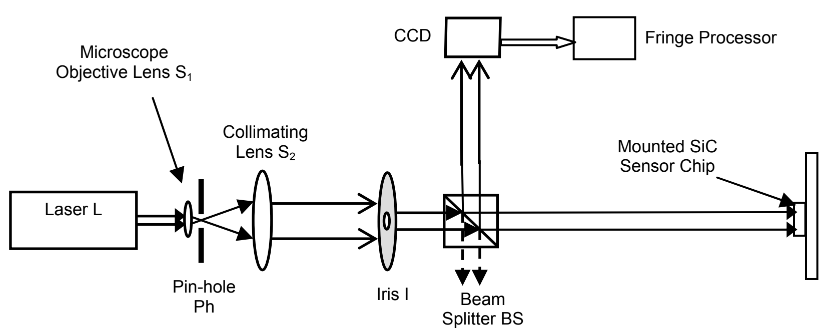


Figure 1: Experimental setup to obtain the interferometric signature of SiC chip.

Optical Sensing Technology and Applications, edited by
Francesco Baldini, Jiri Homola, Robert A. Lieberman, Miroslav Miler,
Proc. of SPIE Vol. 6585, 65850J, (2007) · 0277-786X/07/$18 · doi: 10.1117/12.722636

Each fabricated SiC chip has a characteristic interferometric signature resulting from the interference of the light reflecting from the chip. Figure 1 shows the experimental setup used to get the interferometric signatures of each of the thirty-seven 1 cm x 1 cm square 400 micron thick fabricated 6H single crystal SiC chips. These signatures then tell the optical quality of the chips and their appropriateness for sensor design. He-Ne laser (λ = 633 nm) is used in this experiment while the incident beam size on the SiC chip is 5 mm in diameter. The interferometric signatures obtained for the SiC chips are shown in Figure 2.

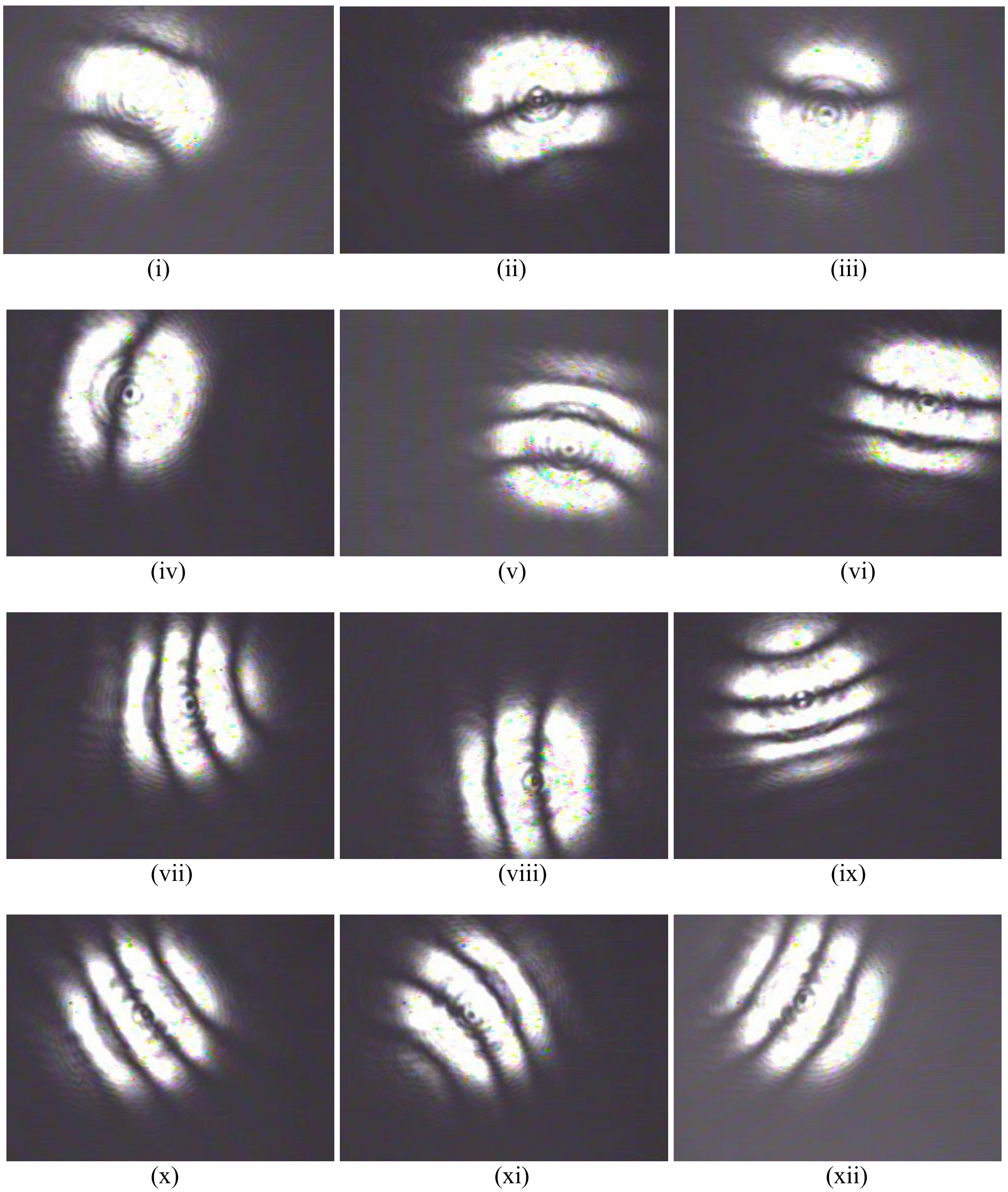
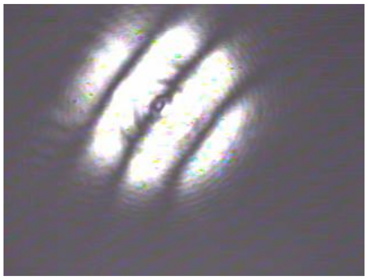
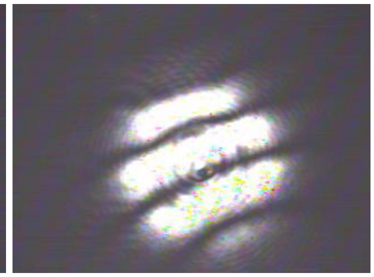
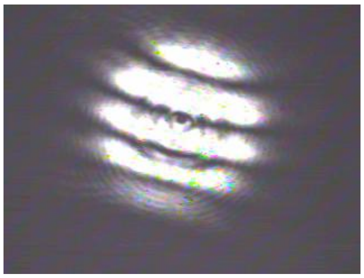
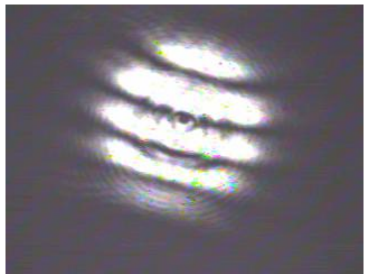
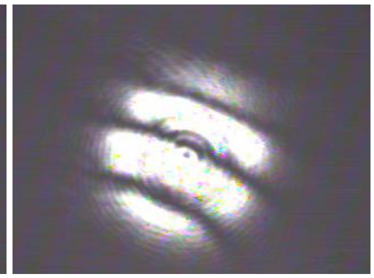
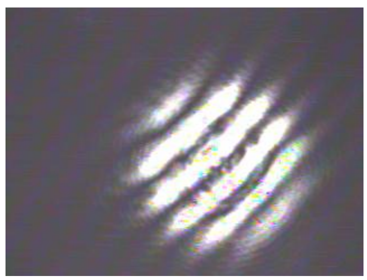
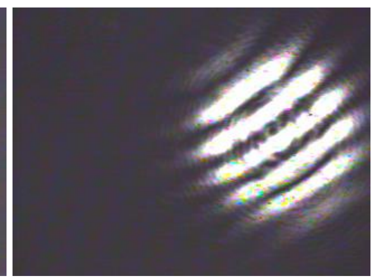


Figure 2 (i) – (xxxvii): Interferometric signatures (@ 633 nm)of the fabricated SiC chips.


(xiii)

(xiv)

(xv)

(xvi)

(xvii)

(xviii)

(xix)

(xx)

(xxi)

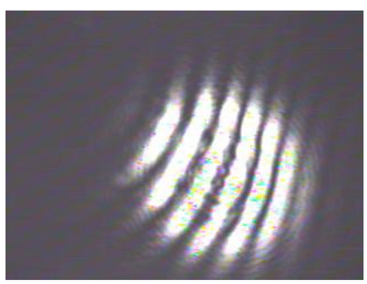
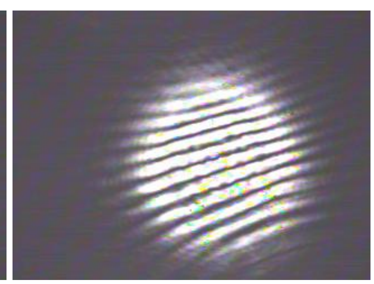
(xxii)

(xxiii)

(xxiv)

Fig.2 (Continued).

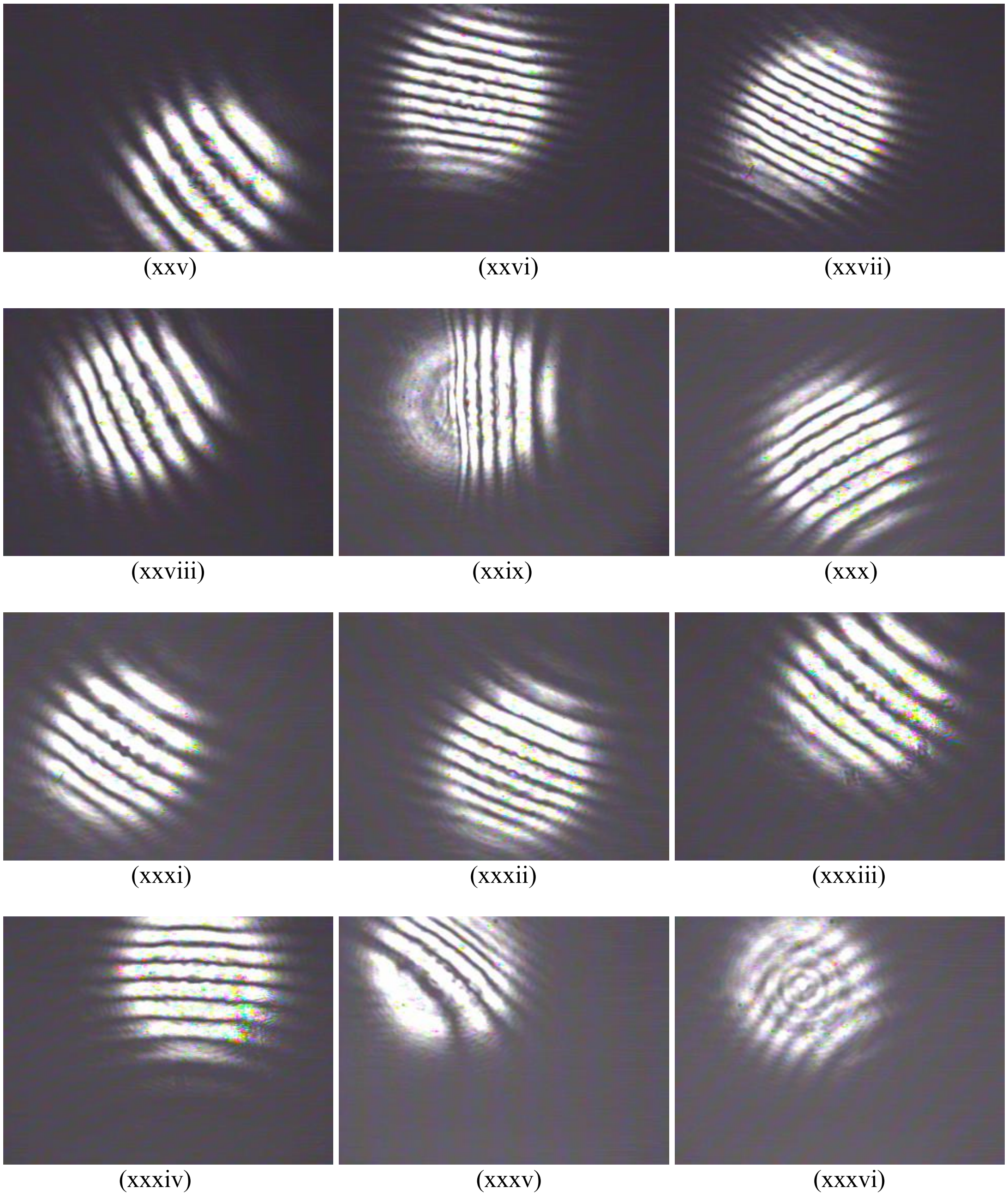


Fig.2 (Continued).

(xxxvii)

Fig.2 (Continued).

Based on the number of fringes observed in the 5 mm diameter spot, chips number (i)-(iv) in Figure 2 were classified as good while chips number (v)-(xix) were classified as moderately good and chips number (xx)-(xxxvii) were deemed non-optimal for use in the probe.

The SiC chips are next checked for polarization independence (an important attribute when designing the probe) using a polarizer and Liquid Crystal (LC cell) as shown in Figure 3.

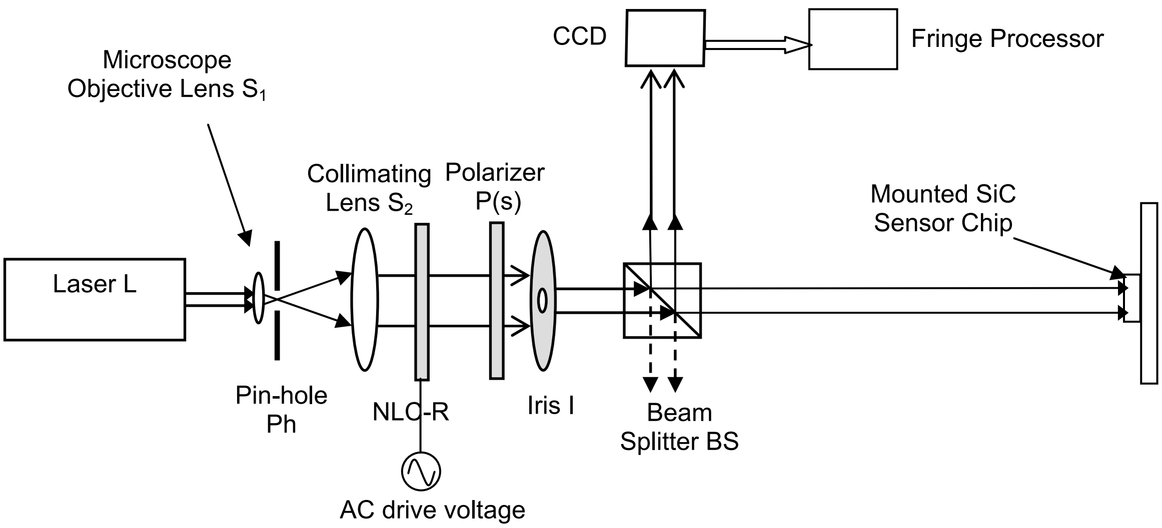


Figure 3: Experimental setup for checking polarization dependence of the SiC chip

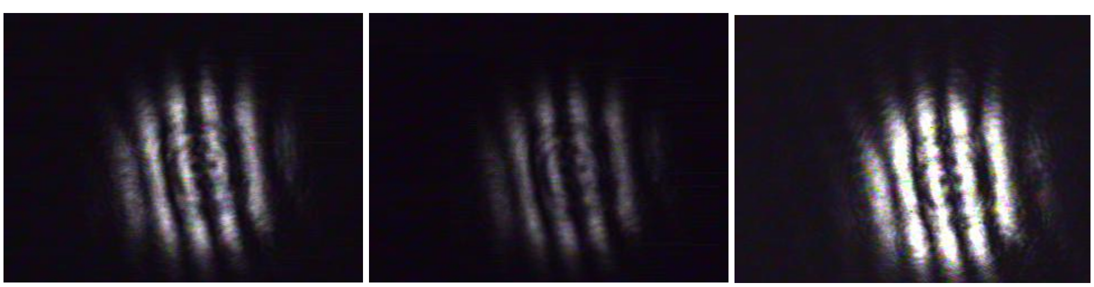


Figure 4 (i): Observed interferograms with general change in probe light polarization.

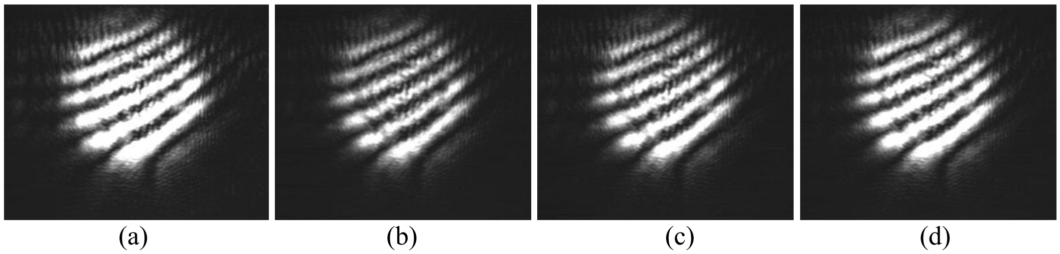


Fig.4 (ii) Recorded interferograms off the SiC chip for incident light linear polarization angles of (a) 0^0 (b) 45^0 (c) 90^0 and (d) 135^0. Observed optical beam diameter is 5 mm. Wavelength used is 633 nm.

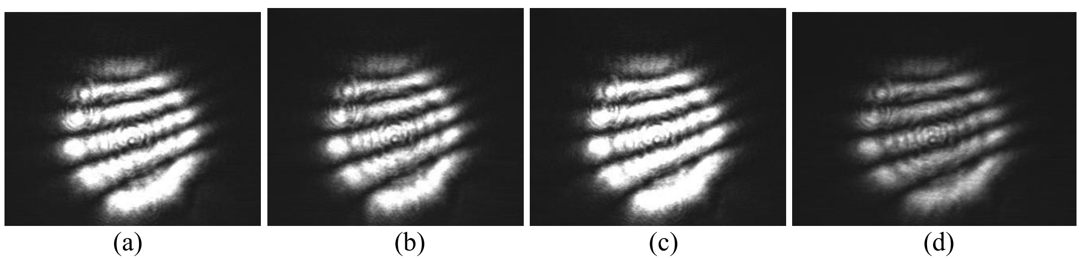


Fig.4(iii) Recorded interferograms off the SiC chip for incident light elliptical polarization state of (a) Eccentricity = 0.69, Tilt = 45^0 (b) Eccentricity = 0.99, Tilt = 29.4^0 (c) Eccentricity = 0.98, Tilt = 9.4^0 (d) Eccentricity = 0.83, Tilt = 7.6^0

These interferogram results are shown in Figure 4(i,ii,iii) and show that interference fringes do not move with change in polarization, indicating the robustness of sensor performance using the proposed chips.

3. PROBE DESIGN BENCH TESTS FOR POLARIZATION ROBUSTNESS

Figure 5 shows the Infrared (IR) band probe design bench test set-up for the chosen optimal SiC chips selected from the general batch of fabricated SiC chips. Here, the tunable laser has a wavelength tuning range of 1520-1600 nm. The fiber Graded Index (GRIN) lens forms its $1/e^2$ minimum beam waist at a distance of 25 cm from the lens. The under test SiC chips are placed at a distance of 44.5 cm from the lens which is the expected minimum length of the probe.

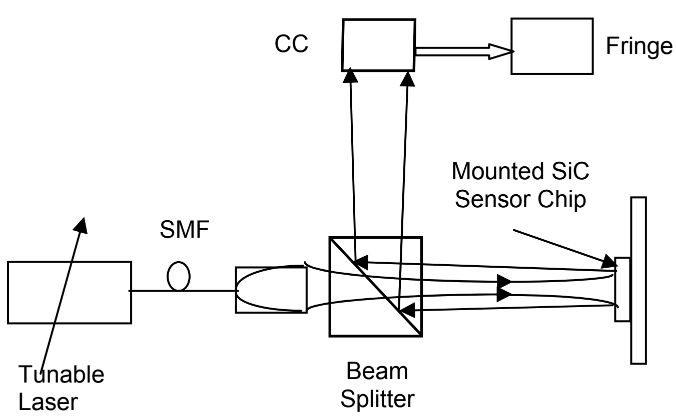


Figure 5: Infrared (IR) band probe design bench test set-up.

Figure 6 shows the beam imaged on the CCD when a plane mirror is placed in place of the SiC chip in the setup of Figure 5. The size of the beam as measured on the CCD is found to be 3.6 mm. Since the beam keeps on diverging, this implies that the size of the beam when it strikes the mirror is less than 3.6 mm.

Figure 6: Image of the IR beam in the probe when reflected by a plane mirror.

Chip (xxi) is now placed in the probe setup and the interferogram is observed on the CCD. The spatial frequency of the interference fringes is given by Eq. (1).

$$\xi = \frac{\sin\theta}{\lambda} \qquad (1)$$

Here, θ is the angle between the two faces of the SiC chip (see Fig. 7). As predicted by Eq. (1), the spatial frequency decreases at a higher wavelength and hence, fewer fringes are observed in IR as compared to the visible (see Figure 8 (a) and (b)). For the specific case of 633 nm visible wavelength and 1550 nm IR wavelength, the number of fringes decrease by a factor of approximately 2.5 when going to the IR band provided the beam size remains the same. To verify that the fringes observed are indeed caused by interference, the wavelength is tuned and the fringes are observed to move (Figure 8 (c) and (d)).

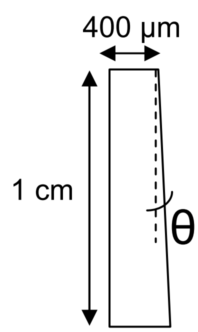


Figure 7: A Typical SiC chip

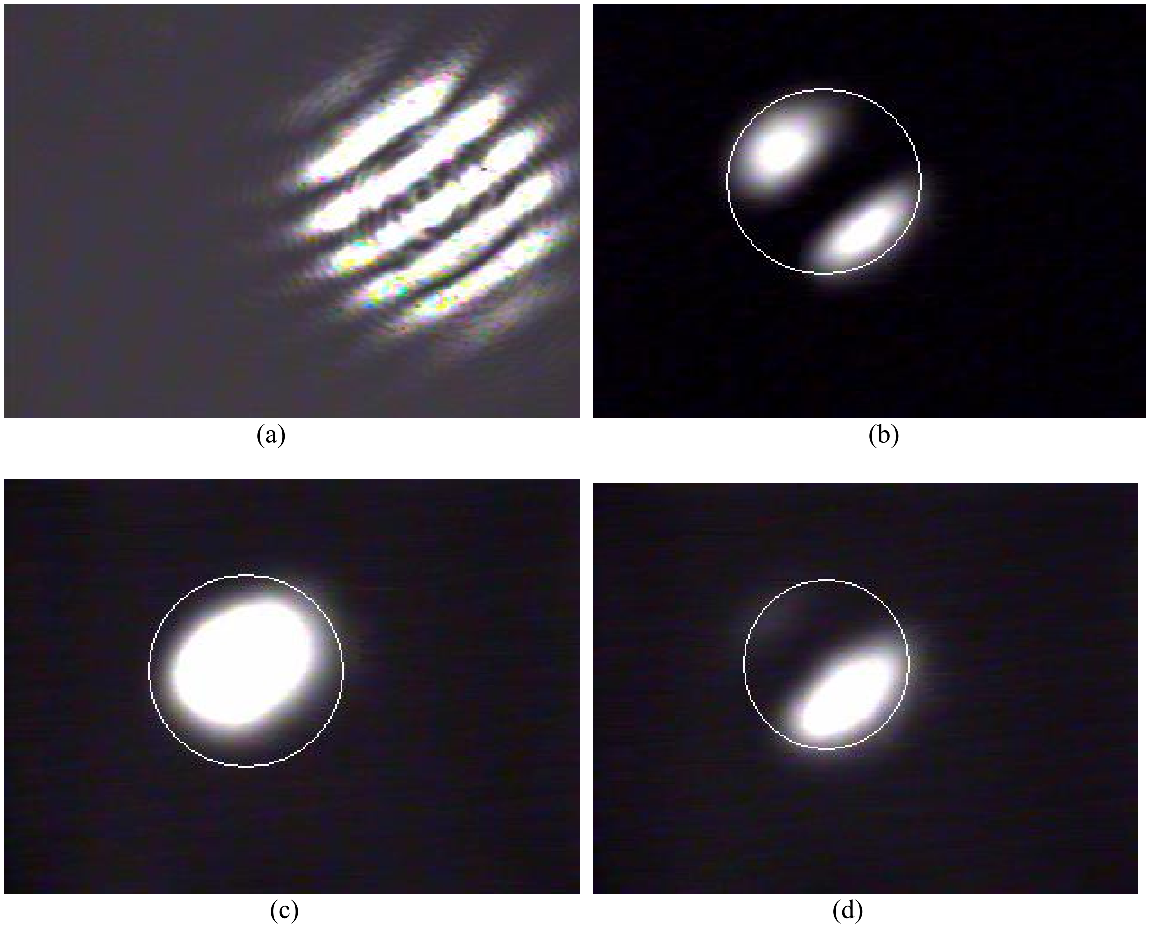


Figure 8: Chip (xxi) interferograms from probe for (a) visible 633 nm (b) IR 1560.66 nm (c) IR 1561.02 nm (d) IR 1561.31 nm.

The polarization insensitivity of this chip is also checked in IR using a fiber-optic polarization controller. The fringes are again observed not to move with change in polarization (see Figure 9).

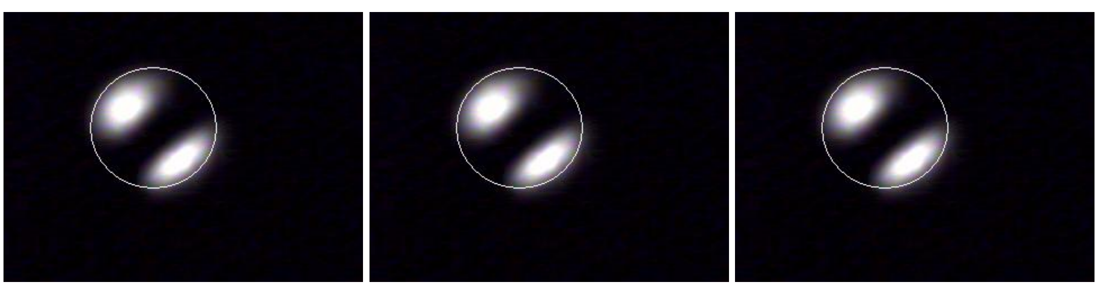


Figure 9: Observed IR interferograms from probe with changes in input polarization.

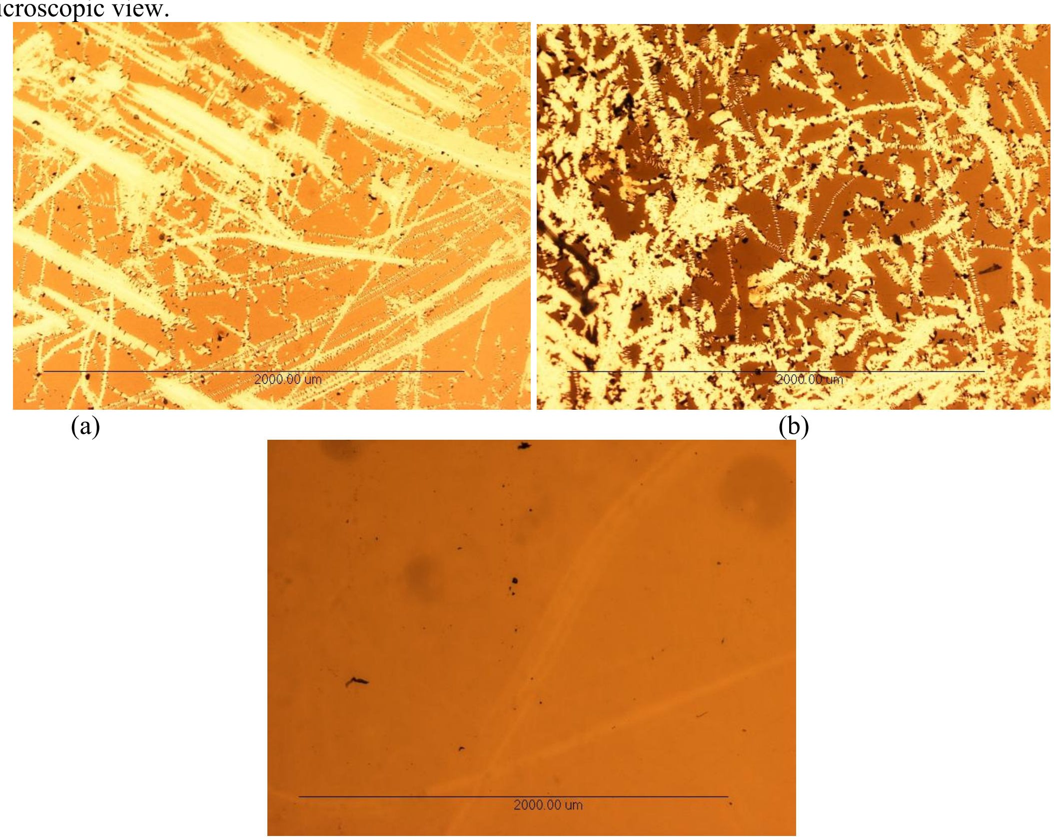
The modulation depth of the interferograms is calculated as:

$$M.D = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

The theoretical value of the modulation depth as given by using the Fresnel reflection coefficients for SiC in the IR band is found to be 0.977. The experimental value found by image processing the IR detector performance limited interferograms is 0.785.

4. PROBE DESIGN BENCH TESTS FOR INDUSTRIAL SOOT ROBUSTNESS

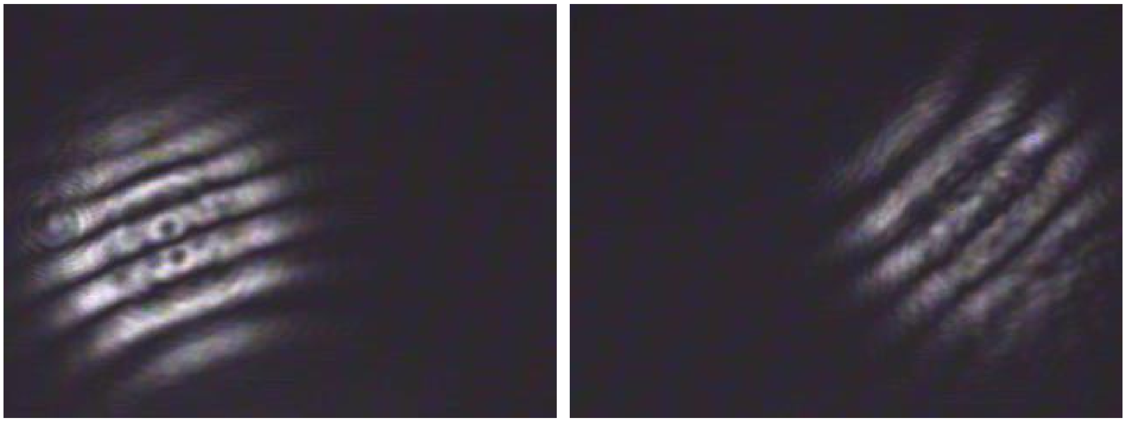
In coal-driven power plants, soot is generated as a by-product. Thus, it is expected that when the temperature probe is inserted into the gas turbine, soot will be deposited on one side of the SiC sensor chip. At our industrial power plant partner test facility, first SiC chips numbers (xxxi) and (xxxiii) have soot deposited on one side using an oxy-acetylene flame as a gas mixture can be safely varied to control the level of soot in the flame to generate power plant soot conditions. Chip (xxxi) is deposited with moderate soot while chip (xxxiii) is deposited with moderately high soot. Figure 10 shows the microscopic photographs of the soot face of the two chips and the clear face of the moderately high soot chip. The figures show that when looking from the clear side of the chip, the soot is not visible in the microscopic view.



(a) (b) (c)

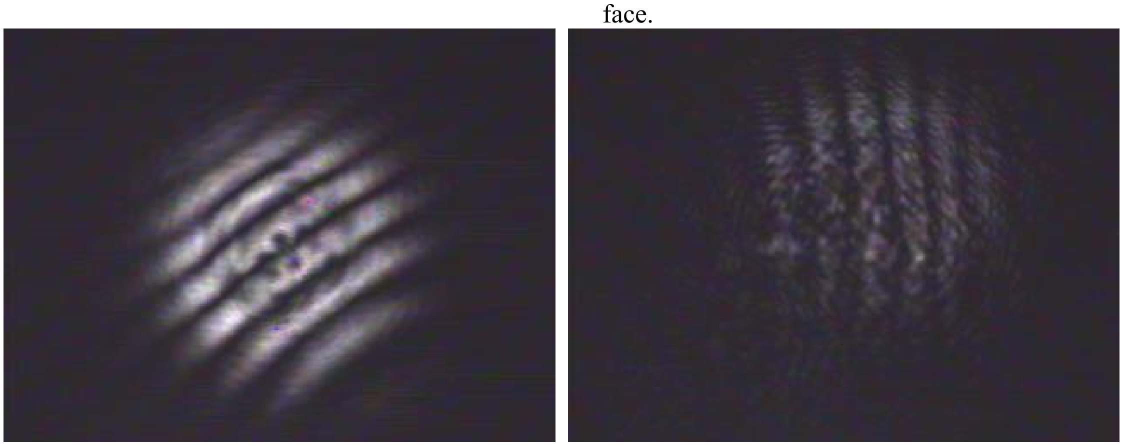
Figure 10: Microscopic photographs of SiC chip faces with (a) moderate soot and (b) moderately high soot levels and (c) a clear chip with no soot.

These chips are then put under test again in the setup of Figure 1. The results (Figure 11 and Figure 12) show that when the light is incident on the clear face of the chip, as would be the case in the proposed probe design, there is no change in the interferometric signature of the chip but when the light is incident on the soot face, the interferogram is covered with a random phase mask thus destroying it, an effect especially visible with the high soot chip.



(a) (b)

Figure 11: Interferometric signature from probe set-up with (a) the moderate soot deposited chip Clear face (b) Soot face.



(a) (b)

Figure 12: Interferometric signature from probe set-up with (a) Moderately high soot deposited chip Clear face (b) Soot face.

These chips are then taken to the IR probe setup of Figure 5 and the interferograms are again observed for the clear side. The results are shown in Figure 13 and Figure 14. Again, it is observed that for the light incident on the clear side, there is no change in the interferogram and its behavior with wavelength tuning.

Figure 13: IR Interferogram of the moderate soot deposited chip with wavelength tuning.

Figure 14: Interferogram of the high soot deposited chip with wavelength tuning.

Next, SiC Chips (xxiii) and (xxxi) are now deposited with very heavy soot and quick heavy soot, respectively. Chip (xxxiii) is deposited with very heavy soot for around 1 minute and then heat soaked with a high temperature torch at 1150 ^{o}C for 30 seconds. The laboratory pictures of the three sooted chips are shown in Figure 15. In these cases, the soot is so dense that no features are visible using a microscope as light is completely absorbed.

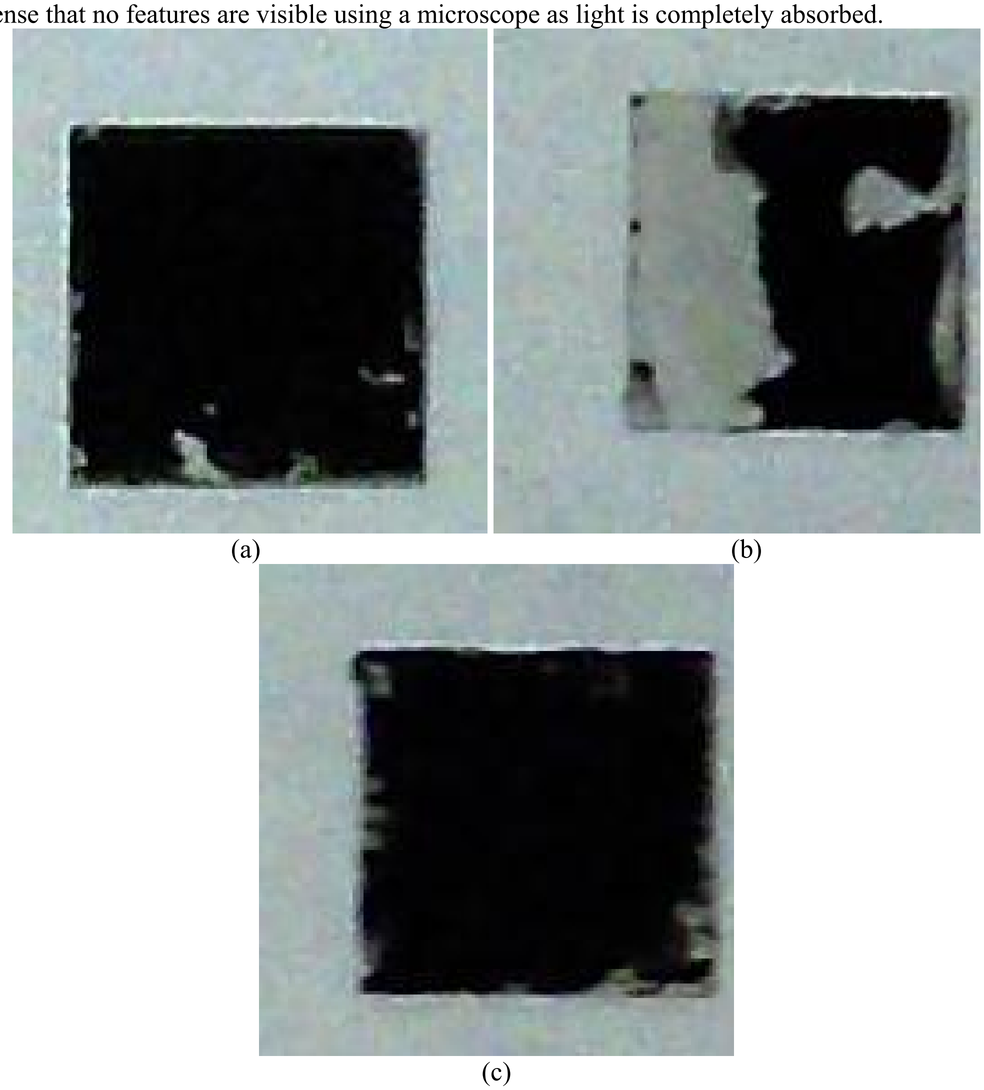


Figure 15: Pictures of the soot side of the SiC soot deposited chips with (a) Very heavy soot layer (b) Quick heavy soot (Soot applied for 1 minute; some soot peeled off with handling), and (c) Very heavy soot for 1 minute with heat soak at 1150 ^{o}C for 30 seconds.

These chips are put under test again with their clear side facing the light beam in the IR probe setup of Figure 5. The interferograms obtained are shown in Figure 16. The interferograms show that there is still no distortion when light is incident on the clear face of the chip in the probe set-up.

(a) (b) (c)

Figure 16: Interferograms for the clear side of (a) Very heavy soot (b) Quick heavy soot and (c) Very heavy soot with heat soak at 1150 ^{o}C for 30 seconds.

5. PROBE DESIGN BENCH TESTS FOR INDUSTRIAL CHEMICAL & SUSTAINED TEMPERATURE ROBUSTNESS OF SIC CHIPS

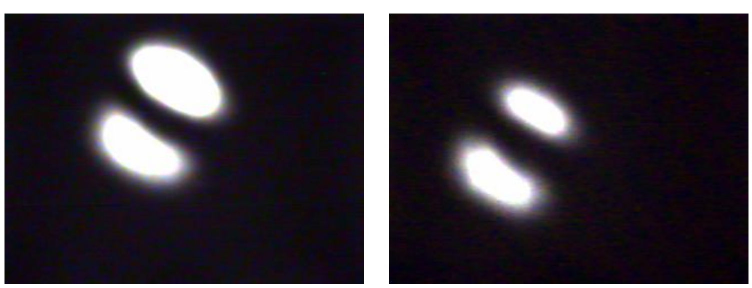
The Single crystal 6H-SiC chips are next tested with harsh chemicals and sustained extreme temperatures. To check whether corrosive chemicals would have an effect on the SiC chip, chip (xx) is placed in concentrated Sulphuric Acid for a period of up to 24 hours. The chip is then put under test in the setup of Figure 5. Figure 17 (i) and (ii) show the interferograms obtained after 1 hour and 24 hours in the acid respectively. The figure clearly shows that there is no change in the interferograms after being placed in the acid.

(i) (ii)

Figure 17: IR interferograms of the chip placed in the acid for (i) 1 hour and (ii) 24 hours.

Chip (xxi) is placed in an oven at a temperature of 1100 ^{o}C sustained for a period up to 2 hours.

The chip is then cooled and put under test again in the set-up of Figure 5. Figure 18 (i) and (ii) show the interferograms obtained after 30 minutes and 2 hours in the oven, respectively. As demonstrated by Figure 18, no change is observed in the interferograms in either case.



(i) (ii)

Figure 18: IR interferograms of the chip placed at 1100 ^{o}C for (i) 30 minutes and (ii) 2 hours.

6. SENSOR PROBE ELEMENTS INDUSTRIAL FEASIBILITY ASSESSMENT SUMMARY

First time batch fabrication and assembly of the 6-H SiC chips shows a ~ 25% yield of good chips that can be deployed in the proposed sensor probe. This study is conducted using analysis of chip visible light interferograms where a low fringe count chip is considered better for probe design. A bench-top IR probe design is implemented to test sensor performance based on various industrial power plant conditions such as changes in light polarization, presence of various soot levels on the sensor SiC chip, exposure of the chip to extreme temperature and corrosive chemical environments. Specifically, a first polarization test is conducted using many linearly polarized beams with the angle of linear polarization sweeping over a 180^o range. This is done by using a manually rotated linear polarizer P with a rotation maximum of 90^o. To produce 90^o to 180^o polarization rotation, a twisted Nematic Liquid Crystal (NLC-R) cell is electrically turned on so input light polarization is no longer rotated by 90^o. With the NLC-R on, the manual polarizer P is again rotated through 90^o. Thus, using NLC-R and manual polarizer P rotation, the SiC chip is exposed to linearly polarized light with different direction of linear polarization in the plane normal to the chip optic axis. Indeed, the interference images do not change in fringe positions as the incident linear polarization is changed. In all cases, the same fringe pattern is maintained; only the image average power changes because of the change in the incident average power due to the manual rotation of P. Next, a polarization test is conducted using many elliptical polarization states using a birefringent-mode parallel-rub phase NLC-P cell that acts as an optical phase shifter for the input vertically polarized light. By controlling the angle of the linear polarizer P and the NLC-P produced phase shift, a variety of elliptically polarized states are generated to test the optical interferometric response of the SiC chip. These interferograms indeed show no fringe pattern change as the input light state of polarization is changed through various elliptical states defined by the classic ellipse eccentricity and tilt parameters. Thus the desired polarization independent operation results show the proposed SiC-based sensors to have a robust sensor design as needed for harsh environment operations where polarizations can vary.

Probe sensor operations are tested using SiC chips exposed to a variety of light, moderate, heavy, and heavy & heat soaked soot conditions on the external face of the chip. Heavy soot shows a clear black external deposit, yet all soot conditions are shown not to effect sensor operations as strong interferograms are measured. Similarly, long heat and acidic chemical soaks do not effect chip interferogram making capability necessary for sensor operations.

7. CONCLUSION

The primary objective of this study was achieved by engaging with a major power generation systems design house (i.e., Siemens) turbine test facility that today utilizes extreme temperature and high pressure probes to make temperature and pressure measurements within a power plant. Specifically, industrial power plant soot was generated directly on the SiC sensor chips to test fundamental sensor operational survivability under power plant conditions of various soot levels. The chips were then also tested for handling high temperature heat soak and long exposure to corrosive acid chemicals. The chip sensing behavior was studied under varying light polarization conditions. Overall, these initial studies attest to the promise and strengths of SiC chip-based optical wireless sensor technology for fossil fuel based power generation system applications.

ACKNOWLEDGEMENTS

This paper was prepared with the support of the U.S. Department of Energy, under Award No. DE-FC36-03NT41923. However, any opinions, findings, conclusions, or recommendations expressed herein are those of the author(s) and do not necessarily reflect the views of the DOE. Industrial Lab. support from Siemens Power Generation, Orlando is appreciated. N. A. Riza is on part leave from UCF.

REFERENCES

[1] N. A. Riza, M.A. Arain, and F. Perez, "Harsh Environments Minimally Invasive Optical Sensing Technique for Extreme Temperatures: 1000 °C and Approaching 2500 °C," in 17th International Conference on Optical Fibre Sensors, OFS 17, Marc Voet, Reinhardt Willsch, Wolfgang Ecke, Julian Jones, Brian Culshaw, eds., Proc. SPIE Vol. 5855, (Int. Soc. Opt. Eng., Bruges, Belgium, May 2005), pp. 687-690.

[2] N. A. Riza, M. A. Arain, and F. Perez, "Harsh Environments Minimally Invasive Optical Sensor using Freespace Targeted Single Crystal Silicon Carbide," IEEE Sensors Journal, Vol. 6, (June 2006).

[3] M. A. Arain and N. A. Riza, "Fiber-Coupled In-Line Heterodyne Optical Interferometer for Minimally Invasive Sensing," IEEE/OSA J. Lightwave Technol., Vol. 23, 2449-2454 (2005).
[4] N. A. Riza, M. Arain, and F. Perez, " 6H- Single Crystal Silicon Carbide Thermo-Optic Coefficient Measurements for Ultrahigh Temperatures up-to 1273 K in the telecommunications infrared band," J. Appl. Phys, Vol. 98, 103512 (2005)
[5] N. A. Riza, F. N. Ghauri, and F. Perez, "Hybrid Optical Sensor using Laser Targeting," in Optical Sensing II, Brian Culshaw, Anna G. Mignani, Hartmut Bartelt, Leszek R. Jaroszewicz, eds., Photonics Europe Proc. SPIE Vol. 6189, Invited Paper No.4., (Int. Soc. Opt. Eng., Strasbourg, France, April 3-7, 2006), pp. 32-46.
[6] N. A. Riza, M. Sheikh, and F. Perez, "Progress on Silicon Carbide Hybrid-Design Optical Sensors for Extreme Environments," OSA 18th International Conference on Optical Fibre Sensors, OFS 18, Cancun, Oct.23, 2006.
[7] N. A. Riza, F. N. Ghauri, and F. Perez, "Wireless Pressure Sensor using Laser Targeting of Silicon Carbide," Optical Engineering, Jan. 2007.
[8] N. A. Riza, F. N. Ghauri, and F. Perez, "Silicon Carbide based Remote Wireless Optical Pressure Sensor," to appear in IEEE Photon. Tech. Lett., 2007.
[9] N. A. Riza and M. A. Arain, " Cryogenic Temperature Measurement using Silicon Carbide-based Wireless Optical Sensor**,"** IEEE Photon. Tech. Lett., Dec. 2006.