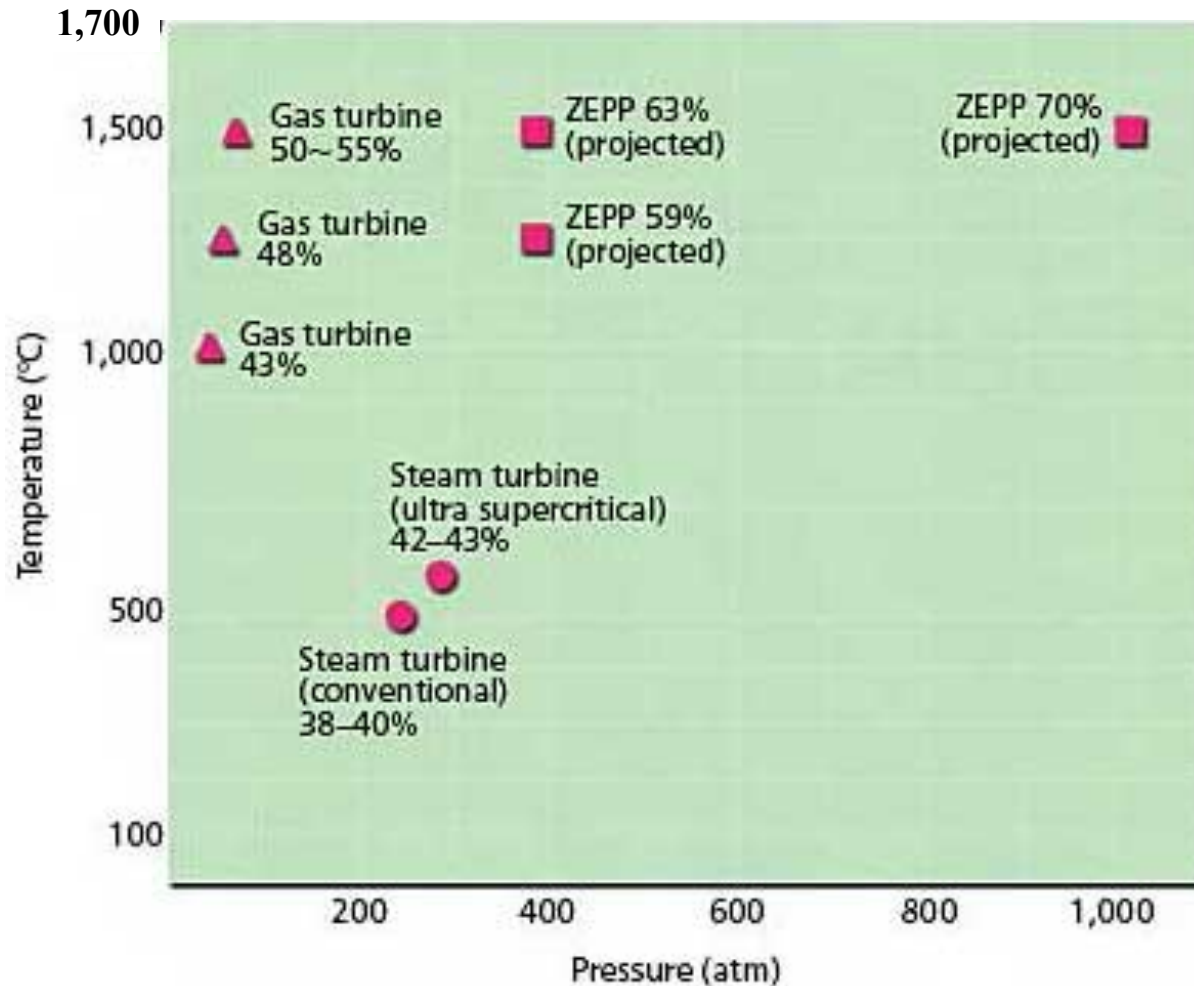


Extreme Temperature Silicon Carbide Optical Sensors for Extreme Temperature Measurement And Pressure Measurement- A Review

**by
Nabeel A. Riza**

Why is Extreme Temperature Sensing Needed --- Greener & More Efficient



Ultimate Goal--ZEPP: Zero Emission Power Plant

Burn Less Fuel



**Less Hazardous
Waste & CO₂**

Higher Pressures



**Liquify CO₂ -Easier
To Transport/Store
Waste**



Greener Plant

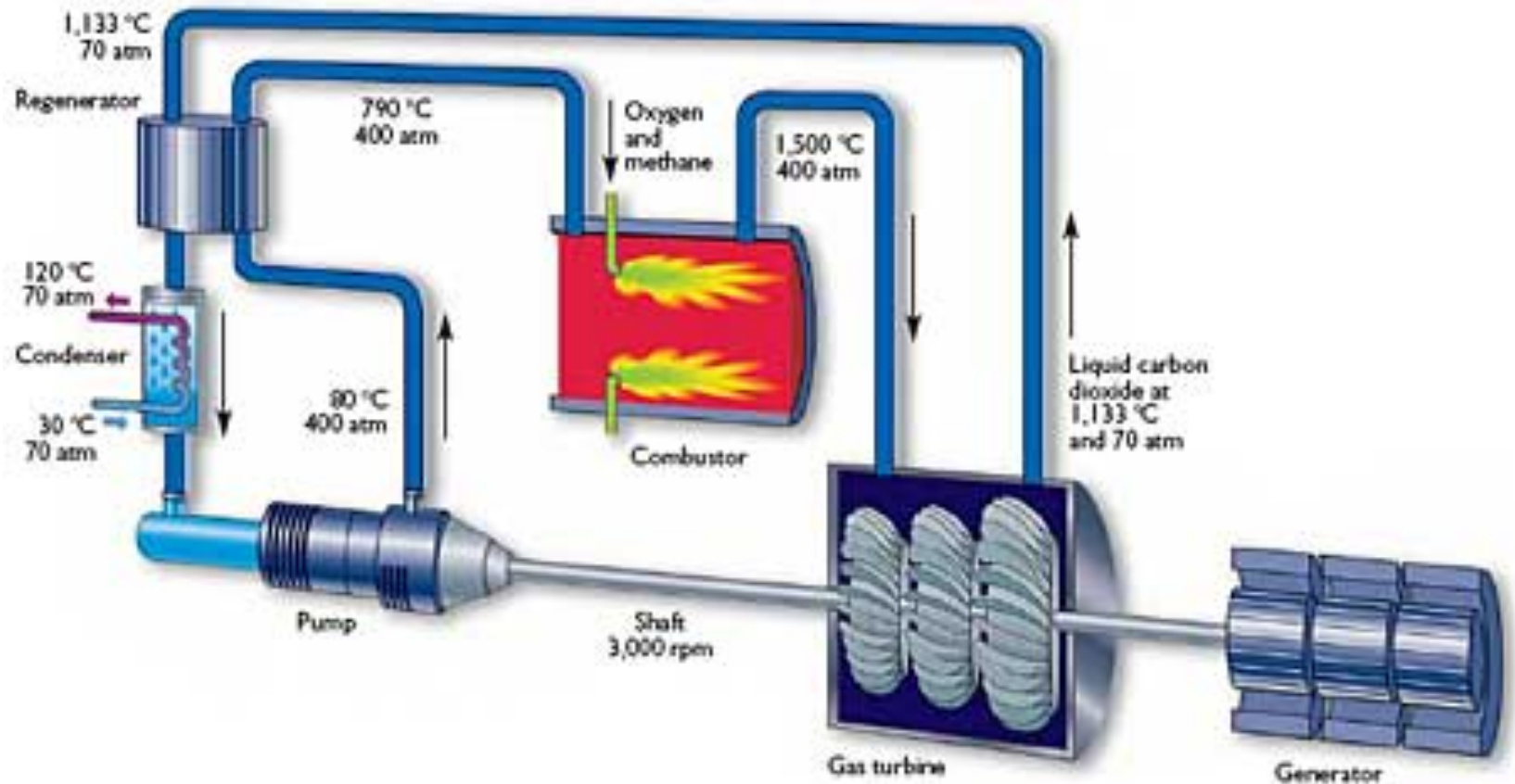
* J. H. Ausubel, "Big Green Energy Machines," The Industrial Physicist, AIP, pp.20-24, Oct./Nov., 2004.

TOKYO ELECTRIC ZERO EMISSION HIGH EFFICIENCY POWER PLANT DESIGN

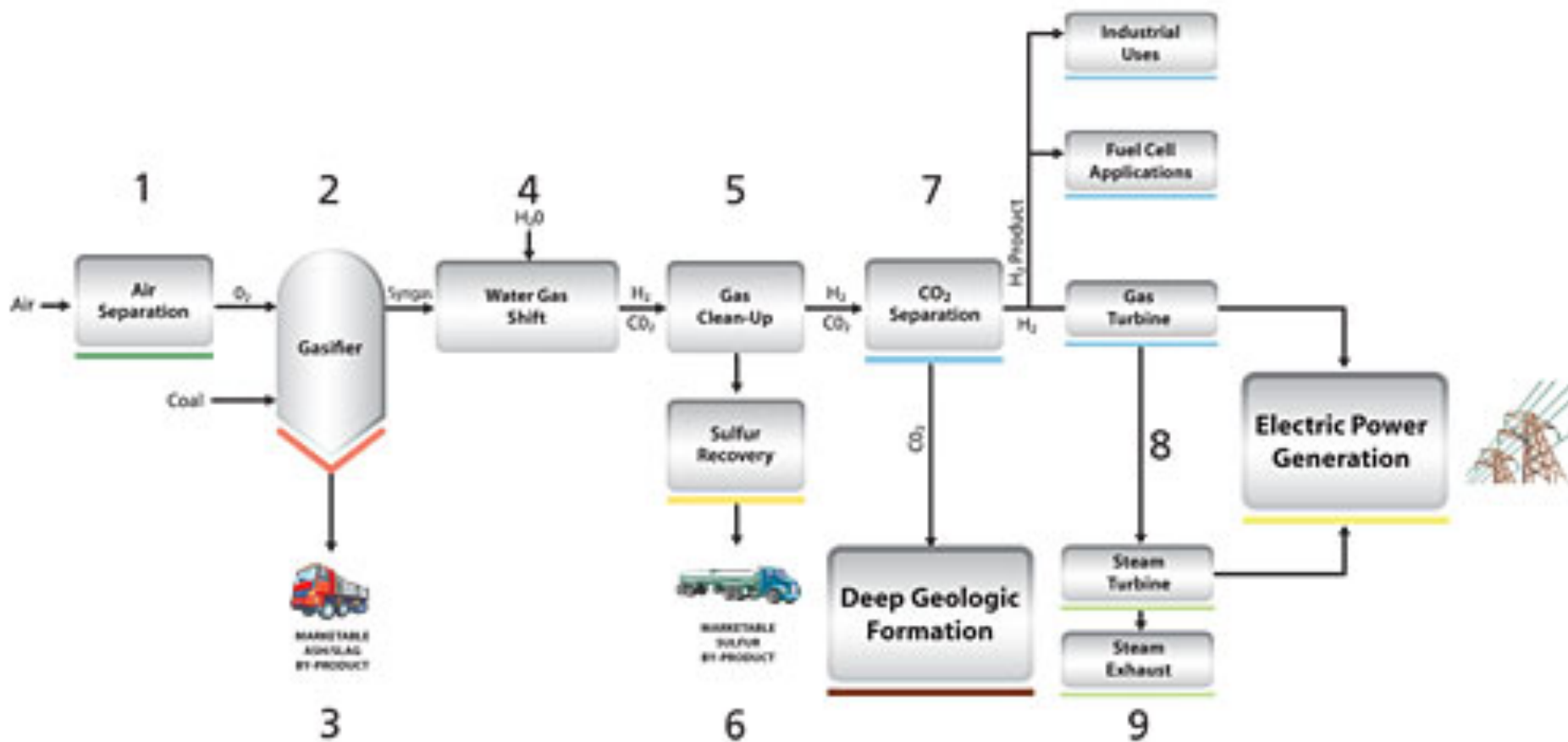
EXTREME ENVIRONMENT:

- > 1500 °C Temperatures
- > 70 atm Pressures
- Corrosive Gases, Liquids (acids), Melts

Methane (Natural Gas: Free from Sulfur, mercury, other hazards)

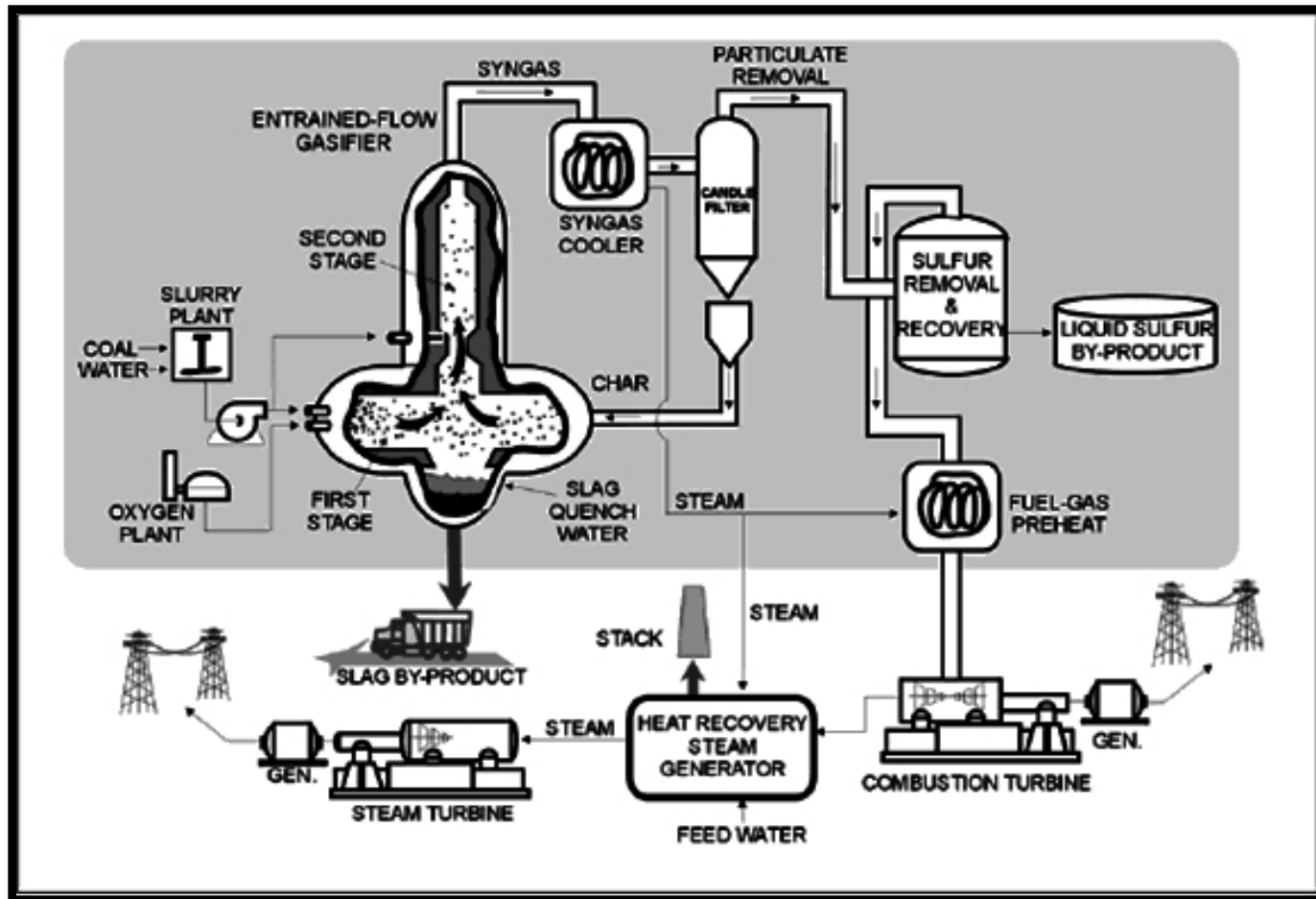


FutureGen's Integrated Technologies



TYPICAL COAL TO ELECTRIC POWER PATH – A DIRTY PROCESS

CHINA 2008 : A NEW COAL POWER PLANT EVERY 2 WEEKS



Ref: Call for Undergraduate Research in Energy & Sustainability Summer Internships for 2008, Department of Chemical & Biological Engineering, *Illinois Institute of Technology*, Prof. Donald J. Chmielewski

GE's H system Gas Turbine



System Test had 3500 gauges and sensors

Uses Firing Temperature of 1430 °C

R. Matta, et.al, “ Power Systems for the 21st Century,” GE Power Systems Publication GER3935B, Oct. 2000.

Siemens Advanced SGT6-6000G Gas Turbine



Produces 58% combined cycle efficiencies with near 250 MW output at 60 Hz.

Combustion Section Temperatures ~ 1500 °C

THE NEED:
PRECISION RELIABLE SENSORS for GAS Temperature and Pressure
Measurement to Keep
Plants at Operating at Super Critical Conditions

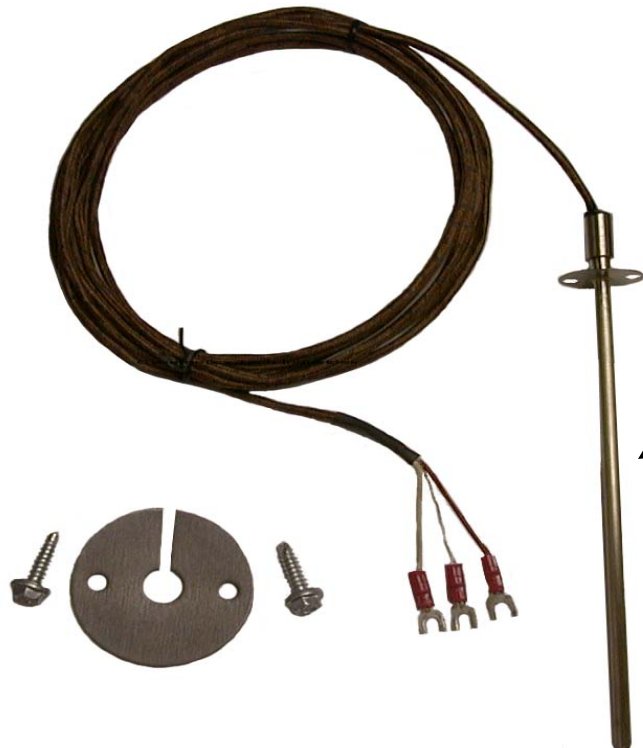
Any Options?

-- ALL Electronic Sensor Chips ? Fail after ~ 500 °C (Insulation Breakdown)

-- Silica/Glass Fiber Optics (Single Mode) – Fail after ~ 900 °C (Grating Erasure)

How does Extreme temperature Measurement get done today?

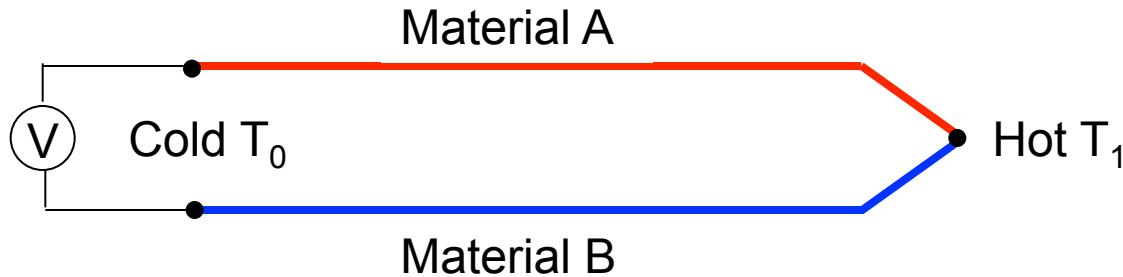
Platinum/Rhodium High Temperature Thermo-Couple (TC)
All-Electrical Technology is used to Measure Extreme
Temperature



Note:
Need to Encase in Custom
Magnesia (MgO) or Alumina
Insulating Ceramics – Can
Reach 1900 °C

Image courtesy: Cybernetics Technical Industries Inc.

Thermocouple Design

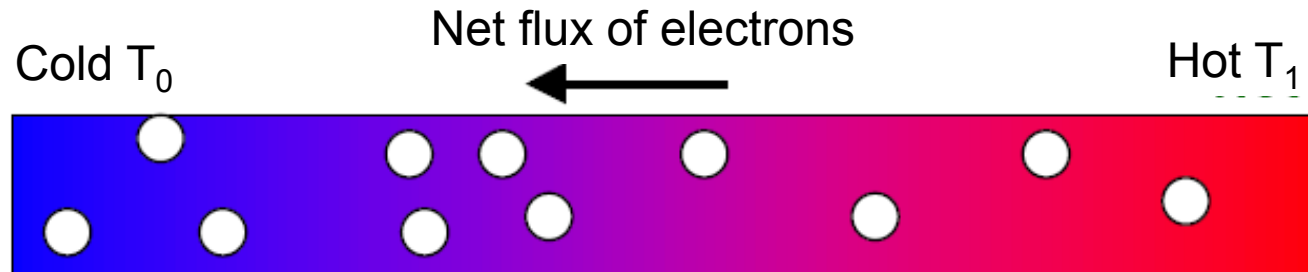


- Dissimilar materials A and B
- Net EMF as measured by the voltmeter is a function of the temperatures T_0 and T_1 and composition of the two materials (Seebeck effect* --- Thomas Johann Seebeck 1821)
- Net EMF = $V_A(T_1, T_0) - V_B(T_1, T_0)$ measured in volts

EMF: Electromotive Force – Measure of Electric Potential/Voltage

*<http://www.uni-konstanz.de/FuF/Physik/Jaeckle/papers/thermopower/node1.html>

How Thermocouples Work



- When two ends of a material are at different temperatures T_0 and T_1 , there is a charge imbalance between the two ends
- This results in an induced thermoelectric voltage $V(T_1, T_0)$ between the two ends

What are the limitations of the Best TC Technology?

Present **TC Technology** under extreme engine conditions are:

- Structurally unreliable (develop cracks in the ceramic insulation – moisture retention making it conductive, can explode)
- Give inaccurate and erratic readings
- Readings intrinsically depend on a % of measured extreme temperature, i.e., gets worse at higher temperatures- caused by Compositional variations in wire alloy – varying EMF properties along length

Type	Combination		Working Temperature Range/°C			Tolerance/°C
	-ve	+ve	Bare wire only		Metal Clad form	
			Continuous use	Intermittent use		
S	Pt	10% Rh/Pt	200-1500	200-1650	200-1300	IEC 584-2 Class 1 or 2
R	Pt	13% Rh/Pt	200-1500	200-1650	200-1300	IEC 584-2 Class 1 or 2
B	6% Rh/Pt	30% Rh/Pt	200-1600	200-1750	200-1450	IEC 584-2 Class 1 or 2
	20% Rh/Pt	40% Rh/Pt	200-1700	200-1850	200-1450	8.0
	Iridium	40% Ir/Rh	1000-2100	-	N/A	10.0
	0.03% Fe/Au	Chromel	1-300K	-	N/A	-

Tolerance Classes

Class 1 = $\pm 1^{\circ}\text{C}$ or $\pm \{1 + (t - 1100) \times 0.0003\}^{\circ}\text{C}$

Class 2 = $\pm 1.5^{\circ}\text{C}$ or $\pm 0.0025t^{\circ}\text{C}$

Class 3 = $\pm 4^{\circ}\text{C}$ or $\pm 0.005t^{\circ}\text{C}$

Whichever is the greater and where t is temperature in °C

Table of tolerance values

Temperature °C	Class 1 ±/°C	Class 2 ±/°C	Class 3 ±/°C
0 - 600 incl.	1.0	1.50	4.0
700	1.0	1.75	4.0
800	1.0	2.00	4.0
900	1.0	2.25	4.5
1000	1.0	2.50	5.0
1100	1.0	2.75	5.5
1200	1.3	3.00	6.0
1300	1.6	3.25	6.5
1400	1.9	3.50	7.0
1500	2.2	3.75	7.5
1600	2.5	4.00	8.0
1700	-	4.25	8.5

Availability

Type	Class 1	Class 2	Class 3
S	x	x	
R	x	x	
B		x	x

The temperature scale used in ITS-90 for which the fixed points are as follows:-

Zinc point = 419.53°C

Gold point = 1064.18°C

Palladium Point = 1553.5°C

Platinum Point = 1768.1°C

~ **± 0.2 %** →

Who does TC Probes?

Engine/Turbine Manufacturers design custom Temperature Probes based on Highly Packaged / Protected TC Technology

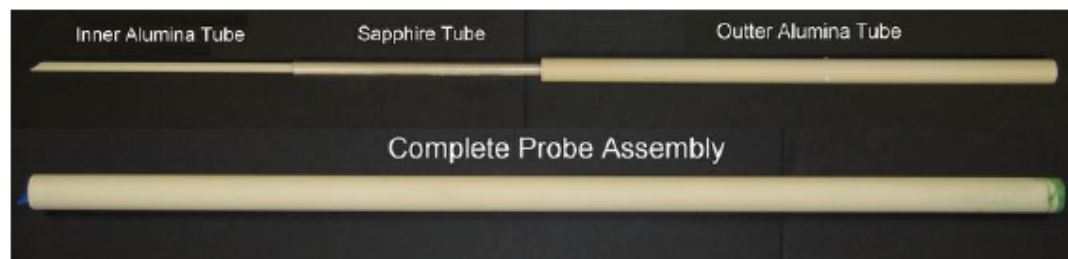
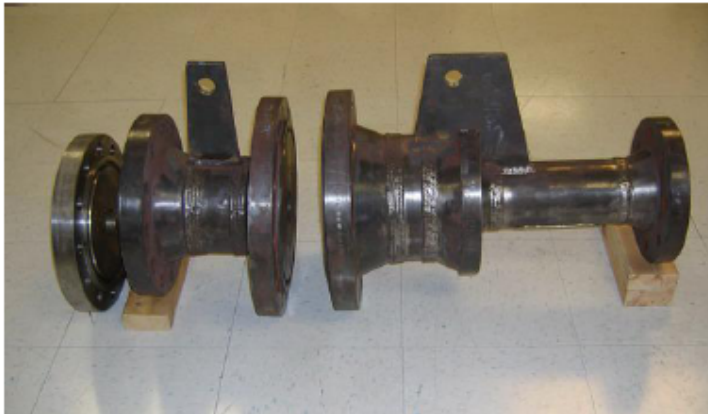
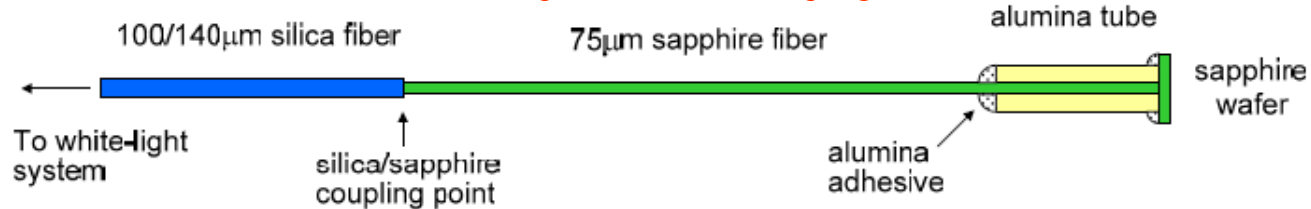


Image courtesy: L&L Kilns Inc.

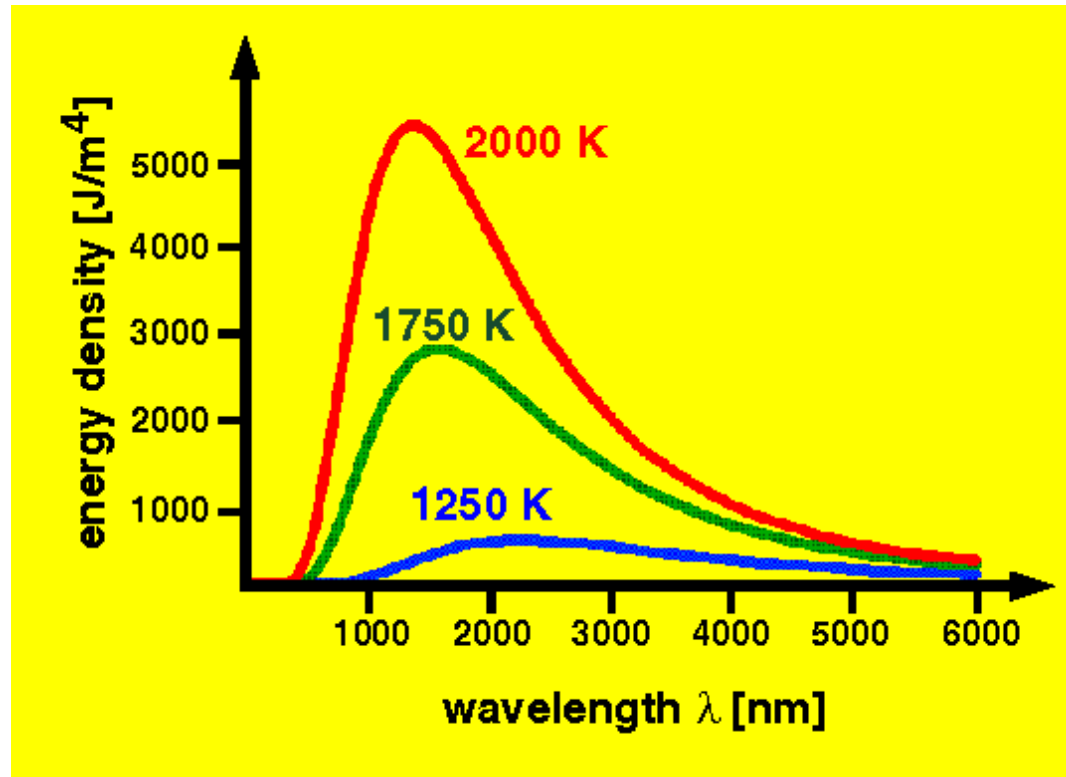
Fiber-Optic Probes?

Same Packaging Problem as TCs – Protect the Flexible and Thin/Brittle Optical Fiber and related frontend optics generally requiring a mix of packaging materials- CTE Mismatches

Multi-Mode Fiber-Optics for Robust Coupling – Causes Multi-Mode Interference/Noise



+100 years of Blackbody Radiation & Temperature Dependence



Max Planck

$$I(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda kT}} - 1} \cdot \varepsilon(\lambda, T)$$

$\varepsilon(\lambda, T)$ Specific Emissivity of Material

Radiation Thermometry - Pyrometers

- Options:

--- **Direct View of Near BB radiation** – Problem- Changing Gas/Combustor Wall Emmissivity Issue

- **Emmissivity Calibration via 2-wavelength** – Problem – Optical Window Dirty

- **OK for fixed clean material production- Steel Melts Production Factory**
(Pioneer: Prof. of Chemical Engg. Hoyt Hottel- 1924-68 at MIT)

--- **Indirect View of Protected Target Material BB radiation**

- OK as No window and changing emissivity issue BUT Problem of light coupling and Multi-material issue (couple light to optical fiber – NASA– Coarse Temperature Resolution and Multi-Material Design – Mechanical Breakdown issues)

**Indeed: There is some Promise in Pyrometry
For Coarse Reliable Temperature Measurements**

Is There An Extreme
Temperature Sensor Design
Without
the TC & Optical Fiber Probe
Packaging
& Reliability Issues?

RELIABLE SOLUTION: THICK SINGLE CRYSTAL SILICON CARBIDE

Melting Temperature ~ 2500 °C
Resistant to Chemical Attack (Acids, Hot Gases)

Mechanically Robust

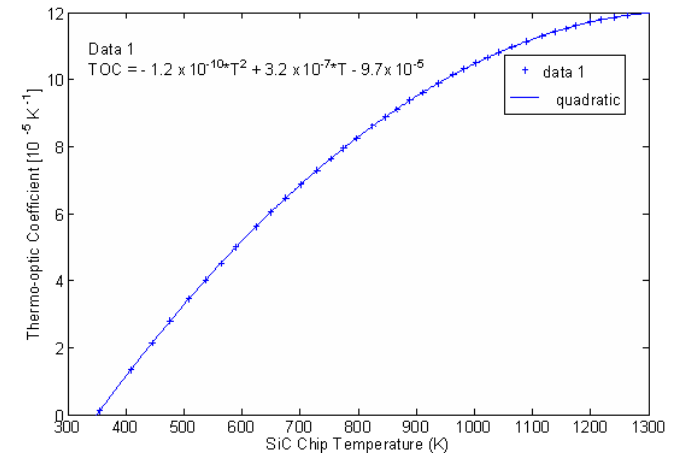
- Handles 1 GPa (10,000 atm) Yield Stress
- Allows Elastic Deformation in the Small Deflection Regime Due to Pressure

Excellent Atomic Scale Flatness
Minimal Optical Wavefront Spoiling

High 2.55 Refractive Index
Strong 20% SiC/Air Reflectivity
At EYE SAFE Infrared Band (1550 nm)

Natural Interferometer Chip

Single
Crystal
SiC
Chip



* Refractive Index “n” Changes With Temperature T
& dn/dT (Thermo-Optic Coeff.) Changes Quadratically with T

For SiC, can make the 2-Beam Interference Approximation:

$$P_m = K \cdot R_{FP} \approx K \left[R_1 + (1 - R_1)^2 R_2 + 2(1 - R_1) \sqrt{R_1 R_2} \cos \theta \right] \quad \theta = \frac{4\pi n(T) d(T)}{\lambda}$$

What is new about our approach?

Wireless

+

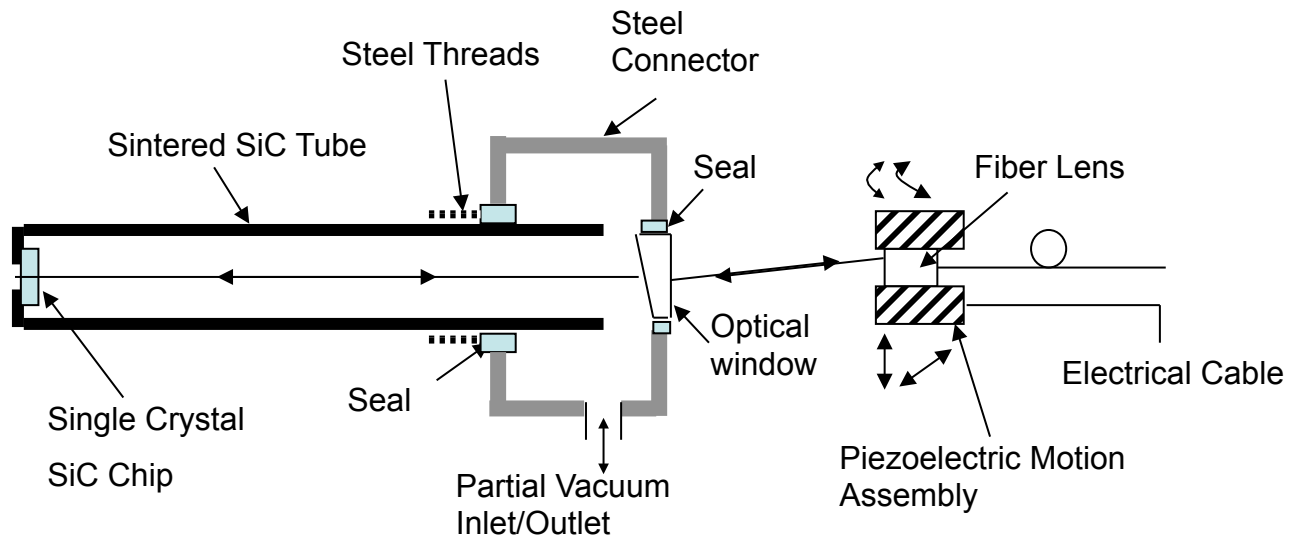
Wired Optics



Extremely Hot

Thermal
Isolation

Cool Section



What is new about our approach?

- Single Crystal SiC + Sintered SiC Probe
- Single material (CTE matched) – Robust frontend for extreme zone
- Temperature Reading Independent of Intrinsic % Increasing Temperature Error

Eliminated Fundamental TC Limitations

Front-End Probe

Unassembled



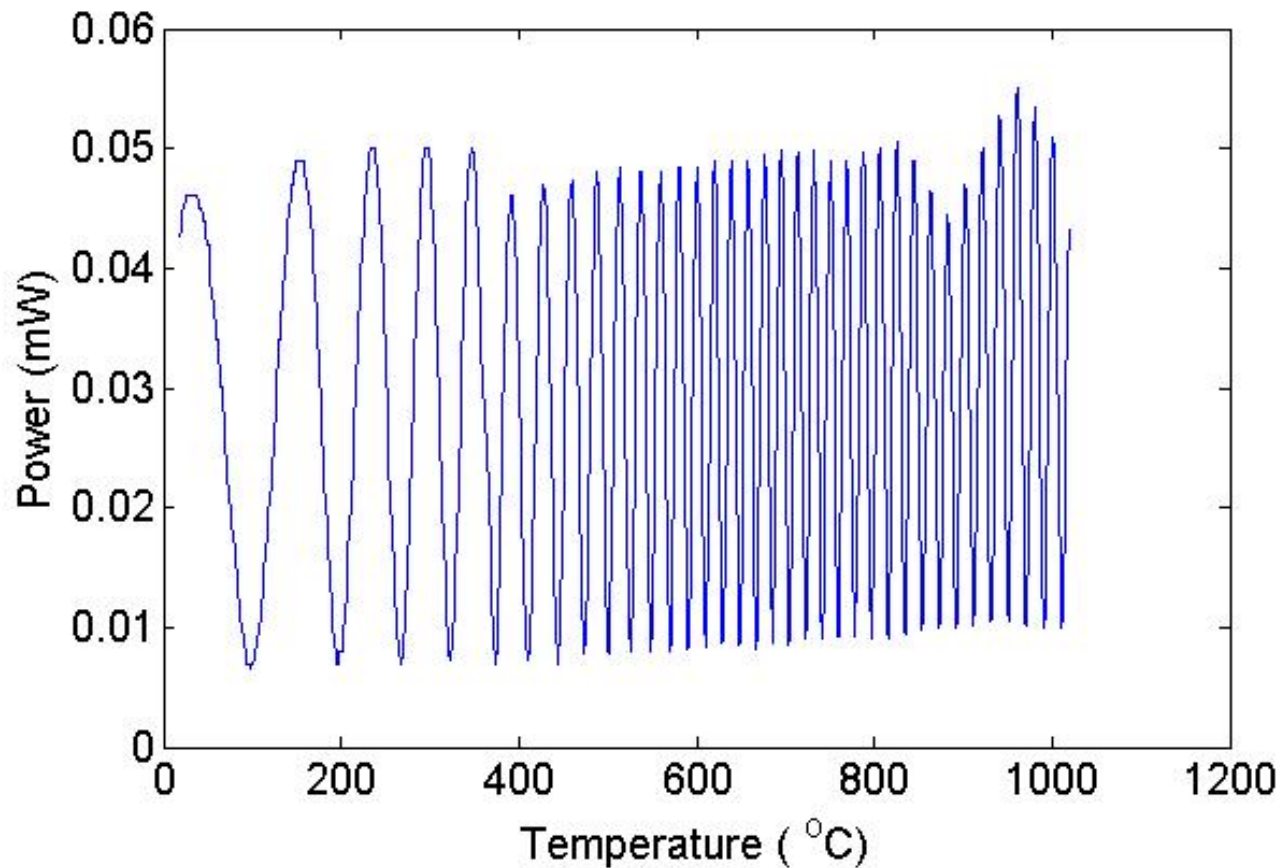
Assembled



Images courtesy: Nuonics, Inc.

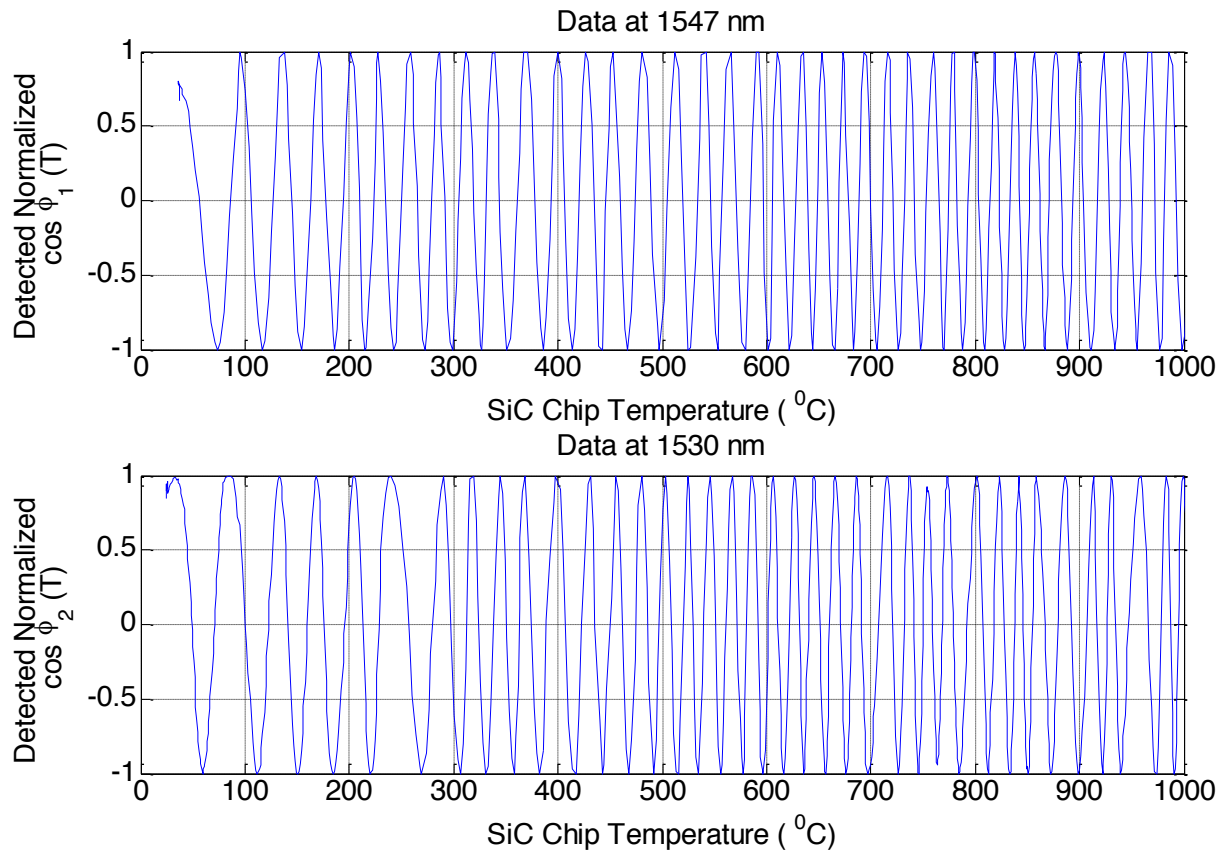
Optical Power Variation with Temperature & Wavelength

Raw power at $\lambda = 1565.32$ nm



Deploy Wavelength-Coded Signal Processing to Find Temperature

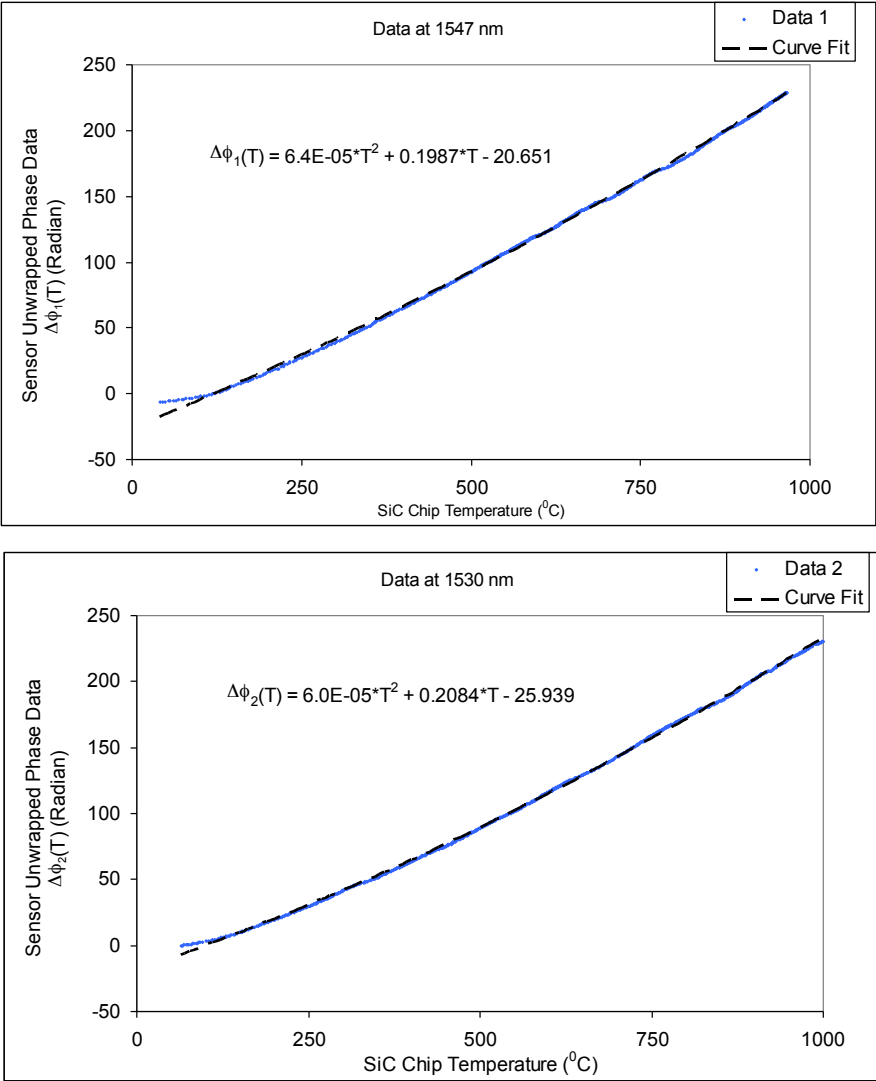
First SiC Wireless Temperature to 1000 °C



Computer Normalized $\text{Cos}\{\phi(t)\}$ Measurements

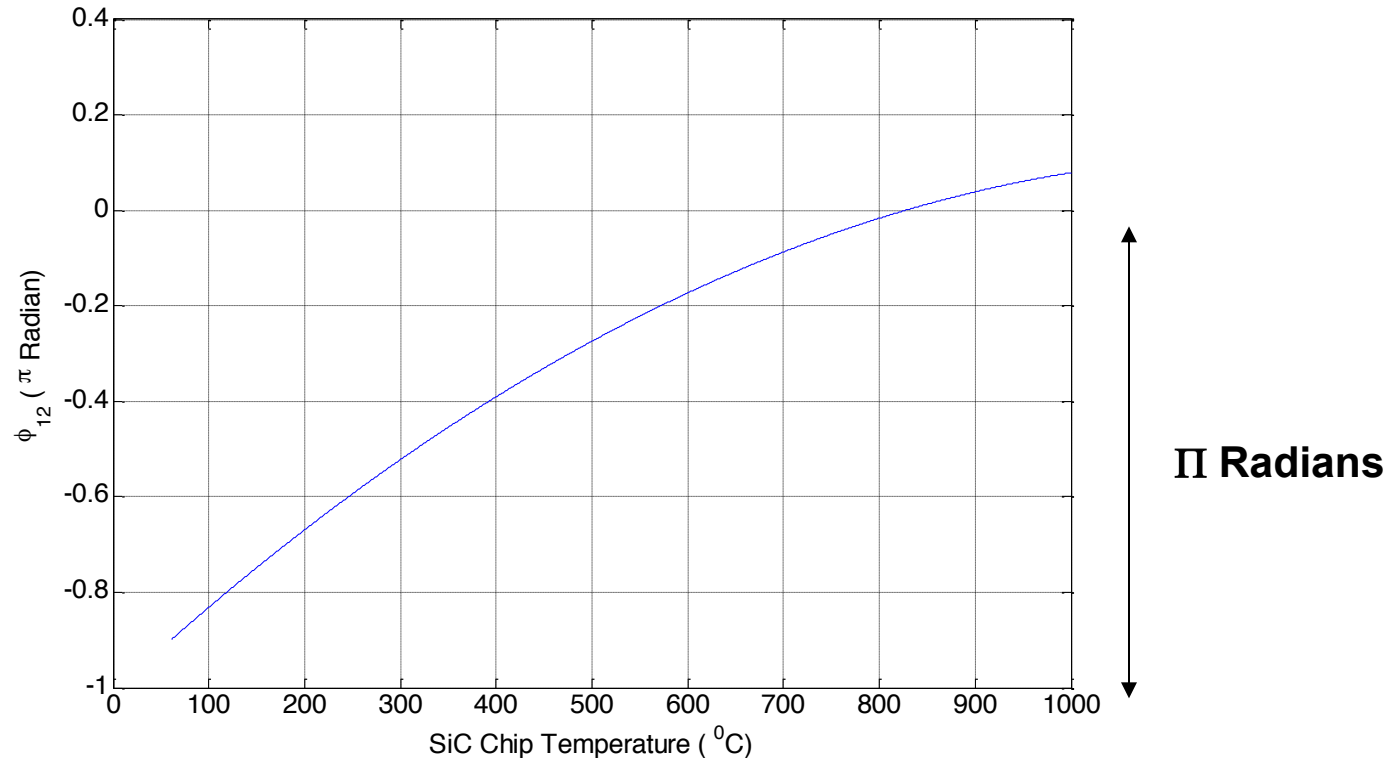
Note: Ambiguous $\text{Cos}(\text{OPL})$ Values Versus Temperature

Sensor Unwrapped Phase Change Data $\Delta\phi$ (T) in Radians versus SiC Chip Temperature with data taken at 1530 nm & 1547 nm. Weak quadratic curve fit is achieved.



$\phi(T)$ phase ambiguity is removed by taking into consideration the number of cycles recorded and adding 2π radians after each cycle to get an unwrapped phase change value across the designed temperature range of room to 1000 C.

Unwrapped Phase Difference $\phi_{12}(t)$ Condition for Unambiguous Temperature Measurement

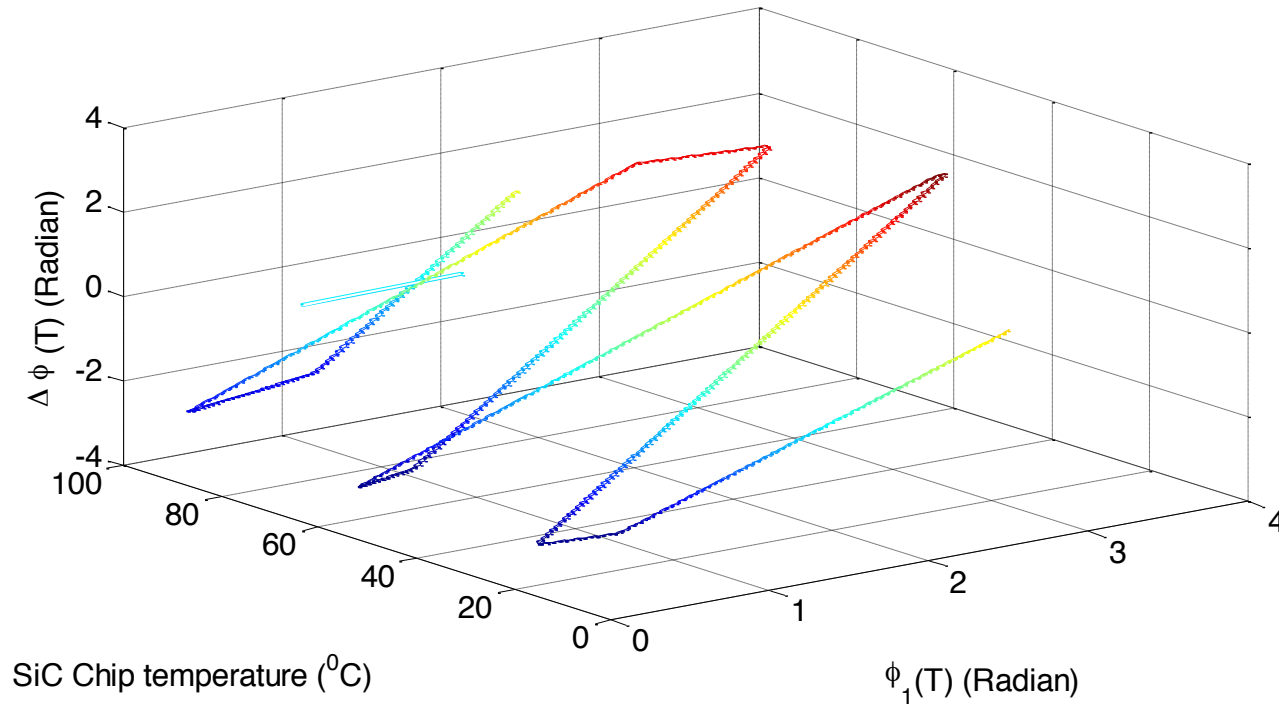


The curve fits to the $\Delta\phi_1$ and $\Delta\phi_2$ data are used to calculate $\phi_{12} = \Delta\phi_1(T) - \Delta\phi_2(T)$ and is plotted above.

-- 37 ambiguous cycles at 1547 nm and 37.5 ambiguous cycles at 1530 nm

-- Unambiguous temperature measurement via Instantaneous Wrapped Phase Processing using a 3-D Sensor Calibration Table

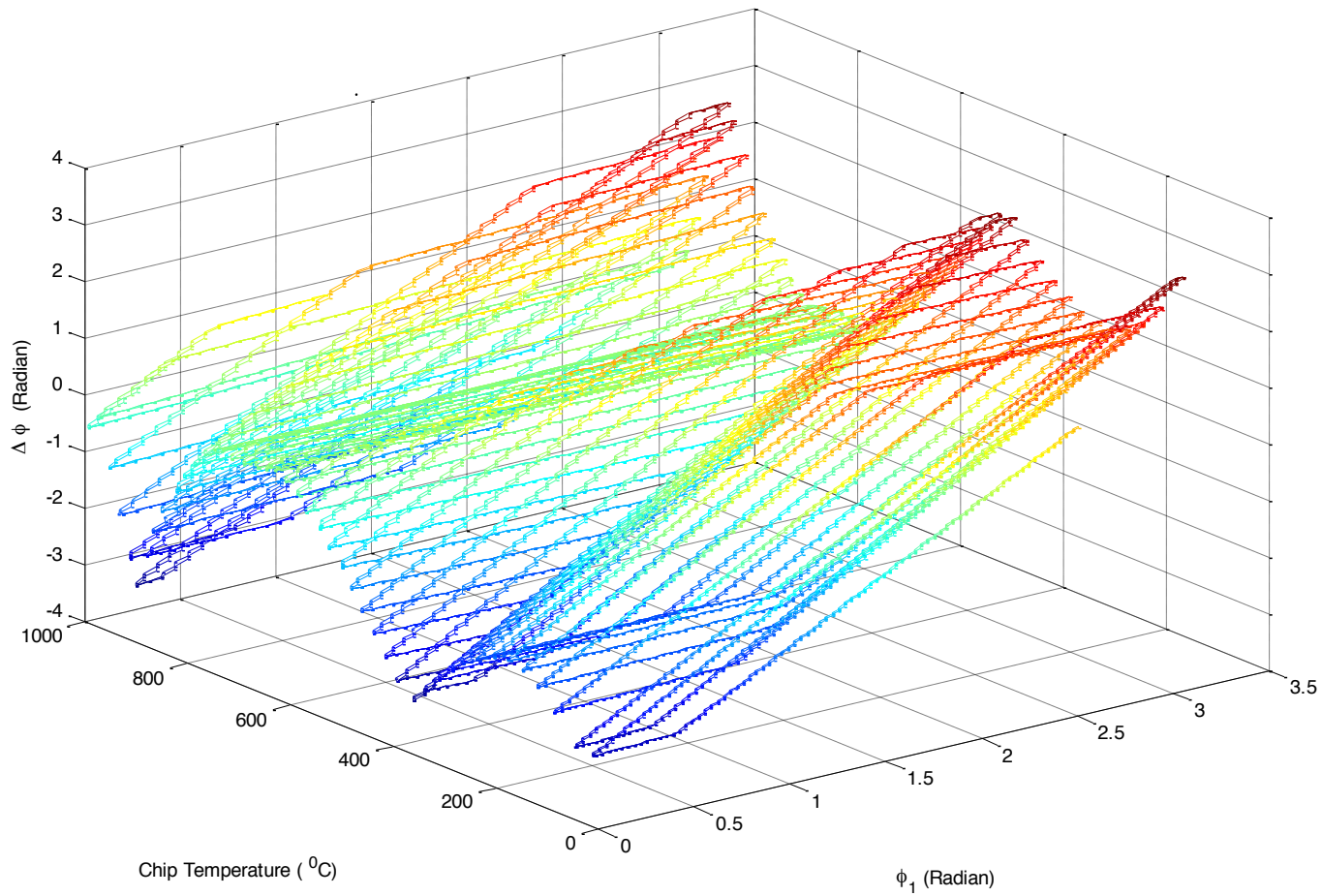
3-D Representation of The Sensor Calibration Chart For The Unambiguous Temperature Measurement of Temperature From Room Conditions To 100 C



Shown is a helical spring like behavior where for every set of values of $\Delta \phi$ and ϕ_1 , there is only one value of the temperature corresponding to that data set

3-D Calibration Chart

Room Temperature to 1000 °C



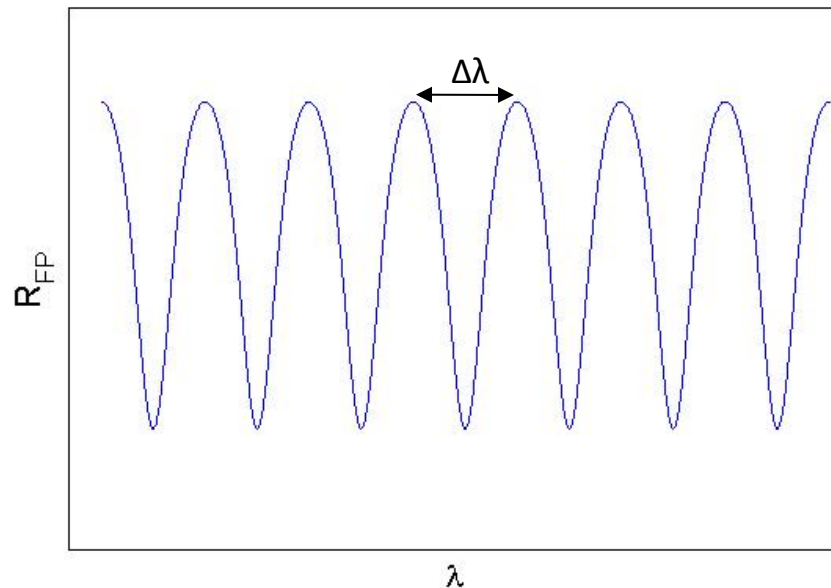
- 1.3 C Temperature Sensitivity; 30 % Sensor Optical Power Efficiency

Alternative Signal Processing Technique for SiC Temperature Sensor Theoretical Analysis

Classic Fabry-Perot Etalon Reflectance

$$R_{FP} = \frac{R_1 + R_2 + 2\sqrt{R_1 R_2} \cos \varphi}{1 + R_1 R_2 + 2\sqrt{R_1 R_2} \cos \varphi}$$

$$\varphi = \frac{4\pi}{\lambda} n(\lambda, T) t(T)$$



$\Delta\lambda$ is the Free Spectral Range (FSR) of the FP etalon

Theoretical Analysis

Difference between maximas or minimas

$$\frac{4\pi}{\lambda_1} n(\lambda_1, T) t(T) - \frac{4\pi}{\lambda_2} n(\lambda_2, T) t(T) = 2\pi k$$

k is an integer

$$\lambda_2 = \lambda_1 + \Delta\lambda \quad n_1 = n(\lambda_1, T) \quad n_2 = n(\lambda_2, T) \quad \Delta n = n_2 - n_1$$

$$\frac{2t(T)}{\lambda_1} \left[n_1 - \frac{n_2}{(1 + \Delta\lambda/\lambda_1)} \right] = k$$

$$\frac{2t}{\lambda_1} \left[n_1 - n_2 \left(1 - \frac{\Delta\lambda}{\lambda_1} \right) \right] \approx k$$

Theoretical Analysis

$$\frac{2t}{\lambda_1} \left[-\Delta n + n_2 \frac{\Delta \lambda}{\lambda_1} \right] = k$$

$$\frac{2t}{\lambda_1} \left[-\Delta n + (n_1 + \Delta n) \frac{\Delta \lambda}{\lambda_1} \right] = k$$

$$\frac{2t}{\lambda_1} \left[-\Delta n + n_1 \frac{\Delta \lambda}{\lambda_1} \right] = k$$

$$\Delta \lambda = k \frac{\lambda_1^2}{2tn_1} + \lambda_1 \frac{\Delta n}{n_1}$$

Theoretical Analysis

For small changes in λ ,

$$\Delta n \approx \frac{dn}{d\lambda} \Delta\lambda$$

$$\Delta\lambda = k \frac{\lambda_1^2}{2tn_1} + \frac{\lambda_1}{n_1} \frac{dn}{d\lambda} \Delta\lambda$$

$$\Delta\lambda = \frac{k \frac{\lambda_1^2}{2tn_1}}{1 - \frac{\lambda_1}{n_1} \frac{dn}{d\lambda}}$$

Theoretical Analysis

Sellmeier Equation for Silicon Carbide

$$n^2(\lambda) = A + \frac{B\lambda^2}{\lambda^2 - C} \quad A = 1, B = 5.5515, C = 0.026406 \times 10^{-12}$$

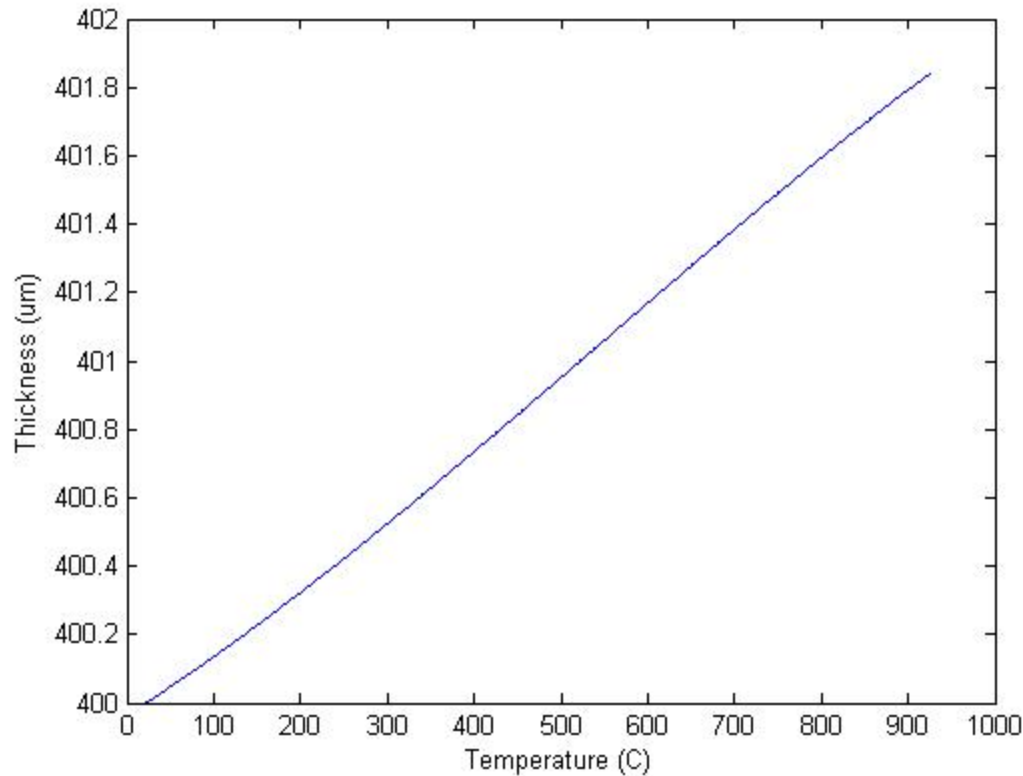
$$\frac{dn}{d\lambda} = \frac{-\lambda BC}{n(\lambda^2 - C)^2}$$

Wavelength separation between maximas or minimas

$$\Delta\lambda = \frac{k \frac{\lambda_1^2}{2t(T)n_1(T)}}{1 + \frac{\lambda_1^2 BC}{n_1(T)(\lambda_1^2 - C)^2}}$$

SiC Chip Thickness as a function of Temperature

$$t(T) = [1 + \alpha \Delta T] t(T_i) \quad \alpha = -1.68 \times 10^{-12} T^2 + 3.60 \times 10^{-9} T + 3.19 \times 10^{-6}$$



Z. Li and R. C. Bradt, "Thermal Expansion and Elastic Anisotropies of SiC as Related to Polytype Structure," Silicon Carbide Symposium (1987).

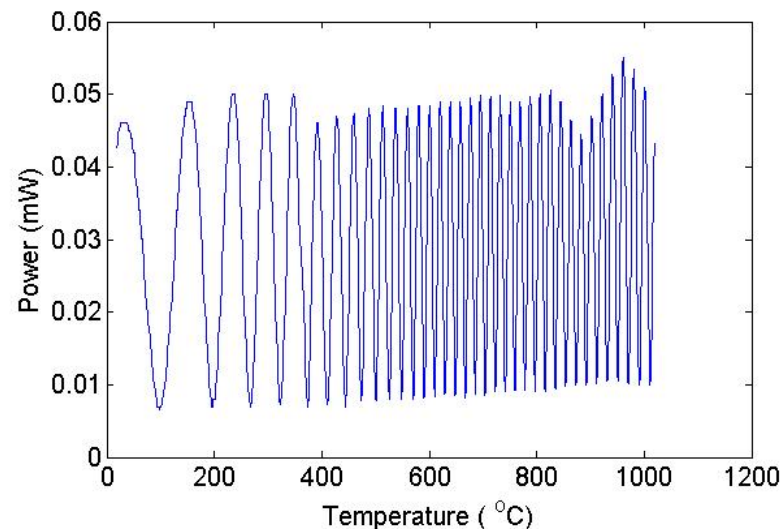
Refractive Index Calculation via Experimental Optical Data

Refractive index as a function of temperature

$$n_1(T) = \frac{\Delta\phi(\Delta T)\lambda_1}{4\pi t(T)} + \frac{n_1(T_i)t(T_i)}{t(T)}$$

$\Delta\phi$ is the unwrapped
phase difference

Raw power at $\lambda = 1565.32$ nm



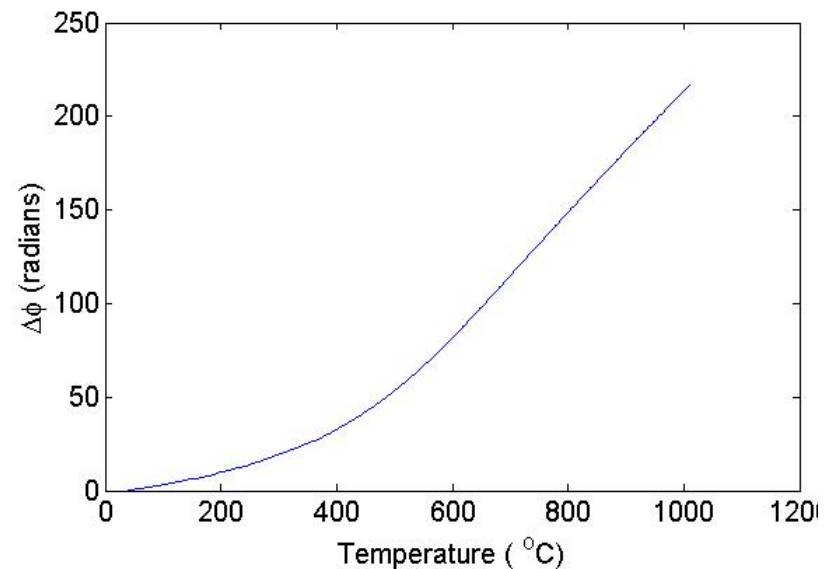
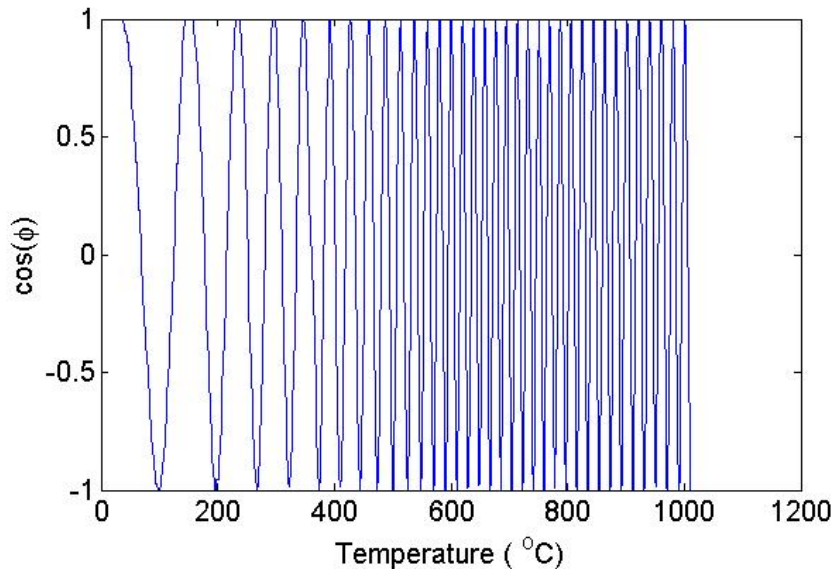
Refractive Index Calculation

Cosine phase

$$\cos(\phi) = 2 \frac{P_m - 0.5 \times (P_{\max} + P_{\min})}{P_{\max} - P_{\min}}$$

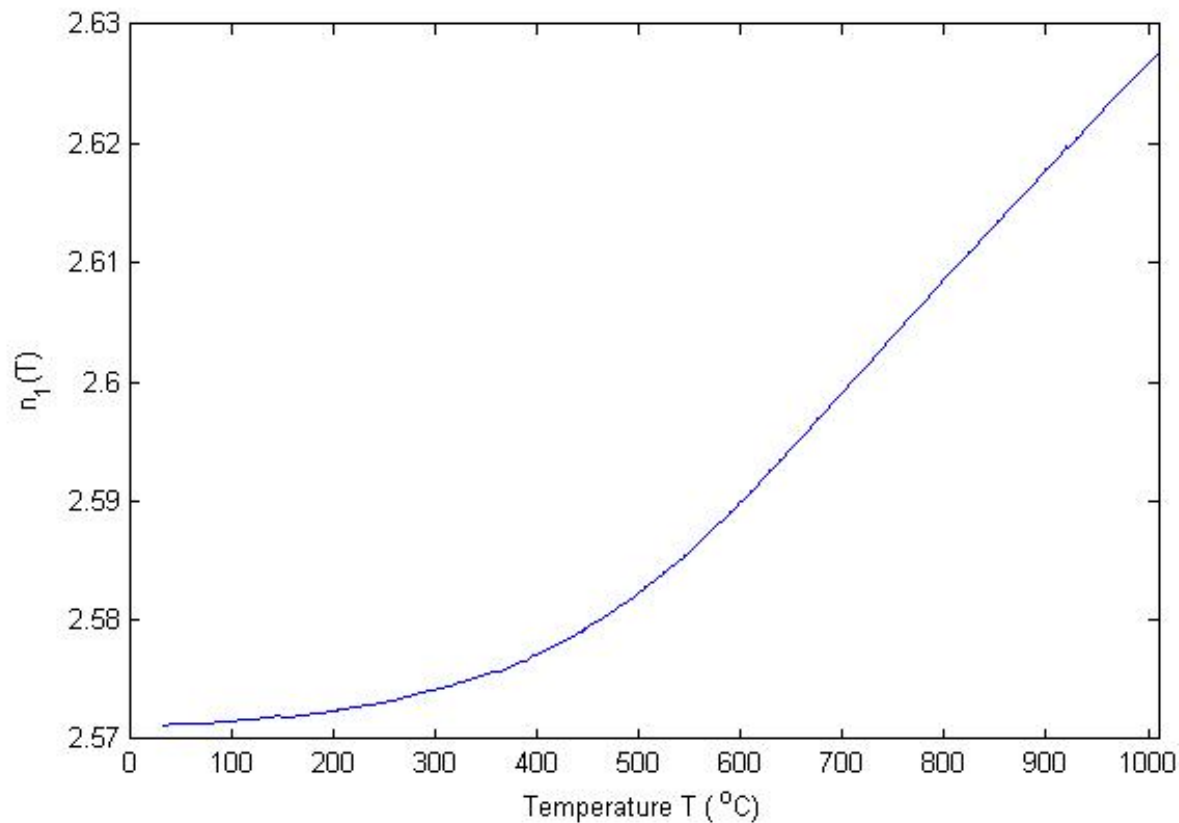
P_m is the raw optical power

Unwrapped phase $\Delta\phi$

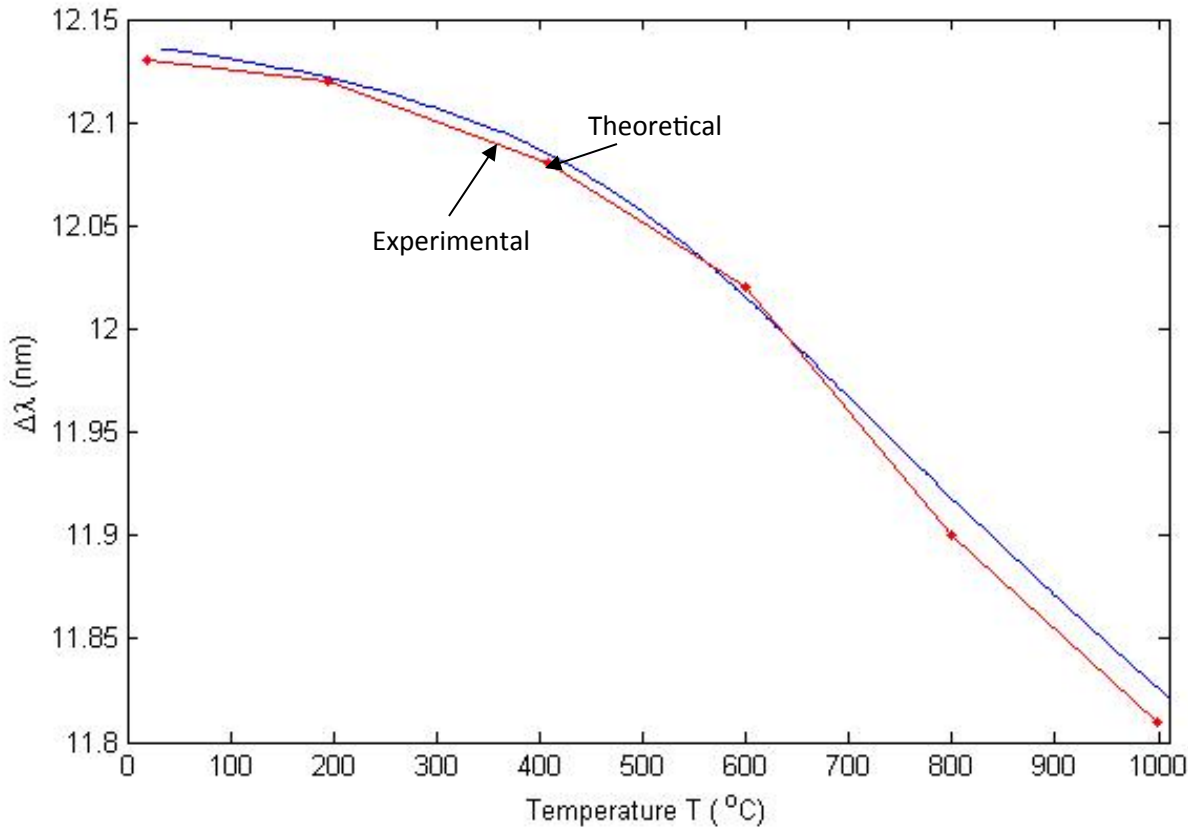


Refractive Index Calculation

SiC Refractive index as a function of temperature



Wavelength Spread vs. T Experimental Data



λ range: 1550 – 1565 nm
SiC chip thickness: 389 μm
 k : 10 (arbitrary)

Total $\Delta\lambda$ change from r.t. to 1000 $^{\circ}\text{C}$: 0.31 nm

Typical T Measurement Resolution: 15 – 20 deg-C

Classical FP Peak Shift

Classic Fabry-Perot Etalon Reflectance

$$R_{FP} = \frac{R_1 + R_2 + 2\sqrt{R_1 R_2} \cos \varphi}{1 + R_1 R_2 + 2\sqrt{R_1 R_2} \cos \varphi}$$

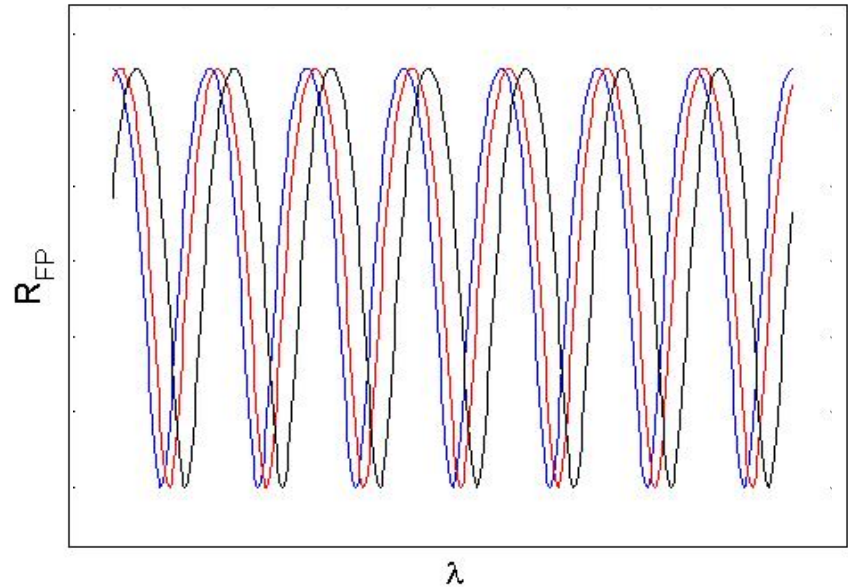
$$\varphi = \frac{4\pi}{\lambda} n(\lambda, T) t(T)$$

At maximas

$$\cos \varphi = 1$$

$$\frac{4\pi}{\lambda_{peak}} n(\lambda_{peak}, T) t(T) = 2m\pi$$

m is an integer



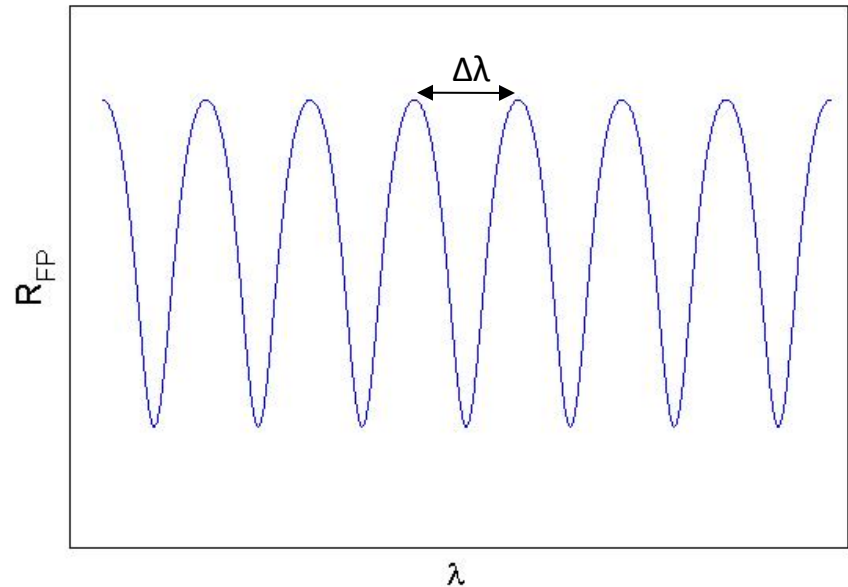
Classical FP Peak Shift

$$\frac{4\pi}{\lambda_{peak}} [n(\lambda_1, T) + \Delta n] t(T) = 2m\pi$$

$$\Delta n \approx \frac{-\lambda BC}{n(\lambda^2 - C)^2} \Delta \lambda$$

$$\Delta \lambda = \lambda_{peak} - \lambda_1$$

$$\lambda_{peak} = \frac{\frac{2t}{m} \left[n_1 + \frac{\lambda_1^2 BC}{n_1(\lambda_1^2 - C)^2} \right]}{1 + \frac{2t\lambda_1 BC}{mn_1(\lambda_1^2 - C)^2}}$$



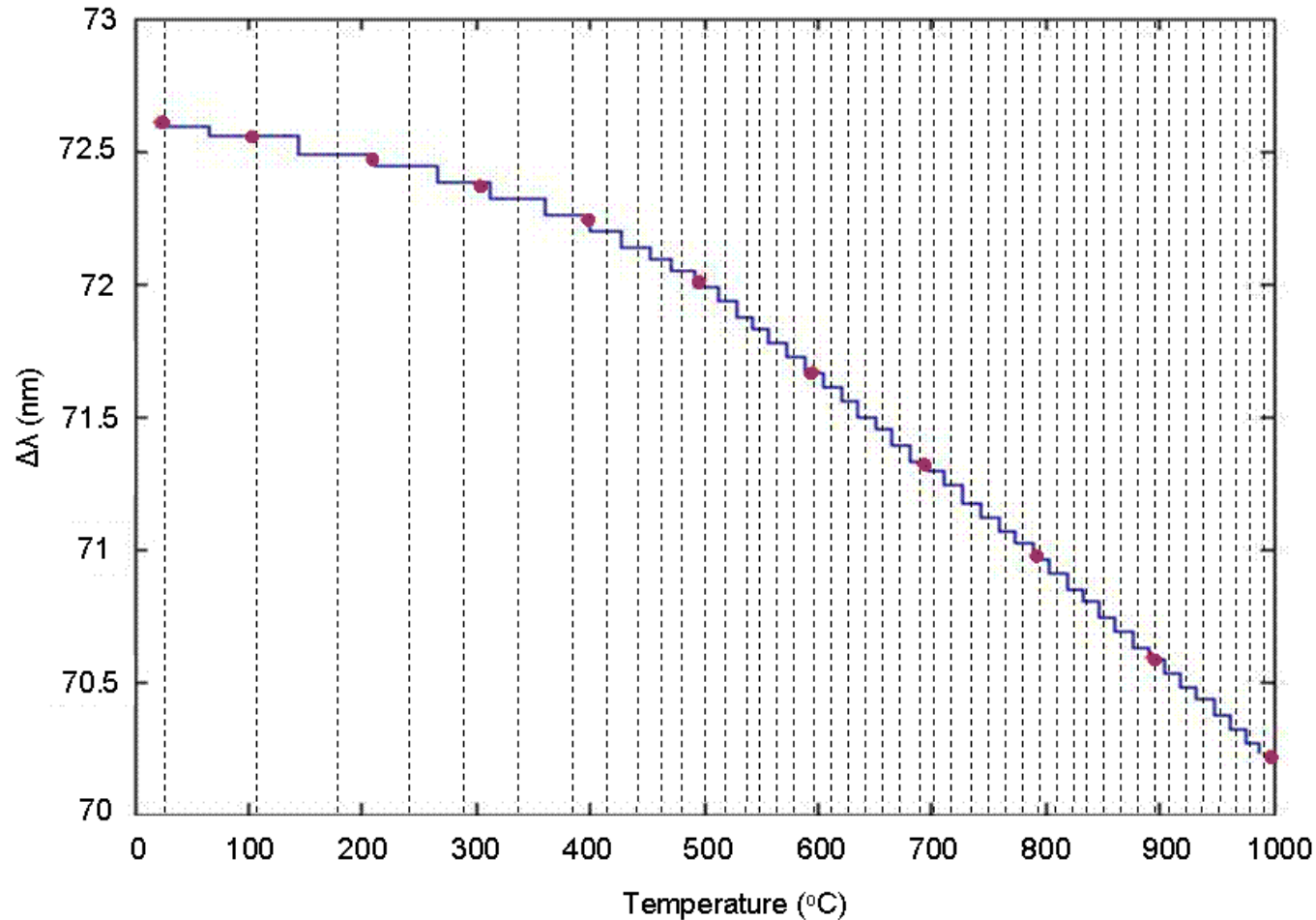
Can be used to **accurately** measure temperature within **one FSR** of the FP etalon

Combine Two Temperature Measurement Techniques

- $\Delta\lambda$ gives a coarse value
- k-value needs to be sufficiently high
- λ_{peak} gives a precise value

M. Sheikh and N. A. Riza, "Direct Measurement High Resolution Wide Range Extreme Temperature Optical Sensor using an all-Silicon Carbide Probe," Opt. Lett., Vol. 34, No. 9, May 2009.

Coarse Measurement Experiment

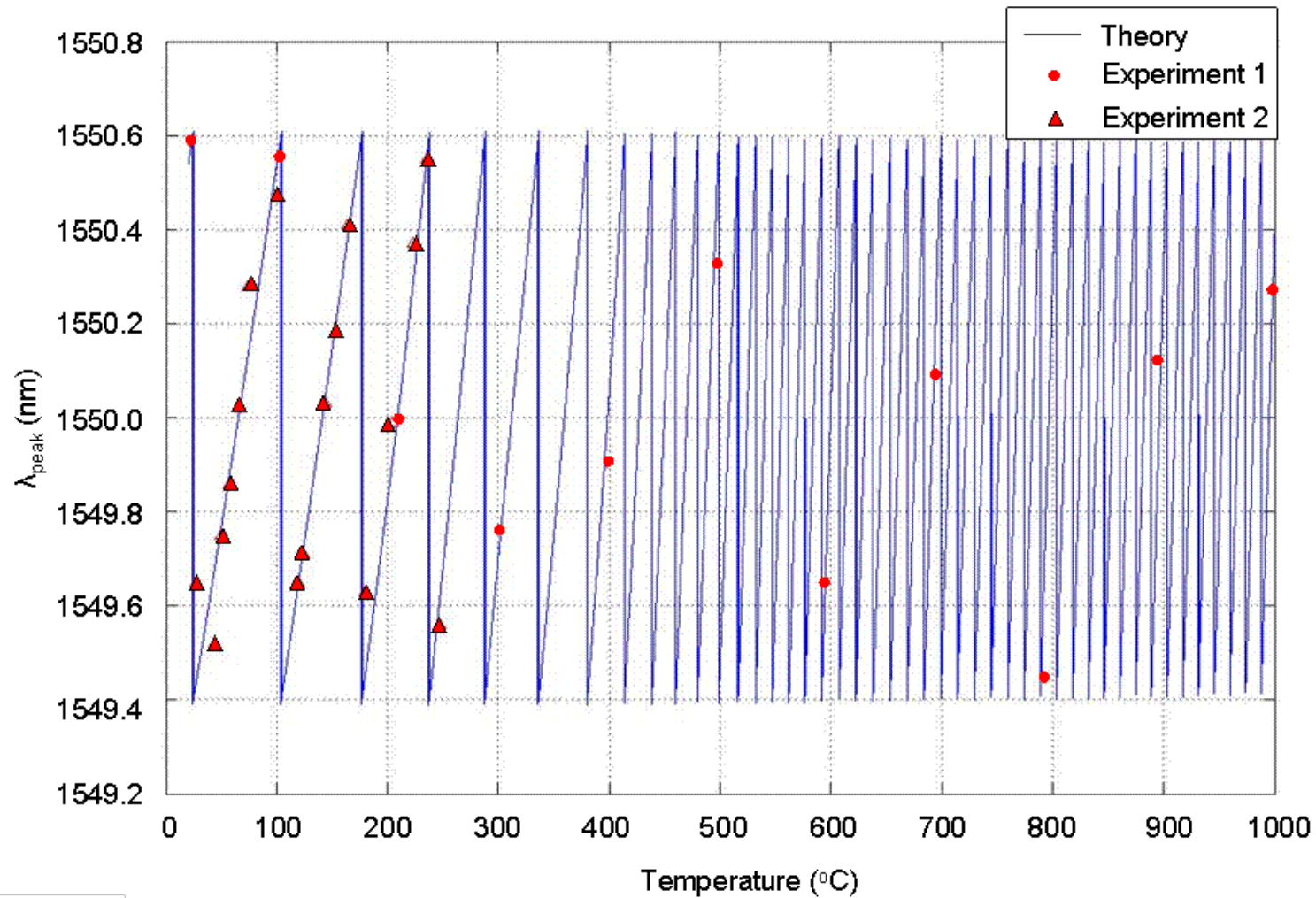


λ range: 1520 – 1600 nm

k : 60 (arbitrary)

Δ ($\Delta\lambda$): 0.04 – 0.05 nm

Fine Temperature Measurement Experiment



Centre wavelength : 1550 nm

Comparative Results

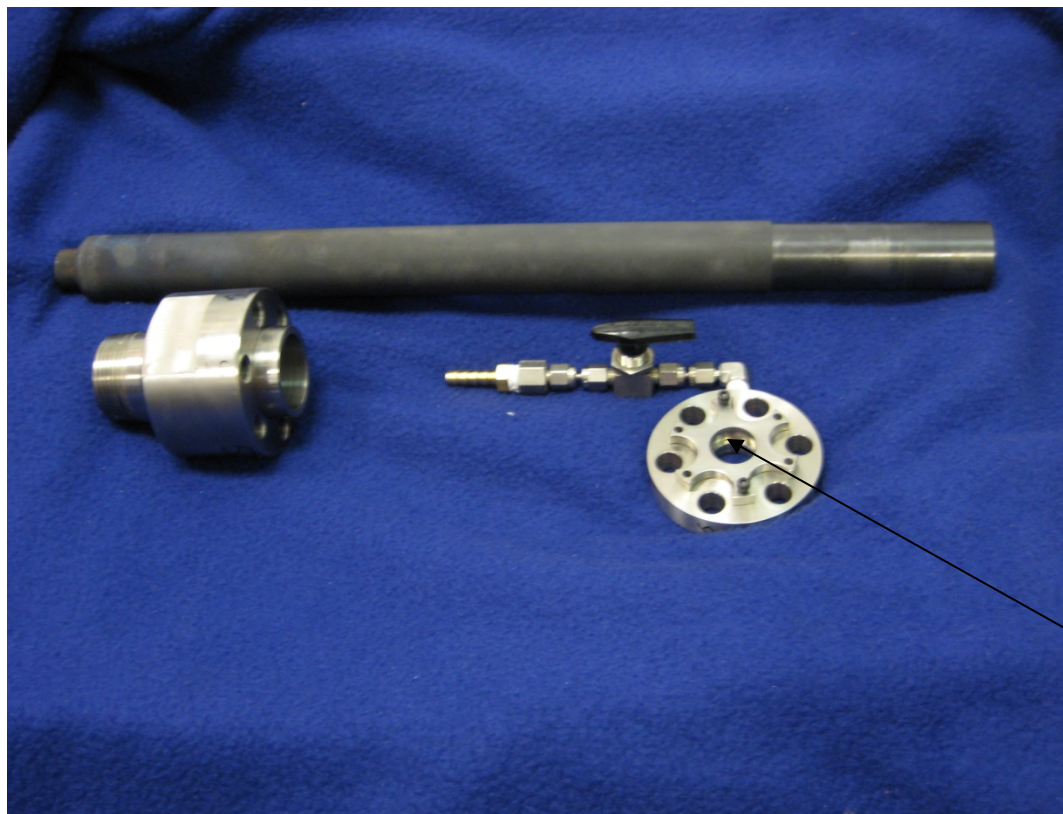
TC T (°C)	OPTICAL SENSOR T (°C)	% DIFFERENCE
21.8	22.9	5.0
102.0	100.8	1.2
209.0	209.1	0.048
303.0	302.3	0.23
397.6	395.7	0.48
496.2	494.6	0.32
595.7	594.9	0.13
693.3	692.8	0.072
791.5	789.3	0.28
894.0	897.6	0.40
997.2	998.4	0.12

Dual Method Signal Processing Summary

- Achieved Direct measurement, wide range, high resolution temperature sensor
- Smaller coarse bin size at higher temperatures
- Resolution varies from 0.66 °C at room temperature to 0.12 °C at 1000 °C
- Comparable to Thermo-Couples

. Un-Assembled SiC Temperature Probe

Solution: Use Sealed Optical Window – Close the Wireless Cavity

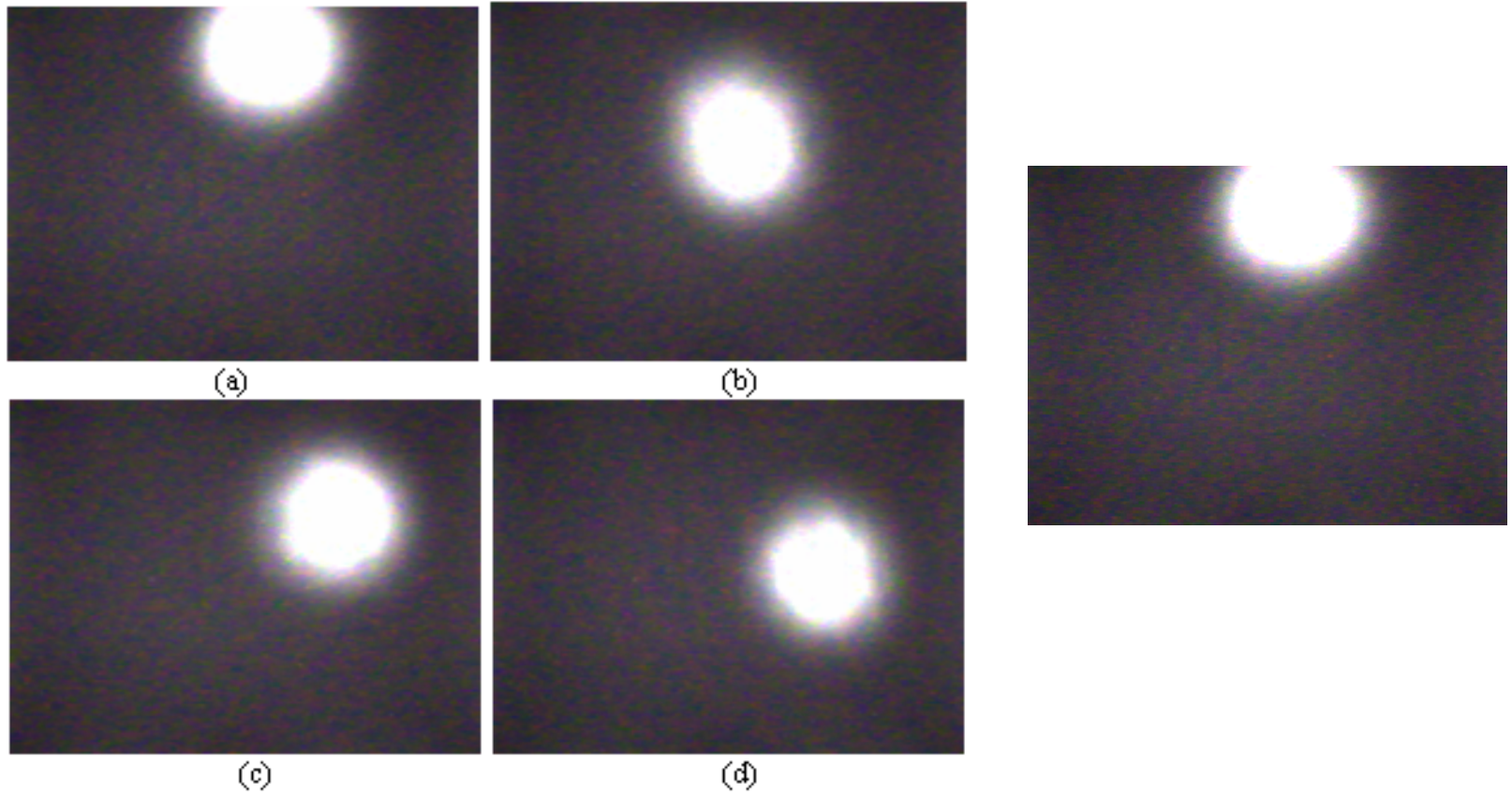


High
Temperature
Window

. Assembled SiC Temperature Probe



1550 nm Beam Motion at ~1000 deg-C due to Air Currents when Probe Input End is Open



Images seen at 1 second intervals at an Oven set temperature of ~1000 deg-C.
Camera view of 8.8 mm (horizontal) by 6.6 mm vertical.

SiC Probe Optical Response Video With Changing Temperature between 450 - 1000 deg-C in Oven

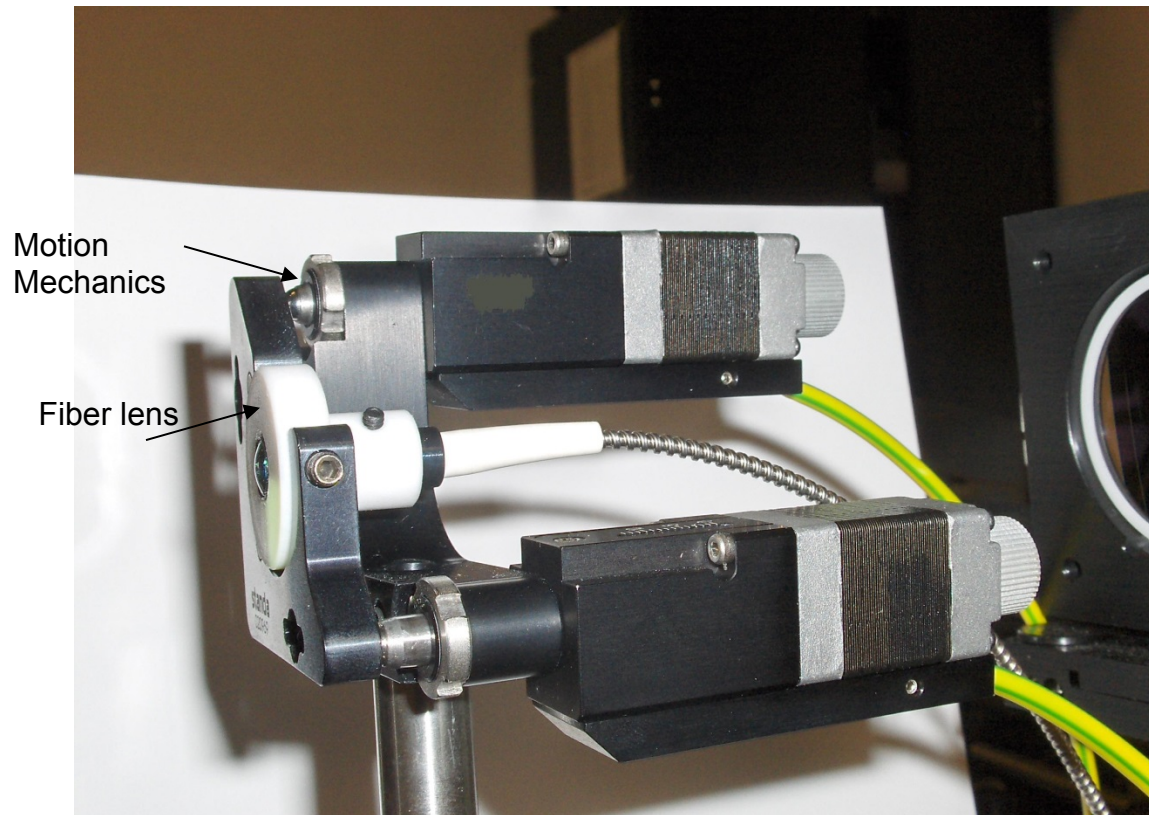


Note

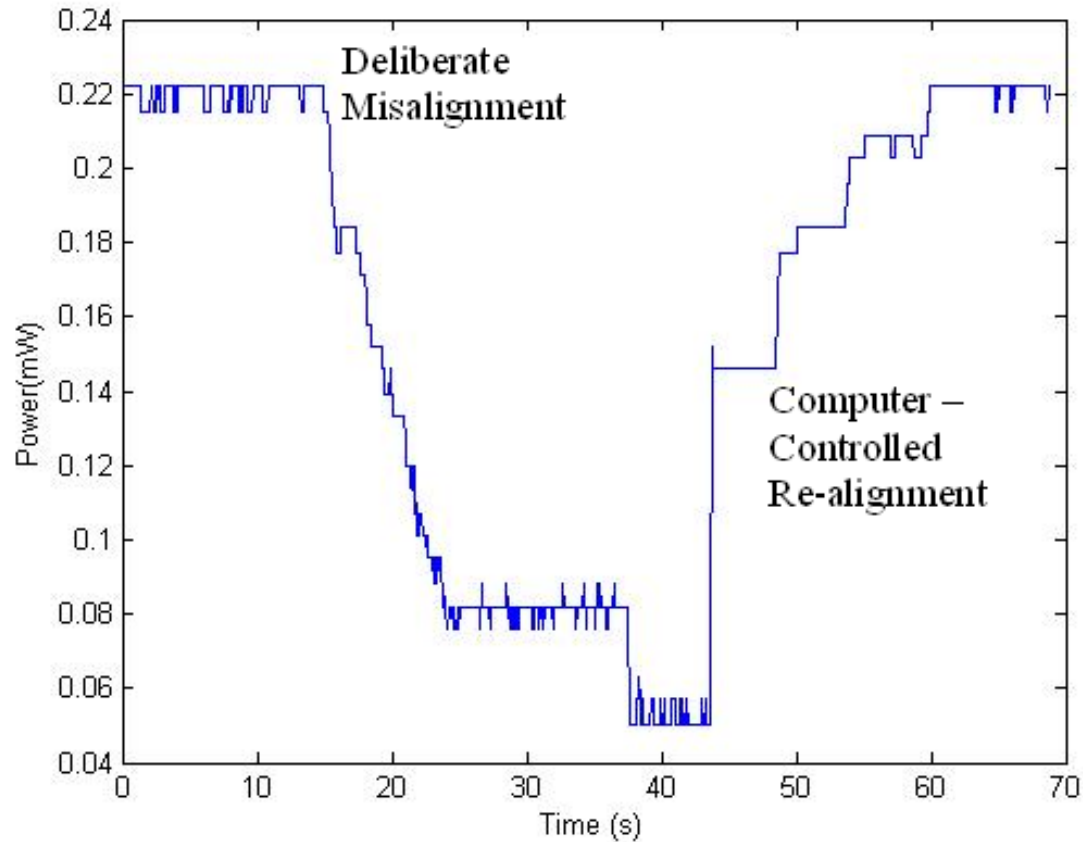
-- Received Beam Motion due to Air Turbulence Effects in Tube Cavity

-- Excellent Bright and Dark States (20 :1)

Designed and Assembled Laser Beam Smart Transceiver Module for Sensor

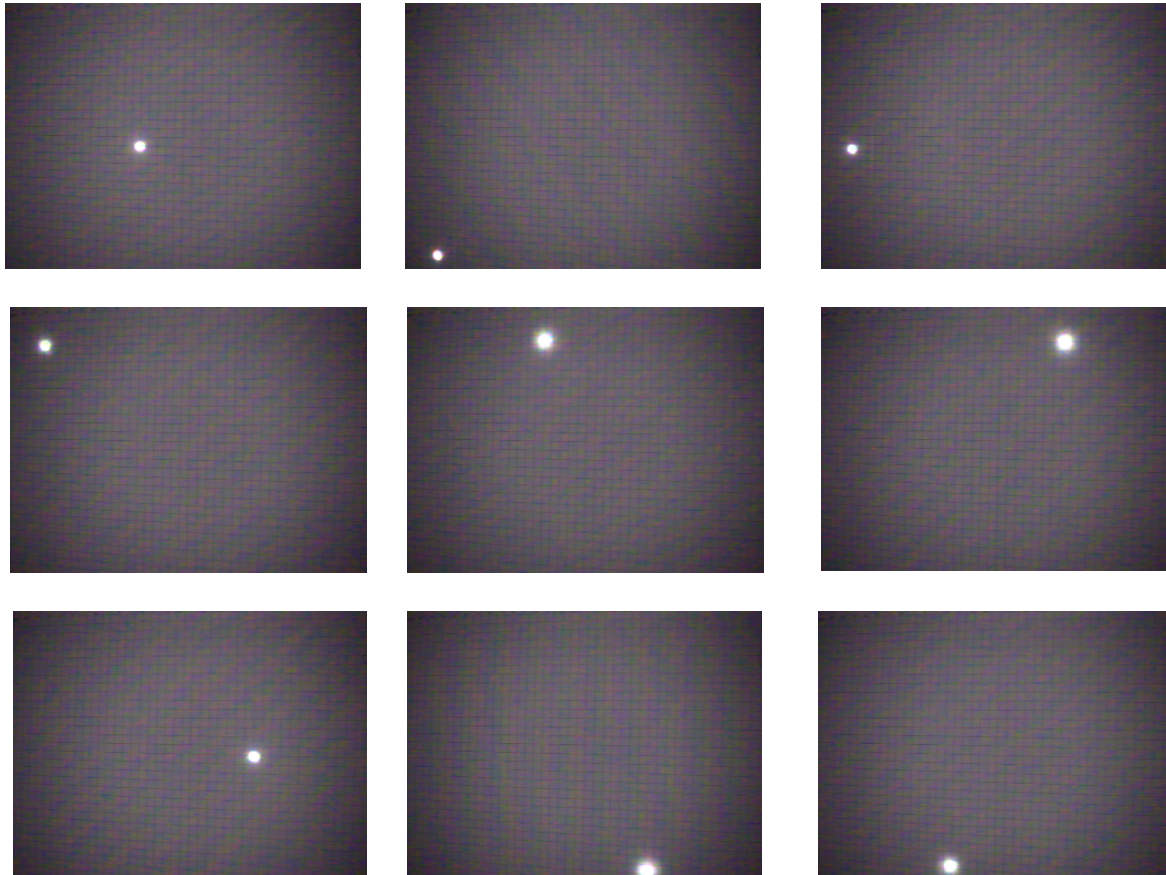


Alignment using Piezoelectric Motion Stages



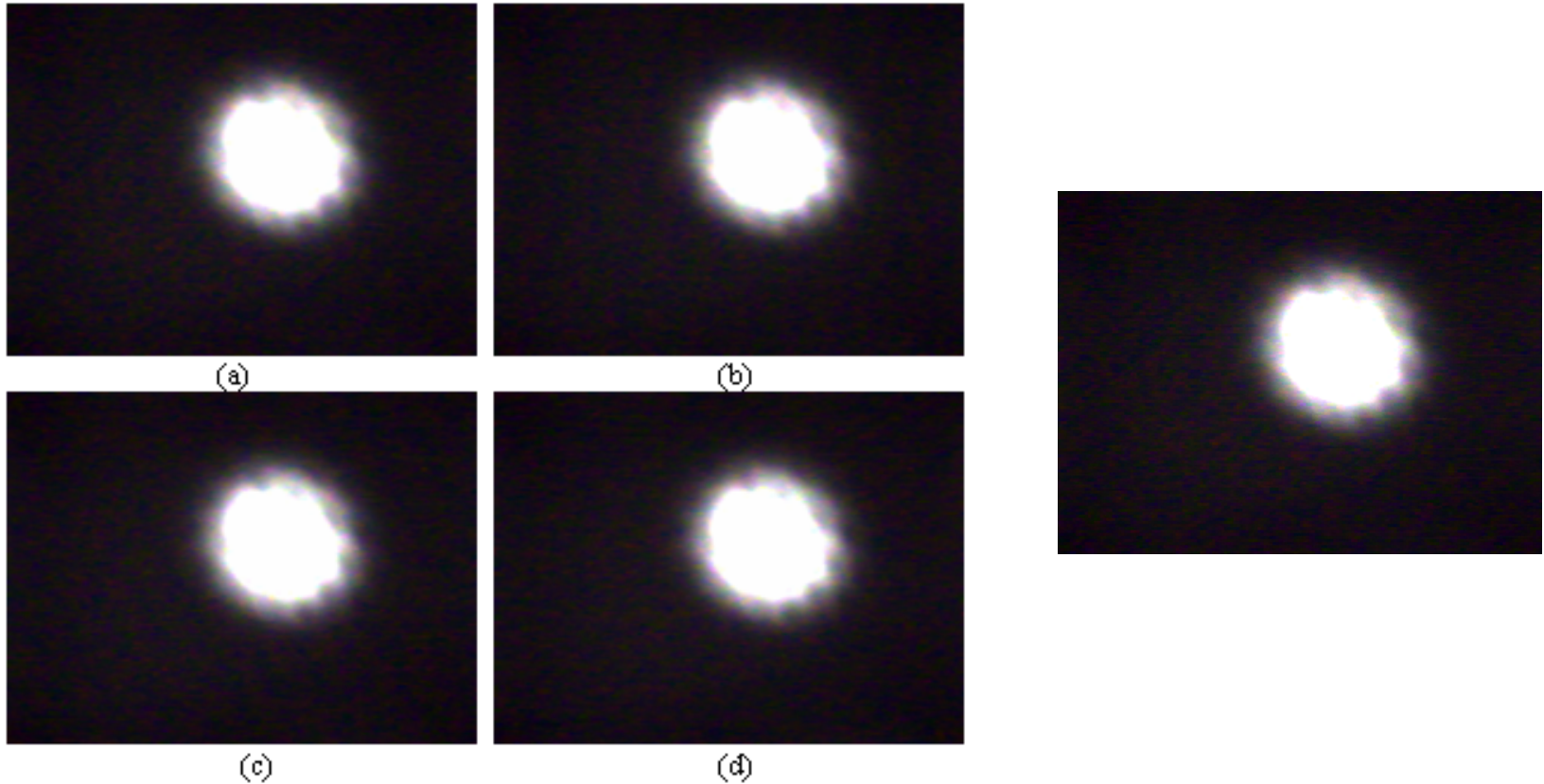
IR Laser Beam Scanning Test Over ± 4.5 degrees

Beam Diameter ($1/e^2$) at Chip: 500 micron



Camera Shots at SiC Chip Plane at 60 cm from Fiber Lens

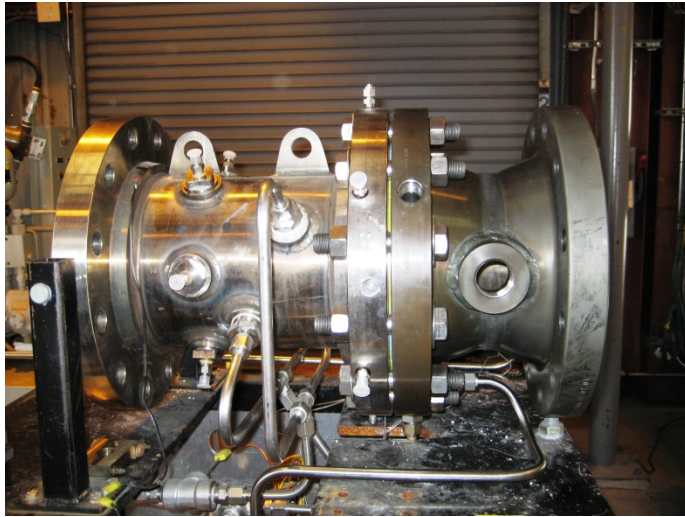
1550 nm Stable Received Beam at **~1000 deg-C**
when Probe Input End is Closed with Window



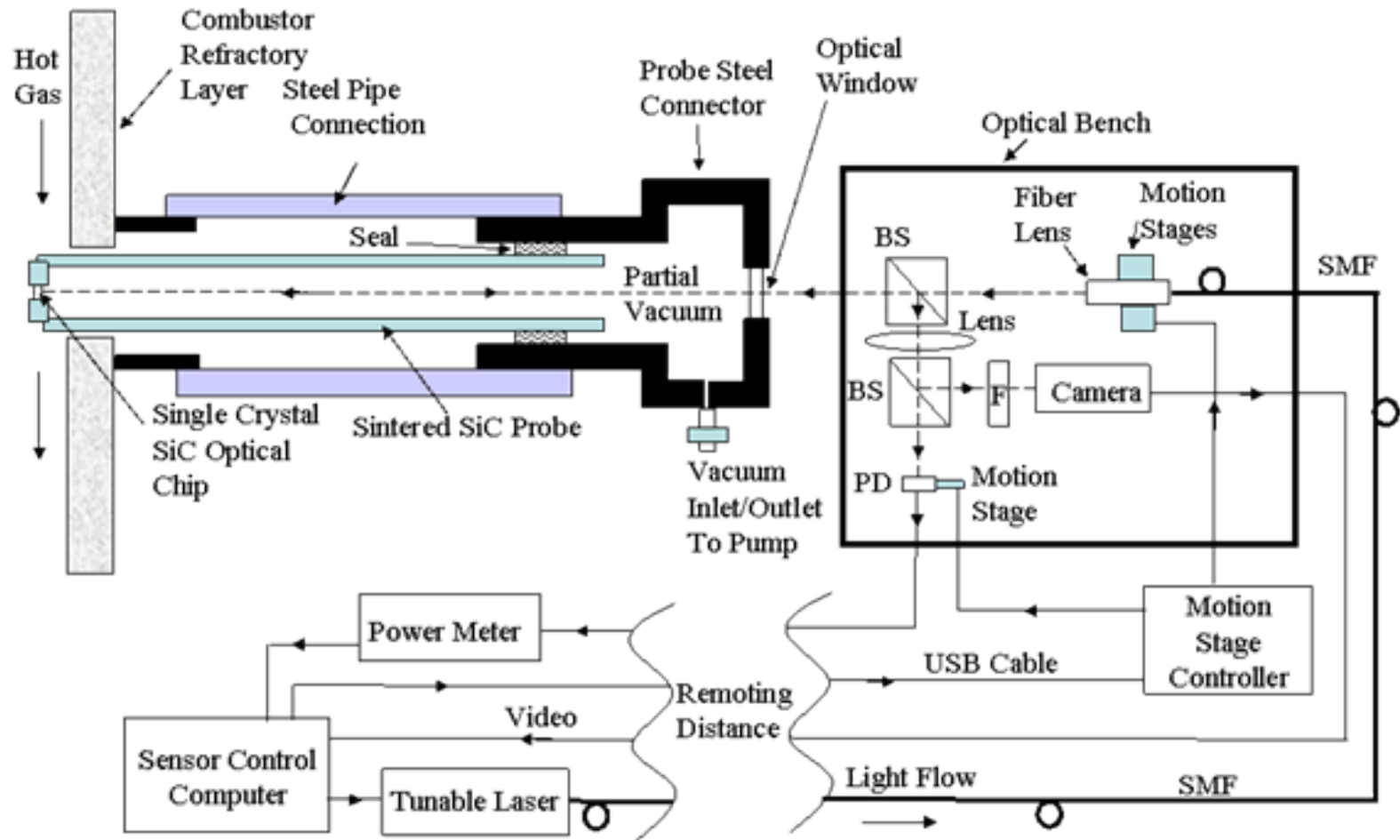
Images seen at 1 second intervals at an Oven set temperature of **~1000 deg-C**.
Camera view of 8.8 mm (horizontal) by 6.6 mm vertical.

GAS TURBINE TEST RIG FACILITIES

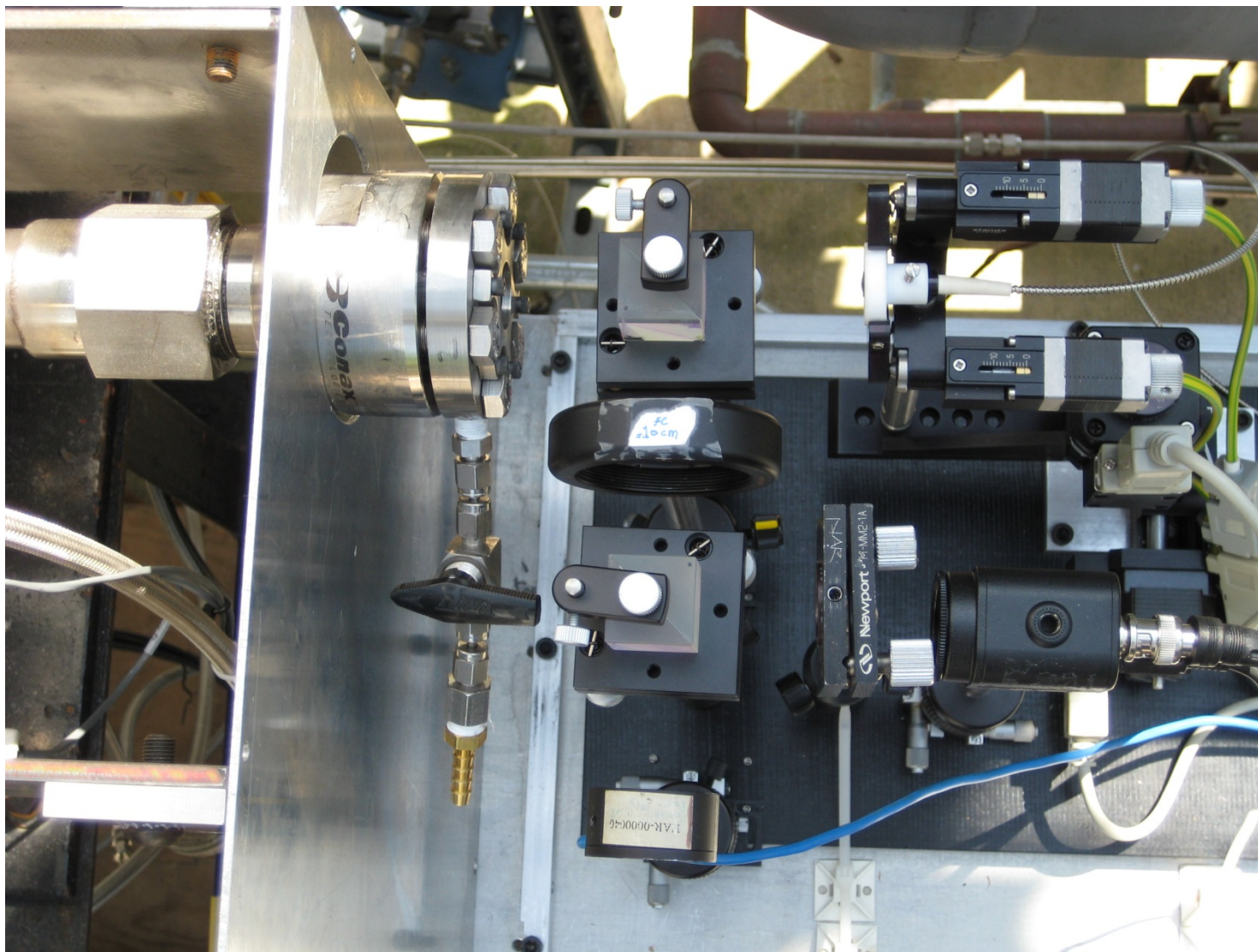
(Nuonics/Siemens Testing)



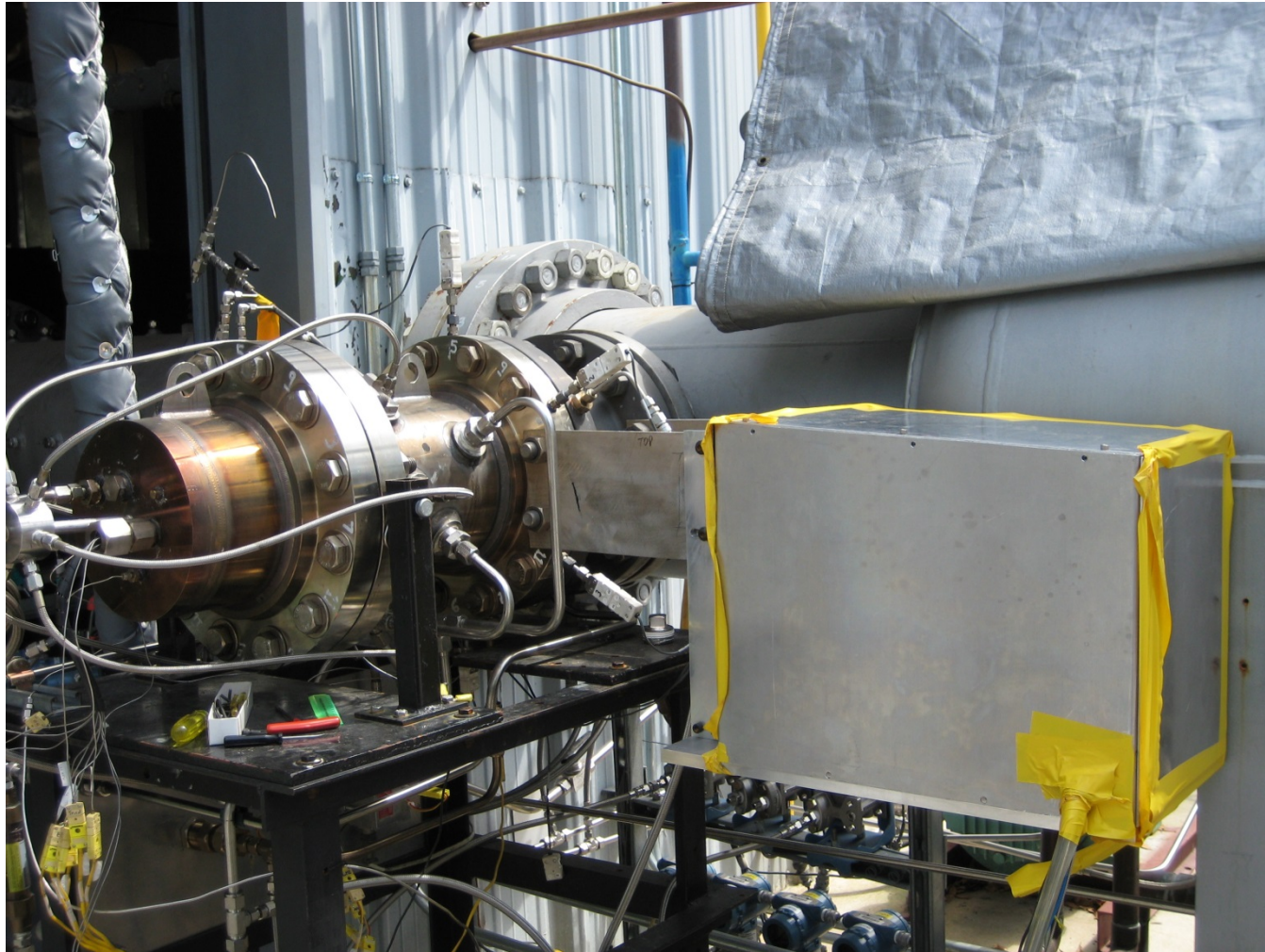
All-SiC Frontend Probe-based Optical Sensor System For Extreme Gas Temperature Measurements In Combustion Engines



OPTICAL TRANSCEIVER DESIGN (Top View) AT GAS TURBINE TEST RIG



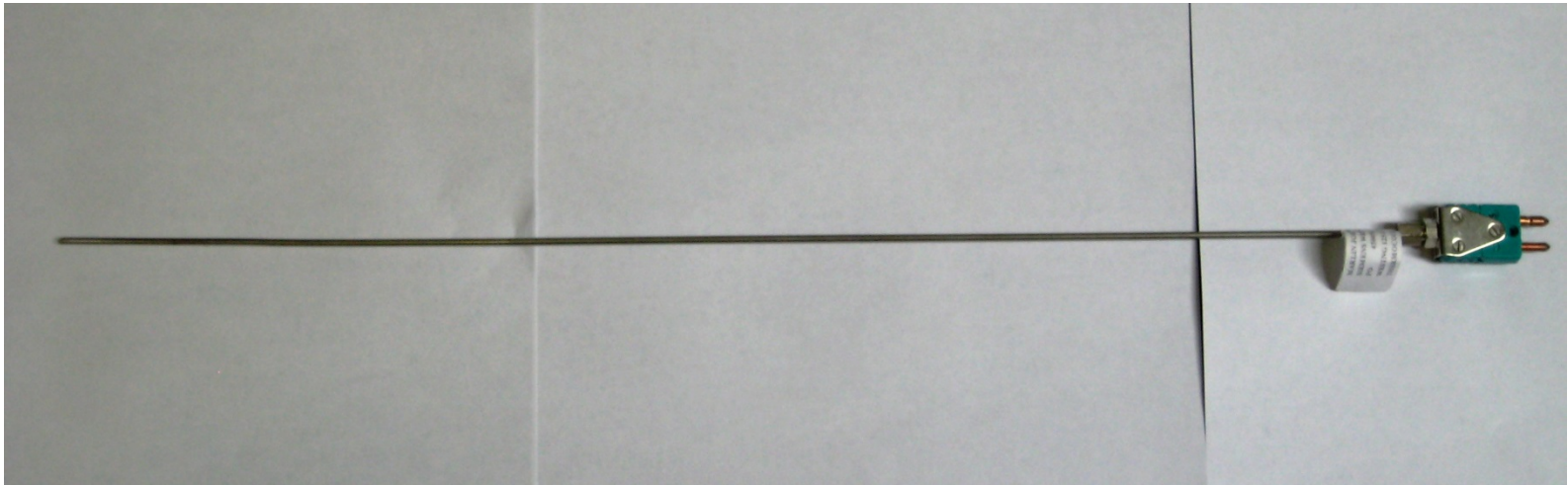
INSTALLED OPTICAL SENSOR AT GAS TURBINE TEST RIG



6 Thermo-Couples (TCs) Placed in Circular Ring Format At Exit of Combustor

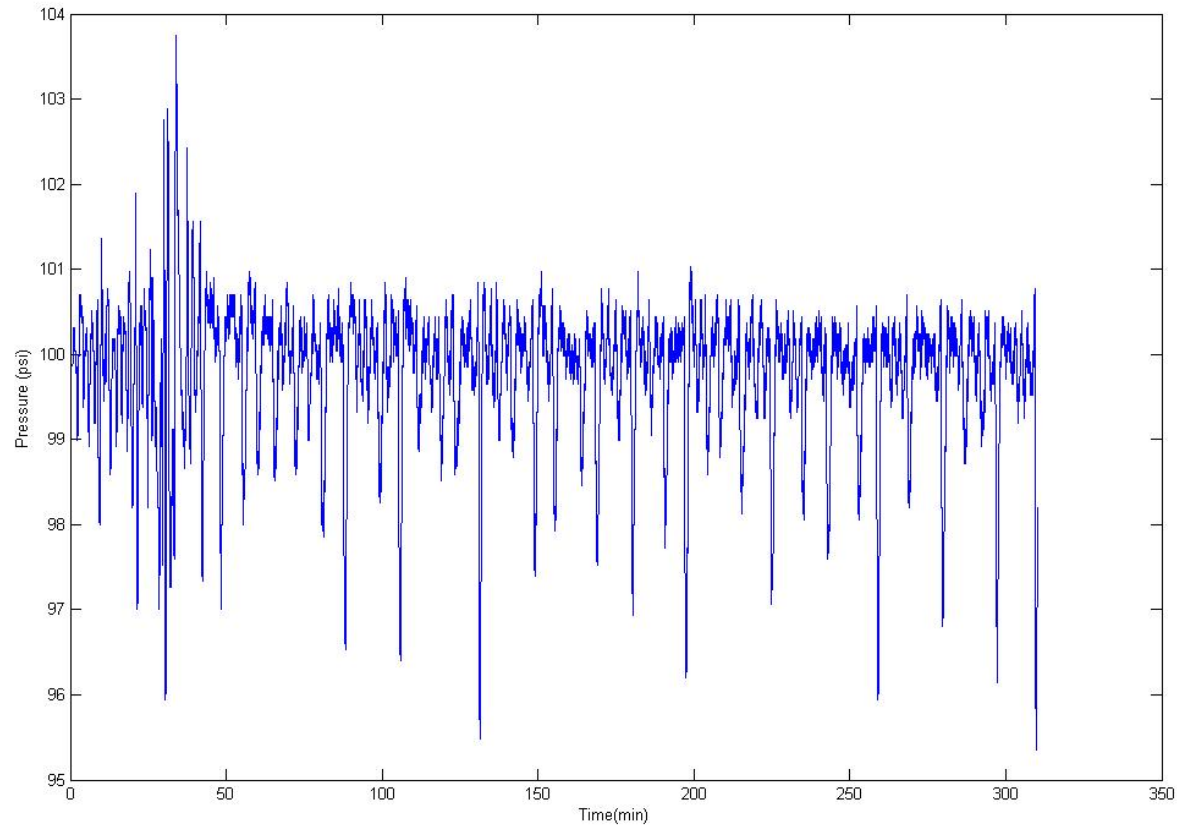
Optical Probe about 6 inches From TC positions in Combustor Exhaust Section

Typical Type R Platinum/Rhodium Grounded Thermo-Couple Similar to Used in Gas Turbine Rig



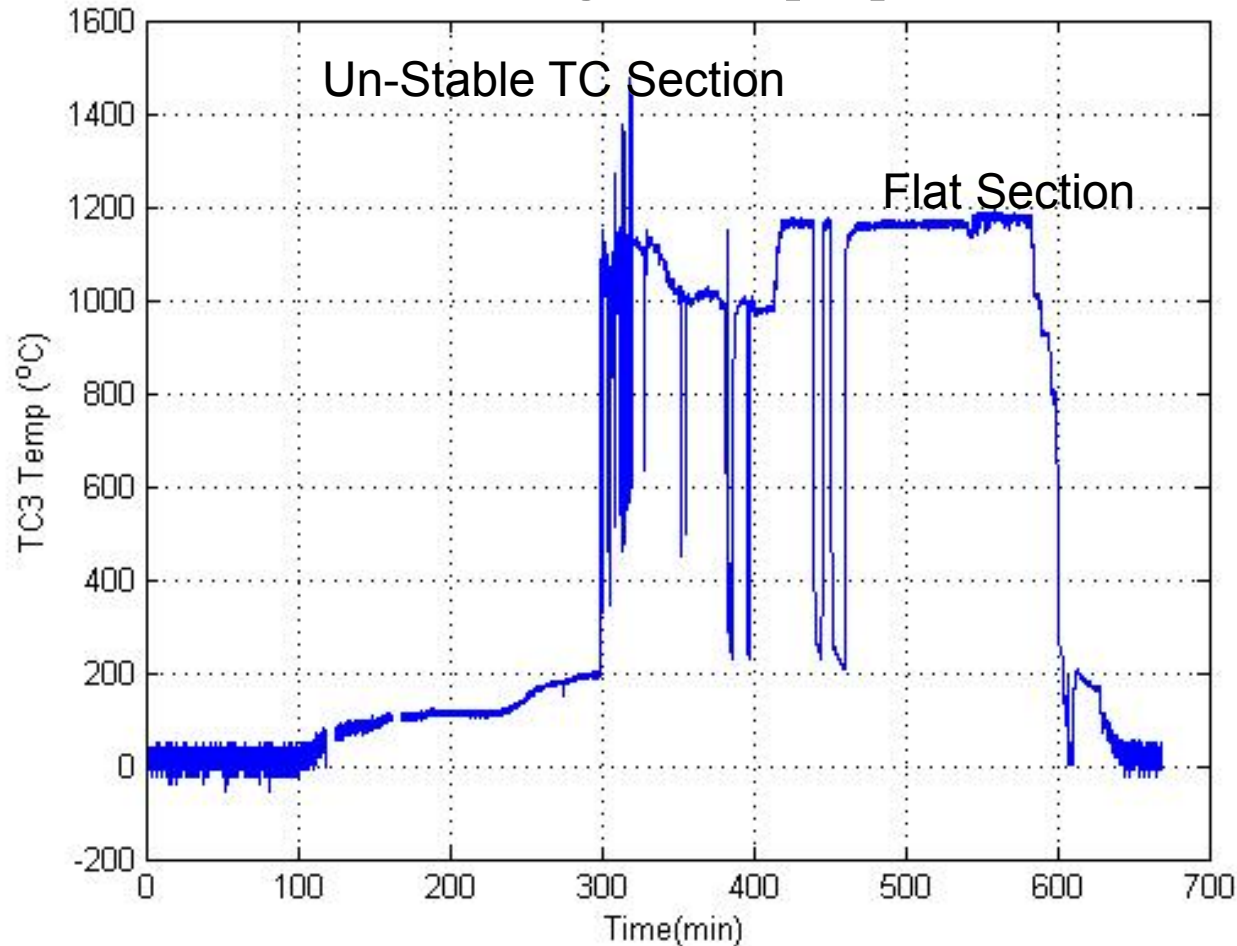
24 inches

GAS TURBINE TEST RIG- Pressure versus Rig Operation Time



Average
Pressure
100 psi

Example Behavior of B-type Platinum/Rhodium Thermo-Couple during Gas Turbine Rig Start-Up Operations Over ~ 6.7 Hours



**Combustor Steady
State Conditions:**

Temp: ~ 1200 deg-C

**Avg Pressure: ~100 psi
(~ 7 atms)**

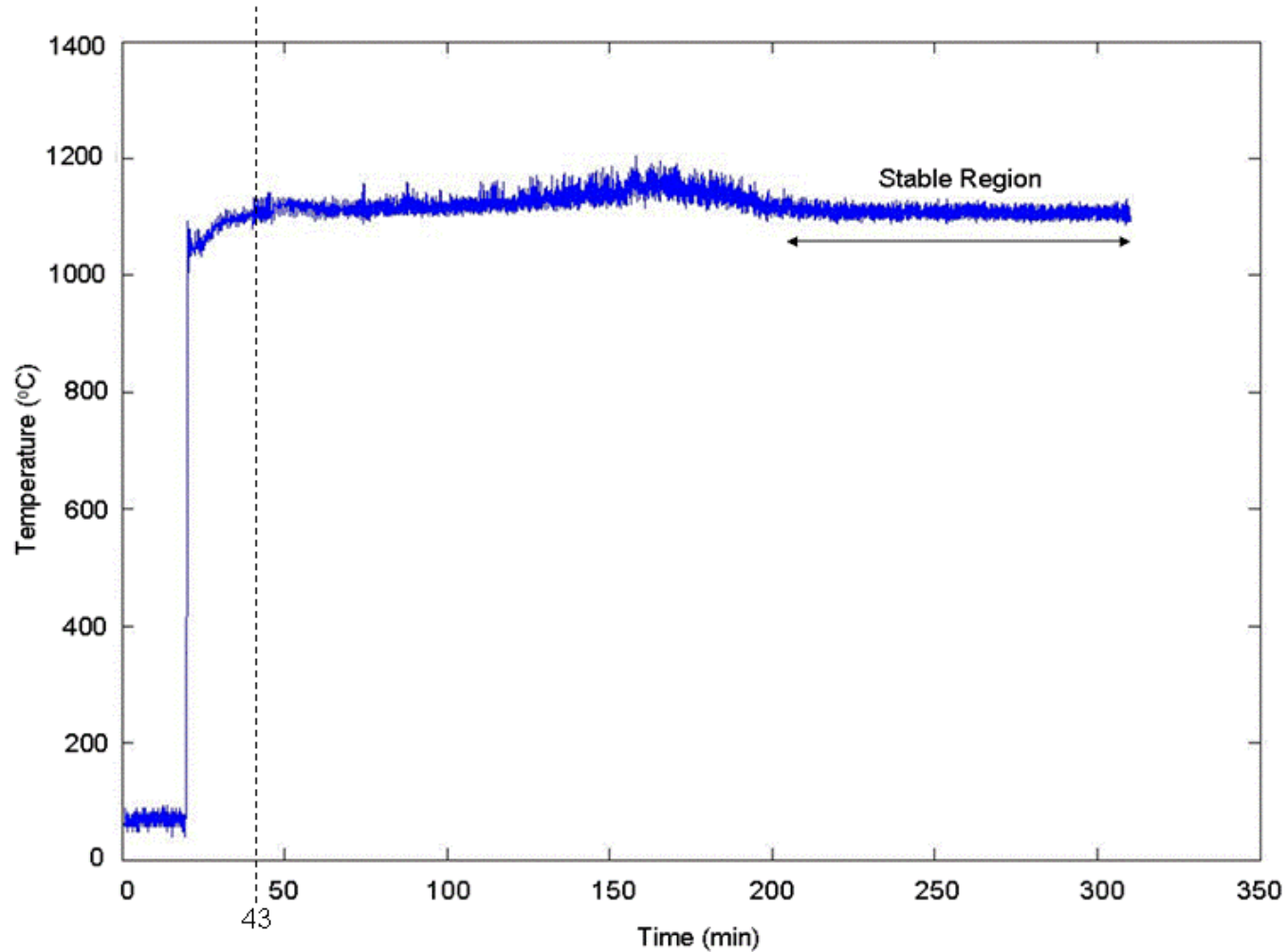
TC recording
Every 1 sec.

- **FLAME LIT: > 1000 deg-C Thermal Ramp in a Few (< 5 sec)**
- **Thermo-Couples (TCs) Can be Unstable**
- **High Temperature TCs are not accurate at the Lower Temperatures**

Type B: Operation Zone: 870 to 1700 deg-C

GAS TURBINE TEST RIG –TC RESPONSE

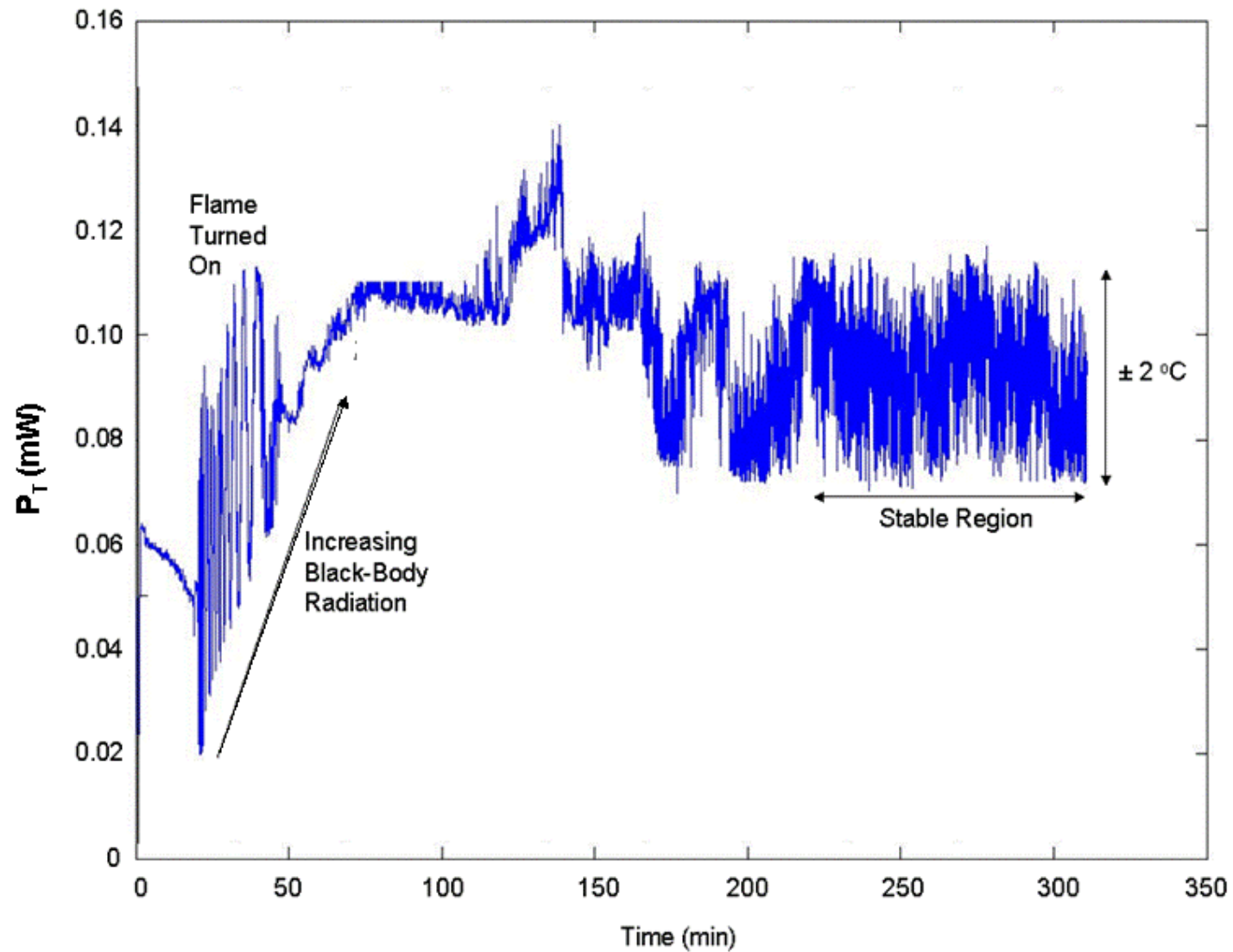
Single Thermo-Couple (TC4)



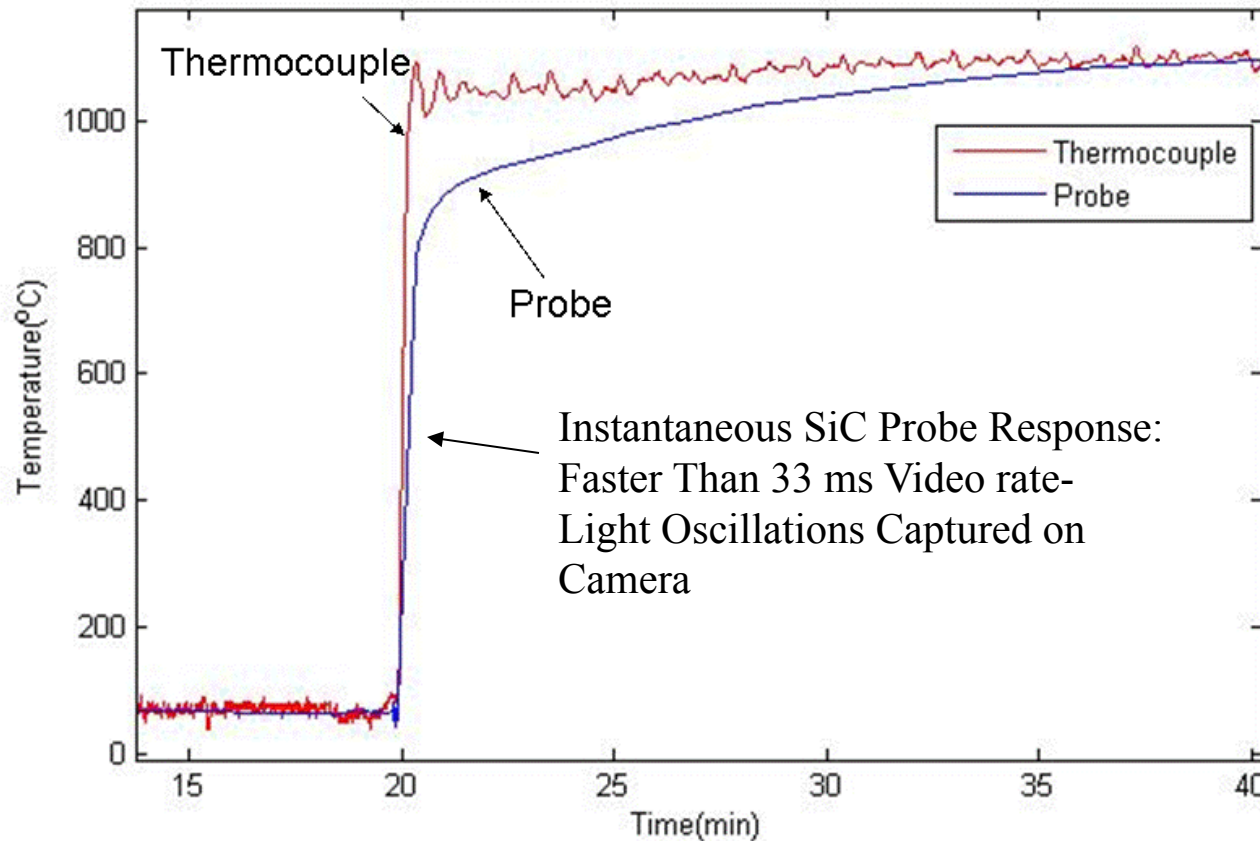
23 minutes from Flame on to High Temperature Zone > 1050 deg-C

GAS TURBINE TEST RIG – OPTICAL RESPONSE

Unprocessed Optical Data



GAS TURBINE TEST RIG – OPTICAL RESPONSE VS TC RESPONSE



$$T_f = 1050 \text{ }^{\circ}\text{C}$$
$$T_i = 87 \text{ }^{\circ}\text{C}$$

$$\text{Probe } \tau = 18 \text{ s}$$

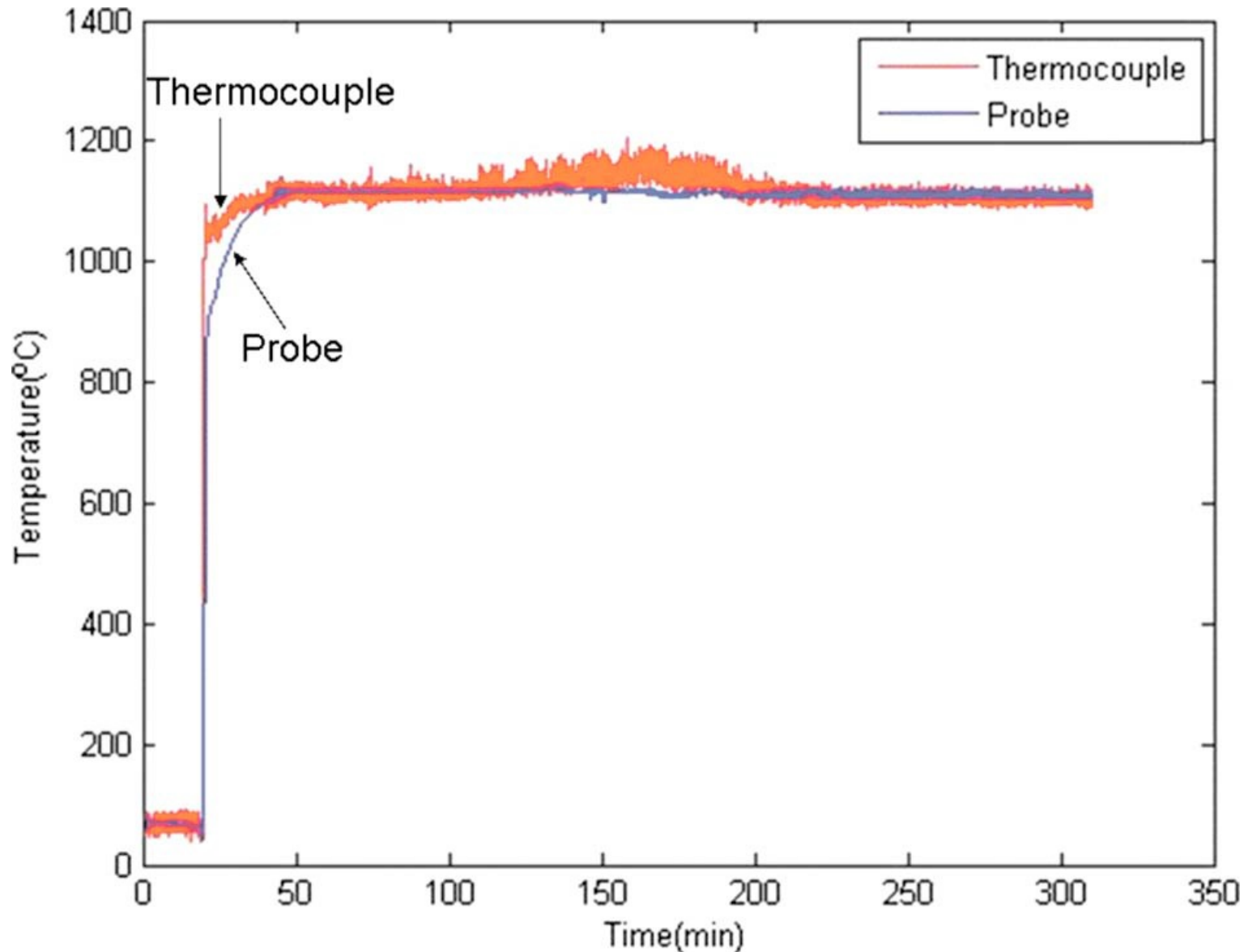
$$\text{TC } \tau = 10 \text{ s}$$

Probe Thermal Mass
& Refractory Limitations:
16 min to reach
Final Gas Temp.

**Measured elevated temperature model: $T \text{ (}^{\circ}\text{C)} = [T_f - T_i][1 - \exp(-t/\tau)] + T_i$,
where T_i and T_f are the initial and final temperatures**

Thermal Time Constant τ : Time to Reach 695 °C or 63.2% (or $1 - 1/e$) of Final Temp. of 1050 °C

GAS TURBINE TEST RIG- Optical Probe Temperature Reading After Signal Processing and using TC4 for Temperature Calibration



PROBE EXTERNAL APPEARANCE & VACUUM STATUS AFTER GAS TURBINE 1st RIG TEST



Start Vacuum:
25 inch Hg

After 14 hrs: 22.5 in-Hg (85kpa)
(over-night) (0.75 atm)

After 6 hr Rig Test: 20 in-Hg
After 42 more hrs: 19 in-Hg

Partial Vacuum Holding

- First Test for 6 Hours (4.5 Hrs flame on and 1.5 hrs Blower on)
- See Discoloration of Front-end
 - Optical and Structural Integrity Maintained
 - Rig Temperatures reaching 1239 deg-C

Handled Extreme Thermal Shock (1000 deg-C in 3 sec and Chemical Attack

OPTICAL PROBE AFTER GAS TURBINE RIG TESTS

AFTER 28 DAYS IN RIG



SEE COPPER SULPHATE DEPOSITS —————→

- Combustor is Made from Copper
- Sulphur in Cooling Water Vapor

1550 nm Observed Received Beam when
Gas Flame Lighted in Combustion Rig with Temperature
Rising from ~ 100 C to ~ 1100 C in a few Seconds

Thermal Ramp
> 1000 deg-C
in a few Seconds

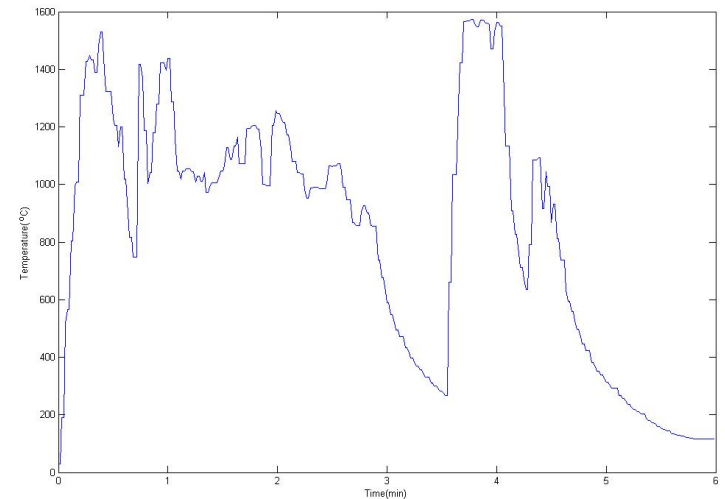


Also shows
Stable Optical
Beam in
Presence of RIG
Vibrations

**Real-time Images seen showing Optical Probe Response
Camera view of 8.8 mm (horizontal) by 6.6 mm vertical.**

OPTICAL PROBE EXTREME TEMPERATURE TEST

Oxy-Acetylene Torch Flame Application – 1600 deg-C



Flame Application: 5 minutes

NOTE: Type R Thermo-Couple Started to Melt
Optical Probe Mechanical/Structural Integrity Unchanged

Images courtesy: Nuonics, Inc.

GAS TURBINE RIG TESTING SUMMARY

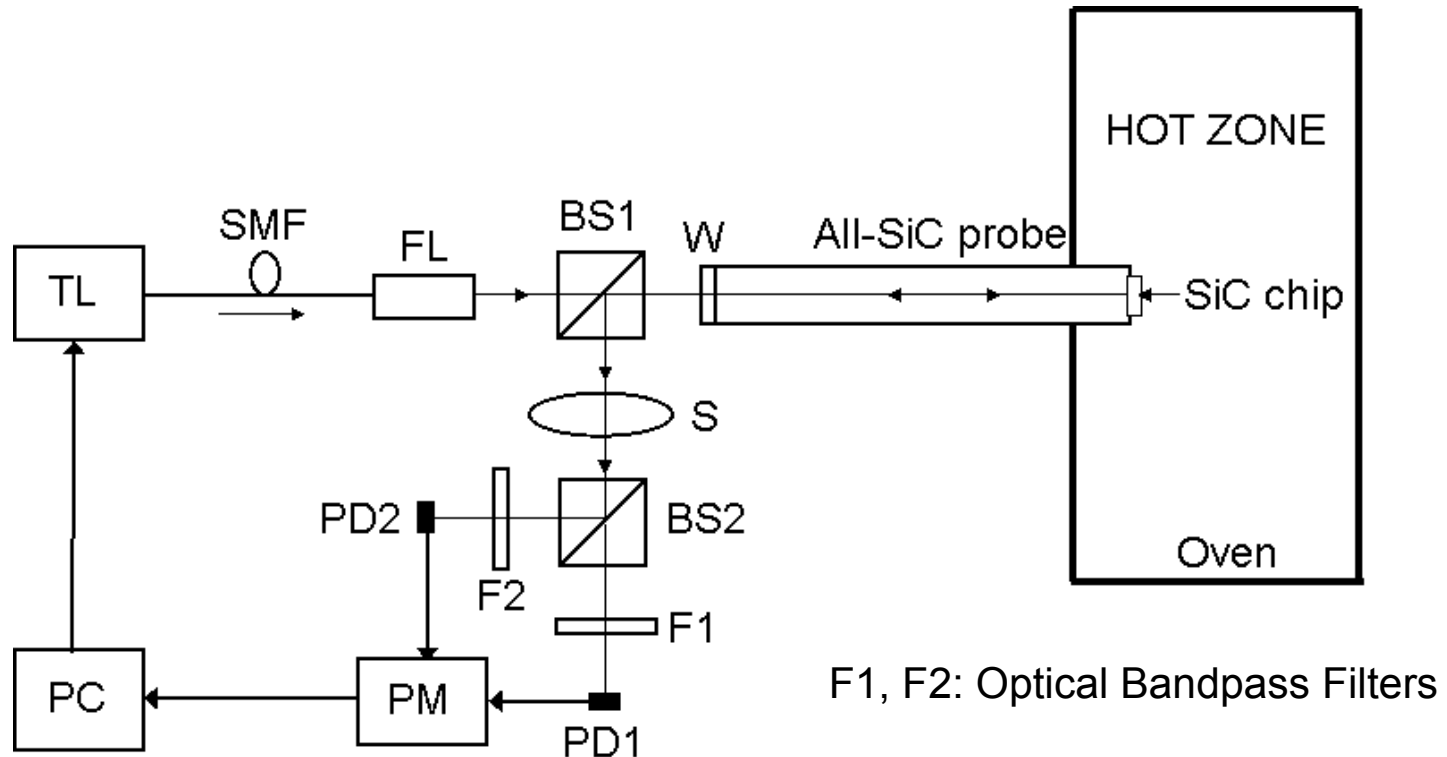
COMBUSTION RIG FLAME ACTIVE OPERATION	6 DAYS
NO. OF TIMES PROBE EXPERIENCED FLAME LIGHT AND THERMAL SHOCK (TEMPERATURE RAMP OF 1000 DEG-C IN 3 SECONDS)	8 (1 DAY 3 FLAME LIGHTS, 5 DAYS 1 FLAME LIGHT/ DAY
OPERATION WITH FLAME ON	26 HOURS
OPERATION WITH FLAME OFF AND BLOWER ON	13.5 HOURS
NUMBER OF COMBUSTION HEAT AND COOL CYCLES	8
DAYS IN EXTERNAL RIG ENVIRONMENT	28 DAYS

Robust Hybrid Temperature Sensing Approach- Use Two wavelength Pyrometry+Laser Interferometry

- Find a coarse value of temperature using two-color pyrometry
- Measure laser reflected power
- Measure $P_{\max}$ and $P_{\min}$ by tuning the wavelength and use these to find P_{norm}
- Find the sign of $dP/d\lambda$ to find which half of the 2π cycle is the temperature
- Resolution is 0.1 °C
- Comparable to TC

Proposed Dual-Signal Processing-Mode Sensor Design

A First Hybrid Design: Pyrometry + Laser Interferometry



N. A. Riza, M. Sheikh, “Silicon Carbide-based High Resolution Extreme Environment Hybrid Design Temperature Sensor using Optical Pyrometry and Laser Interferometry,” IEEE Sensors Journal, Feb. 2010.

Two-Color Pyrometer

- Measure radiation power at two wavelengths and take the ratio

Wein Approximation $I(\lambda, T) = \frac{2hc^2}{\lambda^5} e^{-\frac{hc}{\lambda kT}} \cdot \varepsilon(\lambda, T)$

$$R = \frac{P_{\lambda_1}}{P_{\lambda_2}} = A_s \left(\frac{\lambda_2}{\lambda_1} \right)^5 \frac{\varepsilon(\lambda_1, T) + a(\lambda_1, T)}{\varepsilon(\lambda_2, T) + a(\lambda_2, T)} \exp \left[-C_2 \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2} \right) \frac{1}{T} \right]$$

A_s : system-specific constant – takes into account optical and detection components

$a(\lambda, T)$: specific emissivity of the background

$C_2 = hc/k$

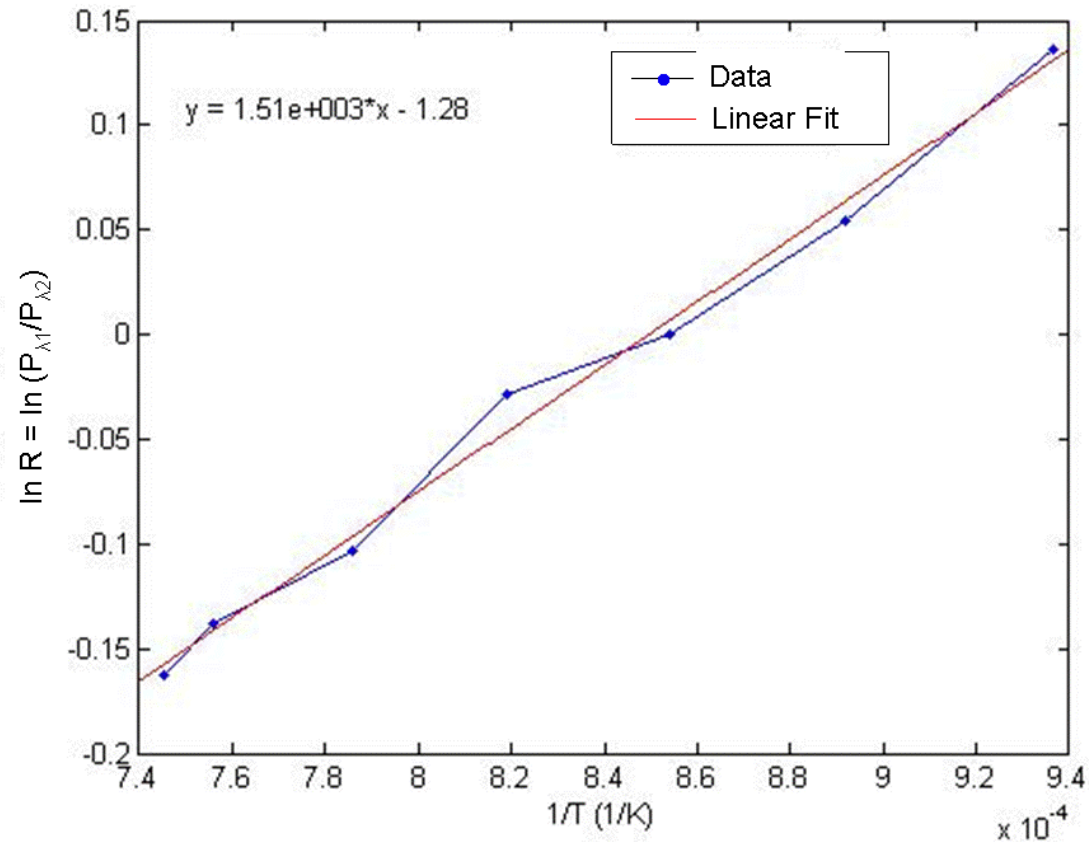
Two-Color Pyrometer

- Specific emissivity has a weak dependence on wavelength
- If the two wavelengths are selected close to each other, then the emissivity ratio can be approximated to a constant

$$R = \frac{P_{\lambda_1}}{P_{\lambda_2}} = A_s \left(\frac{\lambda_2}{\lambda_1} \right)^5 \frac{\varepsilon(\lambda_1, T) + a(\lambda_1, T)}{\varepsilon(\lambda_2, T) + a(\lambda_2, T)} \exp \left[-C_2 \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2} \right) \frac{1}{T} \right]$$

$$\ln R = \alpha + \frac{\beta}{T}$$

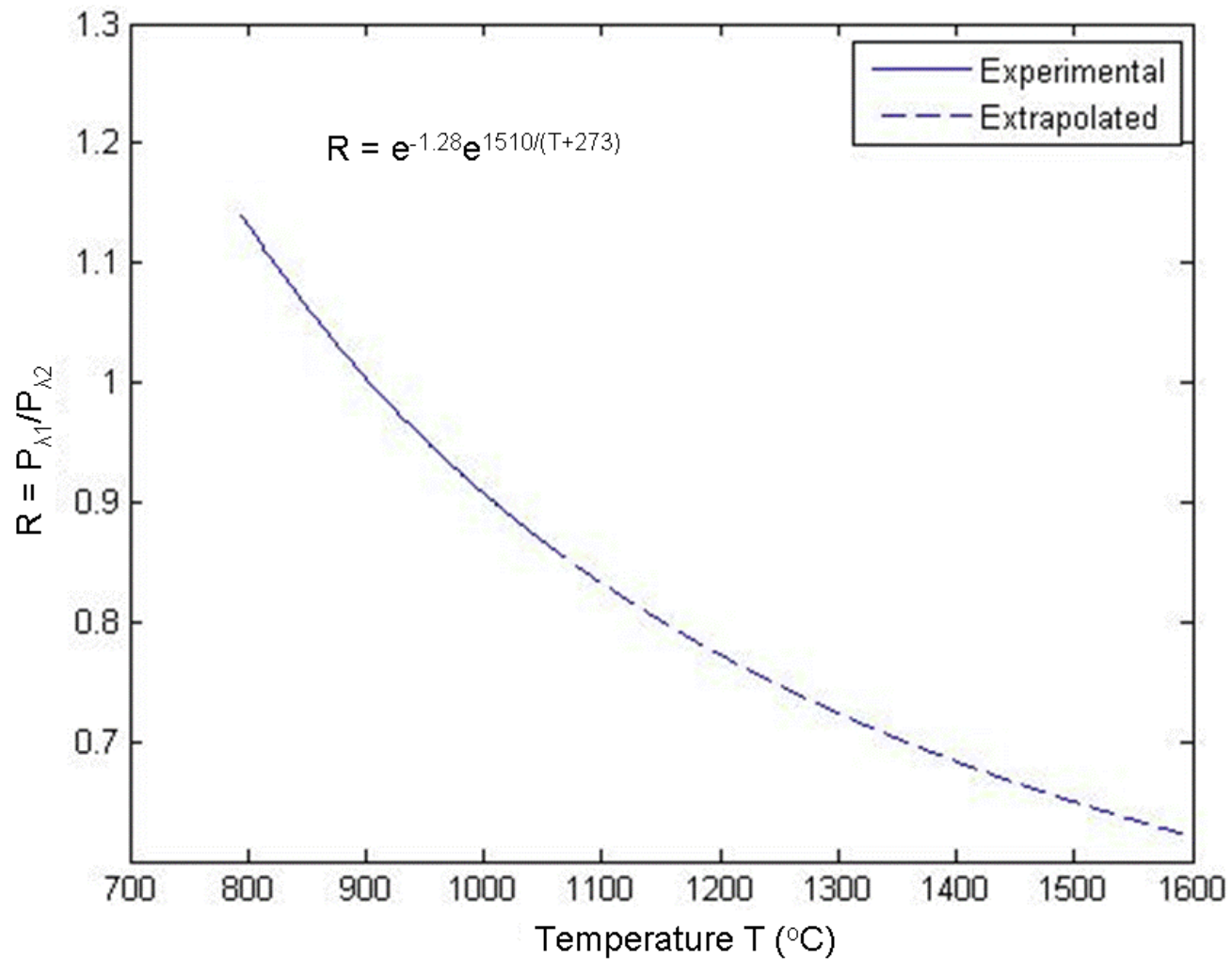
Proposed SiC Sensor Calibration Experimental Results



F1: Center wavelength: 1550 nm, FWHM: 30 nm

F2: Center wavelength: 1300 nm, FWHM: 30 nm

Calibration Curve from Data



Discussion on Results

- Works best beyond $\sim 800\text{ }^{\circ}\text{C}$
- Resolution depends on the smallest change in radiation power that can be detected
- Estimated resolution varies between $5.8\text{ }^{\circ}\text{C}$ at $795\text{ }^{\circ}\text{C}$ to $2.7\text{ }^{\circ}\text{C}$ at $1077\text{ }^{\circ}\text{C}$
- Can be used to give a coarse value of temperature

Proposed Fine Temperature Sensing Technique using Fixed Wavelength Power and Power Slope Measurement

Classic Fabry-Perot Etalon Reflectance

$$R_{FP} = \frac{R_1 + R_2 + 2\sqrt{R_1 R_2} \cos \varphi}{1 + R_1 R_2 + 2\sqrt{R_1 R_2} \cos \varphi} \quad \varphi = \frac{4\pi}{\lambda} n(\lambda, T) t(T)$$

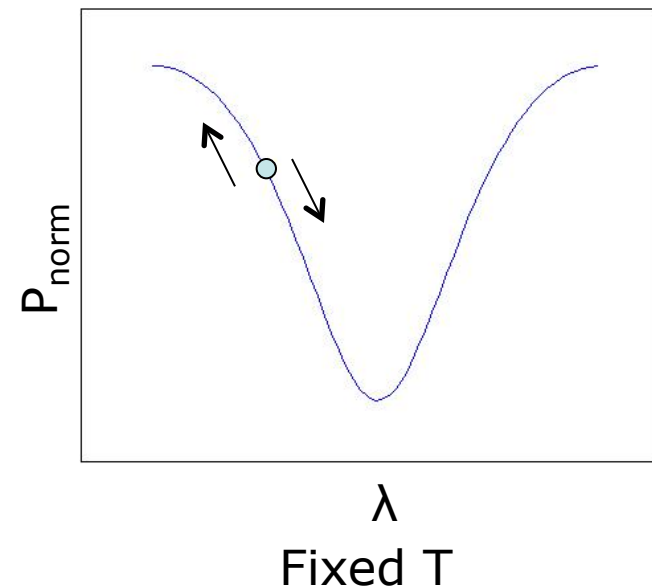
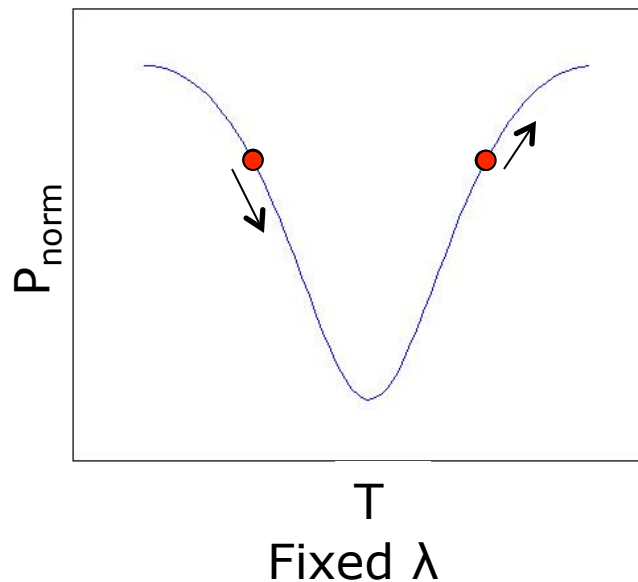
Detected Power $P \propto R_{FP}$

$$P_{norm} = \frac{P - P_{min}}{P_{max} - P_{min}}$$

$$\frac{dP}{d\lambda} = \frac{dP}{d\varphi} \frac{d\varphi}{d\lambda} = -\frac{4\pi}{\lambda^2} n(T) t(T) \frac{dP}{d\varphi}$$

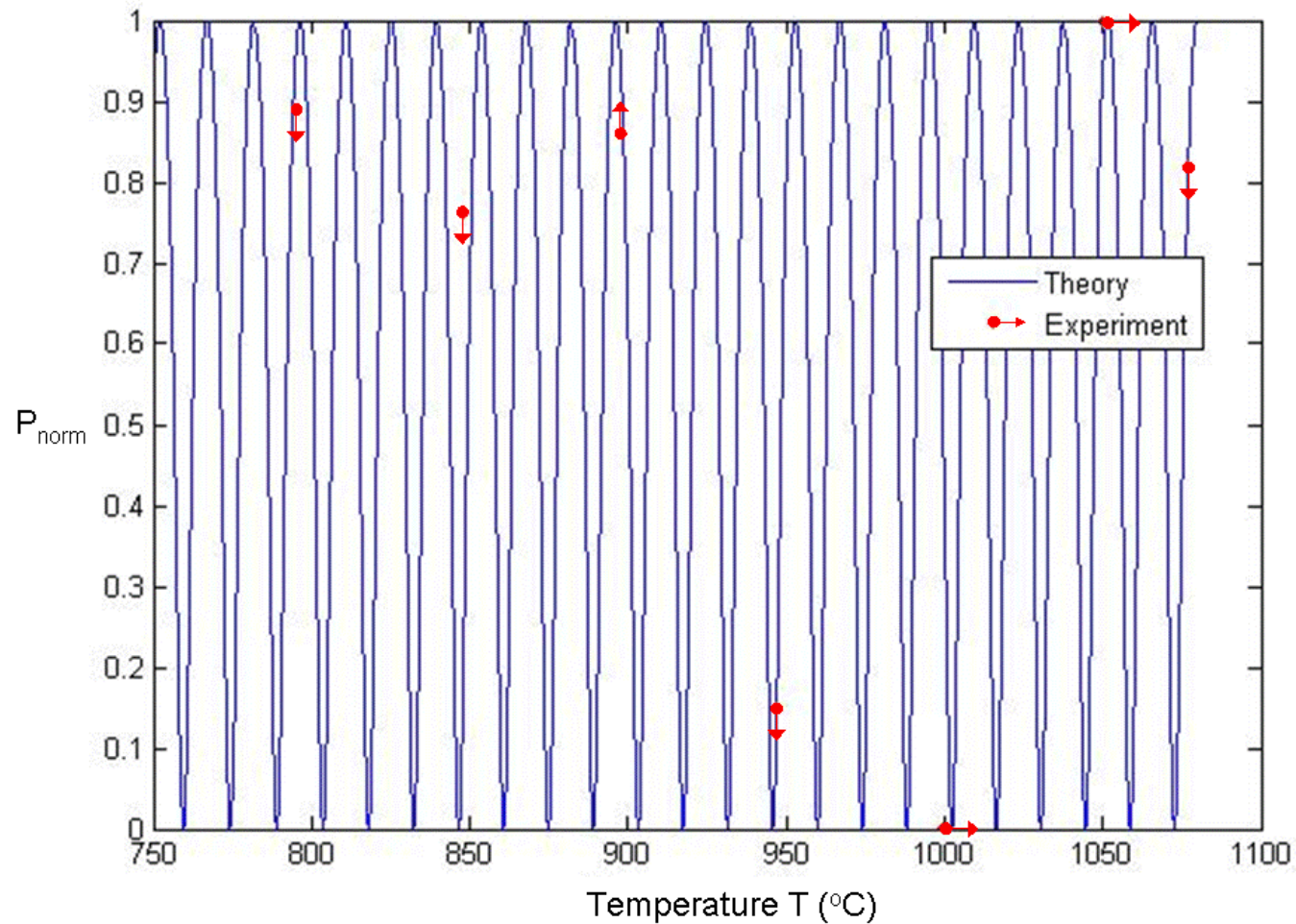
- If $dP/d\lambda$ is positive, then $dP/d\varphi$ would be negative and vice versa
- φ at a fixed wavelength changes only because of temperature

Normalized Power vs. Temperature Curve



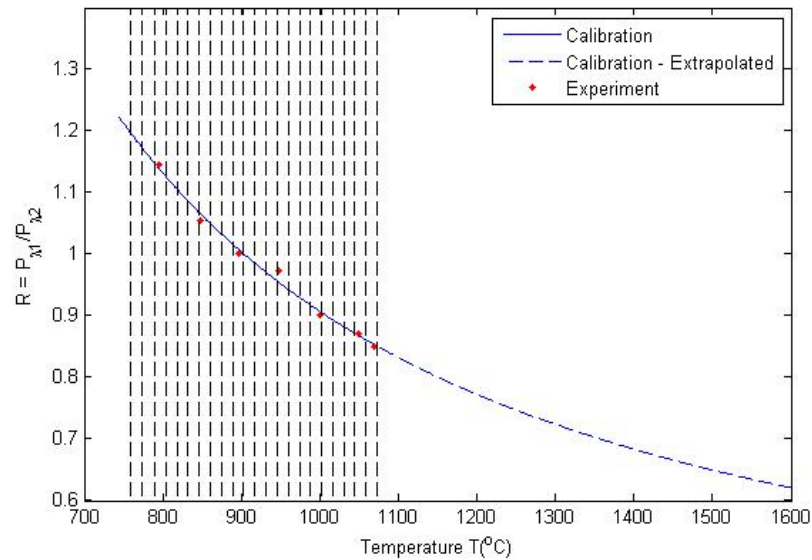
Within each cycle, for any P_{norm} value, there are two possible values of temperature

Experiment

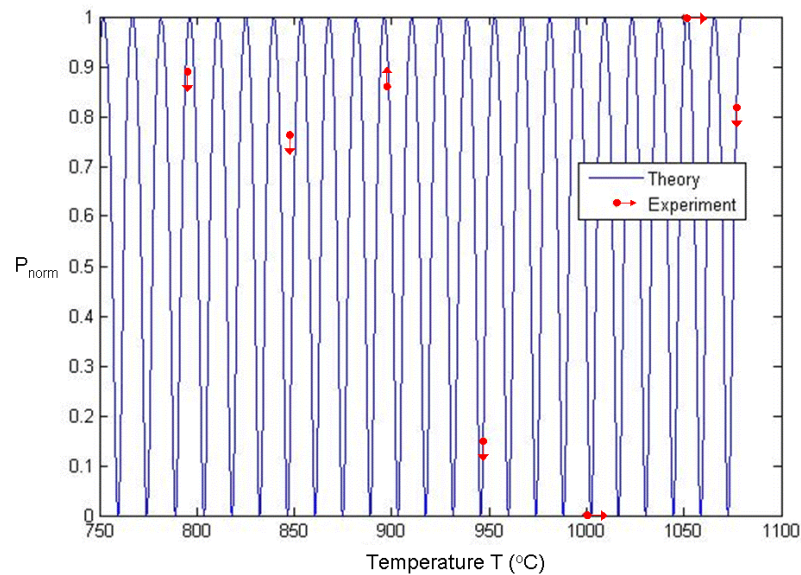


Fixed Wavelength λ : 1550 nm
Arrows denote the sign of $dP/d\lambda$

Pyrometry-Laser Interferometry SiC Probe



2-Wavelength Pyrometry



Laser Interferometry

Summary of Hybrid Temperature Sensing Approach

- Find a coarse value of temperature using two-color pyrometry
- Measure laser reflected power
- Measure $P_{\max}$ and $P_{\min}$ by tuning the wavelength and use these to find P_{norm}
- Find the sign of $dP/d\lambda$ to find which half of the 2π cycle is the temperature
- Resolution is 0.1 °C
- Comparable to TC

THE NEED



EXTREME TEMPERATURE PLUS PRESSURE SENSOR

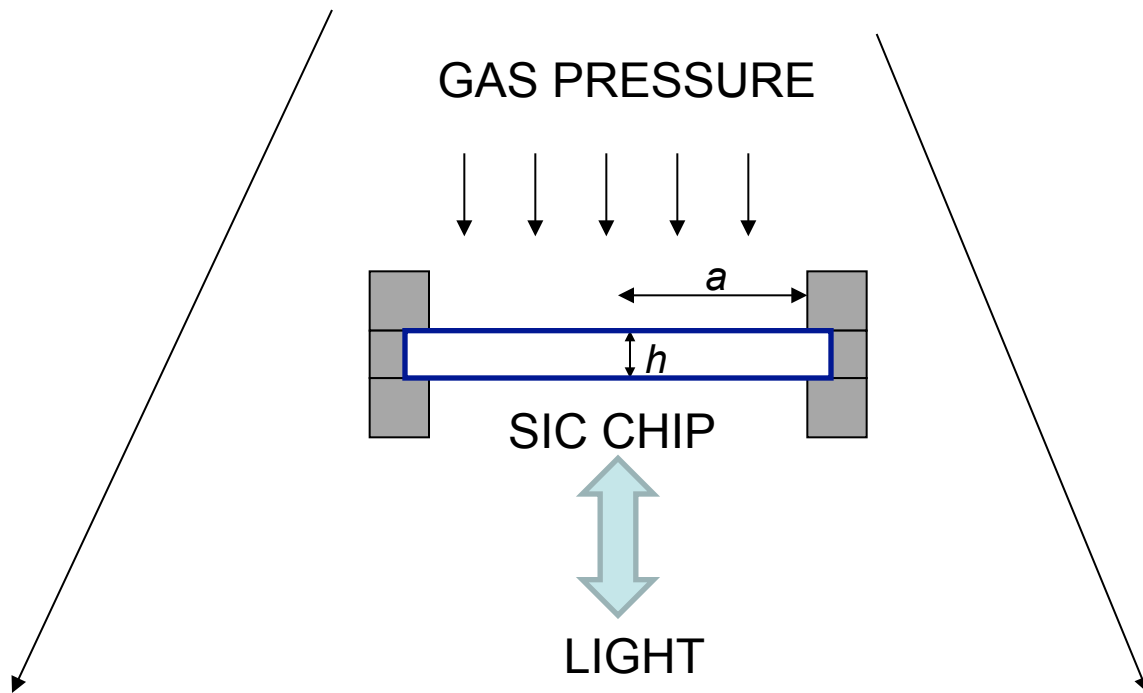


Example: Operates up-to 2000 °C and 100 atm

IS THERE A ROBUST SOLUTION
THAT WORKS WITH CORROSIVE FLUIDS
AND HOT GASES?

Proposed Wireless Hybrid Optical Sensor for Simultaneous Temperature and Pressure Measurements

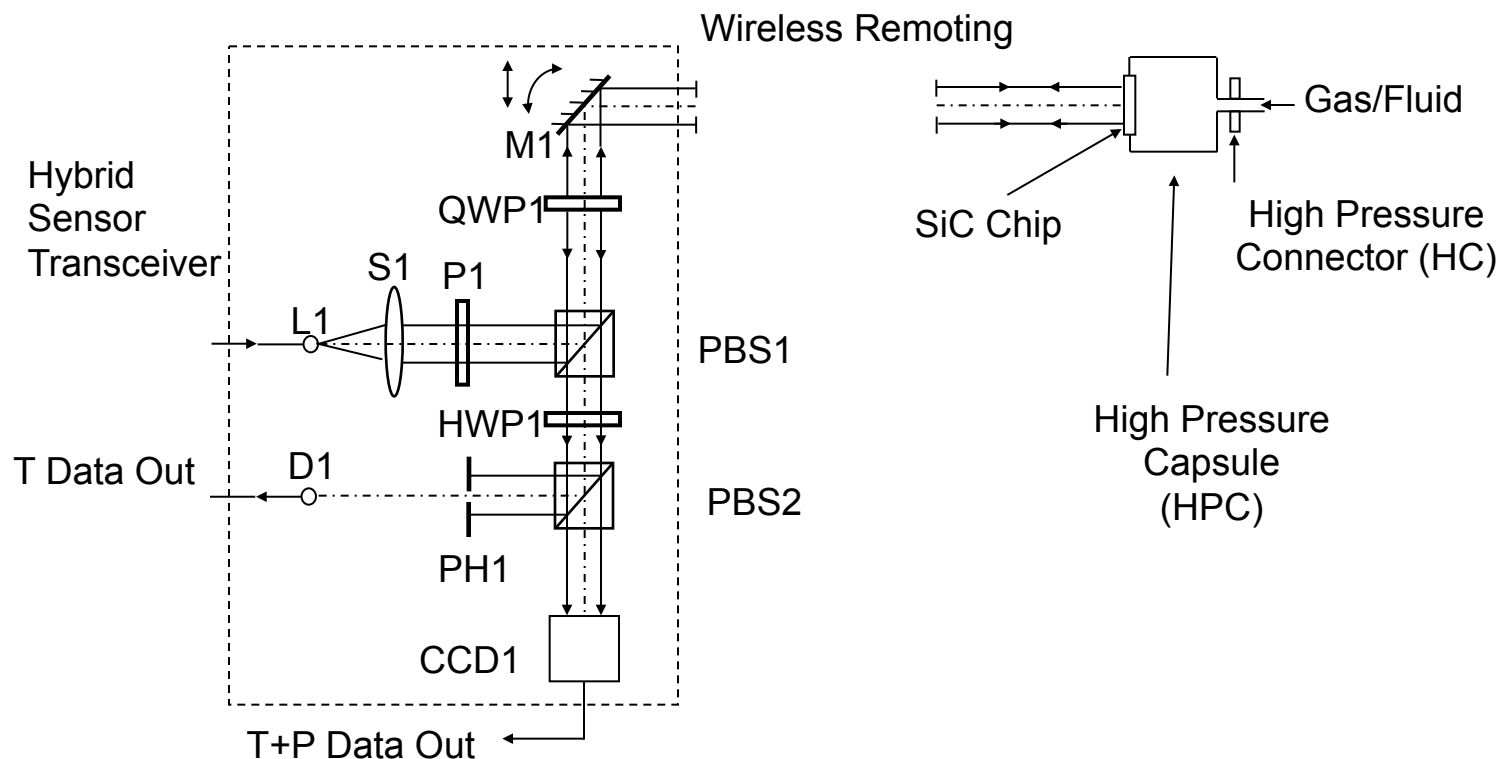
Measurement Principles



**Temperature: Localized OPL Change
(Measure Phase Shift Change)**

**Pressure: Global Wave-front Spoiling/Lensing
(Measure Magnification Change)**

Proposed Wireless Hybrid Optical Sensor for Simultaneous Temperature and Pressure Measurements



Concept:
Remote Optical Interrogation of Hybrid (Optical/Steel-Ceramic) High Pressure Capsule

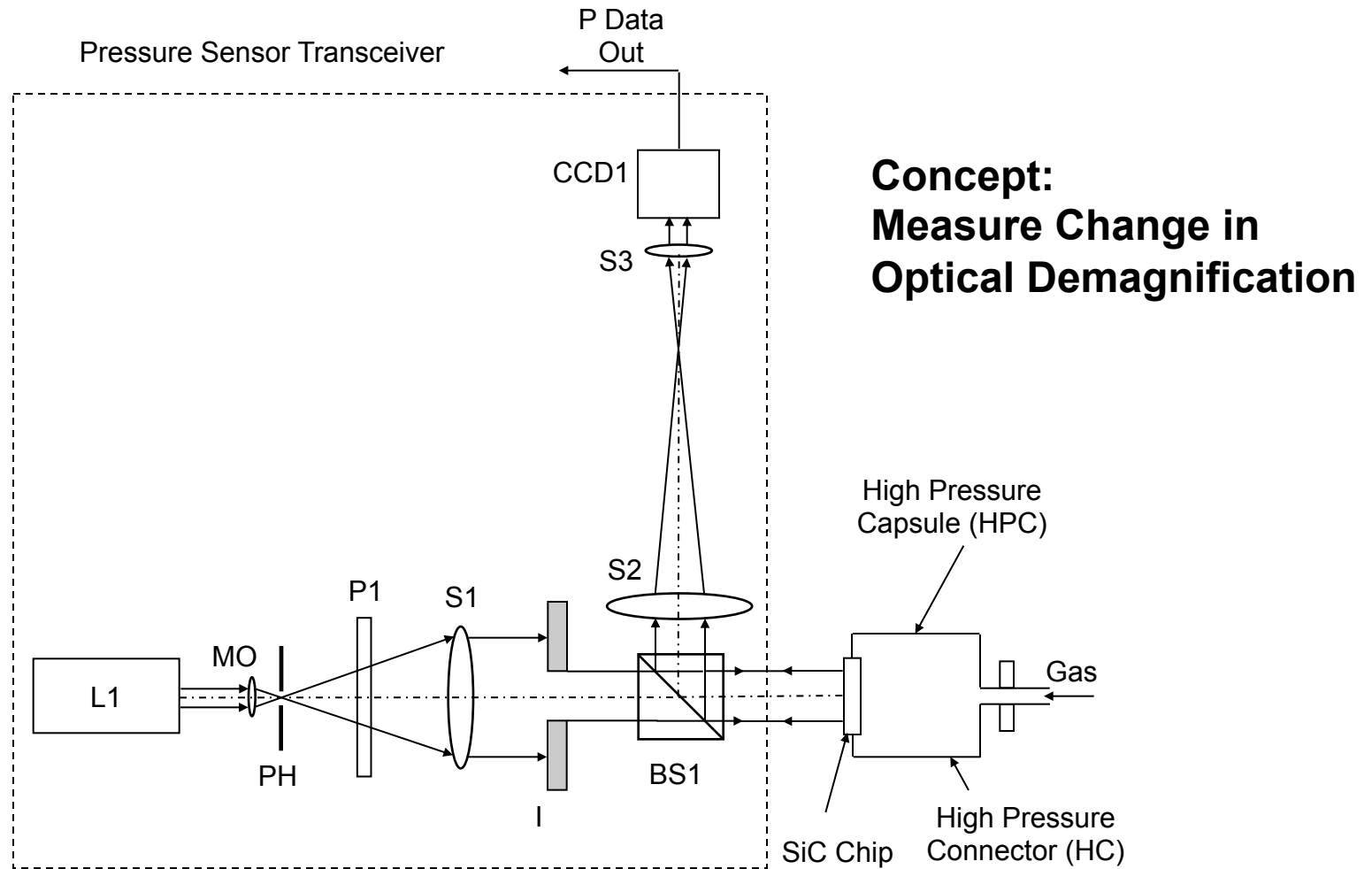
Measurement Principles:

**Temperature: Localized OPL Change
(Measure Phase Shift Change)**

**Pressure: Global Wave-front Spoiling/Lensing
(Measure Magnification Change)**

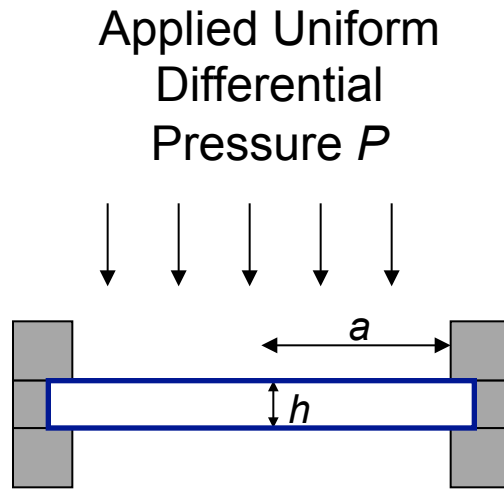
L1: Laser Source, PBS1/PBS2: Polarization Beam Splitter.

6H-SiC-chip based wireless optical pressure sensor system configuration.

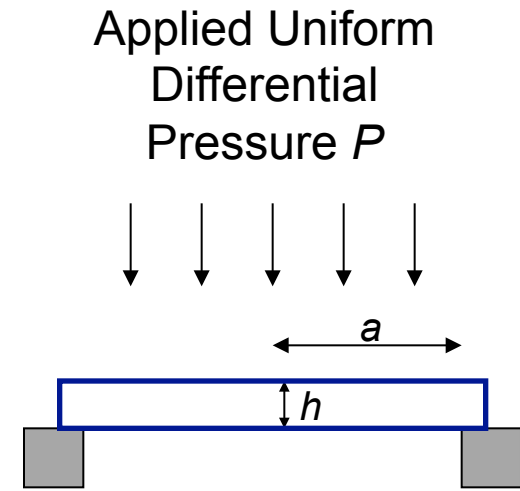


L1: Laser Source, MO: Microscope Objective Lens, PH: Pin-Hole
S1/S2/S3: Biconvex Lenses, I: Iris, BS1: Beam Splitter.

Key Mechanical Models used to Analyze the SiC Chip Mechanical Deformation Behavior seated in the High Pressure Capsule.



(a) Clamped Edge model



(b) Simply Supported model

a = radius of plate; h = thickness of SiC

Theoretical Analysis of 6H-SiC Chip Mechanical Deformation Behavior

(a) Clamped Edge model

$$w(r) = \frac{P}{64D} (a^2 - r^2)^2 \quad \text{where} \quad D = \frac{Eh^3}{12(1-\nu^2)},$$

$$w_{\max} = \frac{P}{64D} a^4 \quad (r = 0)$$

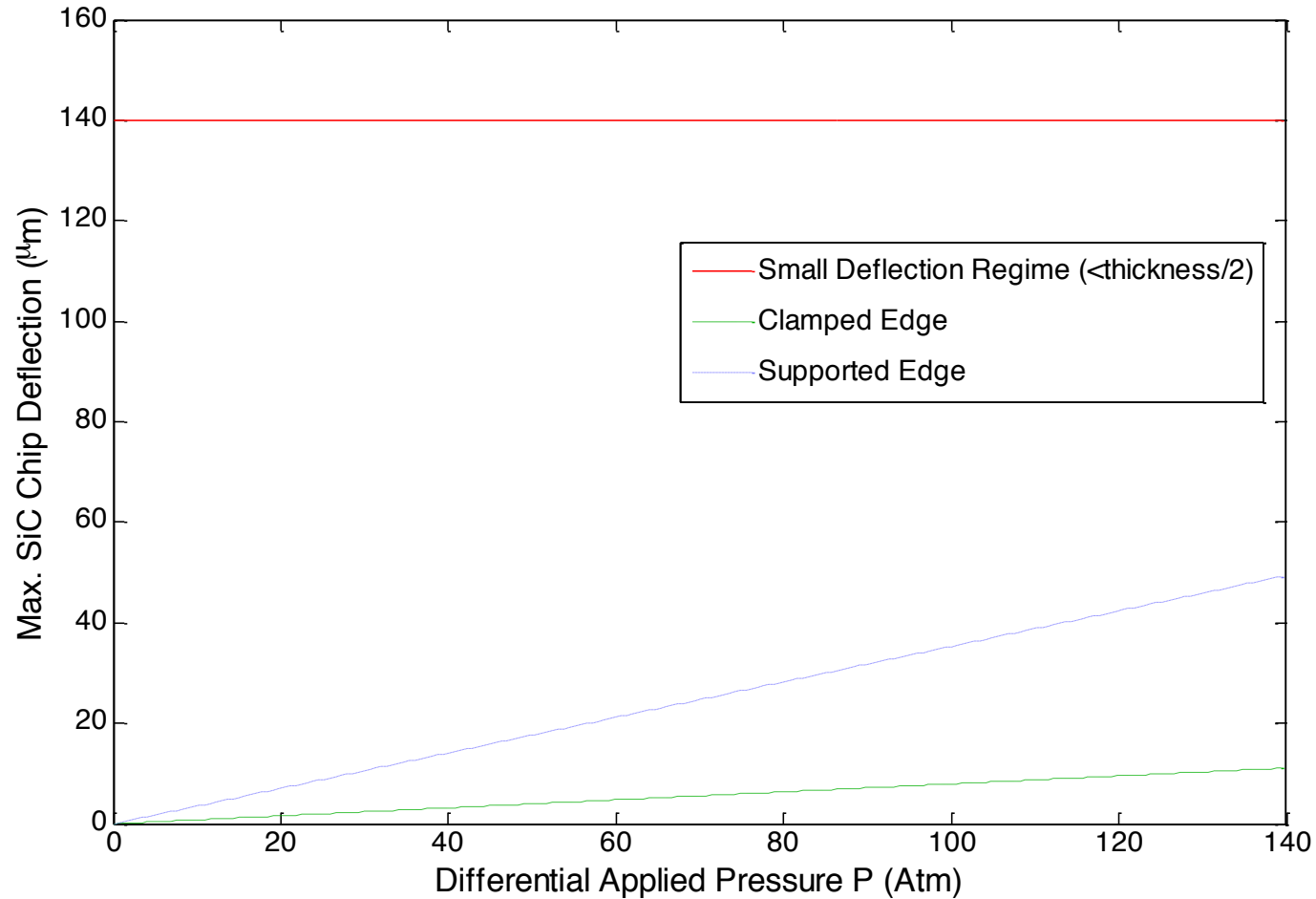
(b) Simply Supported model

$$w(r) = \frac{P}{64D} (a^2 - r^2)^2 \quad \text{where} \quad D = \frac{Eh^3}{12(1-\nu^2)},$$

$$w_{\max} = \frac{P}{64D} a^4 \quad (r = 0)$$

w = deflection under pressure along Z-axis; D = Rigidity Constant;
 E = Young's Modulus; P = pressure; ν = Poisson's Ratio;
 a = radius of plate; h = thickness of SiC

Maximum Expected Sensor chip Deflection ' $w_{\max}$ ' under Applied Pressure for the Clamped Edge and Supported Edge boundary condition models.



$a = 2.5 \text{ mm}$, $h = 280 \text{ μm}$, $E = 415 \text{ GPa}$, $\nu = 0.16$

Theoretical Stress Failure Analysis of 6H-SiC Chip

(a) Clamped Edge model

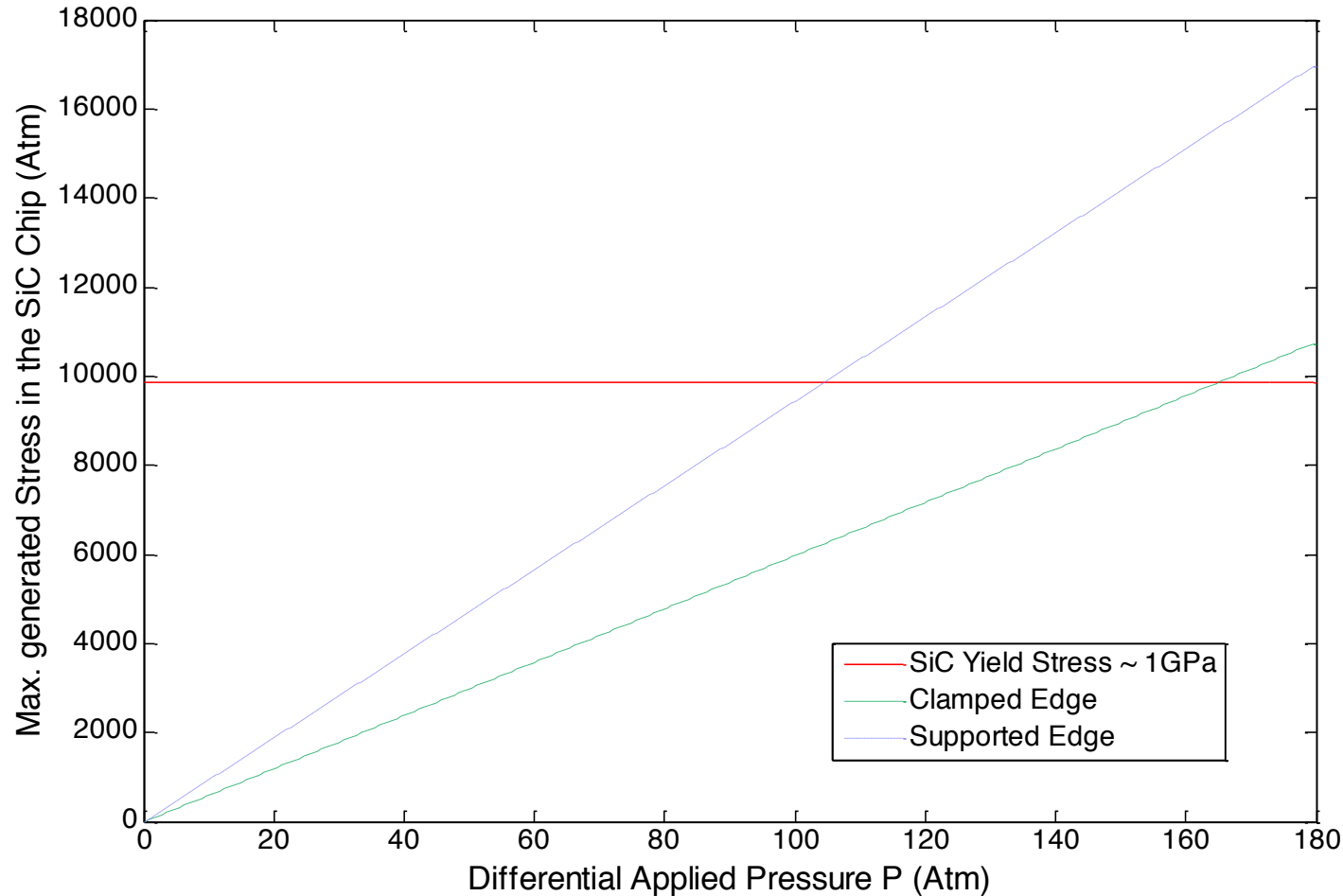
$$(\sigma_r)_{\max} = \frac{3Pa^2}{4h^2}$$

(b) Simply Supported model

$$(\sigma_r)_{\max} = \frac{3Pa^2(3+\nu)}{8h^2}$$

$(\sigma_r)_{\max}$ = Maximum Generated Stress; D = Rigidity Constant;
 P = pressure; ν = Poisson's Ratio; a = radius of plate; h = thickness of SiC

Expected Stress Generated in 6H-SiC sensor chip for the Clamped Edge and Supported Edge boundary condition models.

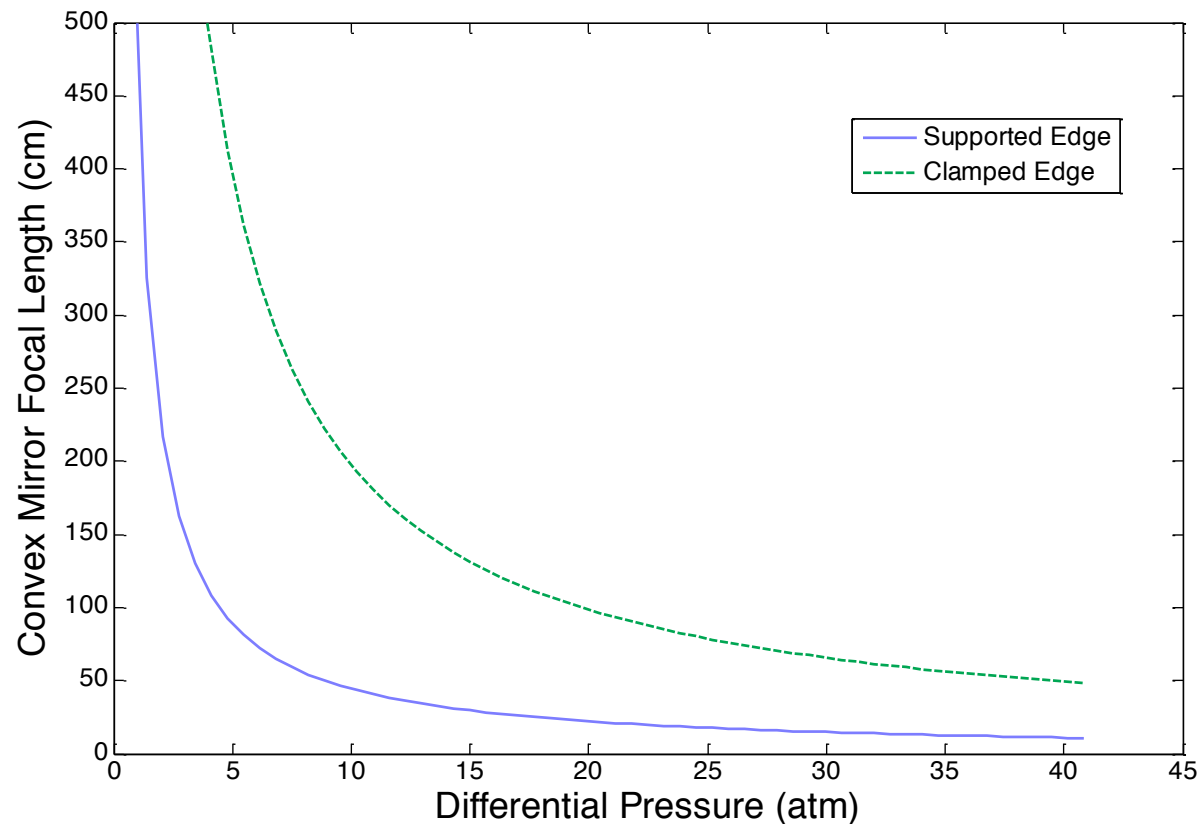


$a = 2.5 \text{ mm}$, $h = 280 \text{ }\mu\text{m}$, $\nu = 0.16$
SiC Yield Stress = 1 GPa (approx.)

Approximation of the 6-H SiC Sensor chip surface and hence the Theoretical Optical Response of the chip by a Weak Lens

$$f_m = \frac{R}{2} = \frac{w_{\max}^2 + a^2}{4w_{\max} \times 10^4} \text{ cm},$$

(Lens/Mirror Radius of Curvature $R \gg$
Lens/Mirror Central Thickness $w_{\max}$)



Effective theoretical focal length ' f_m ' of the SiC chip under applied pressure

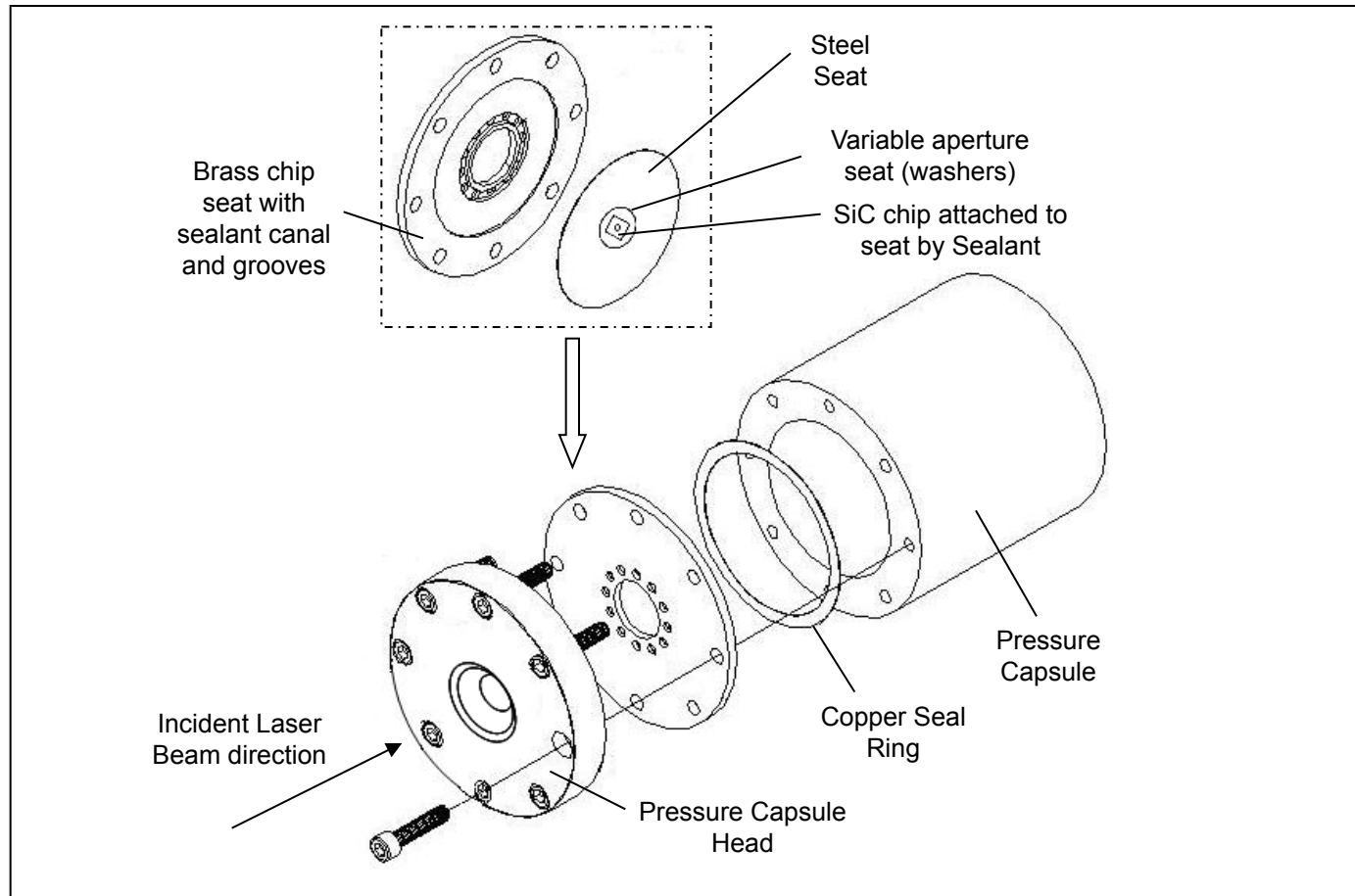
Pressure Dependent Magnification/Demagnification M for the Imaging System

$$M = \frac{F_3}{f_e} = \frac{F}{f_e} = \frac{f_m}{f_m - F} = \frac{1}{1 - F/f_m}, \quad \text{where} \quad f_e = \frac{F_2(L - f_m)}{L - (F_2 + f_m)}$$

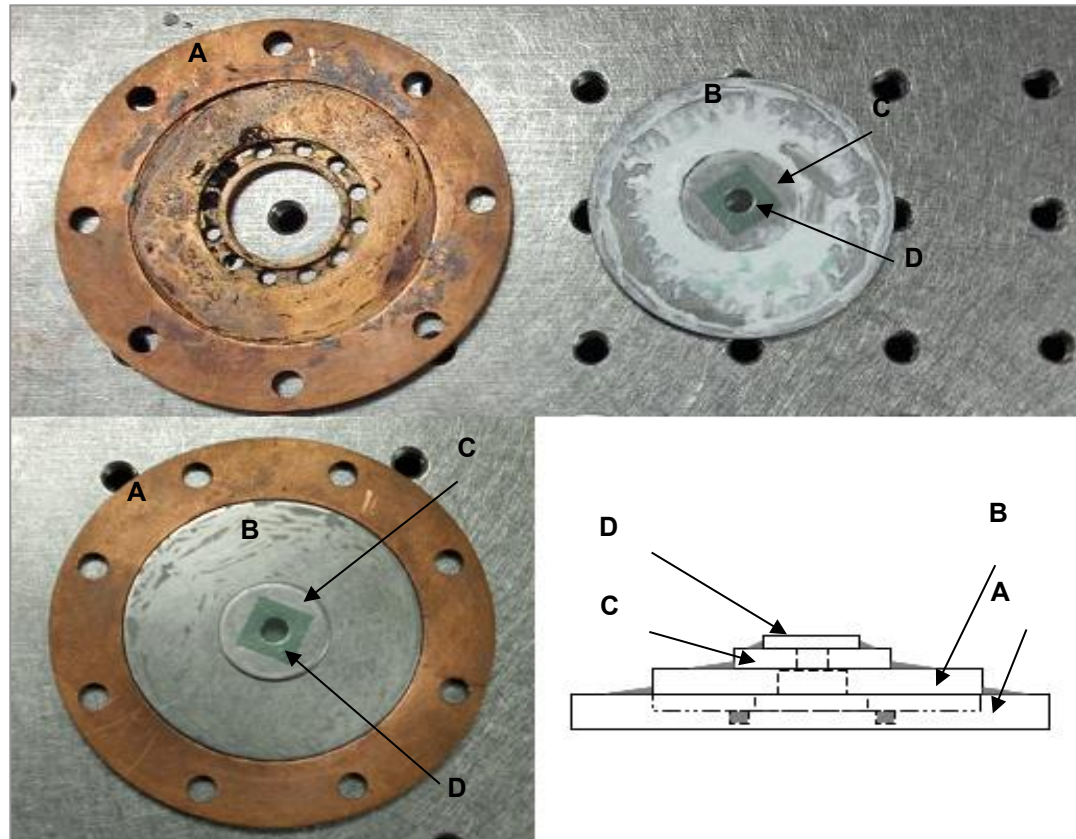
Differential Pressure P		Demagnification M	
		Theoretical	
(psi)	(atm)	Supported	Clamped
0	0	1	1.00
200	13.61	0.76	0.94
300	20.41	0.68	0.91
400	27.21	0.62	0.88
500	34.01	0.57	0.85
600	40.82	0.52	0.83

Comparison of Demagnification corresponding to Theoretical Mechanical Models

Experimental Design used for Seating the SiC chip in the High Pressure Capsule



Experimental Seating of Components in High Pressure Capsule

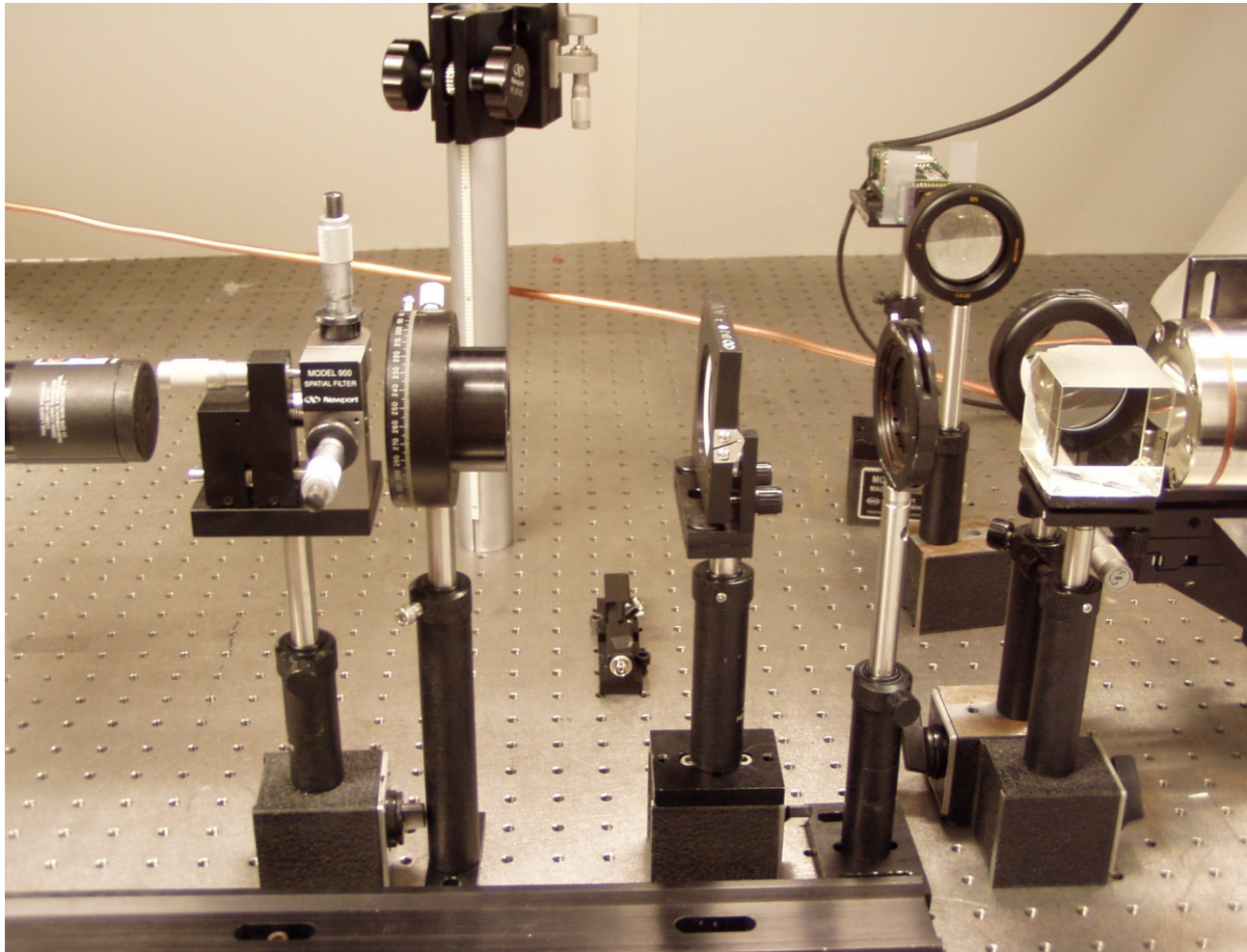


Components in photograph are labeled as: A: Brass chip seat holder with sealant canal and grooves; B: Steel seat; C: Aperture seat (washer); and D: SiC chip.

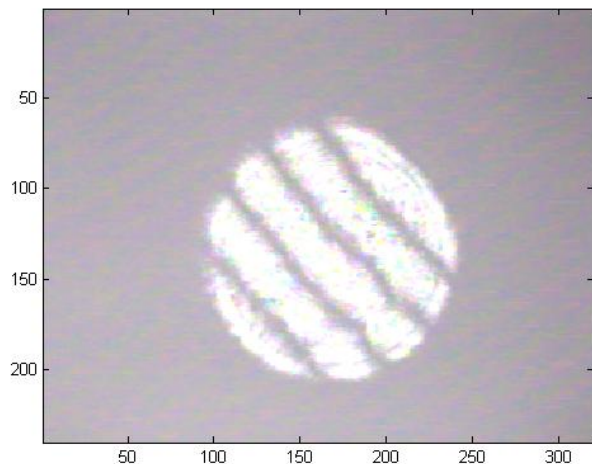
Close-up front-view of the Experimental SiC chip Mounted High Pressure Capsule



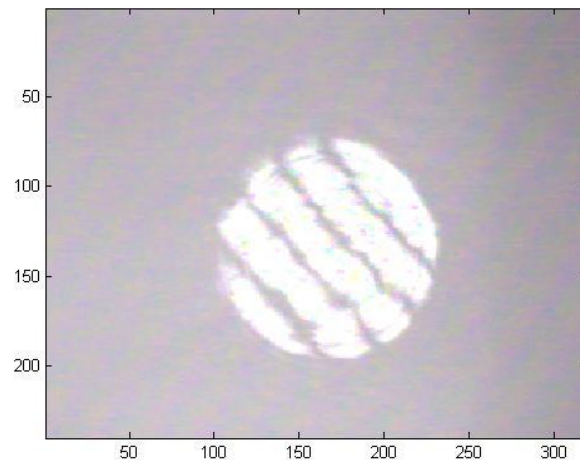
Experimental Laboratory set-up for the 6H-SiC chip-based Pressure Sensor System



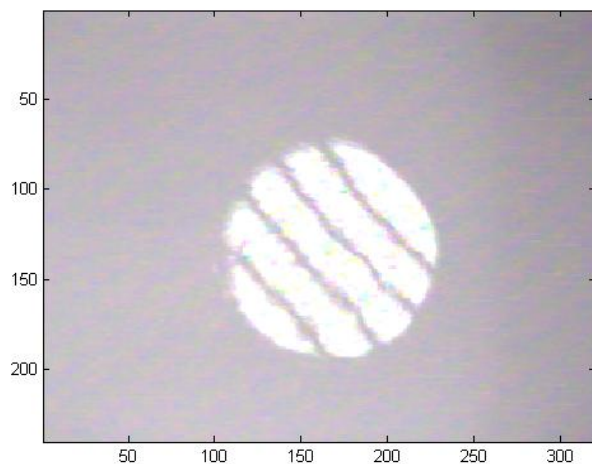
6H-SiC chip-based Pressure System I(x,y) optical images
produced for high differential pressure conditions.
(Axes: CCD pixel count)



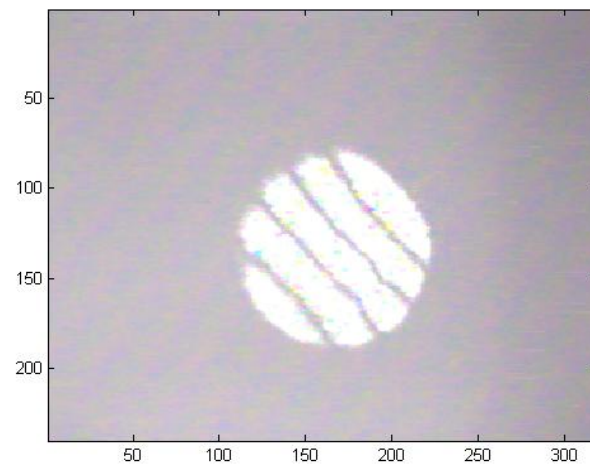
(a)



(b)



(c)

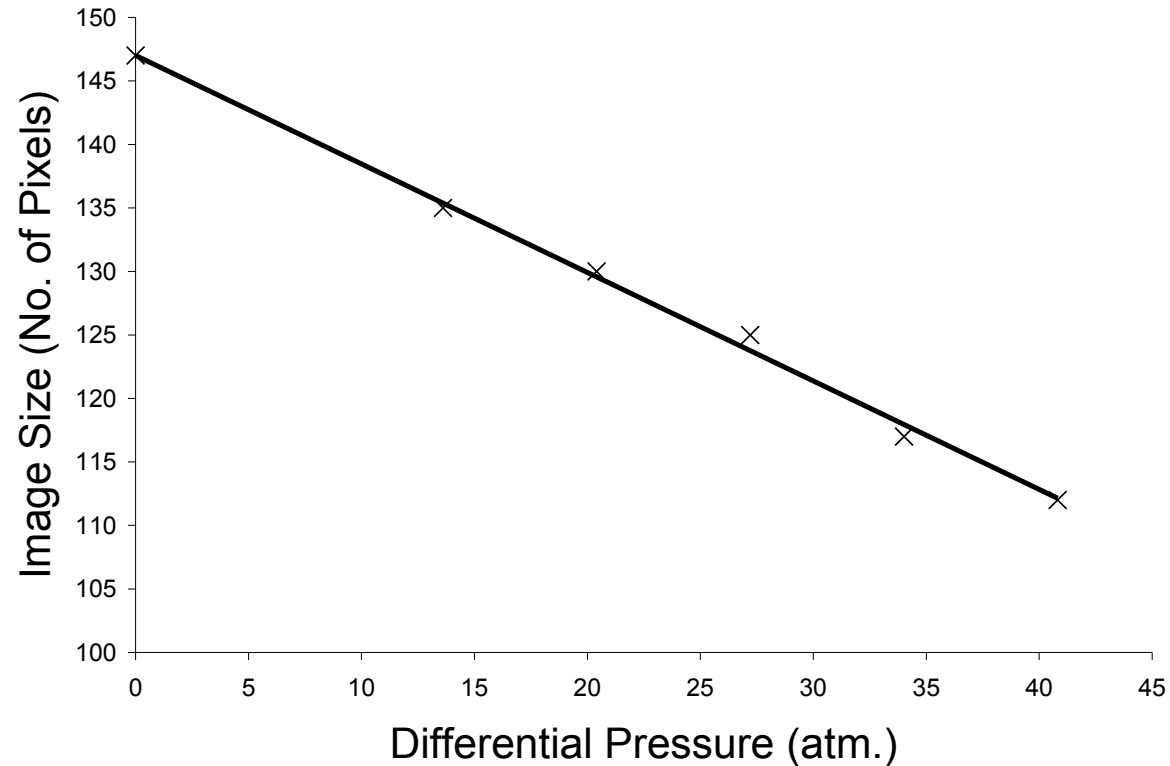


(d)

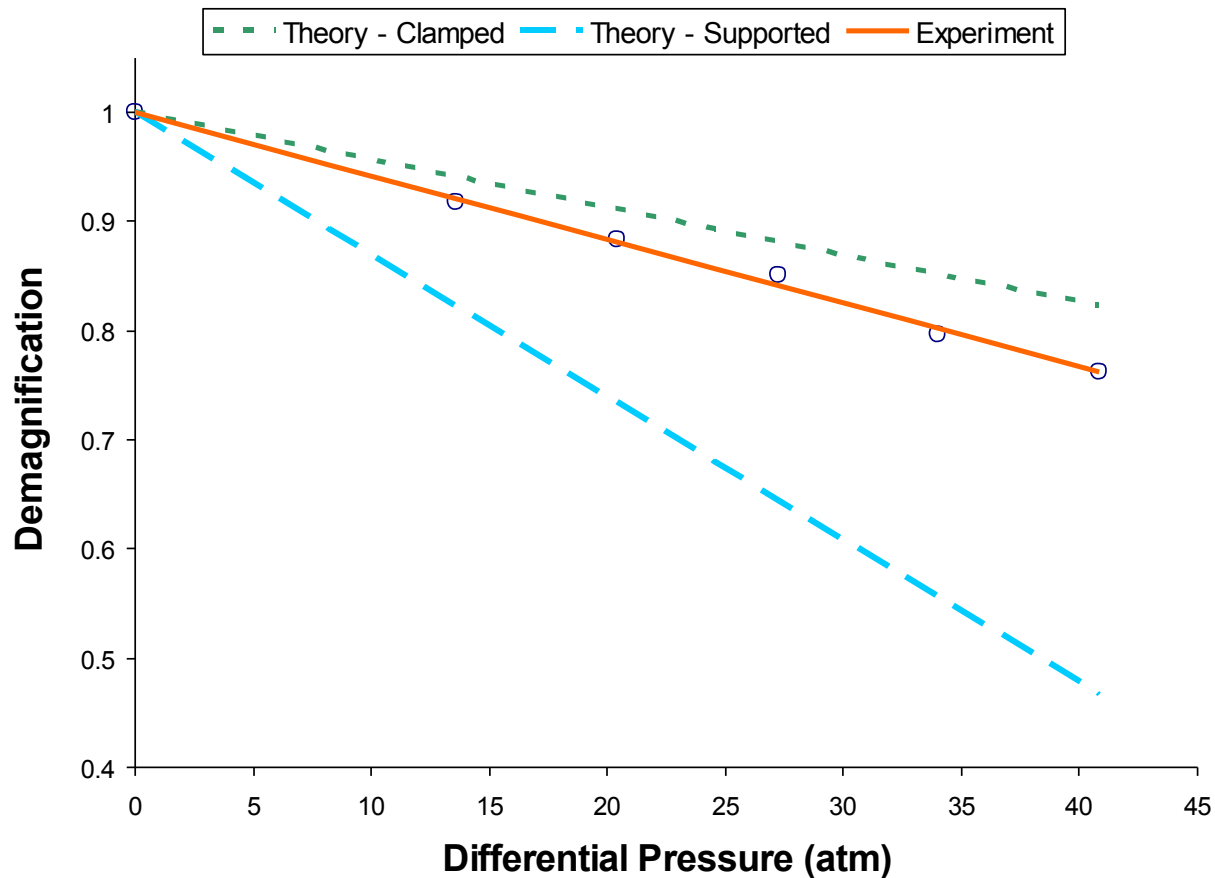
Experimental Optical Image Size & Demagnification M vs. Capsule Differential Pressure P

Differential Pressure P		Image Size	Measured Magnification
(psi)	(atm)	(CCD pixels)	($M = \text{Image Size}/147$)
0	0	147	1.00
200	13.61	135	0.92
300	20.41	130	0.88
400	27.21	125	0.85
500	34.01	117	0.80
600	40.82	112	0.76

Demagnification of Incident Beam Size (retro-reflected from the SiC chip) under acting Differential Pressure



Experimental Beam Demagnification along with the Theoretical Demagnification for Clamped and Supported sensor chip models.



Conclusion

- Proposed a SiC Chip-based Wireless Hybrid Optical Sensor Design For Simultaneous Temperature and Pressure Measurement
- Demonstrated Temperature Sensing up-to 1000 °C
- Designed a Pressure-only Sensor Laboratory System
- Experimentally Demonstrated Wireless Pressure-only Sensing up-to 40 atms
- Theoretical Mechanical and Optical Models of Sensor agree with Experimental Results
- Models Indicate Measurement Capability near 140 atm with Present System

Conclusion- Technology has Potential for Success

- Both single-crystal SiC and sintered SiC are tried and tested material
- Single-crystal SiC is used by US DoD for all high temperature power electronics
- Sintered SiC is used by NASA / ESA as a lightweight material for space platforms and for giant mirrors for telescopes

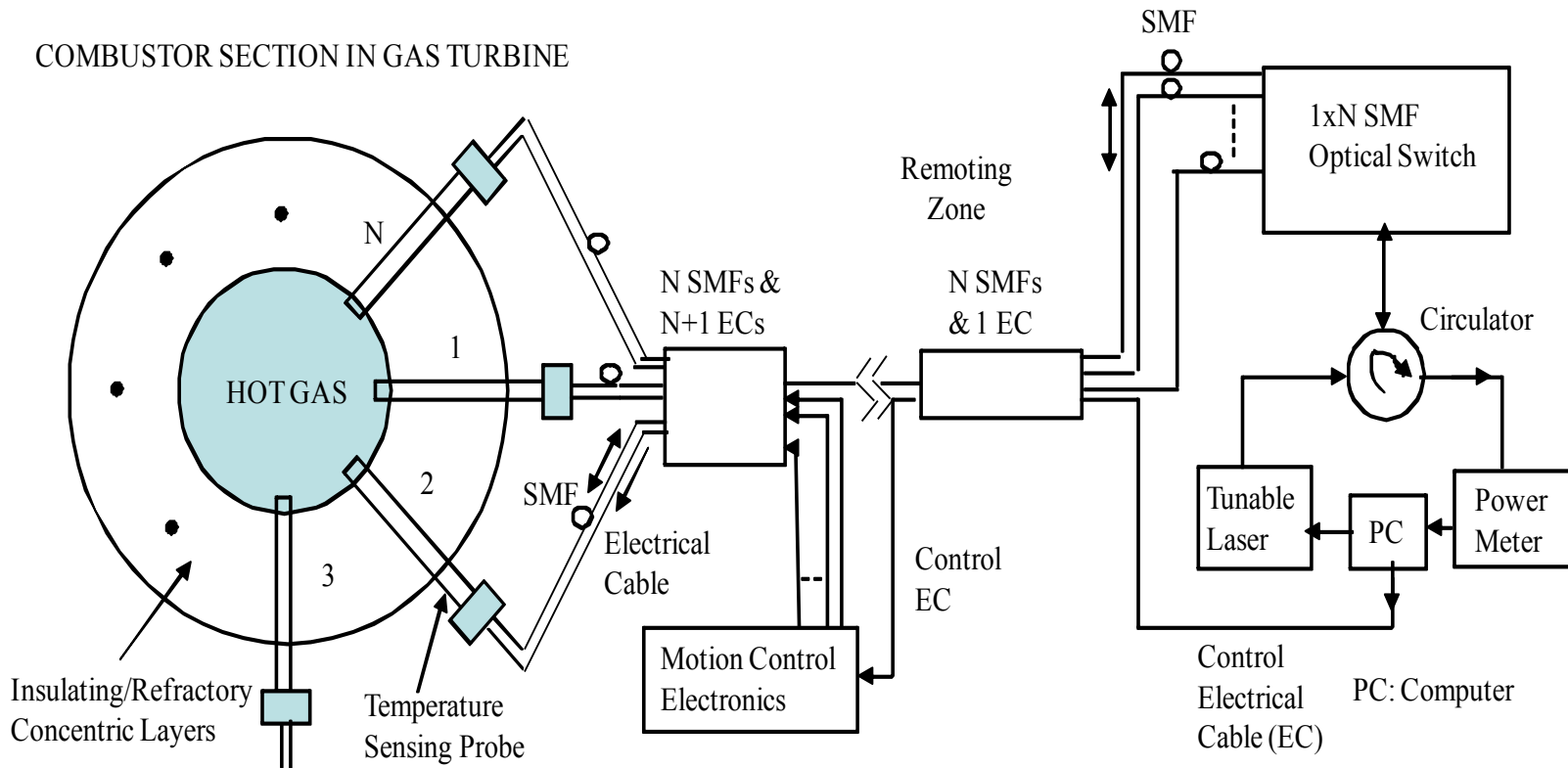


Ref: Seme Lab



Ref.: ESA

Temperature Sensor Network – Basic Design Engineering



Implemented Network Design using MEMS Fiber-Optic Switches

N. A. Riza, M. Sheikh, "All-Silicon Carbide Hybrid Wireless-Wired Optics Temperature Sensor Network Basic Design Engineering for Power Plant Gas Turbines," Int. J. Optomechanics, Vol.4, No.1, Jan-March 2010.

Other Impact-Jet Aviation

Jet Engine industry

Combustion temperatures
>1500 deg-C

Leads to

- Higher system efficiencies and performances
- Faster Jet Speeds
- **Lower and cleaner fuel consumption**
- Longer airplane ranges
- Lower operational costs



“Fahrenheit 3600”, Feature Article, Apr 2007, Mechanical Engineering magazine

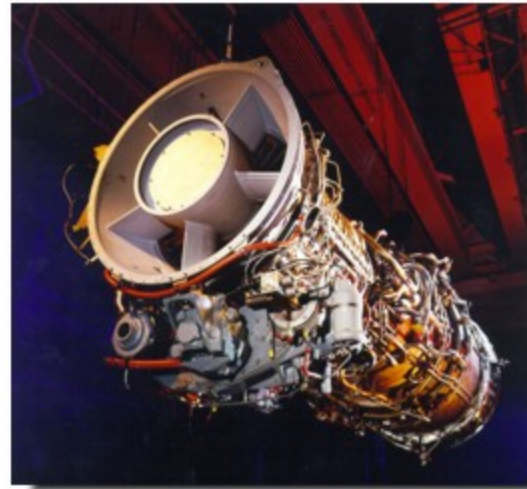
Additional Green Impact: Ship Propulsion-Turbines at Sea

**Ship Propulsion Maritime
industry**

**Combustion temperatures
>1500 deg-C**

Leads to

- Higher system efficiencies and performances
- Faster Ship Speeds
- **Lower and cleaner fuel consumption**
- Longer ship ranges
- Lower operational costs



References for Extreme Temperature SiC Temperature Sensors

- N. A. Riza, et.al., OFS 17, SPIE Proc. Vol. 5855, pp.687-690, Bruges, Belgium, May 2005.
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