Hybrid Wired-Wireless Silicon Carbide-based Optical Sensor for Extreme Sensing Environment Temperature

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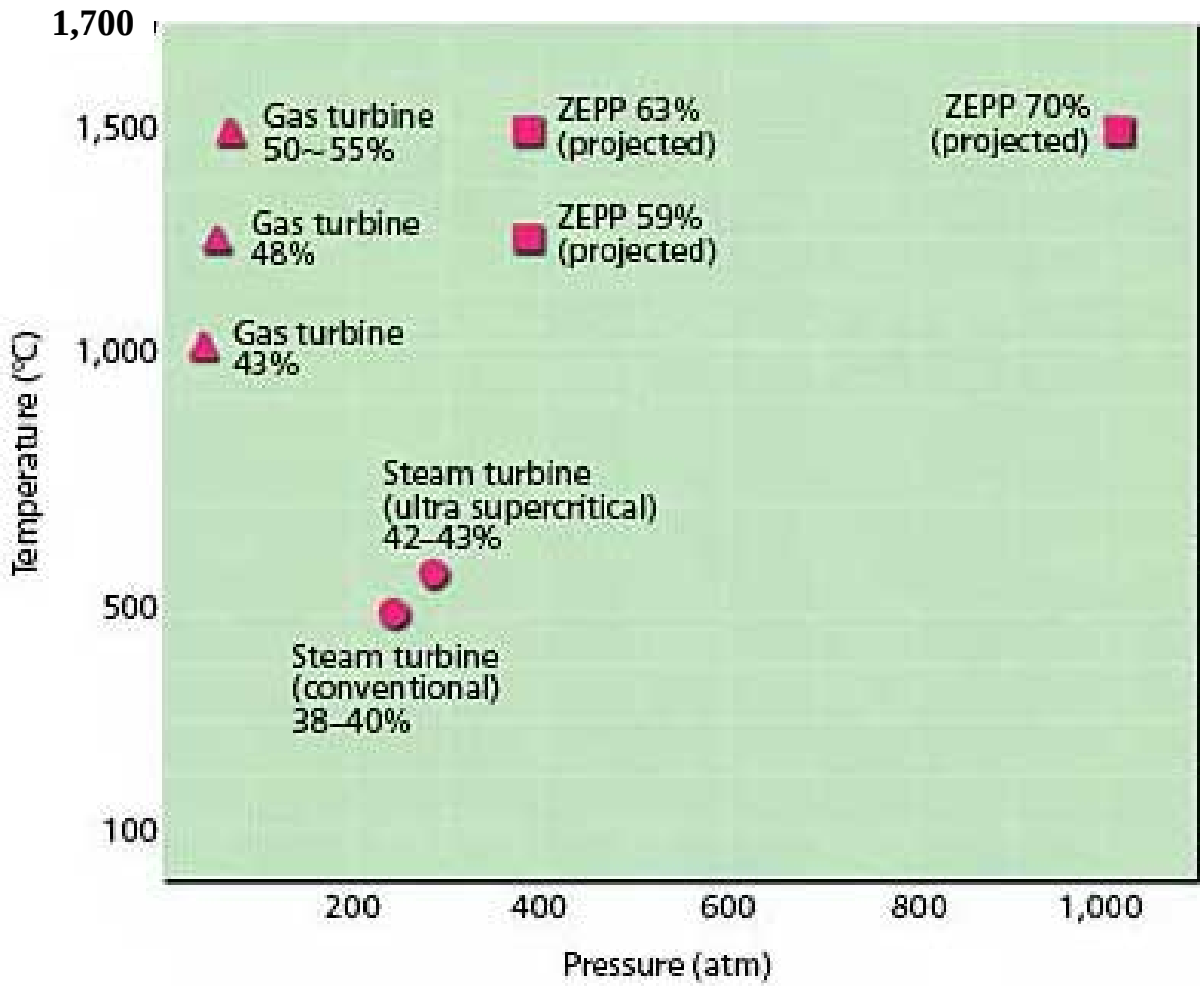
Why is Extreme Temperature Sensing Needed --- Greener & More Efficient



Burn Less Fuel

↓

Less Hazardous Waste & CO_2

Higher Pressures

↓

Liquify CO_2 -Easier To Transport/Store Waste

↓

Greener Plant

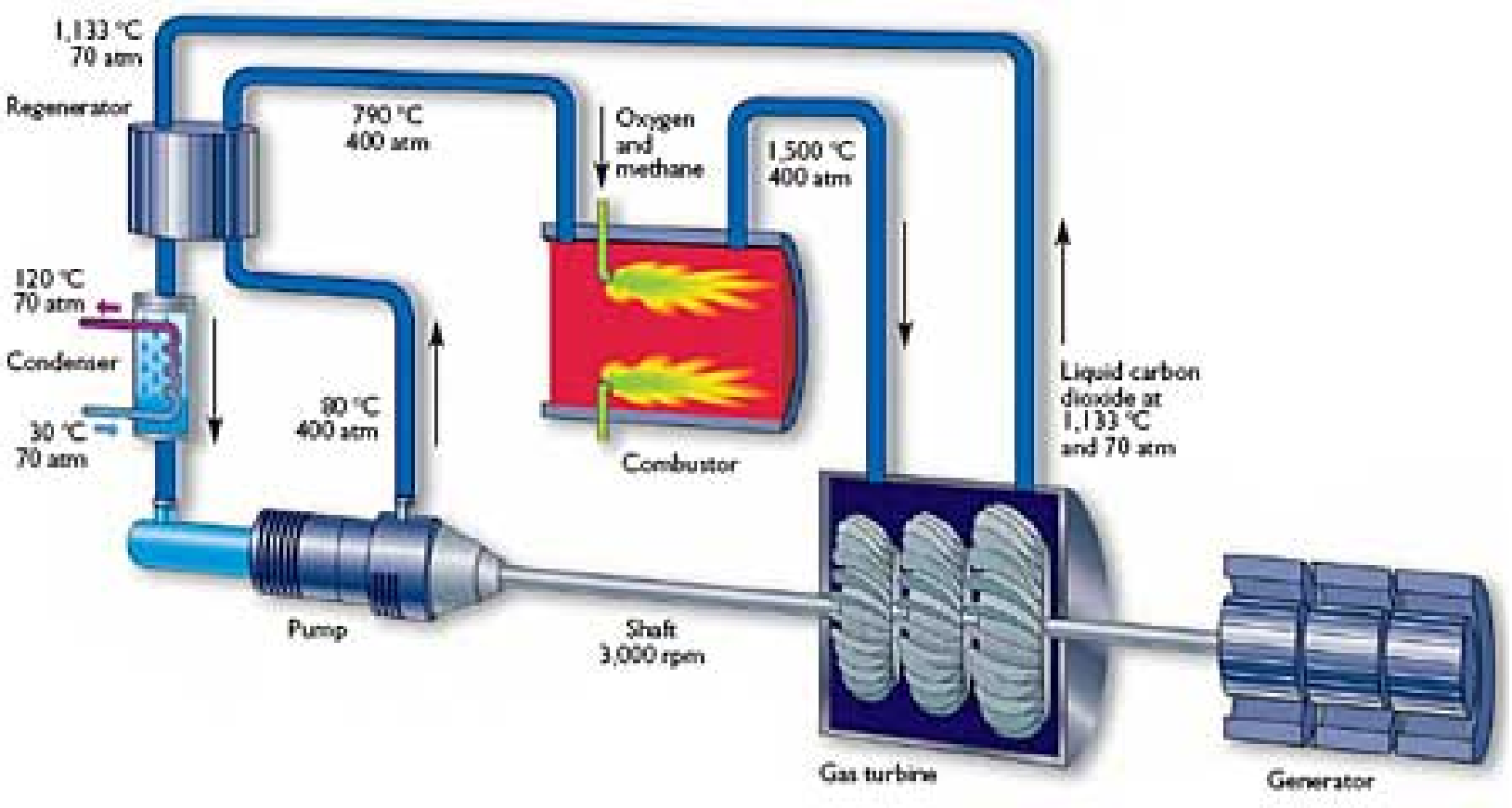
Ultimate Goal--ZEPP: Zero Emission Power Plant

* 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)



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

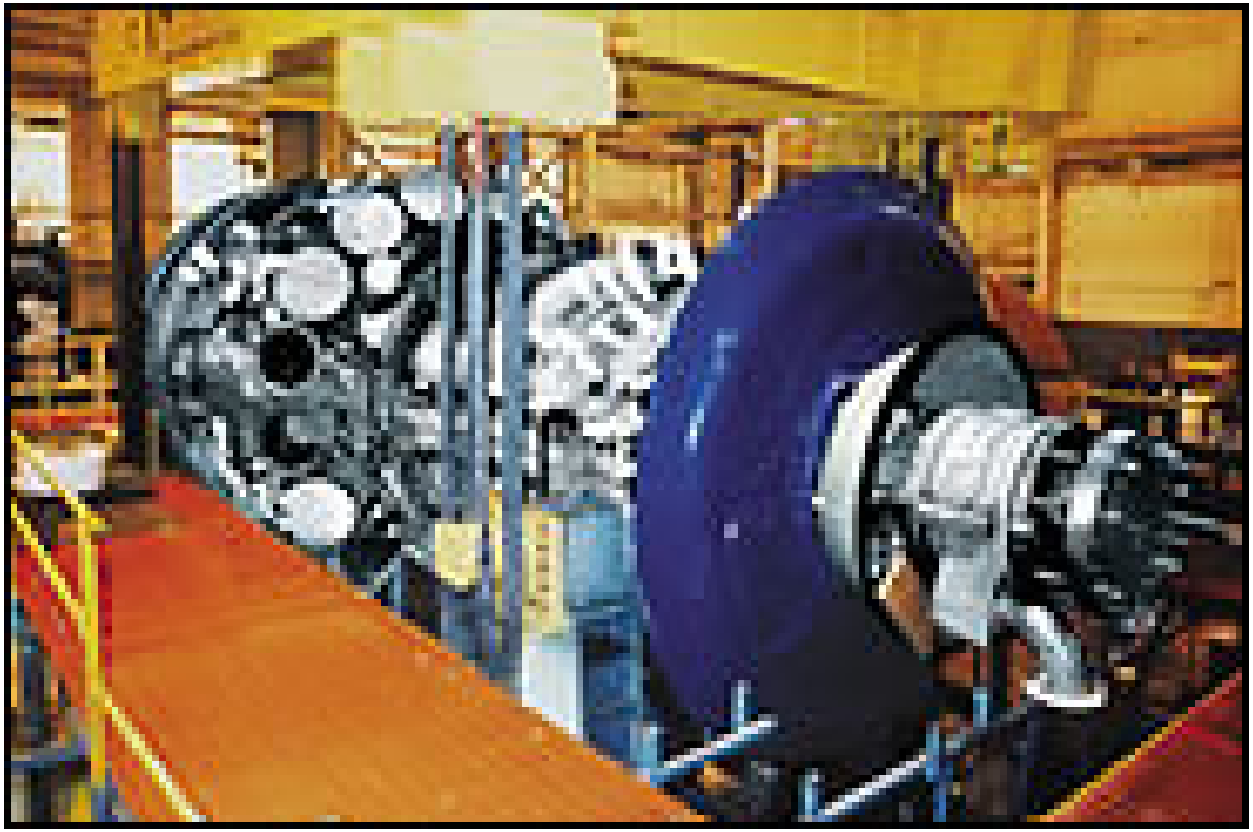
GE's H system Gas Turbine

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 W501G Gas Turbine



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

Combustion Section Temperatures ~ 1500 ºC

How does Extreme temperature Measurement get done today?

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

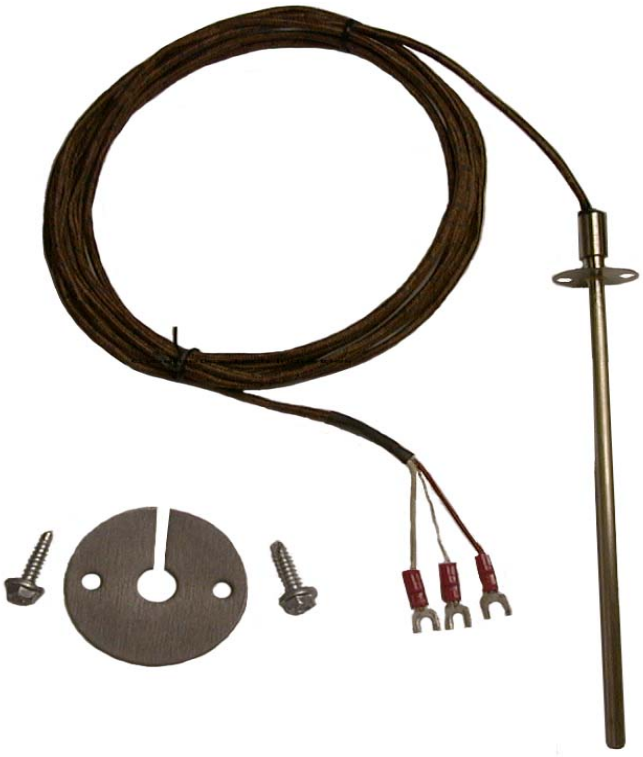


Image courtesy: Cybernetics Technical Industries Inc.

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)
- Give inaccurate and erratic readings
- Readings intrinsically depend on a % of measured extreme temperature, i.e., gets worse at higher temperatures

2009 Table : JM Noble Metals Inc.

www.noble.matthey.com

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 = +/- 1°C or +/- {1 + (t - 1100) x 0.0003}°C
Class 2 = +/- 1.5°C or +/- 0.0025t°C
Class 3 = +/- 4°C or +/- 0.005t°C
Whichever is the greater and where t is temperature in °C

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

Table of tolerance values

Temperature	Class 1	Class 2	Class 3
°C	+/- °C	+/- °C	+/- °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

~ +/- 0.2 % →

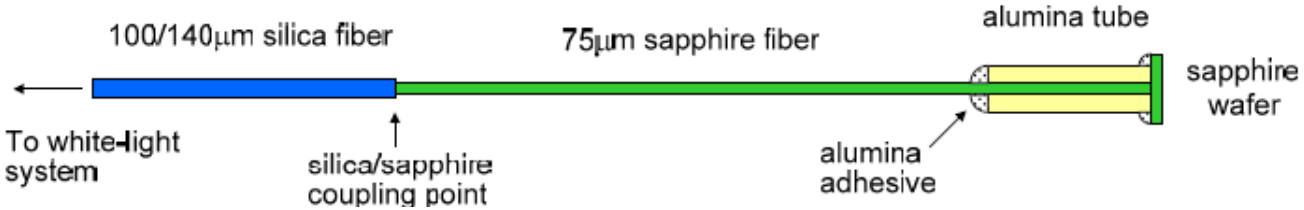
Who does TC Probes?

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

Image courtesy: L&L Kilns Inc.

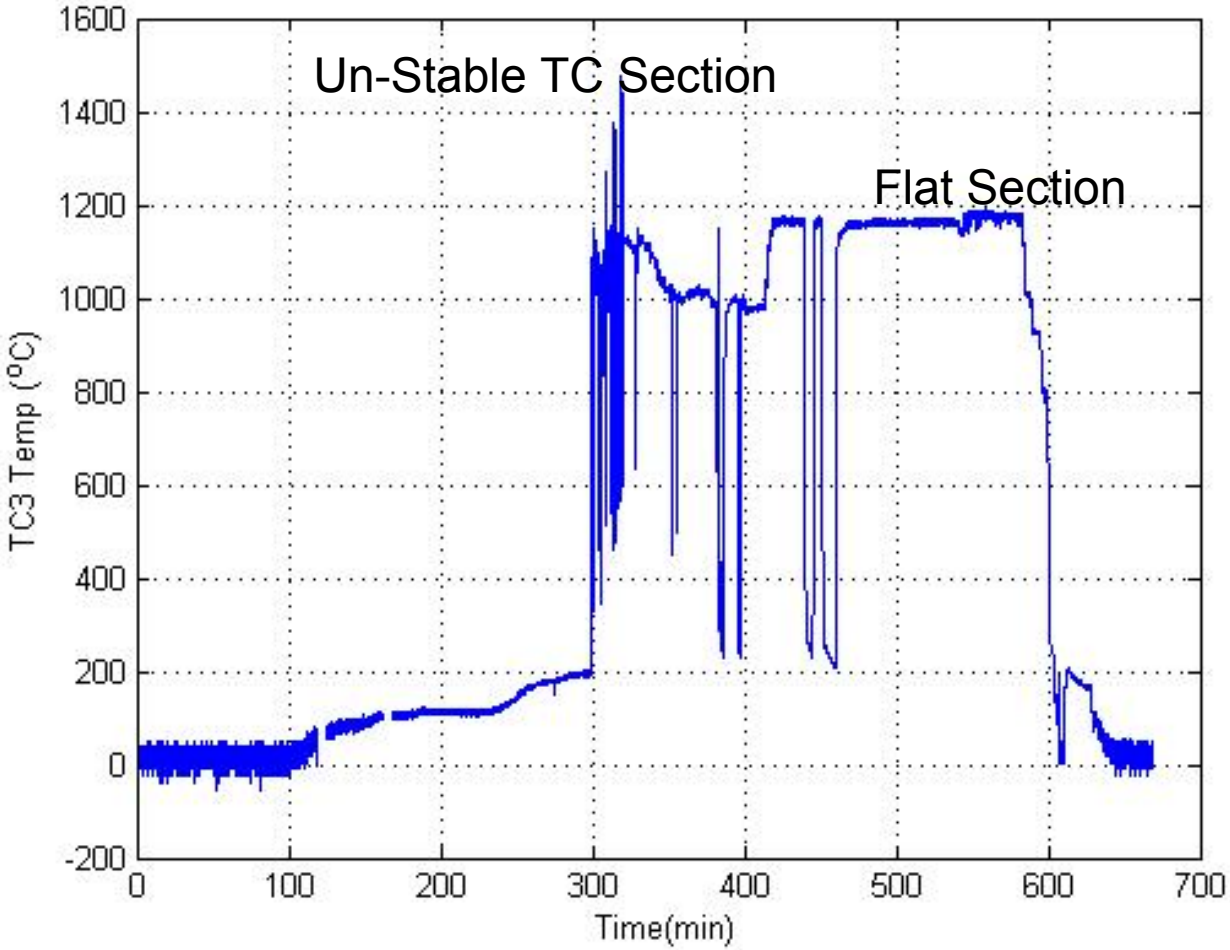
Fiber-Optic Probes?

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



Ref: Virgina Tech, SPIE 2007.

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

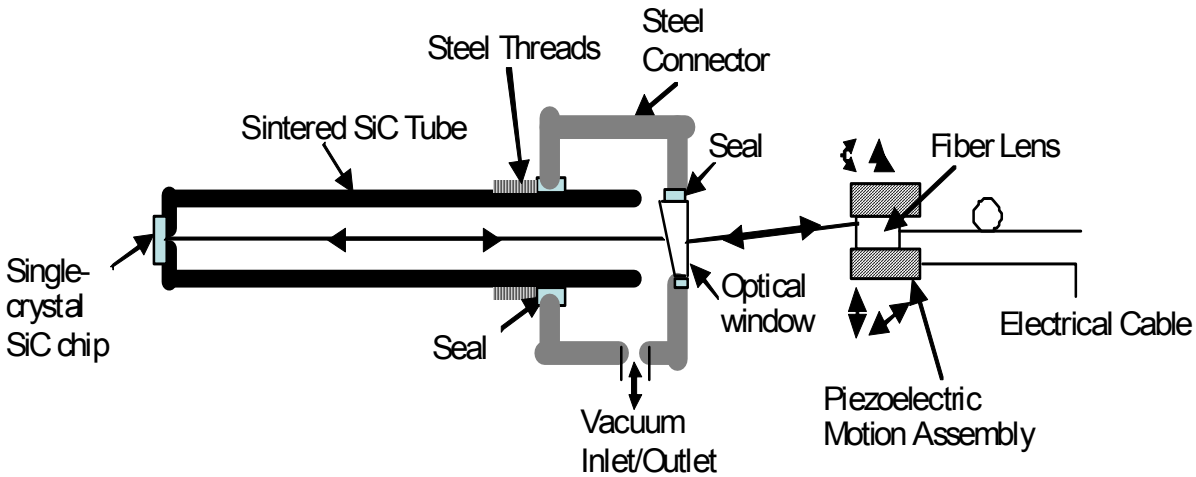
Type B: Operation Zone: 870 to 1700 deg-C

What is new about our approach?

Wireless + Wired Optics

↓ ↓

Extremely Hot Thermal Isolation Cool Section



RELIABLE SOLUTION: THICK SINGLE CRYSTAL SILICON CARBIDE

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

Mechanically Robust

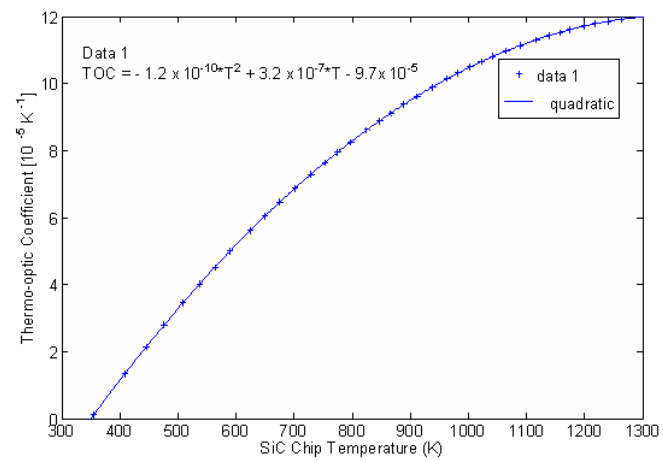
-- Handles 1 GPa (10,000 atm) Yield Stress
-- Allows Elastic Deformation in the Small Deflection Regime Due to Pressure

Excellent Atomic Scale Flatness
Minimal Optical Wavefront Spoiling

Single Crystal SiC Chip

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

Natural Interferometer Chip



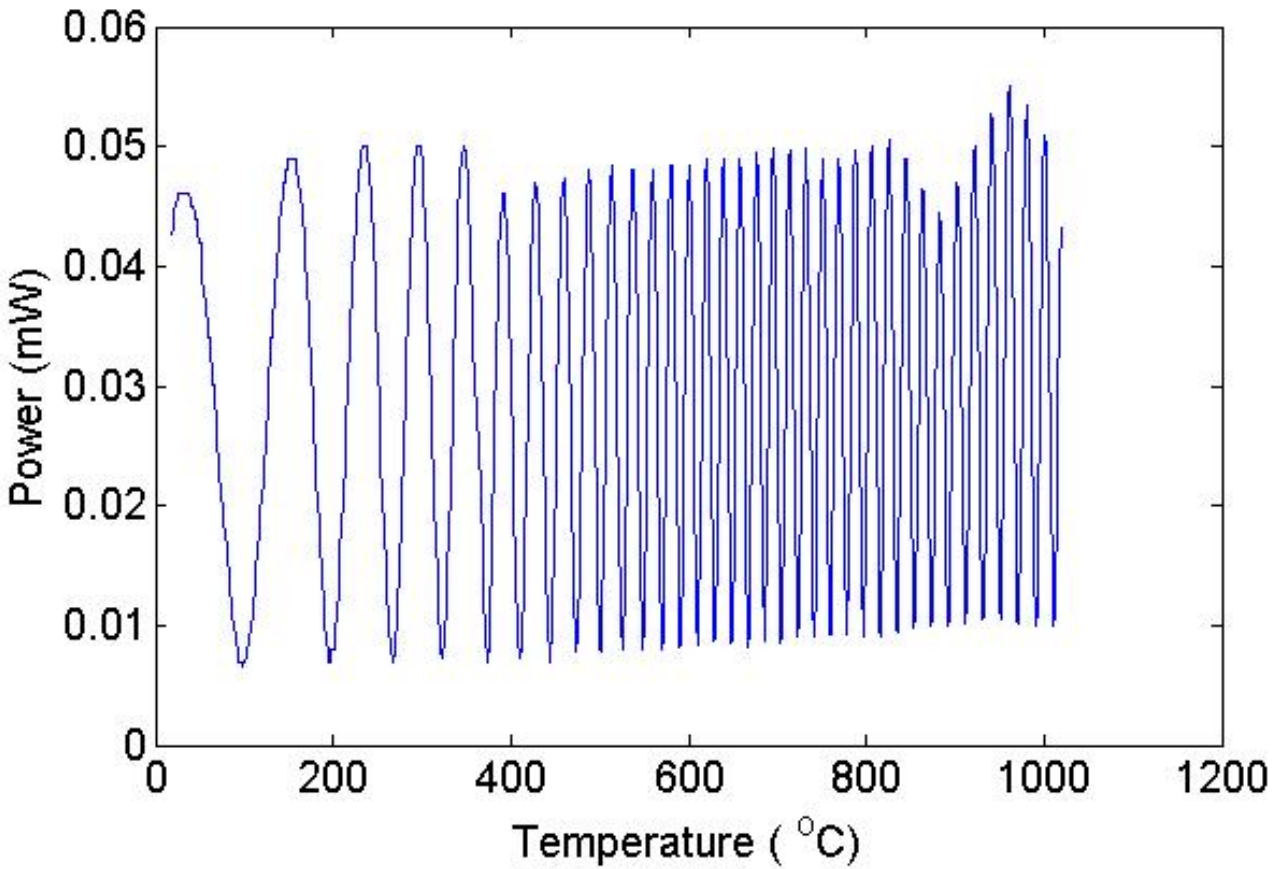
*** Refractive Index "n" Changes With Temperature T**
& dn/dT (Thermo-Optic Coeff.) Changes Quadratically with T

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

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

Optical Power Variation with Temperature & Wavelength

Raw power at λ = 1565.32 nm



Deploy Wavelength-Coded Signal Processing to Find Temperature

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

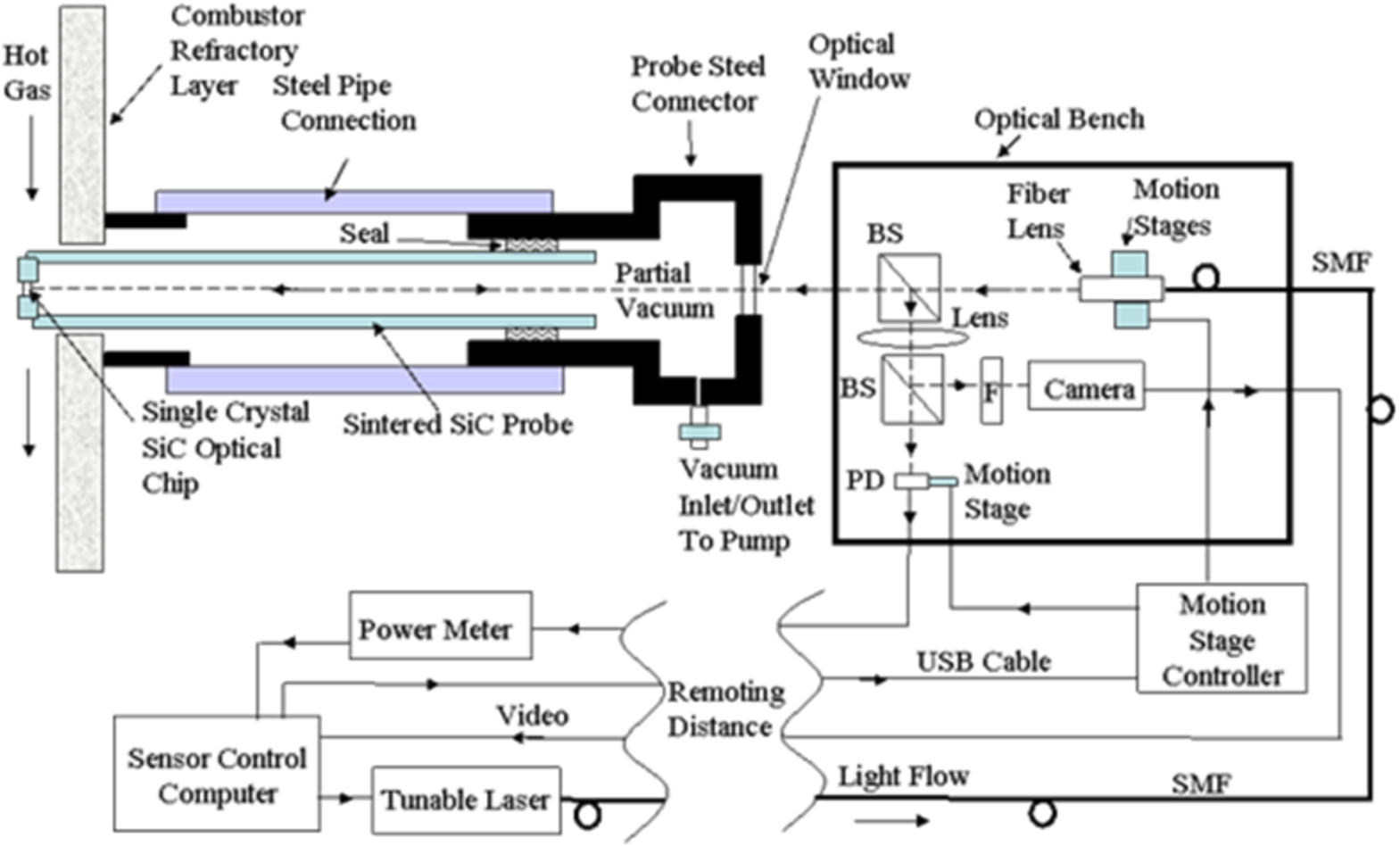
Front-End Probe

Unassembled

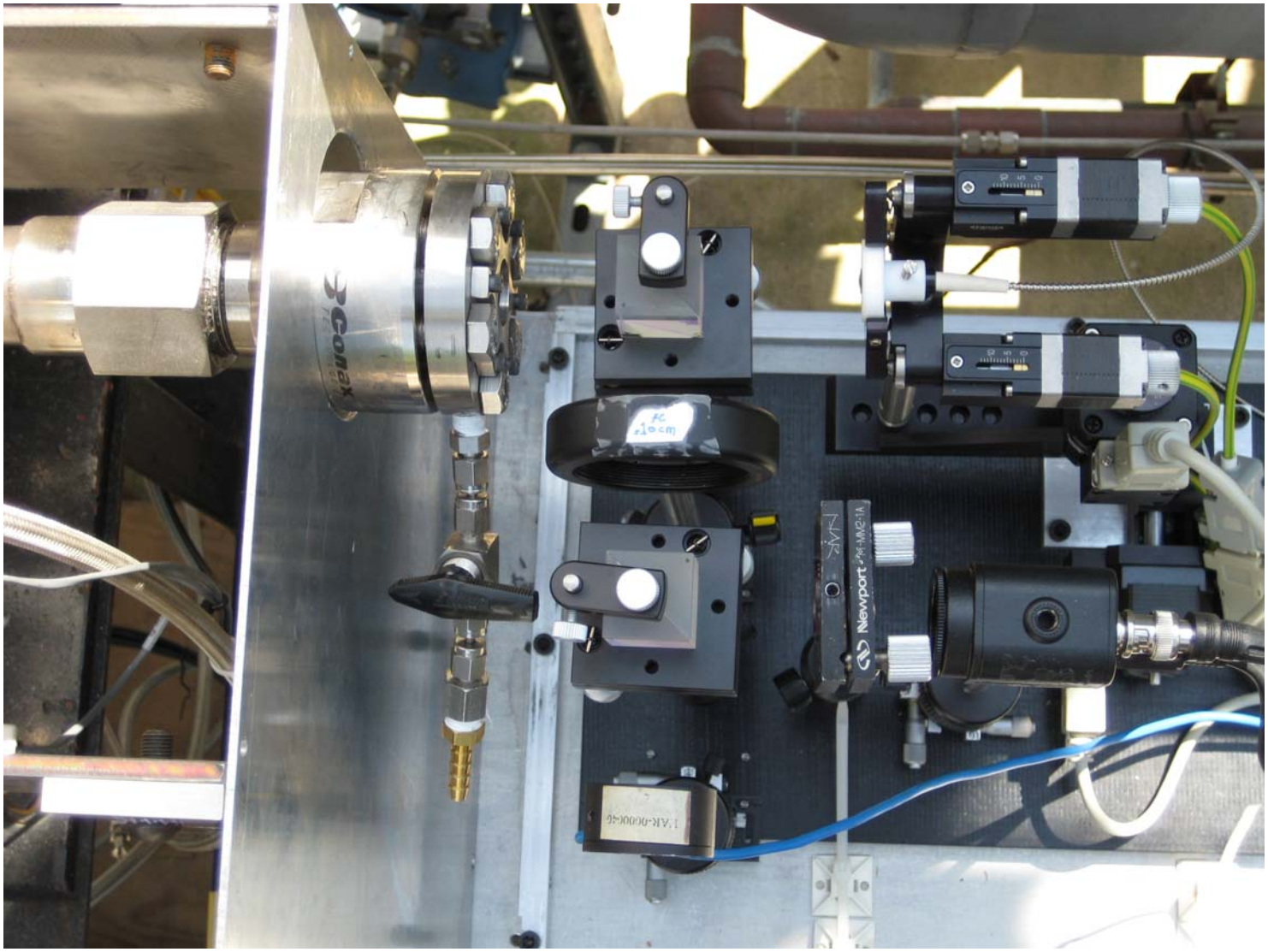
Assembled

Images courtesy: Nuonics, Inc.

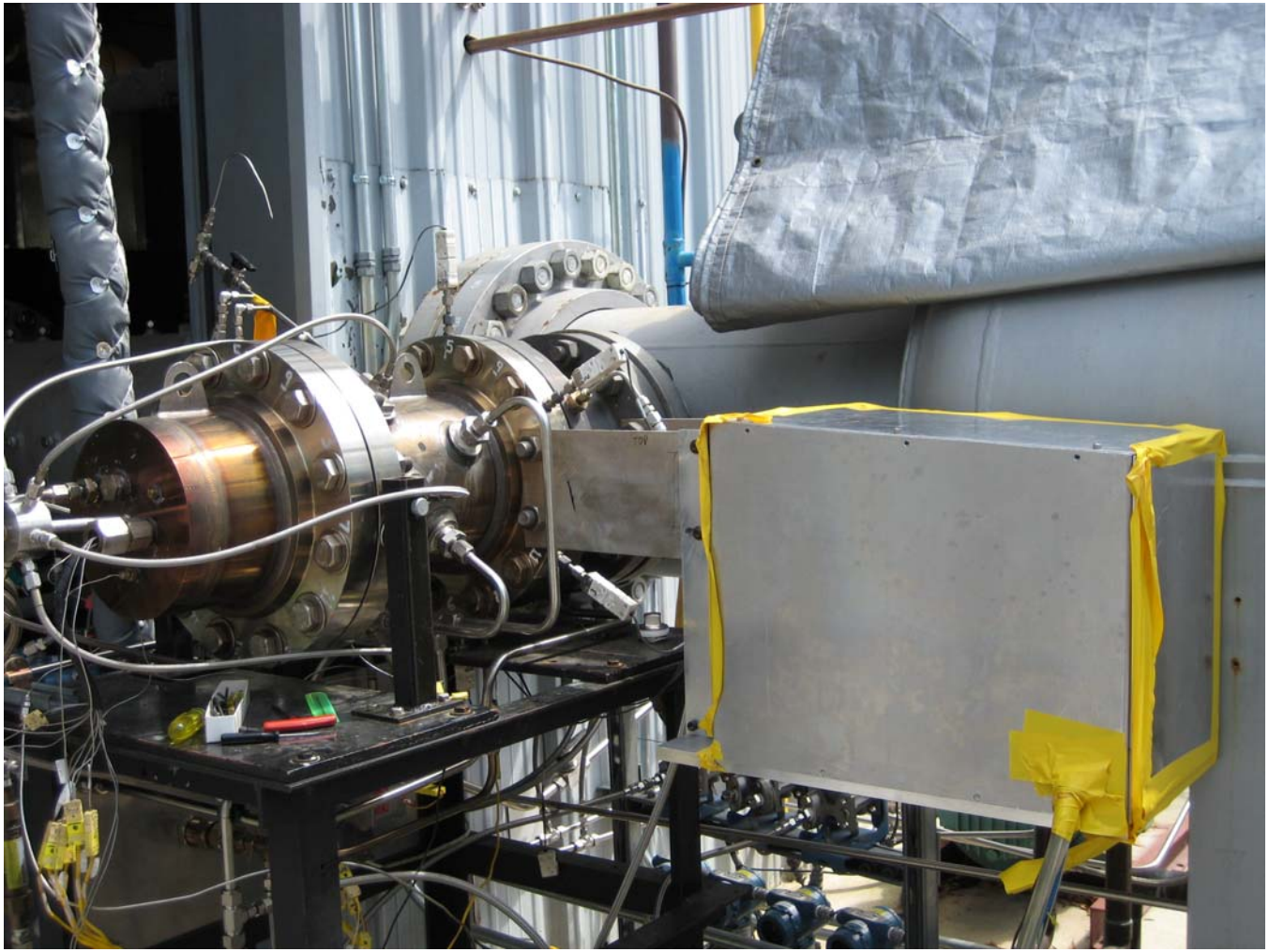
All-SiC Frontend Probe-based Optical Sensor System For Extreme Gas Temperature Measurements In Combustion Engines



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

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)

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

Images courtesy: Nuonics, Inc.

1550 nm Observed Received Beam when Gas Flame Lighted in Combustion Rig with Temperature Rising from ~ 200 C to ~ 1200 C in a few Seconds

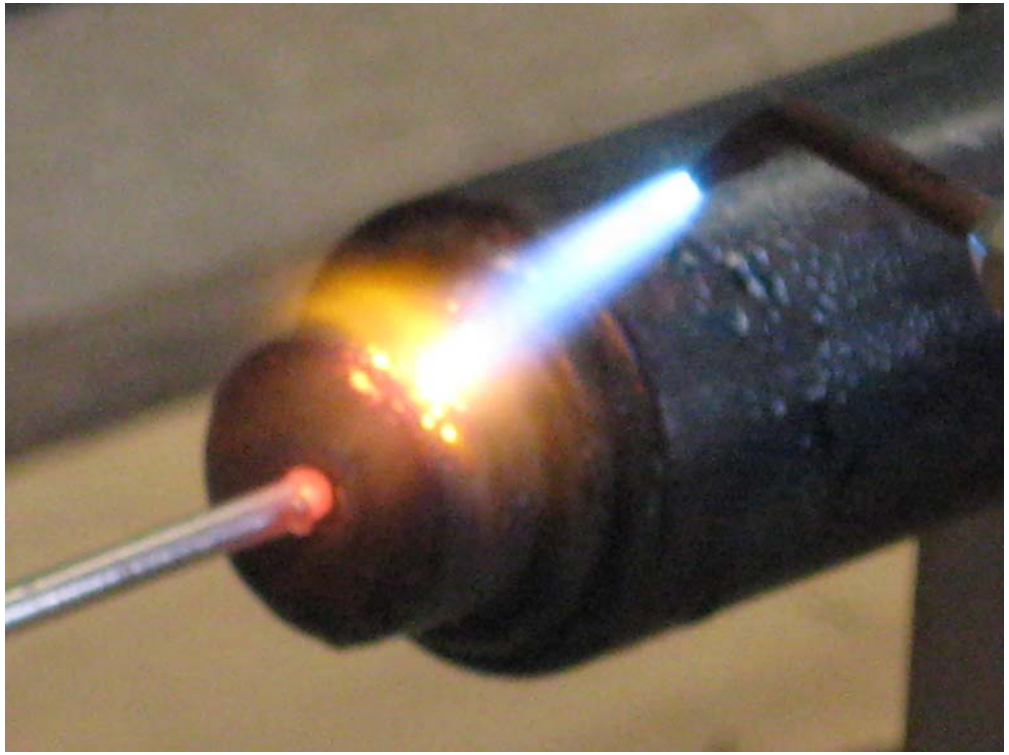
Thermal Ramp
> 1000 deg-C
in a few Seconds

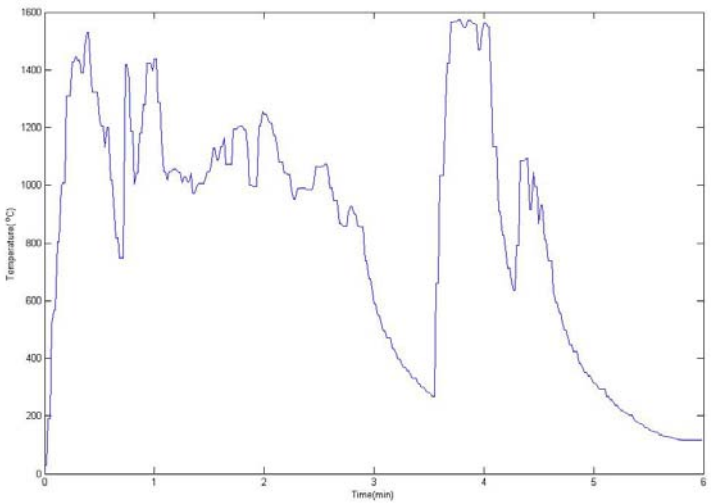
Also shows
Stable Optical
Beam in
Presence of RIG
Vibrations

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-Acetylane Torch Flame Application – 1600 deg-C





Flame Application: 5 minutes

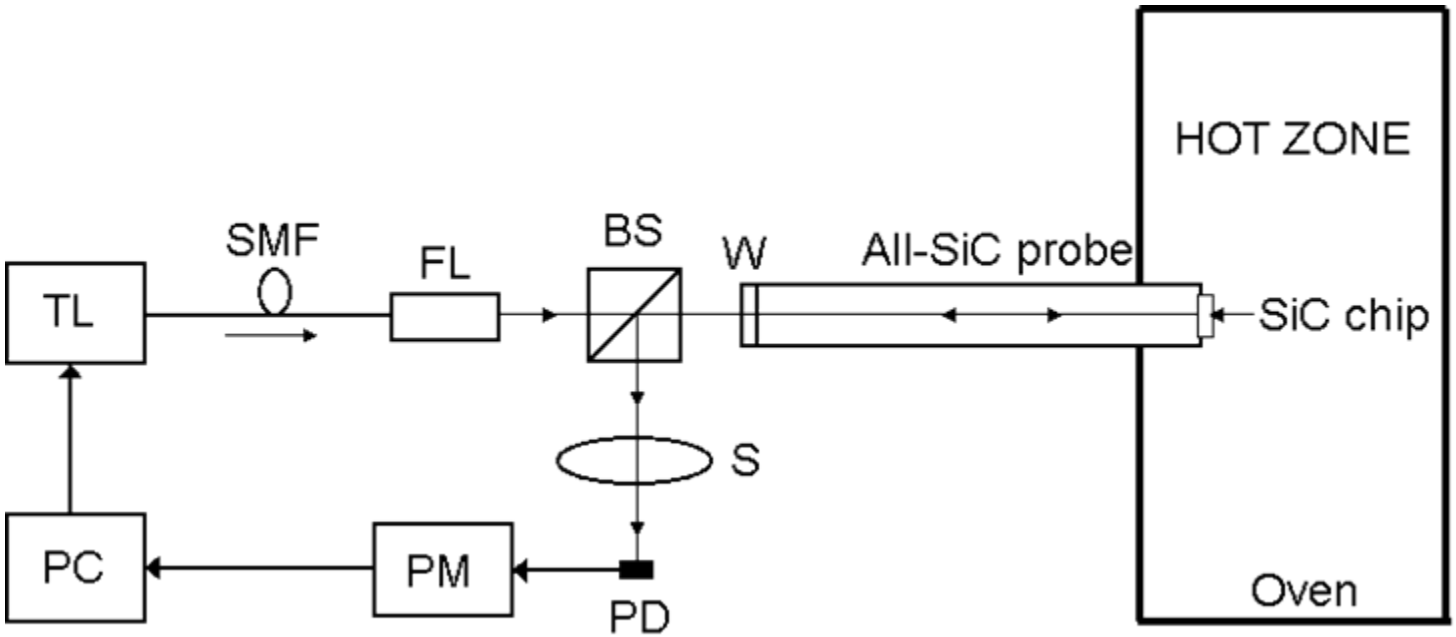
NOTE: Type R Thermo-Couple Started to Melt
Optical Probe Mechanical/Structural Integrity Unchanged

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

Silicon-Carbide based Extreme Temperature Sensor Design

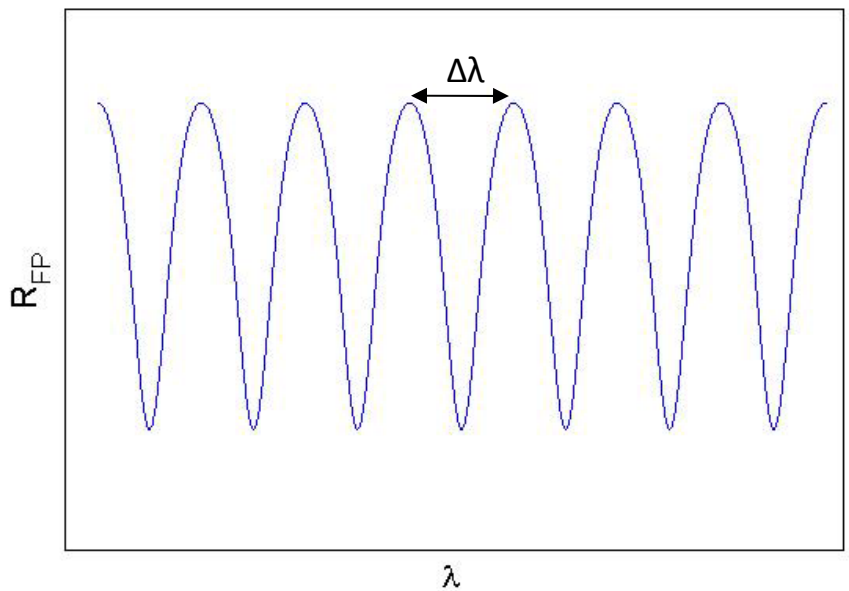


- CTE matched
- Wireless Optics only in Extreme Zone
- Fiber Optics thermally isolated

Theoretical Analysis

Classic Fabry-Perot Etalon Reflectance

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



Δλ 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

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

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

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

N. A. Riza and M. Sheikh, "Silicon-carbide-based extreme environment temperature sensor using wavelength-tuned signal processing," Opt. Lett. May 2008.

Theoretical Analysis

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

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

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

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

Theoretical Analysis

For small changes in λ,

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

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

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

Theoretical Analysis

Sellmeier Equation for Silicon Carbide

$$n^2(\lambda) = A + \frac{B\lambda^2}{\lambda^2 - C}$$

$$A = 1, B = 5.5515, C = 0.026406 \times 10^{-12}$$

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

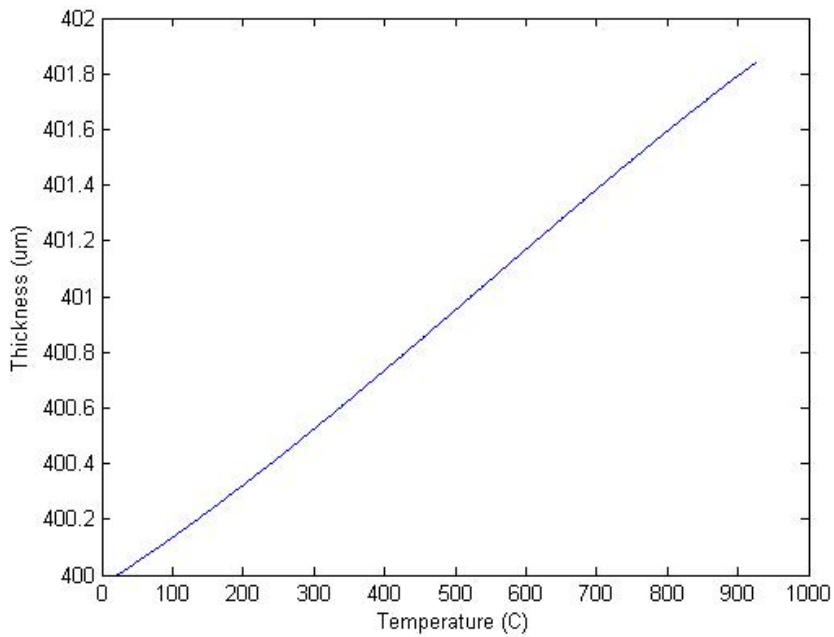
Wavelength separation between maximas or minimas

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

Thickness as a function of Temperature

$$t(T) = [1 + \alpha \Delta T] t(T_i)$$

$$\alpha = -1.68 \times 10^{-12} T^2 + 3.60 \times 10^{-9} T + 3.19 \times 10^{-6}$$



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

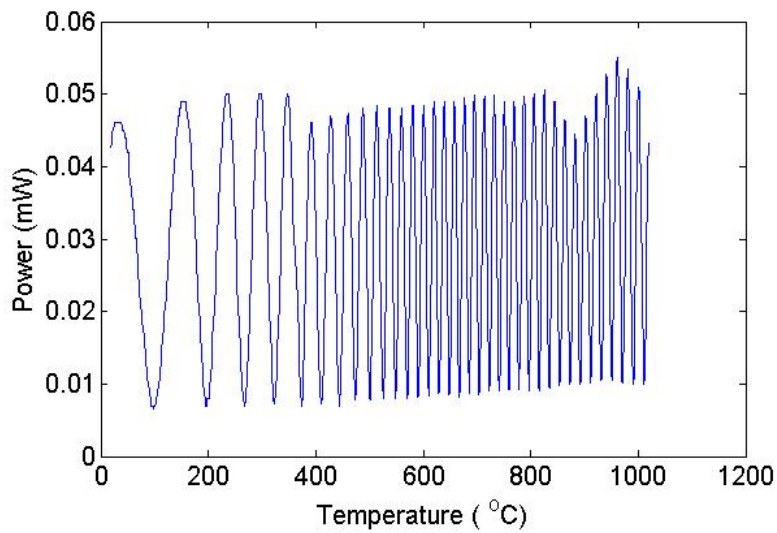
Refractive Index Calculation

Refractive index as a function of temperature

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

Δφ is the unwrapped phase difference

Raw power at λ = 1565.32 nm

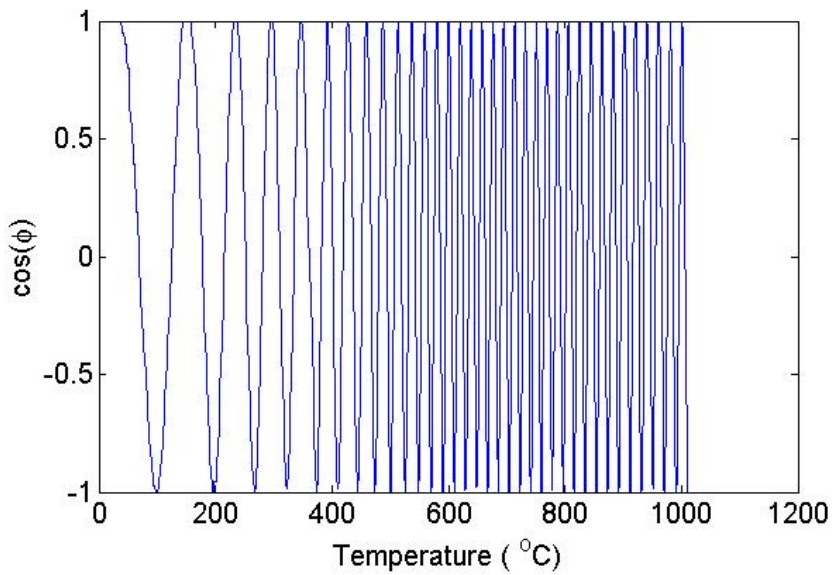


Refractive Index Calculation

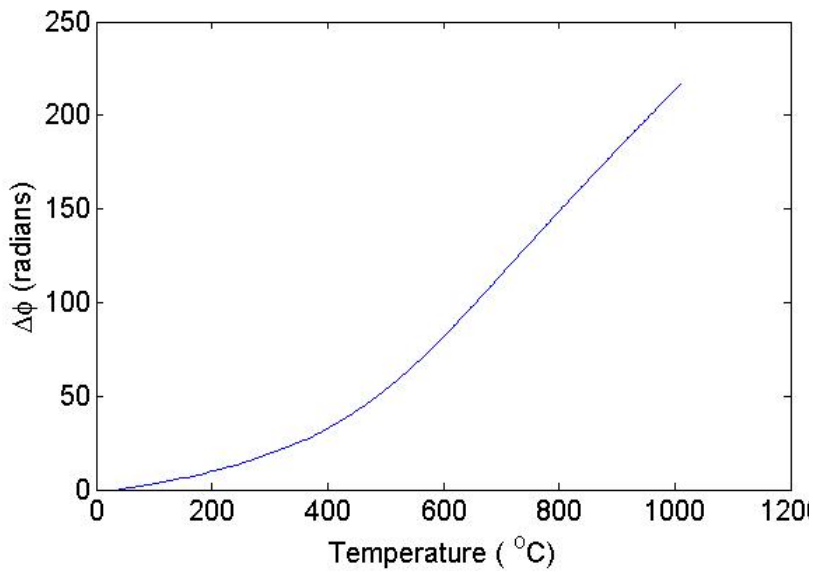
Cosine phase

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

P_m is the raw optical power

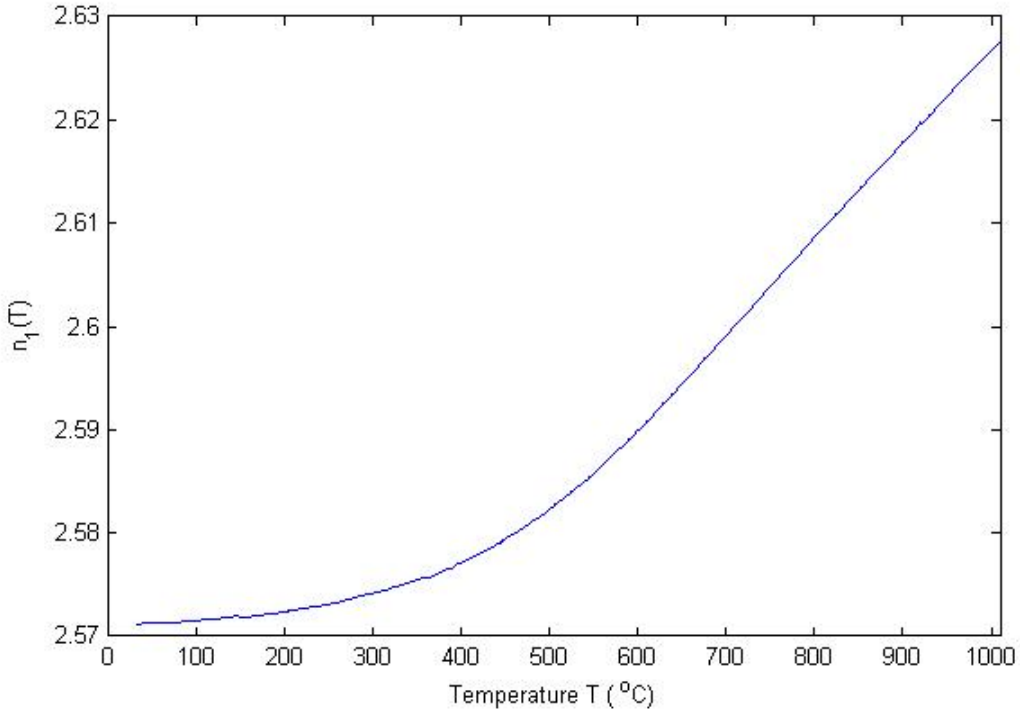


Unwrapped phase Δφ

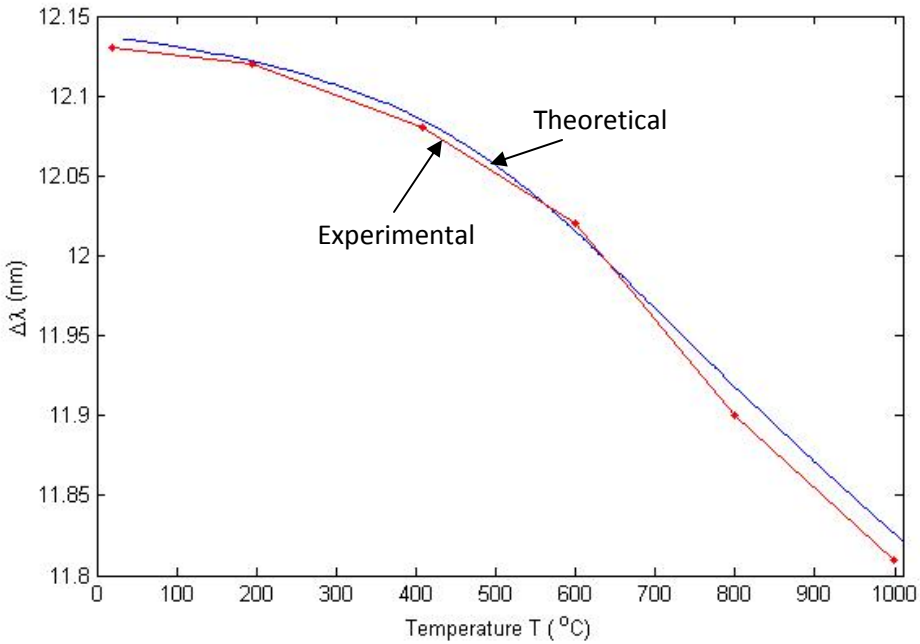


Refractive Index Calculation

Refractive index as a function of temperature



Experiment



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

Total Δλ change from r.t. to 1000 °C: 0.31 nm

Key Points

- Measure integer multiples of FSR (temperature dependent)
- Wide Range Temperature Sensor
- Higher k value, higher resolution
- Coarse direct temperature reading with ~15-20 °C resolution
- Compared to TC, not good enough!

Classical FP Peak Shift

Classic Fabry-Perot Etalon Reflectance

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

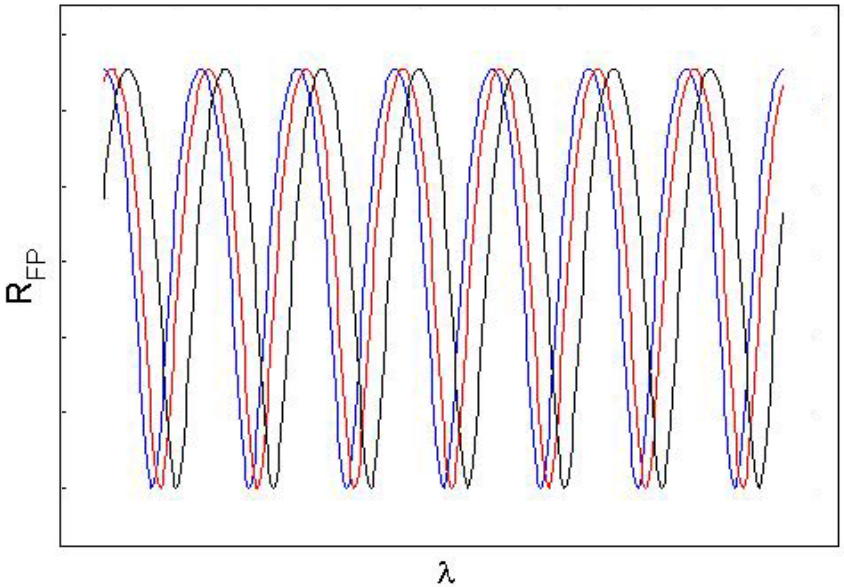
$$\varphi = \frac{4\pi}{\lambda} n(\lambda, T) t(T)$$

At maximas

$$\cos\varphi = 1$$

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

m is an integer



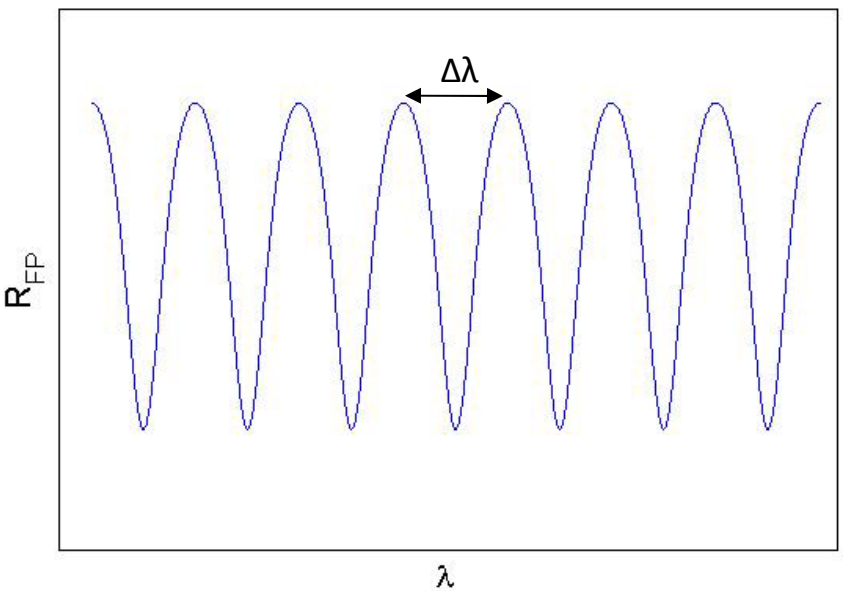
Classical FP Peak Shift

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

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

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

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



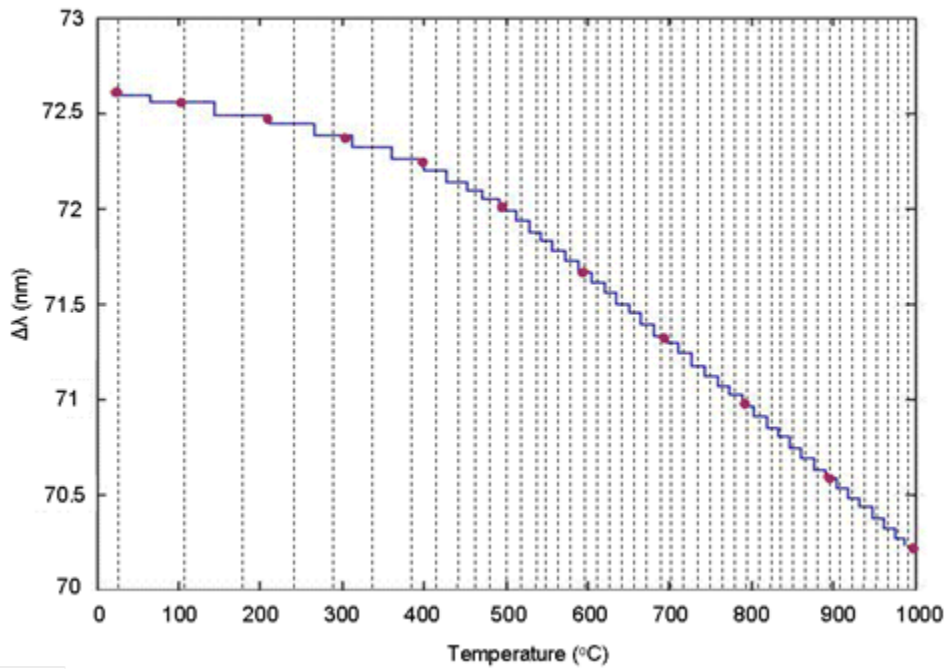
Can be used to **accurately** measure temperature within **one FSR** of the FP etalon

Combine the Two Techniques?

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

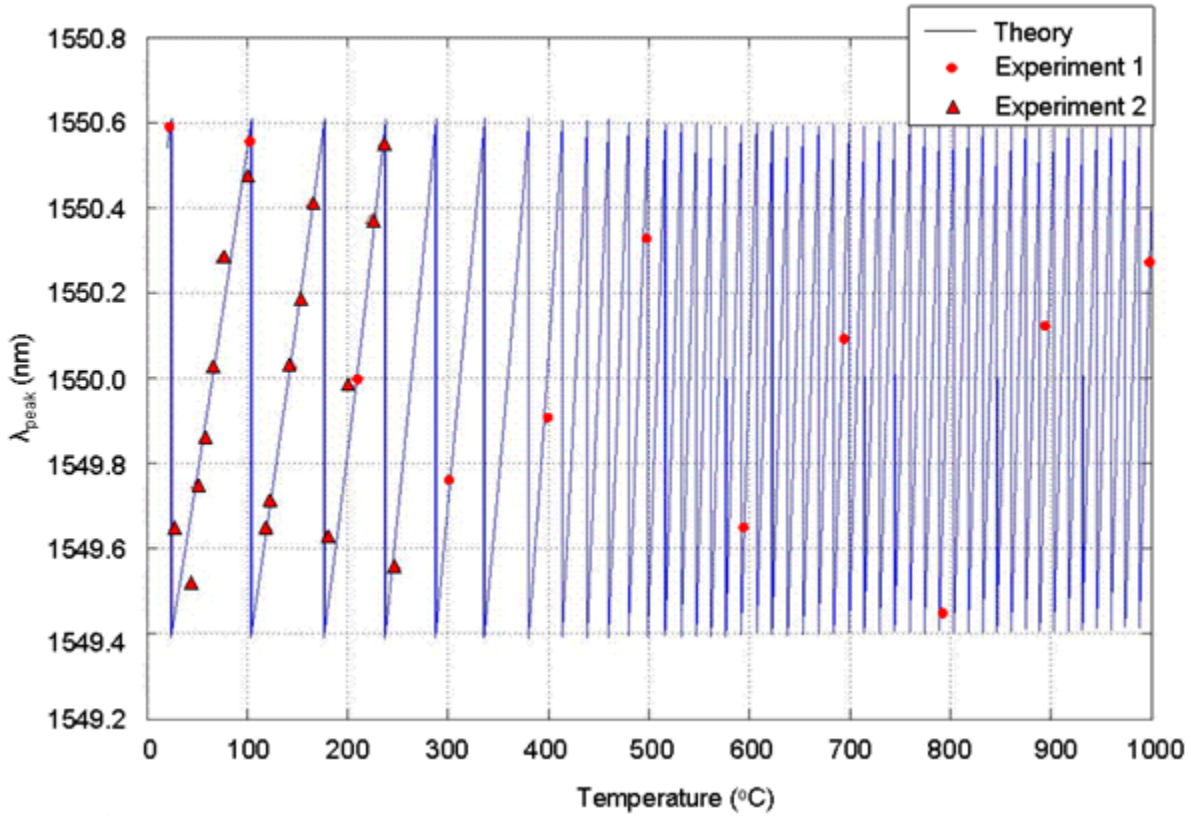
M. Sheikh, N. A. Riza, "Direct Measurement High Resolution Wide Range Extreme Temperature Optical Sensor using an all-Silicon Carbide Probe," Opt. Lett., Vol. 34, No. 9, May 2009.

Coarse Measurement Experiment



λ range: 1520 – 1600 nm
k : 60 (arbitrary)
Δ (Δλ): 0.04 – 0.05 nm

Fine Measurement Experiment



Centre wavelength : 1550 nm

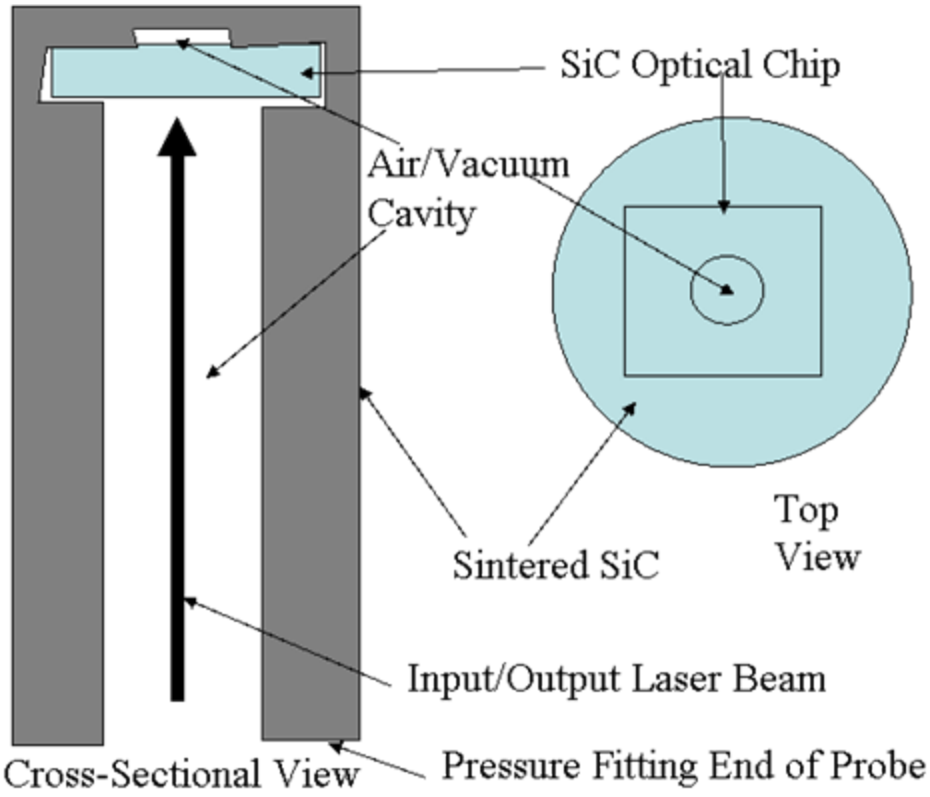
Comparative Results

TC T (^{O}C)	OPTICAL SENSOR T (^{O}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

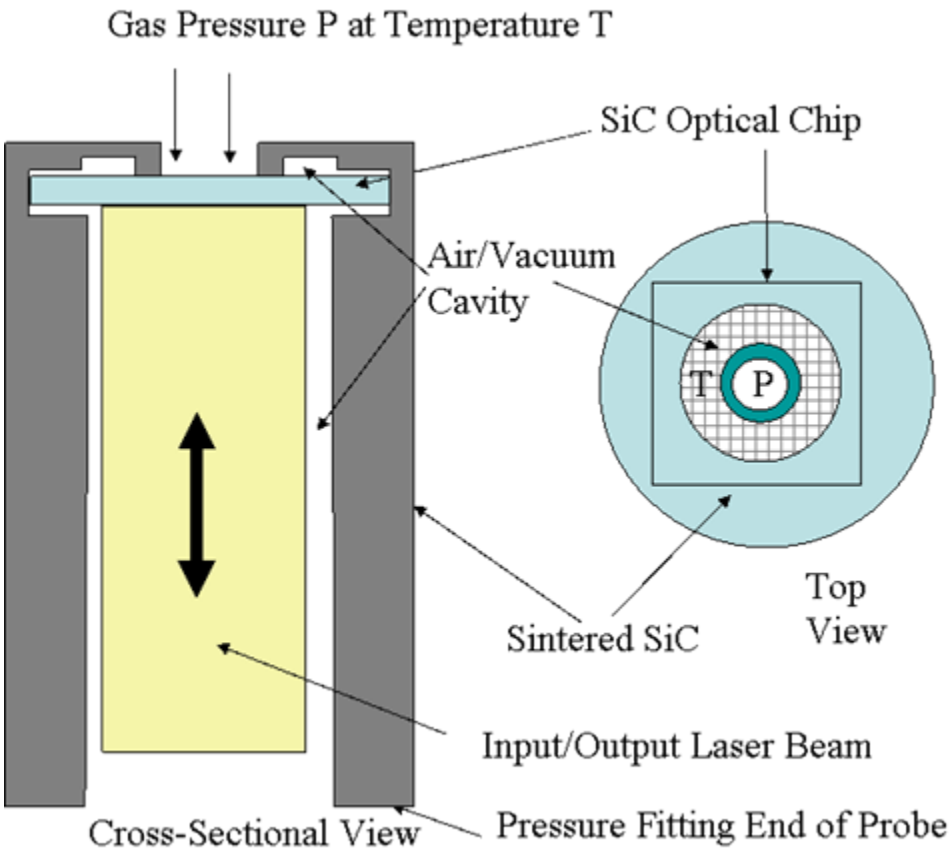
Summary of our Approach

- 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 TC

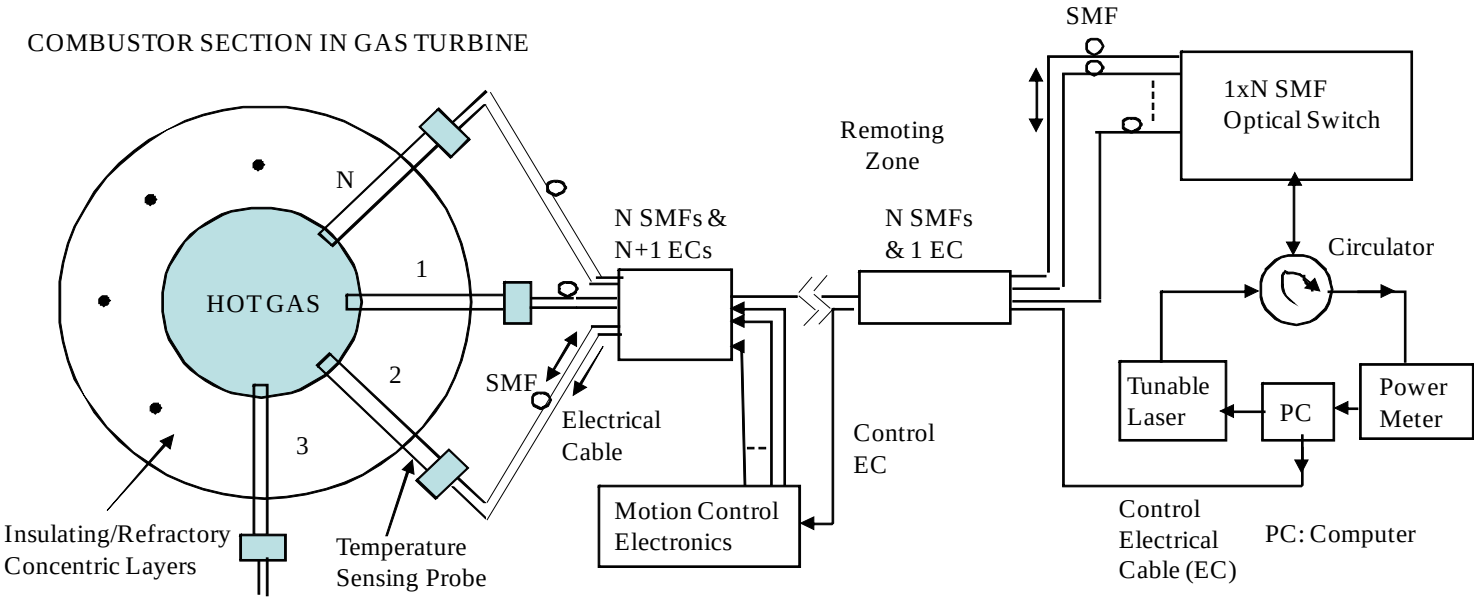
Novel All-SiC Probe Frontend Design Optimized For Temperature Measurement



Novel All-SiC Probe Frontend Design Optimized For Simultaneous Temperature And Pressure Measurement

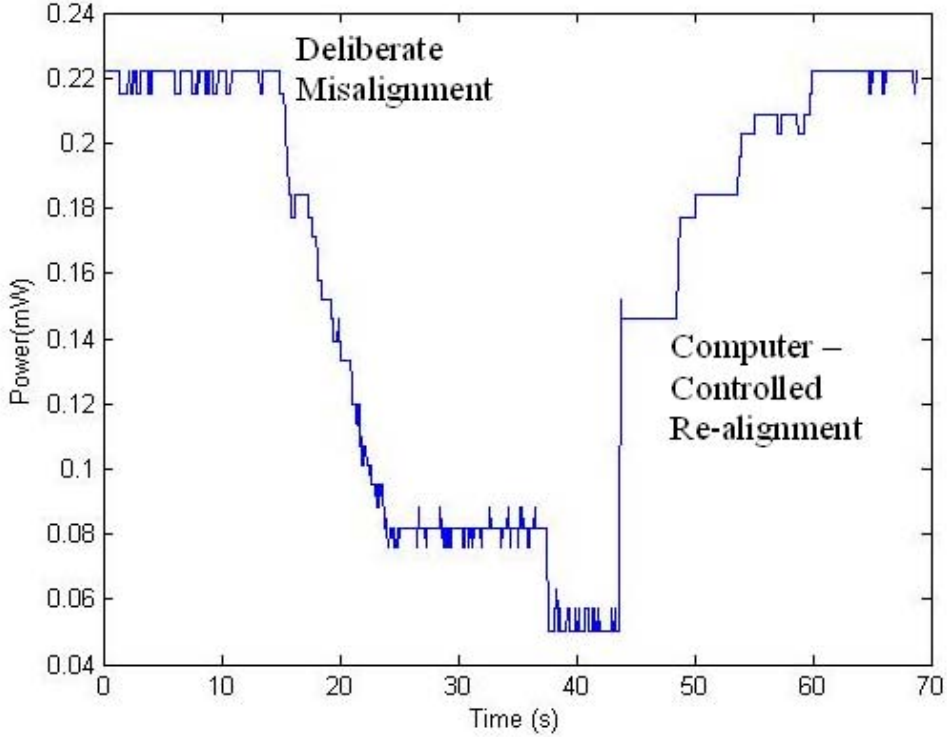


Temperature Sensor Network – Basic Design Engineering



N. A. Riza, M. Sheikh, "All-Silicon Carbide Hybrid Wireless-Wired Optics Temperature Sensor Network Basic Design Engineering for Power Plant Gas Turbines," submitted for publication

Alignment using Piezoelectric Motion Stages



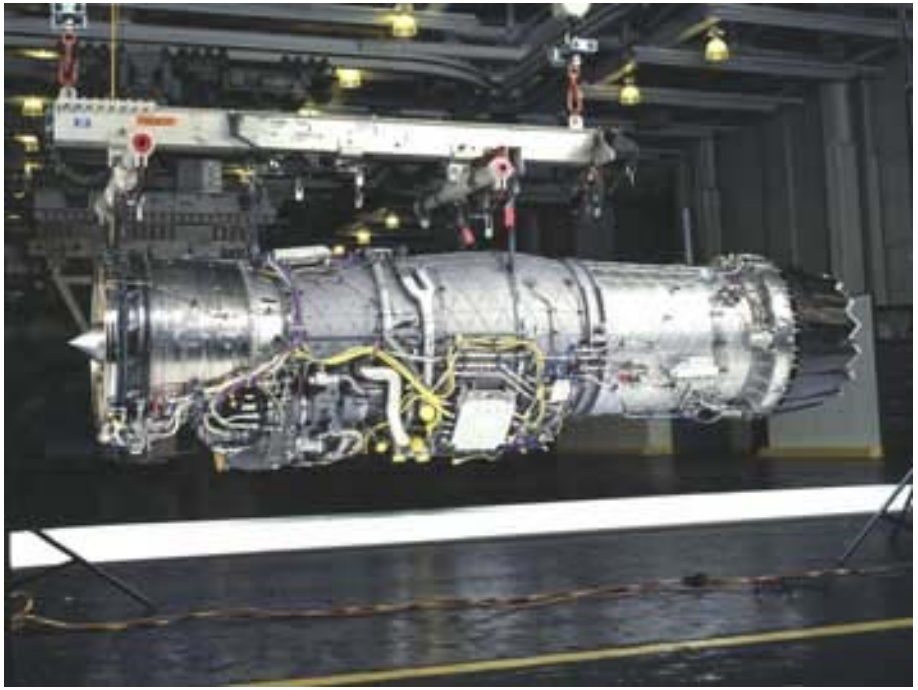
Other Impact-Jet Aviation

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

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

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