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

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Sponsor: US Department of Energy (DOE)

Partners: Nuonics, Inc. and Siemens Power Generation, Orlando, FL

THE ULTIMATE CHALENGE IN FOSSIL FUEL-BASED POWER GENERATION

Dominant Fossil Fuels: Coal and Methane (Natural Gas)

Achieve The Following Basic System Attributes:

- Clean Energy (Reduced Green House Gas Emissions)

- Improved Energy Conversion Efficiencies – More Energy for Less

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A Solution *

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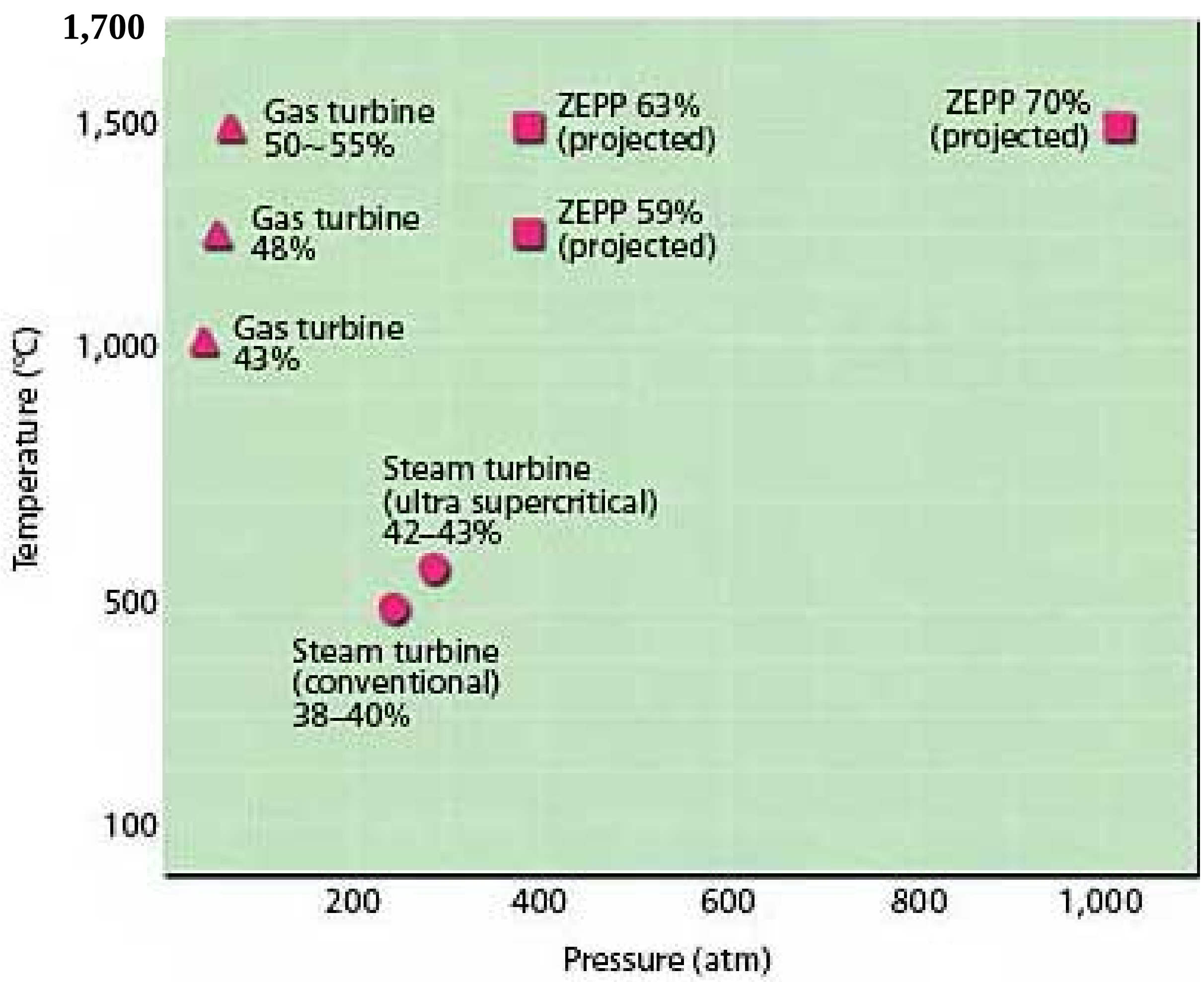
Use Extreme Temperature and Pressure Power Plants

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

Recent New Study on Power Plant Operating Temperatures and Pressures

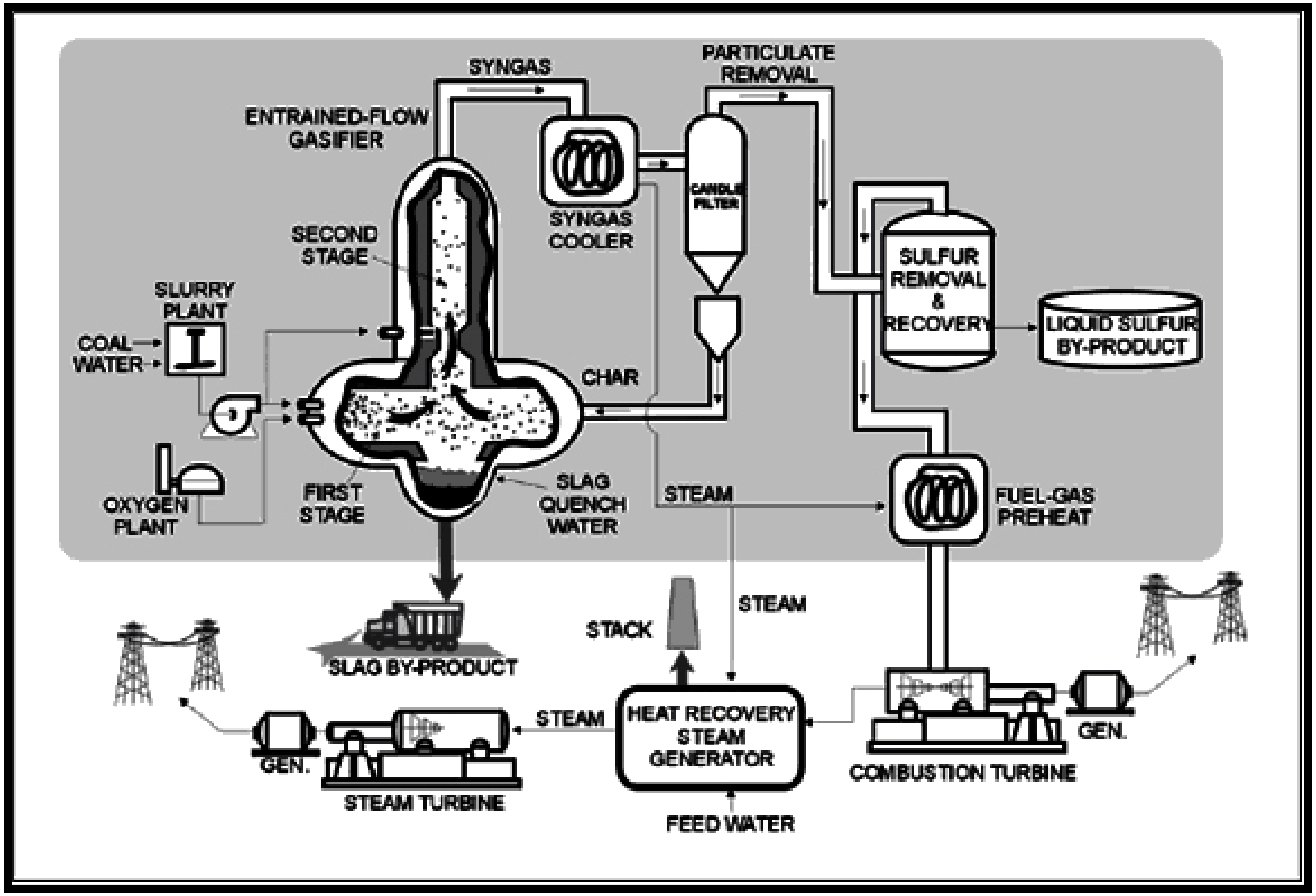


ZEPP: Zero Emission Power Plant

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

COAL FOSSIL FUEL TO ELECTRIC POWER PATH

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

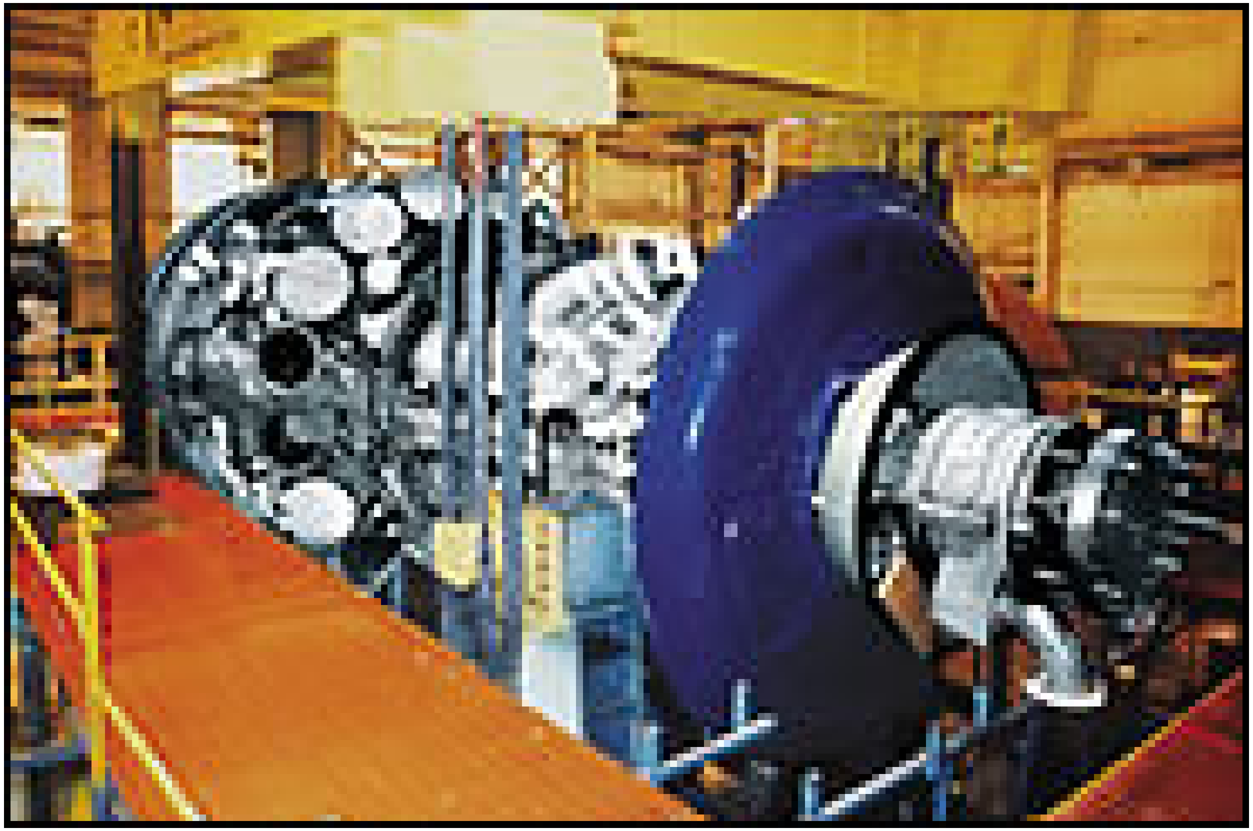
GE’s H system Gas Turbine

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 ºC

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)

What does Power Generation Industry Use Today ?

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Custom Thermo-Couple Probes using Platinum/Rhodium Elements and Magnesia (MgO) or Alumina Insulating Ceramics – 1900 °C

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BIG RELIABILITY/LIFE TIME PROBLEM

Develops Cracks in the Insulation—Picks Moisture- Becomes Conductive and Explodes

RELIABLE SOLUTION: THICK SINGLE CRYSTAL SILICON CARBIDE

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

Mechanically Robust

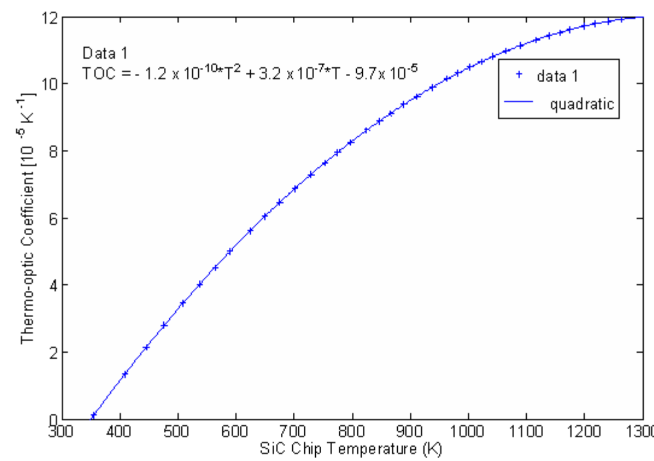
-- Handles 1 GPa (10,000 atm) Yield Stress
-- Allows Elastic Deformation in the Small Deflection Regime Due to Pressure

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

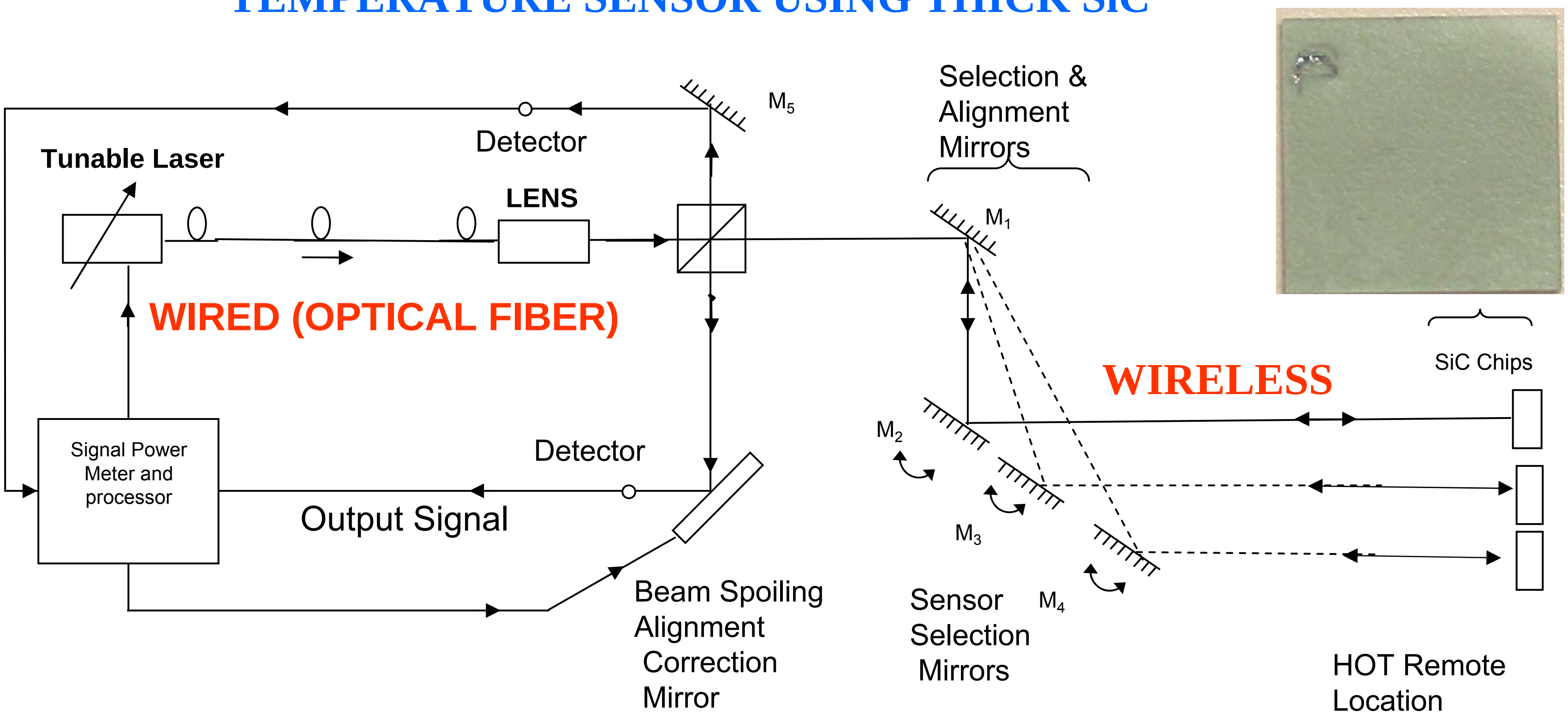


*** Refractive Index "n" Changes With Temperature T**
& dn/dT (Thermo-Optic Coeff.) Changes Quadratically with T

•N. A. Riza, et.al, AIP Journal of Applied Physics, Vol.98, 103512, 2005.

PERFECT FRONTEND OPTICAL CHIP FOR ROBUST WIRELESS SENSING

PROPOSED HYBRID WIRED-WIRELESS TEMPERATURE SENSOR USING THICK SiC



SiC CHIP

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

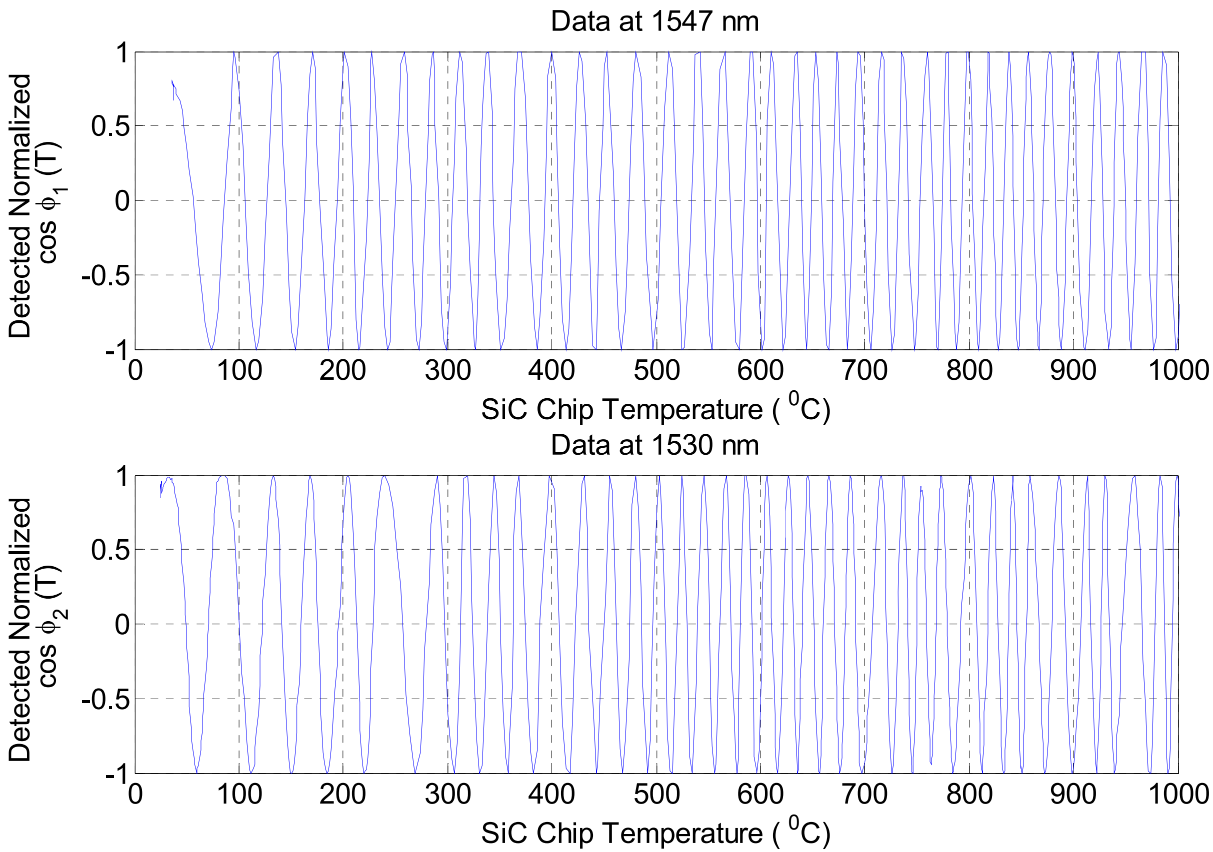
$$P_m = K \cdot R_{FP} \approx K\left[R_1 + (1-R_1)^2 R_2 + 2(1-R_1)\sqrt{R_1 R_2}\cos\phi\right]$$

Where ϕ is the Optical path Length (OPL) and $\phi = \dfrac{4\pi n(T)d(T)}{\lambda}$

Fresnel Power Coefficient= $R_1=R_2=0.19$ for SiC at 1550 nm.

See N. A. Riza, et.al., IEEE Sensors Journal, June 2006.

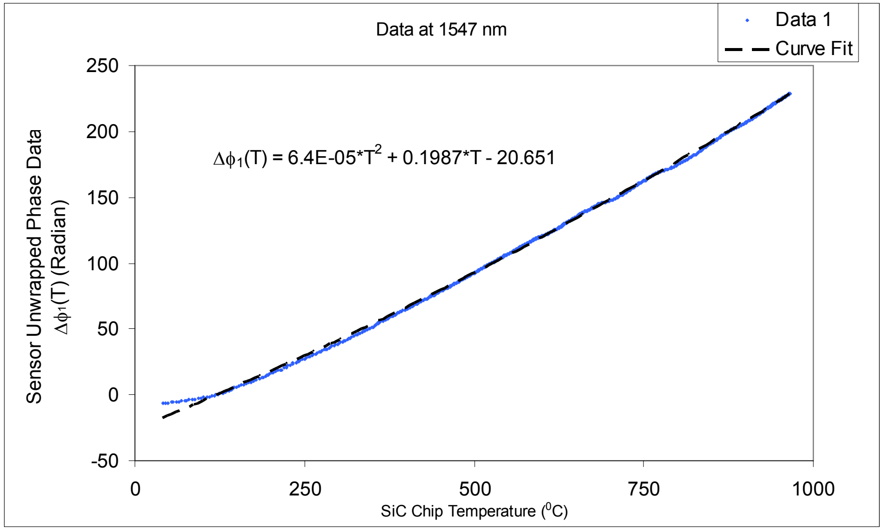
First SiC Wireless Temperature to 1000 °C

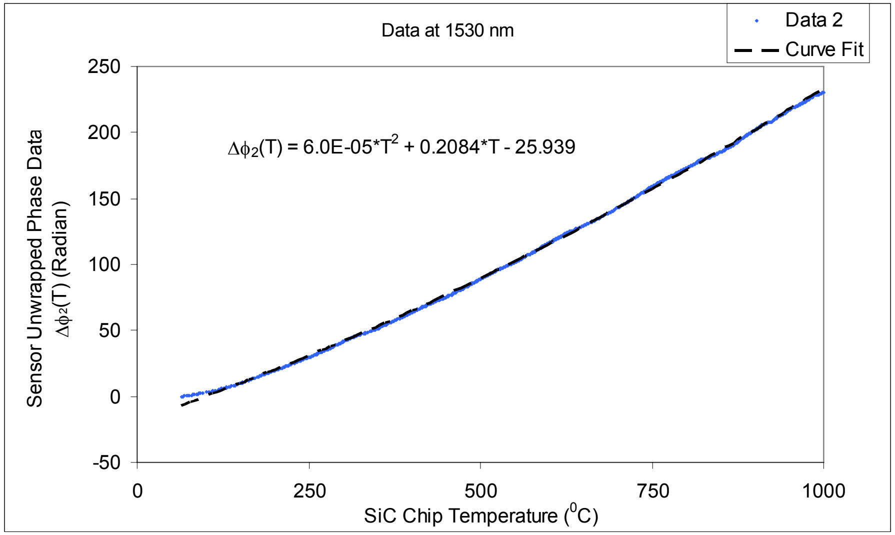


Computer Normalized *Cos*{ϕ(t)} Measurements

Note: Ambiguous Cos(OPL) Values Versus Temperature

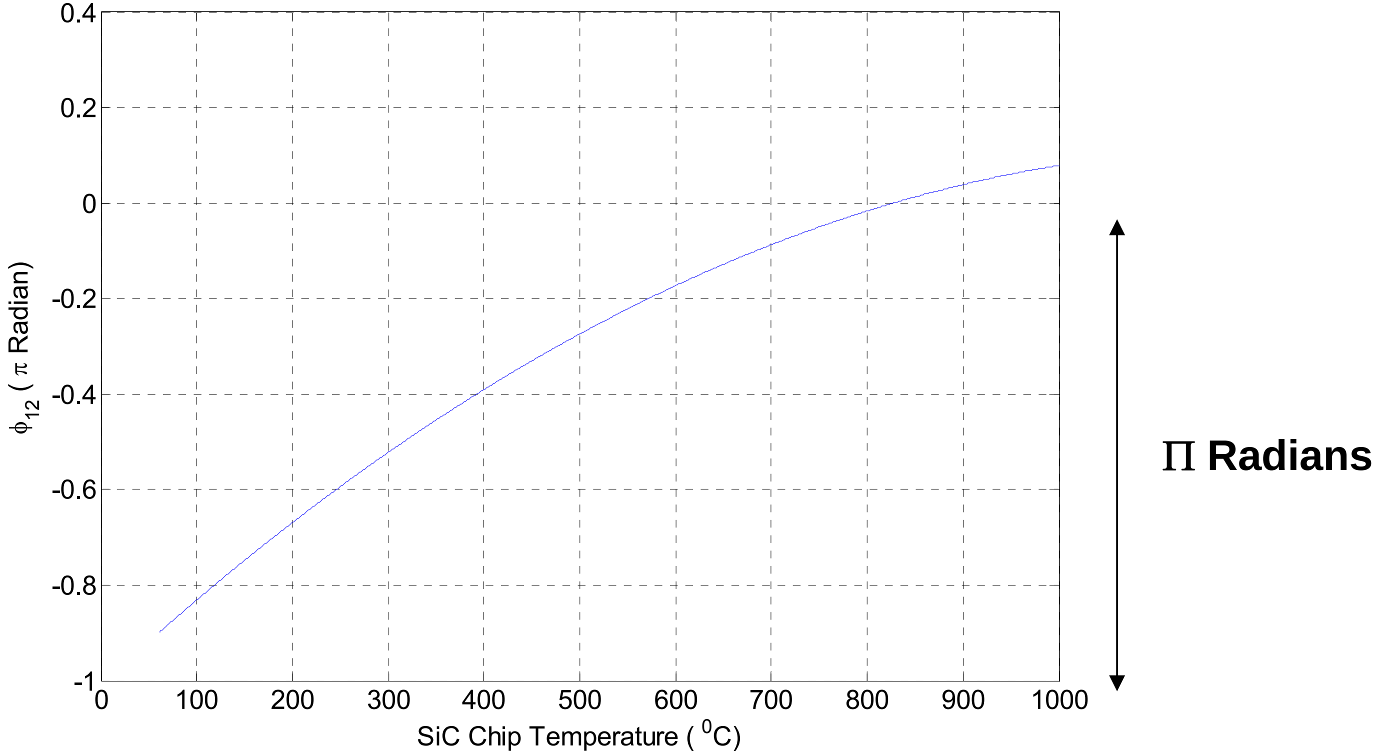
Sensor Unwrapped Phase Change Data $\Delta\phi$ (T) in Radians versus SiC Chip Temperature with data taken at 1530 nm & 1547 nm. Weak quadratic curve fit is achieved.





ϕ(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 ϕ_{12}(t) Condition for Unambiguous Temperature Measurement

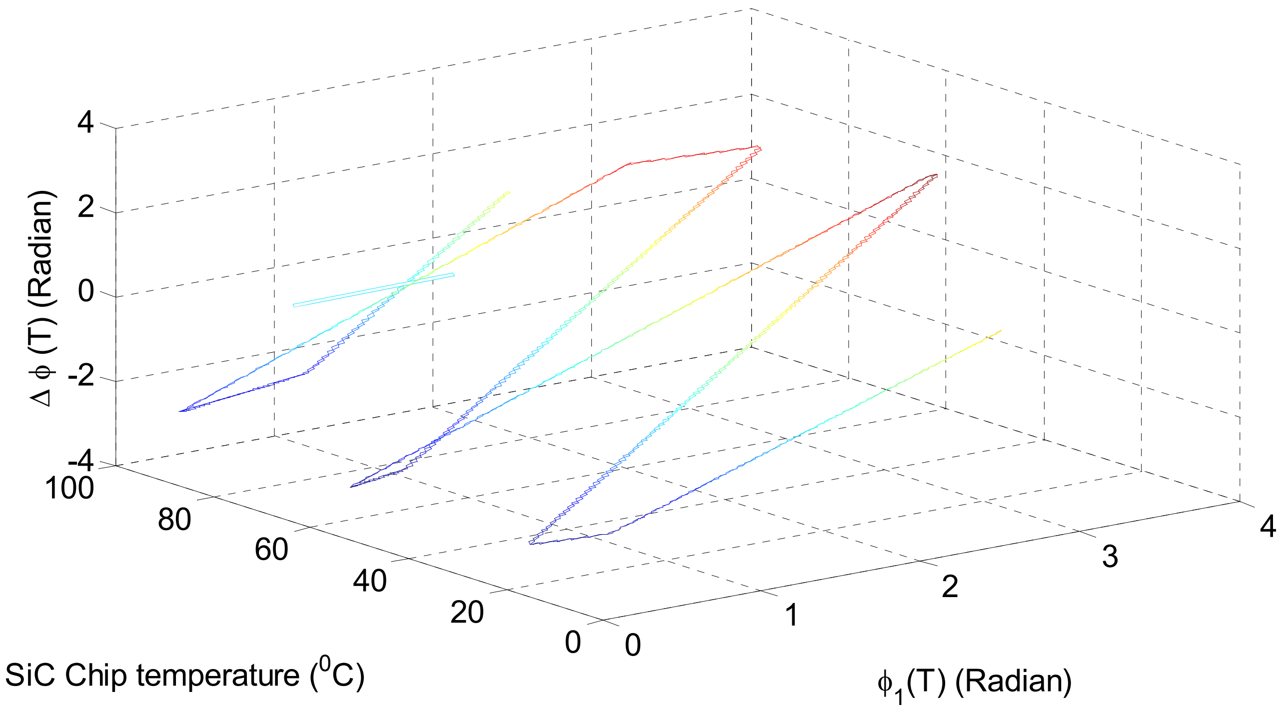


The curve fits to the $\Delta\phi 1$ and $\Delta\phi 2$ data are used to calculate $\phi_{12} = \Delta\phi 1(T) - \Delta\phi 2(T)$ and is plotted above.

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

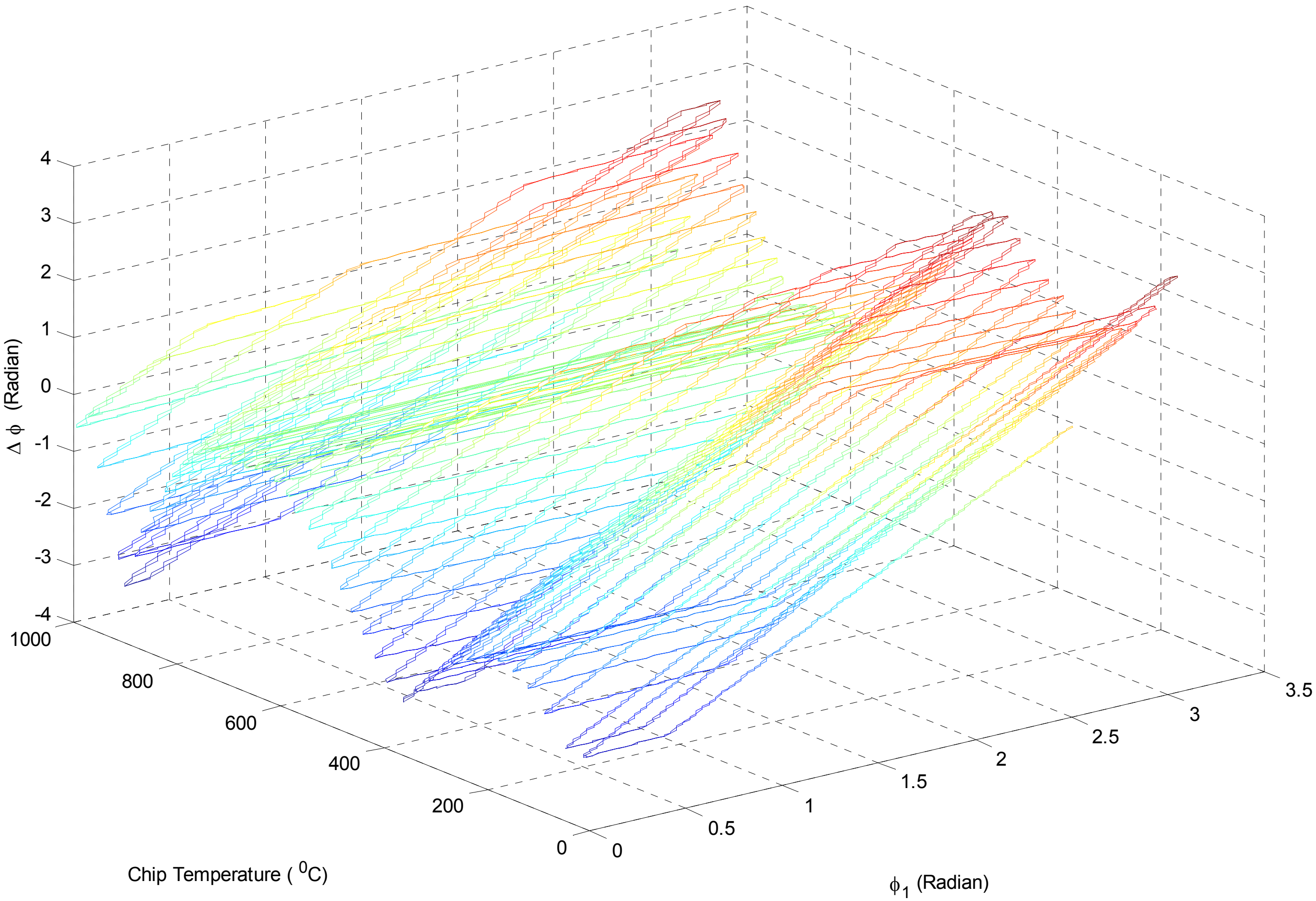
-- Unambiguous temperature measurement via Instantaneous Wrapped Phase Processing using a 3-D Sensor Calibration Table

3-D Representation of The Sensor Calibration Chart For The Unambiguous Temperature Measurement of Temperature From Room Conditions To 1000 C



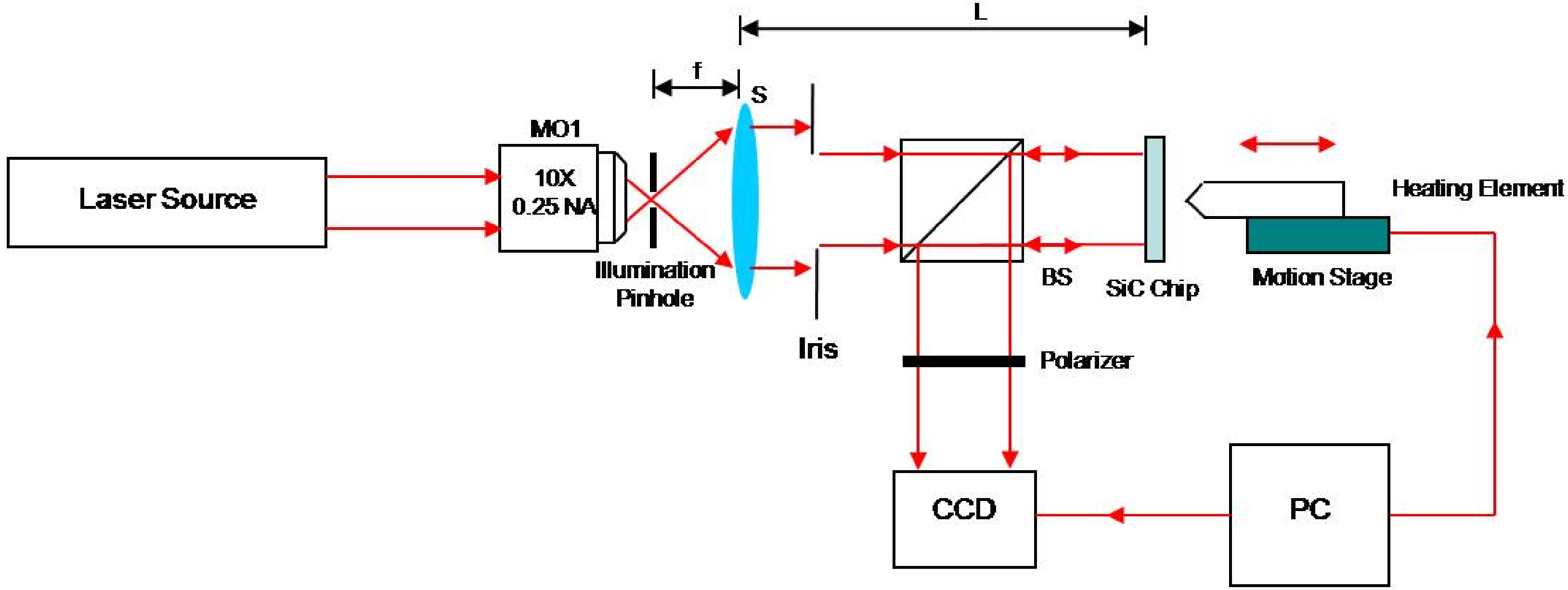
Shown is a helical spring like behavior where for every set of values of Δϕ and ϕ1, there is only one value of the temperature corresponding to that data set

3-D Calibration Chart
Room Temperature to 1000 °C



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

Experimental Set-Up to Measure Temporal Response of SiC Chip to Conductive Heat Step Function

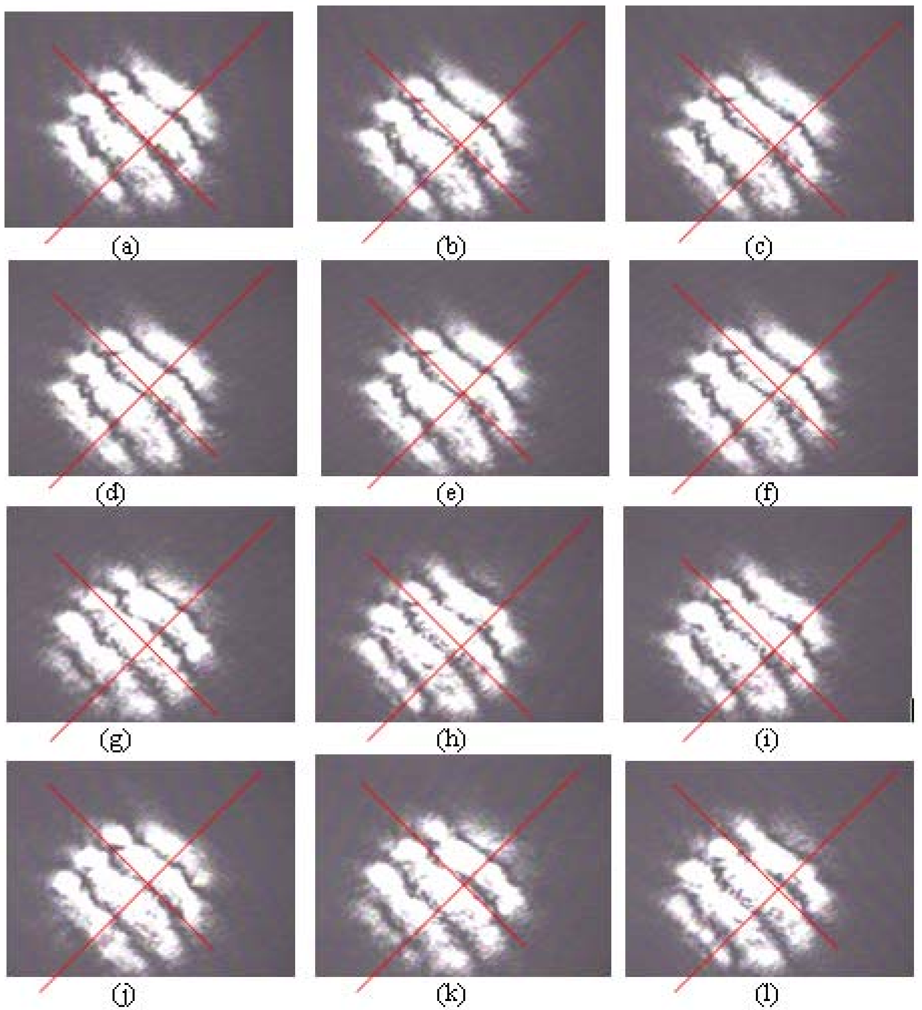


Method: Computer Controlled Digital Step 1 mm diameter Pointed 90 deg-C Heating Element

Experimental Set-Up

Monitoring Fringe Motion Caused by Conductive Tip Thermal Step Function

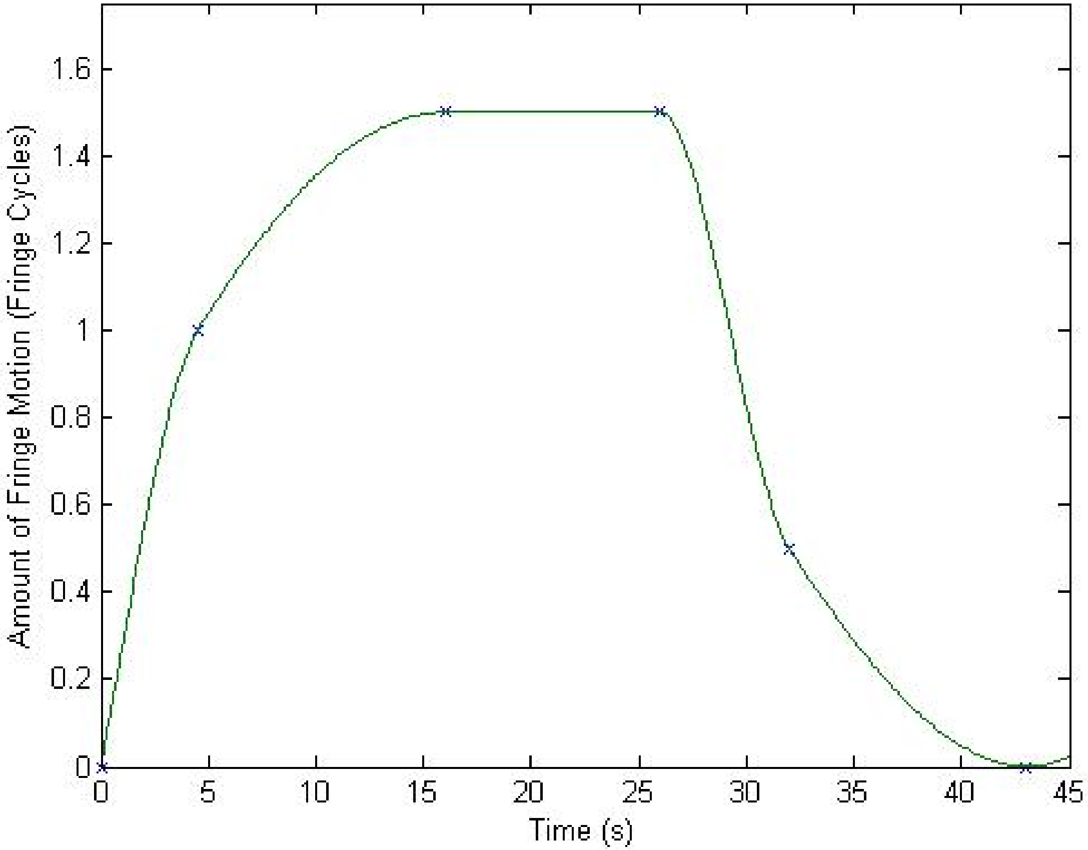
Red Cross Tracks a Reference Fringe Position



Captured frames at 1/30 s intervals

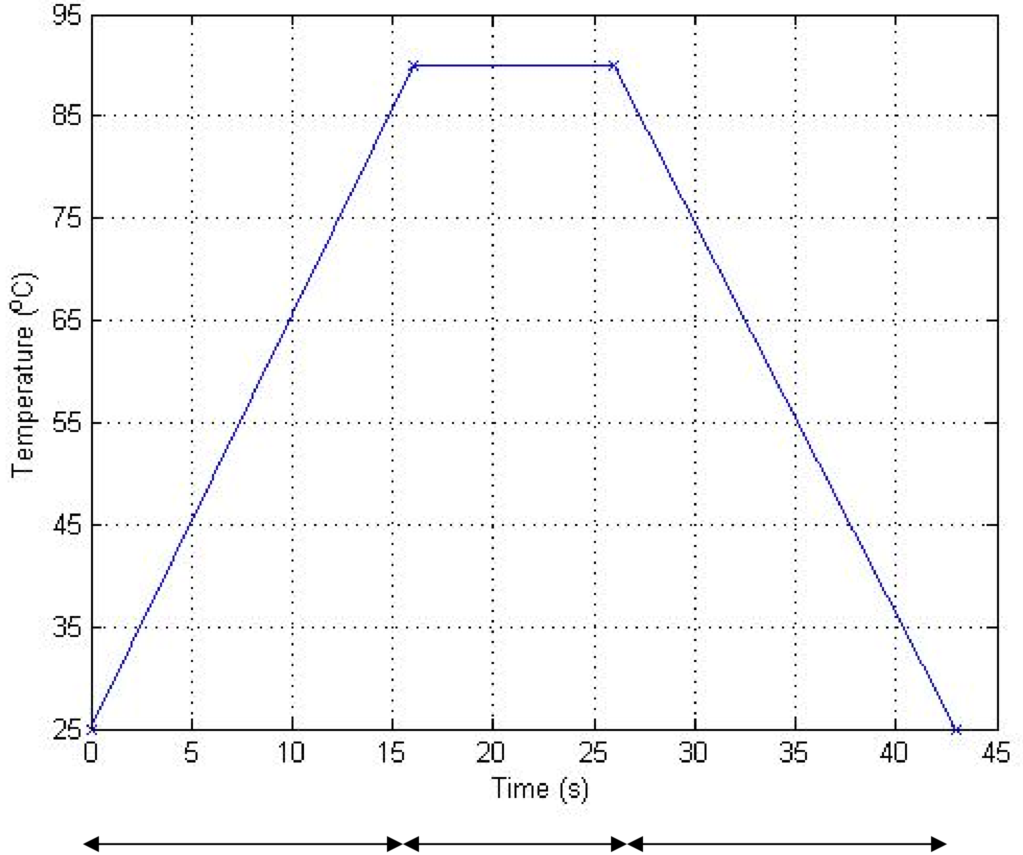
Fringe Motion Occurs each Frame Indicating SiC Response under 1/30 s

Fringe Movement with Time Elapsed after Thermal Step Function Applied to SiC Chip



~ 1.5 Fringe Cycle Shift Over 65 deg-C Temperature Change

Temperature Response of the Heated SiC chip to a Thermal Step Function



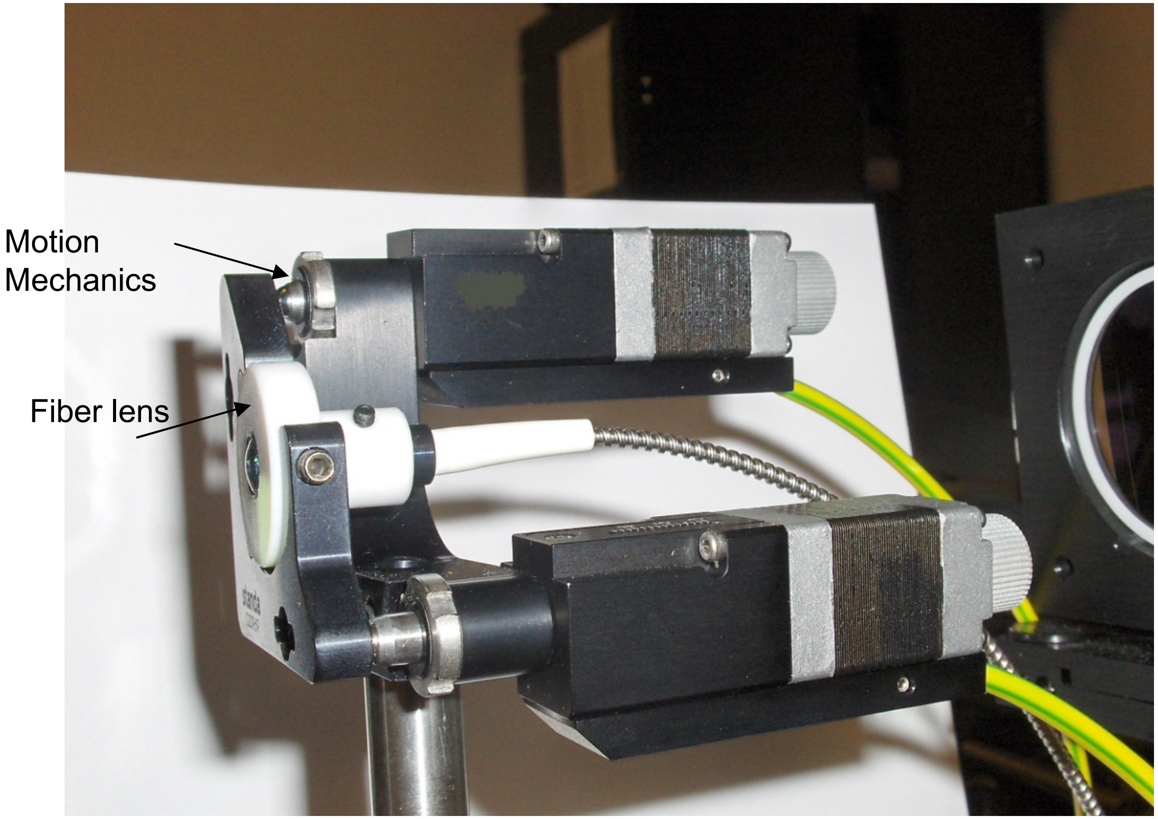
Chip Size;
1 cm x 1cm
X 400 micron
Thick

Conductive
Heat Ramp
Response
~ 15 seconds

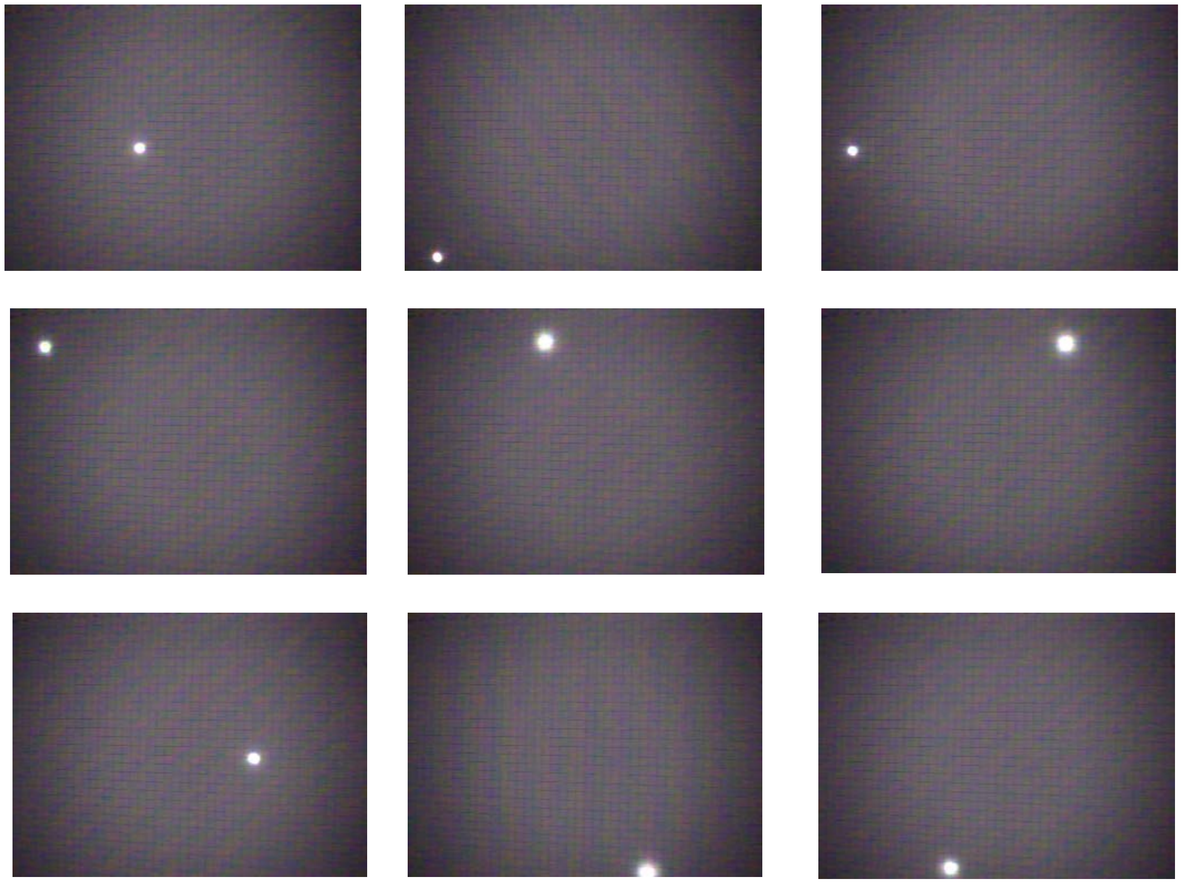
Steady State
90 deg-C
Temperature
~ 10 seconds

Convective
Radiation
Cooling
~ 17 seconds

Designed and Assembled Laser Beam Smart Transceiver Module for Sensor

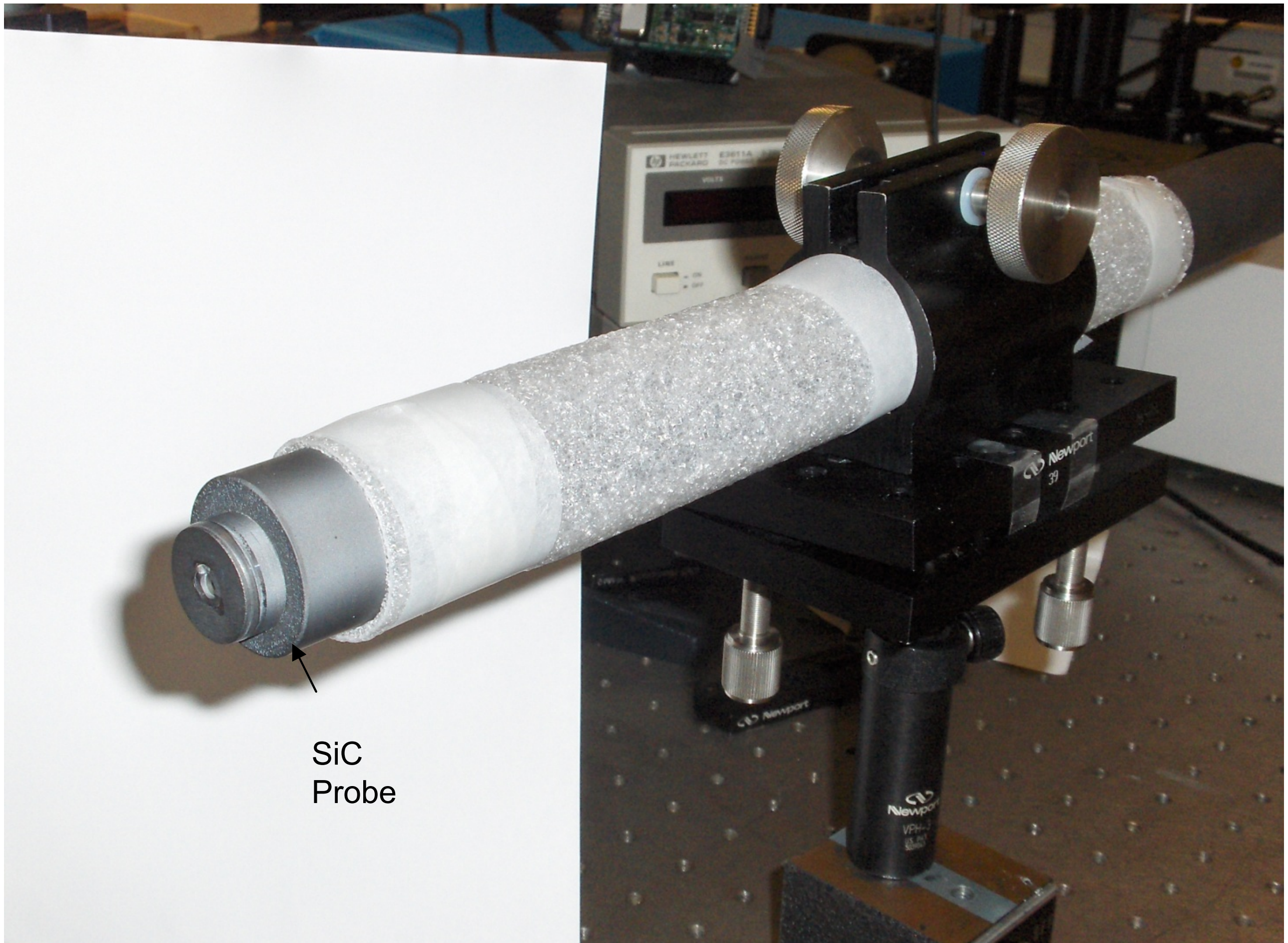


IR Laser Beam Scanning Test Over ± 4.5 degrees

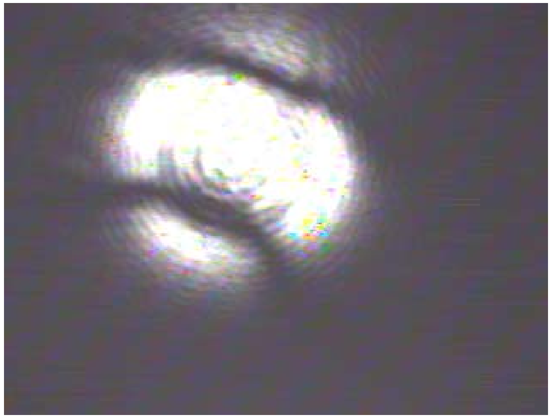


Camera Shots at SiC Chip Plane at 60 cm from Fiber Lens

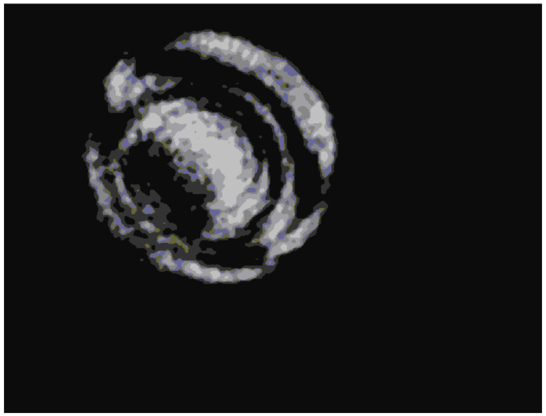
Nuonics Fabricated Frontend Probe using a Sintered SiC Tube and Embedded SiC chip



SiC Chip Interferograms Before and After Packaging at 633 nm



Before



After

Full Positive and Full Negative Interference Test with Assembled Probe using IR wavelength Tuning @1600 nm (Room Temperature)

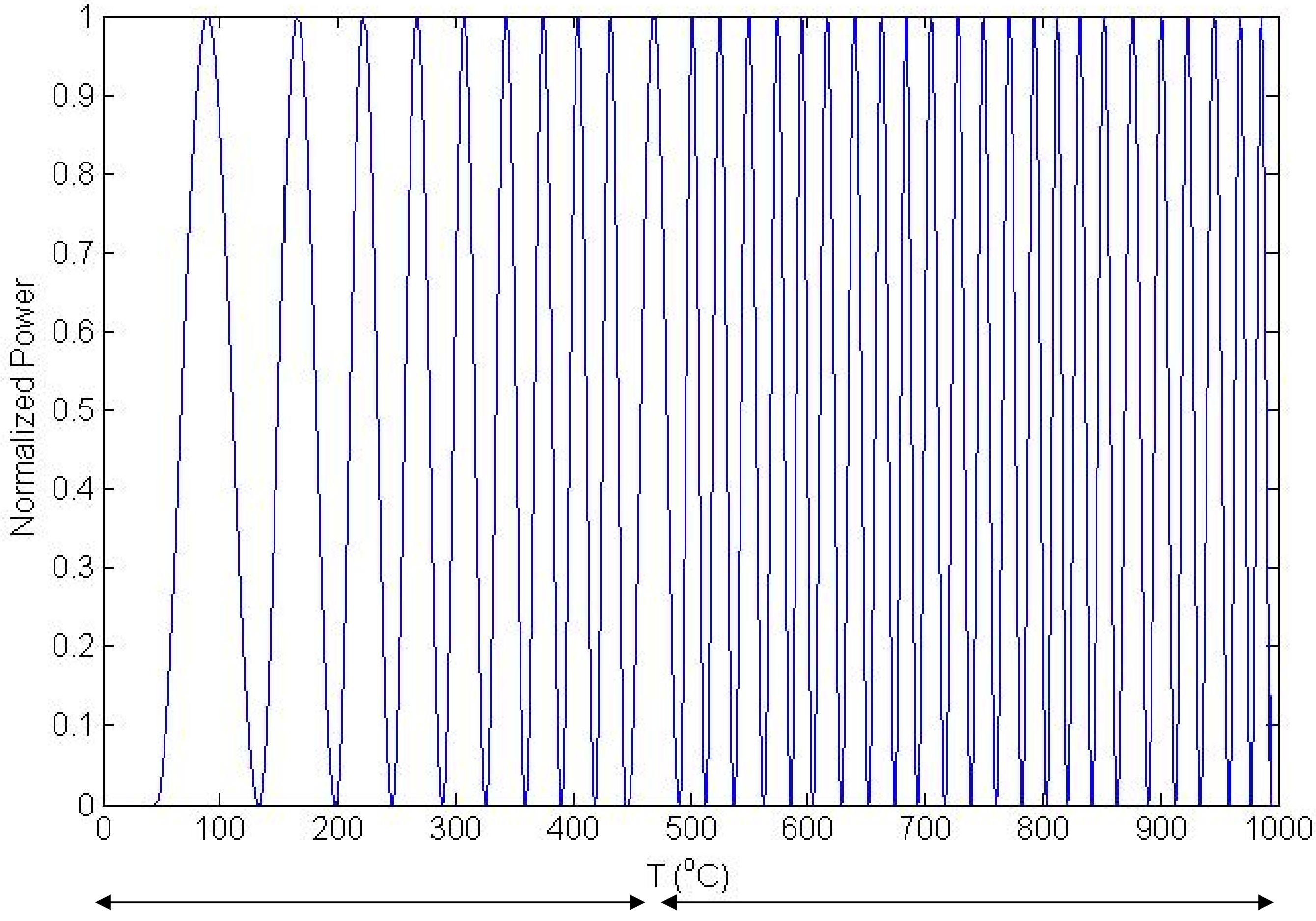
Bright State

Dark State

Shown SiC Chip Retro-reflected IR Camera Images

20: 1 on/off ratio

Processed Initial Probe Data over 1000 °C Temperature Range



Point Photo-Detector Data Till ~ 450 ºC

IR Camera-based Data from ~ 450 ºC to 1000 ºC

Requires Active Alignment for Smooth Data Acquisition

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

Two-Wavelength Technique Limitations

- Limited design temperature range

- Complex signal processing required to determine temperature

- Prior calibration required at the design wavelengths

↓

Solution

↓

A technique that can measure temperature directly and unambiguously

Wavelength Tuned Signal Processing

Classic Fabry-Perot Etalon Reflectance

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

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

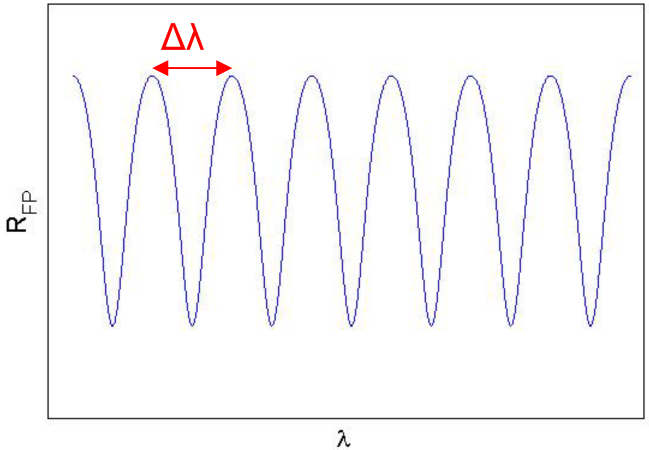
Difference between maximas or minimas

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

k is an integer

$$\lambda_2 = \lambda_1 + \Delta\lambda \qquad n_2 = n_1 + \Delta n$$

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



N. A. Riza and M. Sheikh, "Silicon-carbide-based extreme environment temperature sensor using wavelength-tuned signal processing, " Opt. Lett. Vol. 33, No. 10, pp. 1129-1131, May 2008.

Wavelength Tuned Signal Processing

Sellmeier Equation for Silicon Carbide

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

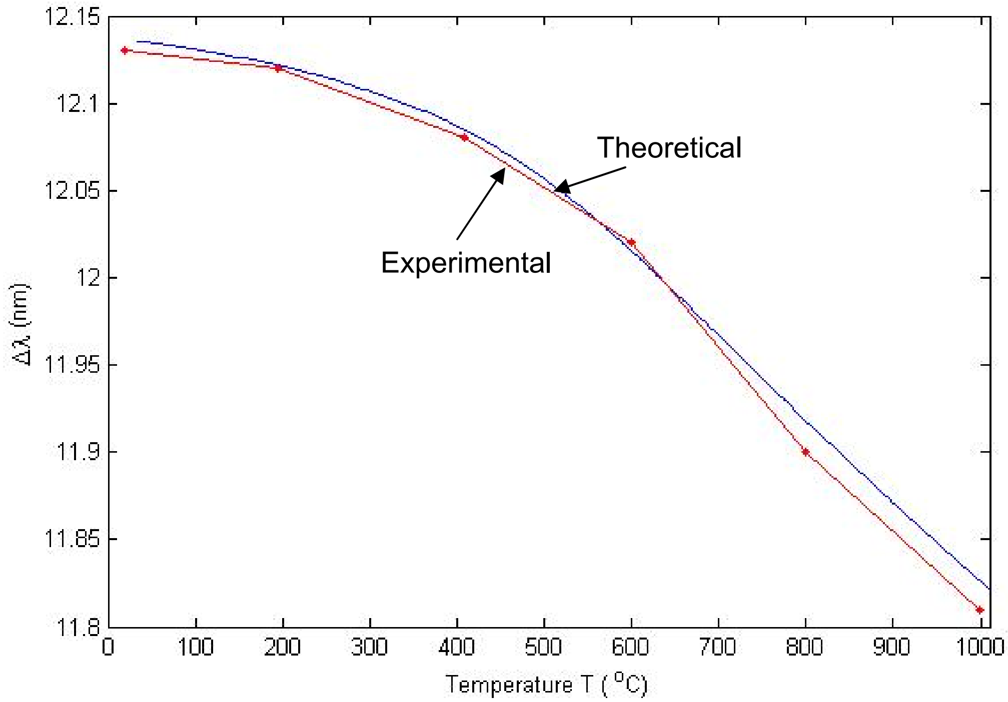
$$\Delta n \approx \frac{-\lambda BC}{n\left(\lambda^2 - C\right)^2}\Delta\lambda$$

Wavelength separation between maximas or minimas

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

Refractive index, $n_1(T)$ calculation is explained later

Wavelength Tuned Signal Processing



Wavelength range: 1550 – 1565 nm

SiC chip thickness, t (25°C): 389 μm

No. of cycles, k : 10

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

Refractive index $n_1(T)$ calculation

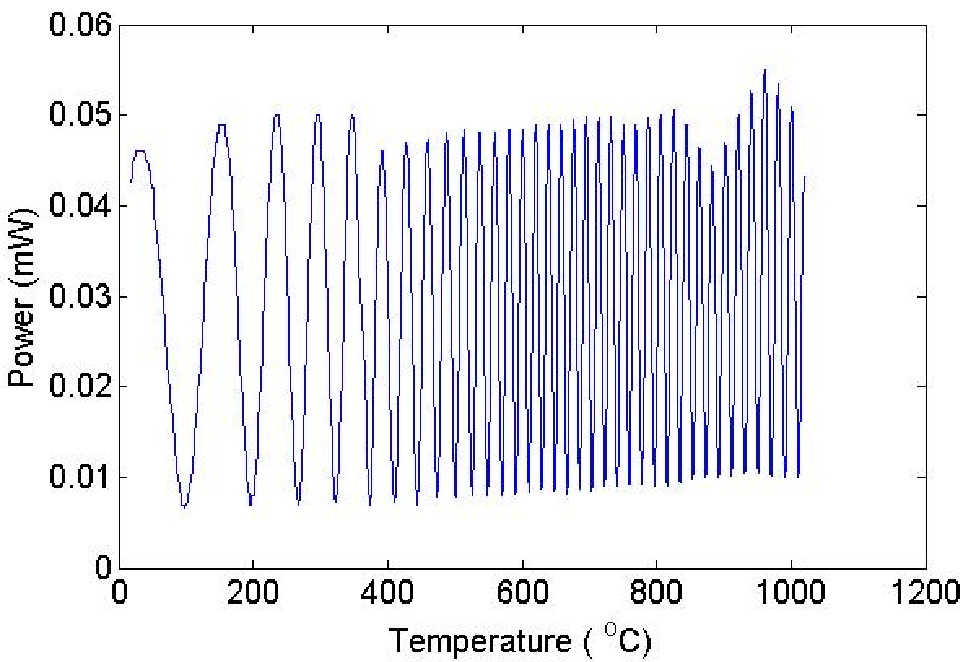
Refractive index as a function of temperature

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

$\Delta\varphi$ is the unwrapped phase difference

T_i is the initial temperature

Raw power at $\lambda = 1565.32$ nm

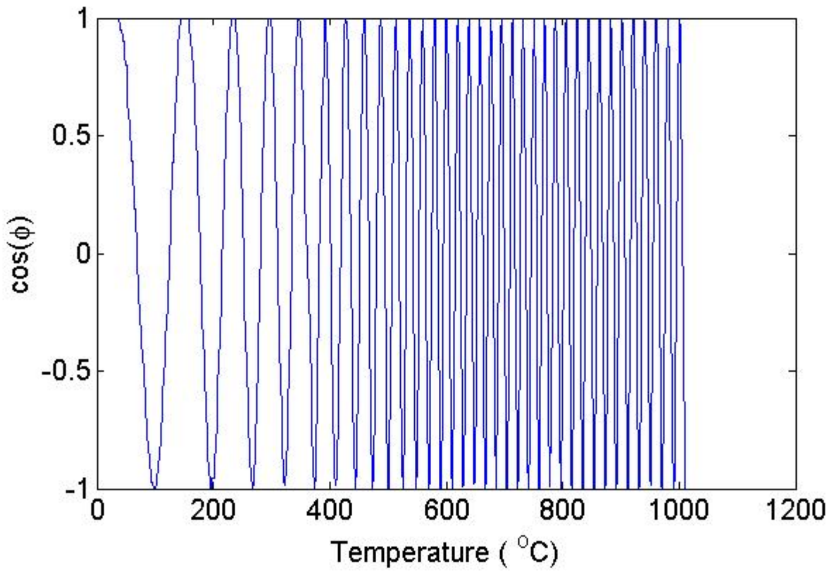


Refractive index $n_1(T)$ calculation

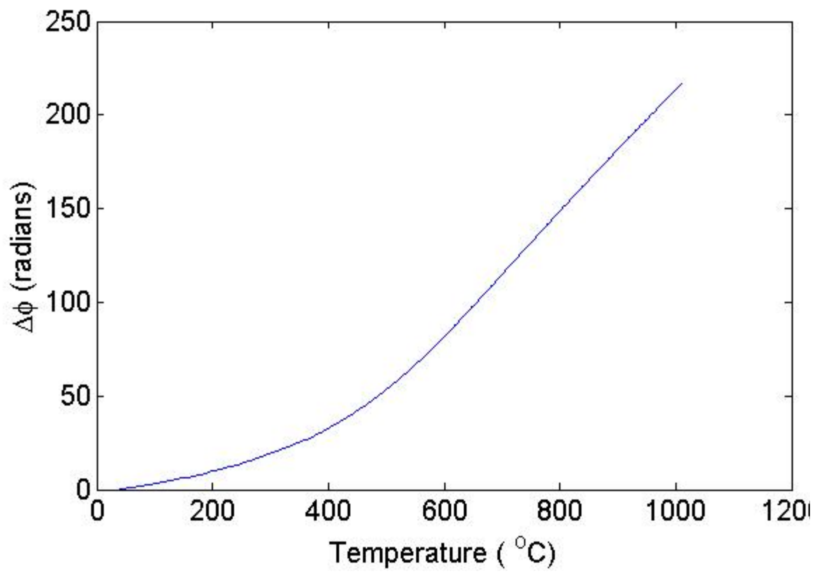
Cosine phase

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

P_m is the raw optical power

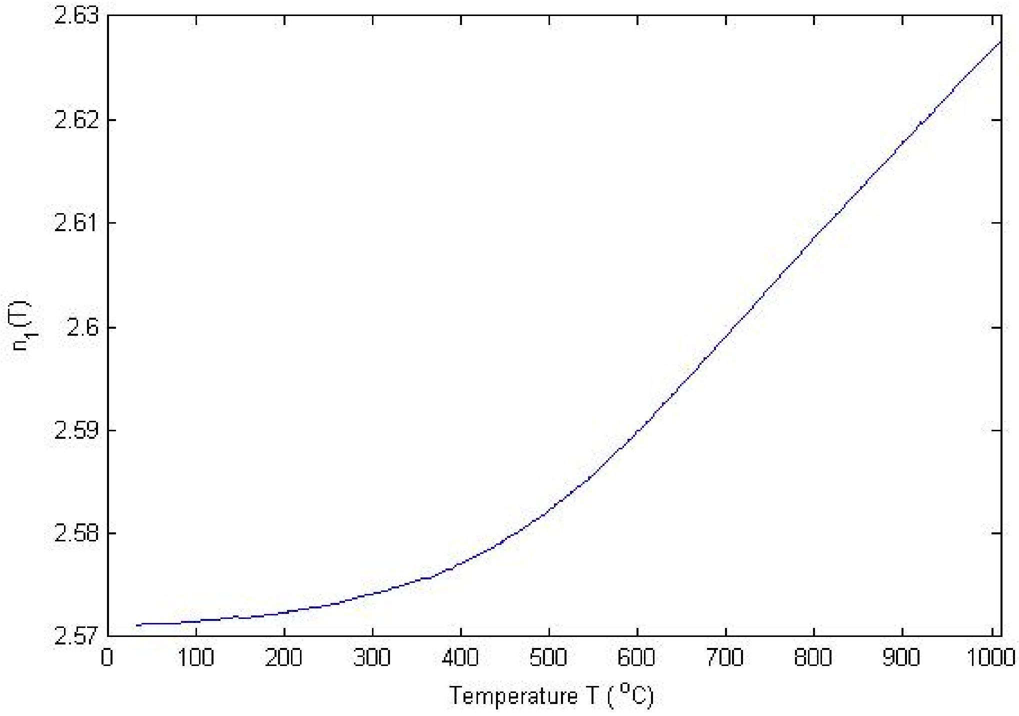


Unwrapped phase Δφ



Refractive index $n_1(T)$ calculation

Refractive index as a function of temperature, $n_1(T)$



Varies from 2.571 @ r.t. to 2.628 at 1000 °C

CONCLUSIONS

- New Signal Processing Technique Developed and Experimentally Proven

- Initial Optical Tests of SiC Chip Temporal Response and Alignment Achieved

- Initial Nuonics Probe and Basic Sensor Operations Test to 1000 °C Achieved

FUTURE WORK

-Completed First Year of 3-year Research Program

-Continue Advances in All-SiC Sensor Design Engineering and Testing Operations

Publications

-OFS 17, SPIE Proc. Vol. 5855, pp.687-690, Bruges, Belgium, May 2005.

-IEEE Sensors Journal, Vol.6, June 2006.

-AIP Journal of Applied Physics, Vol.98, 103512, 2005.

-OFS 18, OSA Conf. Proc., Oct. 2006.

-IEEE PTL Journal, Dec. 2006.

-SPIE Optical Engineering Journal, Jan 2007.

-IEEE Sensors International Conference Proc., Oct. 2007.

- Optics Letters Journal, May 2008.